Impact of relict rock glaciers on spring and stream flow of alpine watersheds: Examples of the Niedere Tauern Range, Eastern Alps (Austria)

Thomas WAGNER[1] *), Marcus PAURITSCH[1] & Gerfried WINKLER[1]

Institute of Earth Sciences, NAWI Graz Geocenter, University of Graz, Heinrichstrasse 26, 8010 Graz, Austria;

*) Corresponding author, thomas.wagner@uni-graz.at

Abstract

In crystalline mountain regions, relict rock glaciers are apparent sediment accumulations that likely influence the runoff in alpine watersheds as a result of their discharge behavior. However, little is known about their impact on the streamflow further downstream. More than 560 mostly relict rock glacier-related landforms have been identified in the Styrian part of the Niedere Tauern Range (Austria). The catchment of a single relict rock glacier (Schöneben Rock Glacier, SRG), and two catchments with relict rock glaciers in their headwaters were investigated with a simple lumped-parameter rainfall-runoff model. The model parameters of the SRG catchment are in agreement with the existing conceptual understanding of the discharge dynamics and provide the parameter configuration to simulate the runoff of ungauged relict rock glacier catchments in the area. In addition, a semi-distributed approach was applied to quantify the impact of relict rock glacier-influenced headwaters on the downstream runoff. The results suggest that the contribution ranges from about a quarter to more than four times its areal share. The highest impact is observed during the late snow melt period and in the late summer. This highlights the relevance of these sediment accumulations in relation to water management issues, in particular concerning altering meteorological conditions due to climate change.

Reliktische Blockgletscher sind augenscheinliche Sedimentanhäufungen in kristallinen Gebirgsregionen, die aufgrund ihrer Abflussdynamik die Entwässerung alpiner Einzugsgebiete beeinflussen. Jedoch ist ihre Auswirkung auf unterstromige Gerinne weitgehend unbekannt. Mehr als 560 meist reliktische Blockgletscher sind im Steirischen Anteil der Niederen Tauern (Österreich) ausgewiesen. Ein über einen reliktischen Blockgletscher (Schöneben Blockgletscher, SRG) entwässerndes Einzugsgebiet und zwei Einzugsgebiete, die ihrerseits reliktische Blockgletscher in ihren hoch gelegenen Anteilen beinhalten, wurden mit Hilfe eines einfachen, räumlich nicht aufgelösten (lumped Parameter) Niederschlags-Abflussmodells untersucht. Die Modellparameter des SRG-Einzugsgebiets stimmen mit dem vorliegenden konzeptionellen Modell überein und dienen als Grundlage der Parameterkonfiguration zur Abflusssimulation anderer Blockgletschereinzugsgebiete in der Region, für die keine Abflussdaten zur Verfügung stehen. Zusätzlich wurde ein semi-distributiver Ansatz angewendet, um den Einfluss von Blockgletscher beeinflussten Einzugsgebieten auf die unterstromigen Gerinne zu quantifizieren. Die Ergebnisse zeigen, dass der Abflussanteil unterstromig von einem Viertel bis zu mehr als dem Vierfachen des Flächenanteils der übergeordneten Einzugsgebiete beträgt. Die höchsten Anteile können gegen Ende der Schneeschmelze und im Spätsommer beobachtet werden. Dies unterstreicht die wasserwirtschaftliche Bedeutung dieser Schuttakkumulationen in alpinen Einzugsgebieten, vor allem unter der Berücksichtigung der sich ändernden meteorologischen Bedingungen im Zuge des Klimawandels.

1. Introduction

Runoff in alpine catchments is strongly affected by water stored in the form of snow and groundwater in the soil and sediment accumulations within the catchment. The influence of snow accumulation and melt is of obvious importance during winter base flows and the subsequent snow melt period, during which large increases in runoff are observable (e.g. López-Moreno and García-Ruiz, 2004). However, their role shifts as climate change progresses; air temperature might increase, periods of solid precipitation are reduced, and snow melt periods will begin earlier in the year (e.g. Barnett et al., 2005; Wagner et al., 2012). The impact of the soil on headwater runoff is usually low in alpine catchments, especially where bare rocks and scree slopes are predominant. Due to this, and the generally lower temperatures compared to valleys and

forelands, evapotranspiration rates are reduced. The hydrological importance of sediment accumulations, such as talus deposits, moraines or rock glaciers, was recently documented (Clow et al., 2003; Millar et al., 2013; Hood and Hayashi, 2015; Winkler et al., 2016b). The storage capacity of these sediments becomes especially noticeable during the summer and autumn months, during which, on the one hand, groundwater is stored during dry periods, and, on the other hand, a water buffer is provided for flood propagation triggered by local storm events. Numerous field observations during summer and autumn showed that springs at the base of relict rock glaciers still provide runoff when other springs have already fallen dry. This is important for the sensitive ecosystem in high alpine catchments. However, the actual observations have not

yet been quantified; especially not on a regional scale. Such an understanding is important for the sustainable use of water for human consumption and for small hydroelectric power plants.

Rock glaciers in general are common morphological features in the Alps (e.g. more than 4790 in the Austrian Alps, Kellerer-Pirklbauer et al., 2012; Krainer and Ribis, 2012) and thus also of great hydrological importance. Recently, knowledge on rock glaciers increased strongly, especially in the Austrian Alps. A state-of-the-art review of recent research related to permafrost in Austria is given in a special issue edited by Krainer et al. (2012). Rock glaciers in general are typical landforms indicating mountain permafrost conditions during their genesis and evolution and can be classified as intact (active and inactive) and relict ones. Active rock glaciers are frozen debris bodies with interstitial ice or ice lenses, gravitationally moving down-slope or down-valley, usually in the order of decimeters to a few meters per year (e.g. Barsch, 1996; Haeberli et al., 2006). Rock glaciers become inactive (but still intact) when movement comes to an end but ice is still present within the rock glacier. Rock glaciers are frequently characterized by distinct flow structures with ridges and furrows at the surface with some similarity to the surface of pahoehoe lava flows. The evolution of first intact, including active and inactive, and later relict rock glaciers is strongly affected by a shift of the lower limit of mountain permafrost and the subsequent disappearance of permafrost ice within the rock glaciers. Relict rock glaciers have a similar shape as intact ones but additionally show clear collapse structures because of the melted ice and the resulting loss of volume. Rock glaciers usually have a thickness in the order of several tens of meters. Monnier et al. (2011) and Monnier and Kinnard (2015) used ground penetrating radar to investigate two active rock glaciers in the French Alps and Chilean Andes. Their results suggest a heterogeneous, layered inner structure of the rock glacier which is in good agreement with the findings of Hausmann et al. (2012) at intact rock glaciers in the Austrian Alps based on surface geophysical investigation methods. Recently Krainer et al. (2015) investigated two drill cores of an active rock glacier in the Italian Alps which showed sequences of ice rich and unfrozen layers and also indicating a layering due to grain size variations. Recent investigations at a relict rock glacier (SRG, the rock glacier studied herein) in the Austrian Alps (Winkler et al., 2016b) also indicate a layered structure with coarse grained upper layer(s) and a fine grained bottom layer confirming first observations at a relict rock glacier in Poland (Zurawek, 2002, 2003). As such, the main feature of the internal structure of a rock glacier seems to be its layering differentiating relict rock glaciers from talus and moraines.

However, still relatively little is known on the hydrological behavior of rock glaciers and areas affected by alpine permafrost in general. Here, the focus is on the hydrology of relict rock glaciers, which are abundant in the Austrian Alps (more than 3000, Kellerer-Pirklbauer et al., 2012; Krainer and Ribis, 2012). To study the hydrology of relict rock glaciers is parti-

cularly important as it can be assumed that permafrost ice of intact rock glaciers is increasingly melting due to the climate change (global warming). A change from intact to relict rock glaciers might lead to a change in the hydraulic properties and drainage behavior of these landforms.

Therefore, the aim of this work is to investigate the impact of relict rock glaciers on the downstream flow using a simple lumped-parameter rainfall-runoff model. Model parameters are interpreted in terms of catchment characteristics; more specifically this study investigates if the sub-catchments containing larger areas of relict rock glaciers yield larger values of model parameters representing storage capacities. This may imply that sediment accumulations represent potential groundwater stores. Moreover, the use of the rainfall-runoff model in a simple semi-distributed manner explicitly accounts for the effects of sub-catchments influenced by rock glaciers and therefore permits separating their contribution from the total streamflow further downstream. This will help to understand the effects of such sediment accumulations for water management issues as well as flood risk assessment.

2. Study area

2.1 Geography and geology

The Styrian part of the Niedere Tauern Range (2440 km²) in the Eastern Alps (Austria) is the regional focus of this investigation (Figure 1a, b). Its subunits, from west to east, are the Schladminger Tauern, the Wölzer Tauern, the Rottenmanner Tauern, and the Seckauer Tauern Ranges (Figure 1a). The boundaries are formed by the Enns valley in the north, the Palten-Liesing valley in the east, the Mur valley in the south, and the upper Mur valley and the border to Salzburg in the west. About half of the area is above 1500 m a.s.l. and 11 % are above 2000 m a.s.l. (Figure 1a). The highest mountain is the Hochgolling with 2862 m a.s.l., in the Schladminger Tauern Range. Geologically, the Styrian part of the Niedere Tauern Range belongs to the Silvretta-Seckau and Koralpe-Wölz nappe system of the Upper Austroalpine subunit and its permo-mesozoic cover sequences. The Niedere Tauern Range mainly consits of various types of gneisses and mica schists (Schmid et al., 2004; Gasser et al., 2009). In the north, the upper rock unit is part of the Greywacke zone.

The data base for the identification of the rock glaciers was an inventory which is described in detail by Kellerer-Pirklbauer et al. (2012). The former inventory was based on a 10 m resolution digital elevation model (DEM), DEM-derived maps such as slope maps, orthophoto analysis and in many cases mapping campaigns. This inventory was modified manually by applying a 1 m resolution DEM based on air borne laser-scan data (ALS; provided by the GIS Service of the Federal Government of Styria; GIS Steiermark). The rock glaciers were identified by morphological features such as flow structures with ridges and furrows, rock glacier fronts and in the case of relict rock glaciers the occurrence of collapse structures (Winkler et al., 2016a).
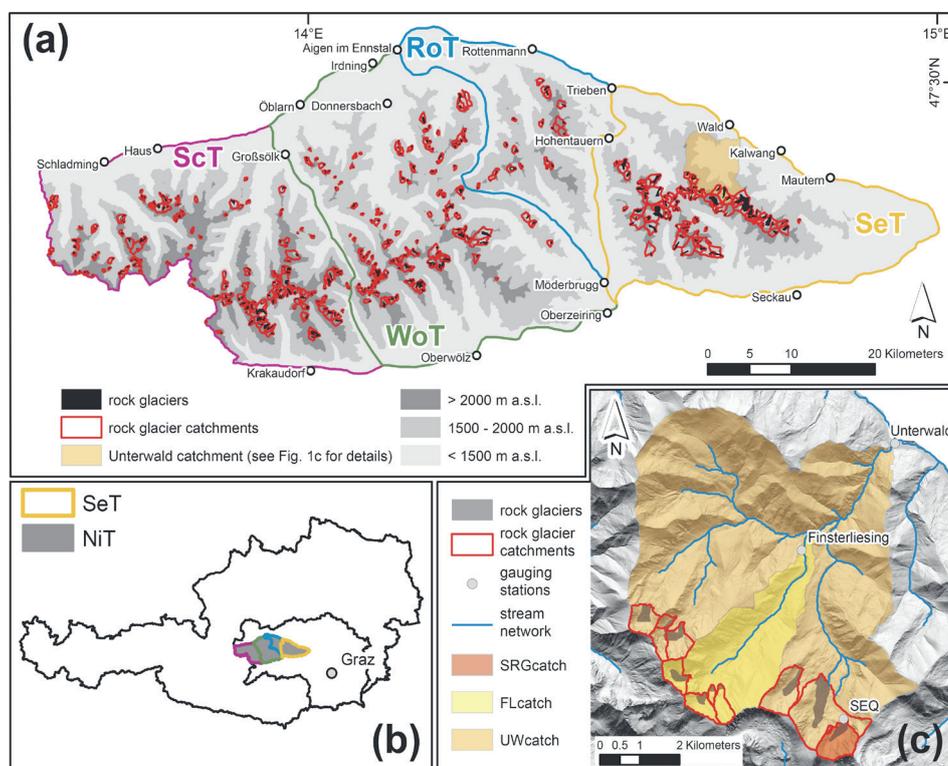
A total of 561 rock glacier-related landforms are distinguished in the area (Winkler et al., 2016a), of which only seven are likely to be still intact rock glaciers (all in the western part of the Niedere Tauern Range), while the remaining ones are relict. Approximately 12 % of the area above 1500 m a.s.l. and 27 % above 2000 m a.sl. are drained through rock glaciers. These percentages increase for the Seckauer Tauern Range (eastern-most subunit of the Niedere Tauern Range) to 22 % and 51 %, respectively (Winkler et al., 2016a). The glaciation of the last glacial maximum has affected the investigation area quite differently from west to east. This is also reflected in the distribution, size, and condition of the rock glaciers (Winkler et al., 2016a). In the west (the Schladminger Tauern Range) there are many smaller rock glaciers, including some presumably intact rock glaciers at high elevations (mean surface area: 0.43 km²; mean elevation: 2013 m). In the east (the Seckauer Tauern Range) rather large relict rock glaciers are dominant and extend down to lower elevations (mean surface area: 0.96 km²; mean elevation: 1832 m). In general, the Niedere Tauern Range is situated in the south of the Northern Calcareous Alps with annual precipitation between 1500-2000 mm/year. The primary weather influence (prevailing winds) is from the west and northwest. Additionally, low-pressure systems from the south can be significant. The prevailing mountain climate is characterized by snow accumulation in winter and a snow melt period in spring. In summer and autumn,

thunder storms might produce strong precipitation events.

In this paper, we focus on the Unterwald/Liesing catchment (UWcatch) in the Seckauer Tauern Range including the two sub-catchments of Finsterliesing (FLcatch) and Schöneben (SRGcatch) (Figure 1c).
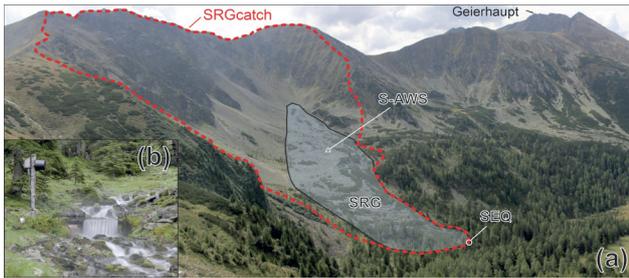
The rock glacier catchments have been delineated using the rock glacier boundaries, and based on a 1 m DEM (ALS data set) the contributing catchment has been extracted using standard ArcGIS hydrology tools. The investigated (sub-) catchments (UWcatch, FLcatch, SRGcatch) are influenced by relict rock glacier catchments to various degrees. Based on the areal coverage of the relict rock glacier catchments in relation to the whole catchment, the influence of these sub-catchments can be quantified by its proportion ranging from 12 % (UWcatch) to 100 % (SRGcatch). In the particular case of the SRGcatch, the catchment is drained completely via the rock glacier (its spring SEQ) and therefor the influence is 100 %. Flow dynamic and storage capacity of the SRGcatch are investigated in detail. The relict rock glacier itself covers about 16.5 % (~0.11 km²) of the catchment with a size of 0.67 km² (Table 1); 56.7 % of the catchment is made up of bare rocks and the remaining 26.8 % are covered by other debris accumulations with sparse vegetation (Figure 2).

SEQ basically shows a fast flow component reacting to precipitation/recharge events within a couple of hours (based on hydrograph analysis and natural tracer data). Additionally it shows a substantial slow flow component with a reaction time in the order of a few months (based on hydrograph analysis and artificial tracer tests) that provides the base flow in the winter months and during longer periods of no precipitation/recharge (Winkler et al., 2016b). A two-component separation of discharge based on electrical conductivity and isotope measrements, triggered by precipitation events, indicates an event water contribution in the order of 20 % in relation to older, longer stored water coming from the aquifer itself (Winkler et al., 2016b). These rather high contributions of pre-event water are in good agreement with observations in other low-order watersheds (e.g. Buttle, 1994; Kirchner, 2003). All this indicates potential buffer capabilities of this relict rock glacier that might be relevant for stream flow further downstream.

Figure 1: Investigation area, (a) overview of the Niedere Tauern Range (NiT) including its subunits, all identified rock glaciers, the related rock glacier catchments and the Unterwald catchment (UWcatch); ScT = Schladminger Tauern Range, WoT = Wölzer Tauern Range, RoT = Rottenmanner Tauern Range and SeT = Seckauer Tauern Range; (b) shows the study area within the Austrian and Styrian boundaries; Graz = capital of Styria; (c) details of the Unterwald (UWcatch), Finsterliesing (FLcatch) and Schöneben (SRGcatch) catchments including the areal extend of relict rock glaciers and their catchments.

Figure 2: The relict Schöneben Rock Glacier (SRG) and its catchment (SRGcatch). The spring (SEQ) and the weather station (S-AWS) are indicated. The highest mountain of the SeT, Geierhaupt (2417 m a.s.l.), is visible in the background; in the neighboring cirque, another relict rock glacier is recognizable. Viewpoint in a south-western direction from a nearby mountain where an automatic remote digital camera (S-RDC) is installed to take daily pictures of the snow cover of the area. The gauging station of SEQ a few meters downstream of the actual spring is shown in (modified after Winkler et al., 2016b).

2.1 Meteorological and hydrological data

The hydrological significance in the area is shown by displaying the long-term mean annual runoff from relict rock glacier-influenced catchments on the downstream stream network (Figure 3). A simple approach would take into account the areal ratio of the relict rock glacier catchments related to the whole catchments at a specific point along the stream network. However, as precipitation and temperature have certain altitudinal dependencies, computing relative runoff from relict rock glacier-influenced sub-catchments allows a more accurate consideration of headwaters and emphasizes their importance. Here, these effects are taken into account in the following way. The discharge (Q) based on the water balance neglecting storage changes was computed (Q = precipitation (P) – evapotranspiration (ETa)). This was estimated from the long-term precipitation and temperature data (1971-2000) obtained from the Climate Atlas Styria (Prettenthaler et al., 2010) on a 50 x 50 m grid provided by the federal state of Styria. The data set has been compiled from all available weather stations in Styria (including an elevation-correlation to consider altitudinal differences and wind-correction for precipitation). The simple temperature based empirical formula of Turc (Gray, 1970) to compute ETa and the formula of Oudin et al. (2005) used later in the rainfall-runoff model to compute potential evapotranspiration were applied herein. Both are designed to cope with limited data availability as is often the case in high alpine catchments. Simplicity in evapotranspiration formulas have been shown to be beneficial for efficient rainfall-runoff modelling (Oudin et al., 2005) and simple temperature based formulas outperformed more data demanding, complex approaches.

For example, the hydrological significance of relict rock glacier catchments on the total long-term runoff is displayed, when considering long-term average runoffs at the outflow of the Ingering creek towards the Mur valley. 24 % of the runoff consists of water draining relict rock glacier bodies (Figure 3). For the Liesing creek, 14 % of the long-term averaged runoff passes through relict rock glaciers; one of them being the

SRG. Values from the Hagen and Gaal creek are even higher. A large influence from the relative area of the rock glacier catchments on these values is obvious. Considering only the relative area, values of 21 % for the Ingering creek and 12 % for the Liesing creek are computed. Although these numbers are not very different, taking the altitudinal effect of precipitation and temperature into account, allows to more accurately consider the alpine headwaters (where relict rock glaciers are to be found). As this first analysis is only a long-term annual average, it is to be expected that seasonal or short term (daily) contributions might show considerable variations.
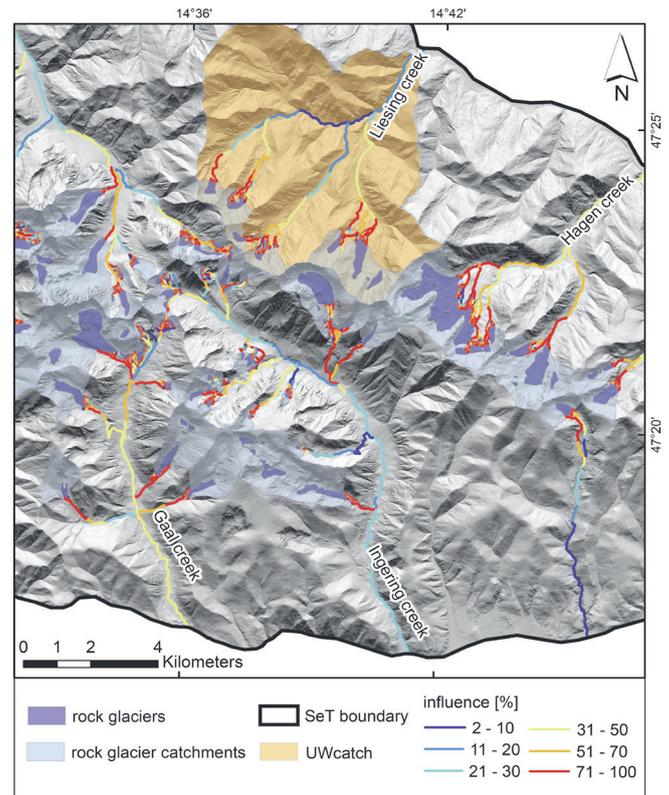
Figure 3: Runoff contribution map of the area: considering long-term runoff estimates based on a simple water balance (discharge (Q) = precipitation (P) – evapotranspiration (ETa)); the proportion (in %) of water draining relict rock glacier bodies are displayed along the downstream stream network approaching the main valleys. The Unterwald catchment (UWcatch) is highlighted in orange.

To be able to provide an analysis of higher temporal resolution, daily data has been investigated. On a daily time scale, the Schöner-ZAMG data set (Schöner and Dos Santos Cardoso, 2004) provides air temperature and precipitation data at a 1km horizontal resolution. It is based on all available meteorological stations of Austria and was used as consistent data input for the various catchments covering a time frame from 1948 to 2007. Moreover, the meteorological data of the weather station S-AWS, which was installed in 2011 directly in the SRGcatch (Figure 2; Winkler et al., 2016a,b), is used as the forcing input for simulating the Schöneben spring (SEQ) discharge. As these two data sets unfortunately do not over-

lap, a direct comparison is not possible. However, using both data sets as input to model the SRGcatch, similar resulting model parameter sets would indicate that both input data sets are consistent. It should be noted that microclimatic effects in mountainous catchments, such as local downpours and short temperature-induced snowmelt or accumulation periods, are not necessarily reflected in both data sets. The undercatch of precipitation measurements under windy conditions and solid precipitation leads to underestimation of precipitation (e.g. Sevruk et al., 2009; Wolff et al., 2015). However, visual snow cover data is available from an automatic remote digital camera (S-RDC) installed in 2011 at the opposite mountain ridge of the SRG, some 500 meters to the northeast at an elevation of 1960 m a.s.l. This information is used to check the physical relevance of the snow module used in the rainfall-runoff model.

The gauging station Schöneben spring (SEQ) belongs to the official spring network of the Hydrographic Service of Styria (HZB number 396762). Unterwald (UW) is also a current official station of the Hydrographic Service of Styria (HZB number 211821), whereas Finsterliesing (FL) is a former official station of the Hydrographic Service of Styria (HZB number HD 2600) that was abandoned in 2008 (Table 1). It should be noted that all three gauging stations are in an alpine setting where data acquisition is difficult and the limitations/errors of discharge measurements (relationship of water level measured at the weir and the discharge) should be kept in mind (e.g. Weijs et al., 2013).

3. Methods

A global, lumped-parameter conceptual rainfall-runoff model (Figure 4) is applied to the SRGcatch using the discharge time series of the spring and meteorological input data from the local weather station S-AWS and alternatively, from a gridded dataset with a 1 km resolution (Schöner-ZAMG data set; Schöner and Dos Santos Cardoso, 2004). A uniform spatial distribution of precipitation is assumed due to the relatively small size of the catchment. The main reason for applying this type of rainfall-runoff model is that data availability in alpine catchments is usually sparse, and temperature and precipi-

tation are the only forcing input parameters available for the area of interest. The simple models for snow accumulation and melt, as well as potential evapotranspiration, have their own limitations (e.g. Andréassian et al., 2004). None the less, this approach allows applying a consistent data set to a number of catchments of different sizes and locations. Moreover, ungauged (sub-) catchments with characteristics comparable to one for which discharge data are available can be analyzed using the parameter set of the calibrated and validated model for the gauged catchment (i.e. regionalization based on physical similarity; e.g. Oudin et al. 2008).

The calibrated and validated rainfall-runoff model is used to aid in aquifer and catchment characterization and further determine storage capabilities/components of the relict rock glacier and its adjacent debris accumulations. The remaining part of the catchment is of little interest for groundwater storage due to its steep slopes composed of bare rock with no obvious weathering zone and scarce vegetation (Figure 2).

After a detailed local study of the SRGcatch for which much additional data is available (Winkler et al., 2016b), a more regional approach is followed where the limits of data availability in alpine catchments is more of a concern. The rainfall-runoff model is applied to the FLcatch and the UWcatch where streamflow is influenced only to some extent by relict rock glaciers in the headwaters (see Figure 1c). The storage parameters of the rainfall-runoff model are then related to catchment characteristics and especially the importance of relict rock glaciers is investigated. Moreover, the model parameter set of the SRGcatch can be applied to the relict rock glacier-influenced parts of the catchments FLcatch and UWcatch in a simple semi-distributed approach. On the one hand, this allows comparing the parameter sets of the lumped approach to the one with the semi-distributed. On the other hand, the direct influence of the relict rock glacier catchments on the downstream sections (at the gauging stations) can be analyzed. As such, the percentage of runoff can be analyzed in more detail as compared to the long-term annual average of the runoff contribution map (Figure 3). In addition to the mean influence of runoff from rock glacier-influenced sub-catchments, the daily and seasonal impacts can be identified.

gauging station	stream	HZB number	area	avg height	relief factor	area RG		area RGcatch		available Q time series
			[km²]	[m]	[m]	[km²]	[%]	[km²]	[%]	
SEQ	Schöneben creek	396762	0.67	2005.8	580.0	0.11	16.56	0.67	100.00	07/2002 – 08/2014
FL	Finster-liesing	- (HD 2600)	7.26	1715.0	1277.2	0.17	2.36	1.07	14.78	01/1998 – 04/2008
UW	Liesing creek	211821	44.10	1521.1	1598.4	1.02	2.31	5.31	12.05	01/1989 – 12/2009

Table 1: Gauging stations Unterwald (UW), Finsterliesing (FL) and Schöneben Rock Glacier spring (SEQ), their related catchment characteristics and the available discharge (Q) time series. Area = total catchment area; avg height = the average elevation of the total catchment; relief factor = difference between maximum and minimum elevation of the catchment; area RG = areal extent of relict rock glaciers within the catchment; area RGcatch = areal extend of the catchments that are drained through rock glaciers (extracted using standard ArcGIS hydrology tools).

Thus, and due to existing data limitations, such simple rainfall-runoff models are important hydrological modelling tools.
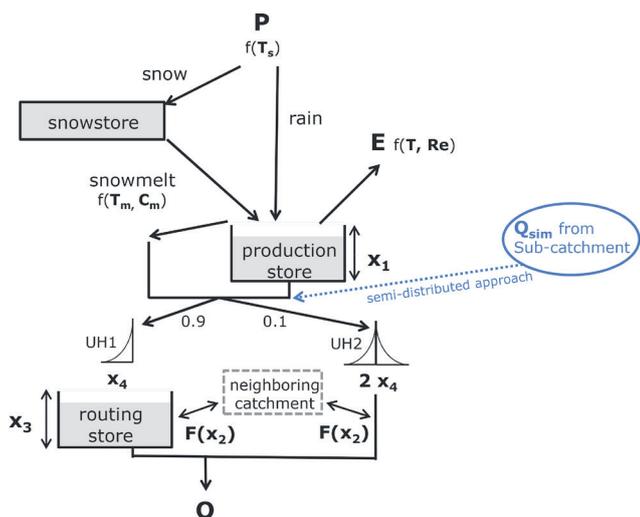
3.1 Lumped-parameter rainfall-runoff model

The simple rainfall-runoff model GR4J of Perrin et al. (2003) with a daily time step was applied and extended using a snow module based on Majone et al. (2010) and the computation of potential evapotranspiration proposed by Oudin et al. (2005). In the study of Perrin et al. (2003), 429 catchments were simulated for developing the GR4J model. These catchments show a great range of climatic conditions from semi-arid via temperate to tropically humid extending over flat as well as mountainous regions. However, no high alpine catchments were analyzed. Catchment areas range from 0.1 to 9890 km², and mean annual precipitation ranges from 300 to 2300 mm. The model has 4 parameters that are free to be calibrated (the symbols are kept as introduced by Perrin et al. (2003) for comparability): x_1 (the maximum capacity of the production or soil moisture accounting store in mm); x_2 (a water exchange coefficient in units of mm that can be positive if water enters the catchment, negative if water exits the catchment unobserved, or zero if there is no water exchange); x_3 (the maximum capacity of the routing store in mm) and x_4 (a time parameter expressed in units of days). The time parameter x_4 is applied for the unit hydrographs UH1 and UH2 that are used to simulate the time lag between a rainfall event and the resulting stream flow. For UH1 the water is distributed over a number of days (smallest integer exceeding x_4) with its maximum at the last day of the hydrograph. For UH2 the water is distributed over a time period about twice the number of days of UH1 (smallest integer exceeding $2* x_4$). The peak outflow is reached at a similar time as the peak for UH1, then the water outflow decreases to zero at the end. The remaining parameters of the model have been found to be of minor importance on the model performance and have been kept constant in the GR4J by Perrin et al. (2003). For example the time lag for the direct runoff unit hydrograph (UH2) has been fixed to be twice the time lag of the unit hydrograph supplying the routing store (UH1). This is understandable, as it causes both unit hydrographs to have their peaks at (nearly) identical times. Moreover, a fixed 1:9 split of a direct and a slower flow component that passes the routing store has been introduced by Perrin et al. (2003). To support the findings of these authors, the influence of the latter on the model performance was investigated by incorporating this ratio as a free parameter. As a result, the approach of Perrin et al. (2003) was followed and analogous to them the parameters were kept constant here as well. Although solid precipitation is observed in some of the 429 catchments, no snow accumulation and melt was explicitly considered in the GR4J. However, as solid precipitation plays an obvious role in alpine catchments, a snow module was added using the simple degree-day snow module proposed by Majone et al. (2010) where only air temperature is required (adding three free parameters, T_s = temperature at which snow starts to fall; T_m = temperature at which snow starts to

melt; C_m = melt factor that allows a certain amount of snow melt per degree temperature increase). In addition the GR4J requires potential evapotranspiration as model input which was determined by using a simple temperature dependent approach proposed by Oudin et al. (2005). This approach was already successfully applied in a modified monthly based version of the GR4J by Wagner et al. (2013) for a complex karst catchment in an alpine region. They could show that changes in the discharge characteristics after a flood event were only reproducible if parameters of the model were adapted. As such, the changes in storage capabilities of the rainfall-runoff model could be related to changes in the functionality of the karst system. It is noteworthy that e.g. Perrin et al. (2003), Mouelhi et al. (2006) and Wagner et al. (2013) pointed out that parameters in such simple models have physical relevance although their values are not comparable to field measurements (e.g. soil thickness).

In the following, we will call the model with its extensions GR4J+. Here, the impact of relict rock glaciers should become noticeable through applying GR4J+ to the catchments of the Seckauer Tauern Range if these landforms represent effective buffers/storage components within alpine watersheds. Moreover, a simple semi-distributed model approach is also applied. The discharge from all the rock glacier-influenced headwaters within the catchments FLcatch and UWcatch is computed separately with the GR4J+ using the modeled parameter set of the SRGcatch. The simulated runoff is then added as an external input (after the production store; Figure 4) to the remaining catchments FLcatch and UWcatch (without the rock glacier sub-catchments). In the following, this approach will be called GR4J+sd. As such, the remaining part of the catchment can be calibrated and validated without considering the relict rock glacier-influenced headwaters.

The model basically solves a water balance equation and common problems related thereto are to be expected (e.g. Uhlenbrook, 2006). Calibration and validation of the model is done by a split sample test (Klemes, 1986) using a combination of the classic Nash-Sutcliffe efficiency criterion (Nash and Sutcliffe, 1970) and the modified Nash-Sutcliffe criteria based on log-transformed and square root-transformed discharges (see Wagner et al., 2013). The classic Nash-Sutcliffe criteria places weight on high flows; the Nash-Sutcliffe efficiency criterion based on square root transformed streamflow places weight on low flow simulations and the third places weight on the intermediate flow (Perrin et al., 2003). All three criteria are computed separately, summed up and divided by 3 to remain within the criteria range (-infinity to 100 %) of the classical Nash-Sutcliffe criteria. We will call this combination $\overline{\text{NSE}}$. To assure that the model is not "right for the wrong reason" (Kirchner, 2006), the model is calibrated/validated and the results of the SRGcatch (the values of the parameter sets) are compared to supplementary information from field work (soil and vegetation cover; geomorphological mapping, surface geophysics, tracer tests, etc.) at the SRGcatch (e.g. Winkler et al., 2016a,b). Although model parameters cannot be estima-

Figure 4: Model structure of the applied lumped-parameter rainfall-runoff model: GR4J+ = GR4J (Perrin et al., 2003) + snow module based on Majone et al. (2010) + potential evapotranspiration computation using the formula suggested by Oudin et al. (2005). Note the location where the simulated runoff from a sub-catchment (or sub-catchments) is added to the model if a simple semi-distributed approach is applied (GR4J+sd). P = precipitation; T = air temperature; T_s = temperature at which snow starts to fall; T_m = temperature at which snow starts to melt; C_m = melt factor that allows a certain amount of snow melt per degree temperature increase; Re = extraterrestrial solar radiation; x_1 = maximum capacity of the production store; F = groundwater exchange term acting on the fast and slow flow components; x_2 = water exchange coefficient; x_3 = maximum capacity of the routing store; x_4 = time parameter; UH1 and UH2 = unit hydrographs to account for the time lag between rainfall and resulting streamflow that depend on the time parameter x_4; Q_{sim} from sub-catchment = external input of runoff from a separately modelled sub-catchment; Q = runoff simulated by the rainfall-runoff model.

ted by field measurements directly (e.g. Mouelhi et al., 2006; Wagner et al., 2013), they do in fact have a physical relevance and a rational interpretation of the model output compared to field data is advised. If for example a catchment is composed of mainly bare rocks (like the SRGcatch) and the model would suggest a large value of x_1, which can be interpreted as the maximum capacity of a soil moisture accounting store (Perrin et al., 2003), the field data would simply question the model output/plausibility.

Rainfall and/or snowmelt (from the snow store) reach the production store (or soil moisture accounting store) with a maximum capacity x_1. A small amount of water percolates from this reservoir depending on the maximum capacity and the actual water level in the reservoir. This percolation is mainly interesting for low flow simulations. The actual evapotranspiration is computed based on the water content in the store relative to the maximum capacity x_1 and the potential evapotranspiration based on Oudin et al. (2005). If the maximum capacity of the store is reached, an outflow is generated. This is followed by a fixed separation of 1:9 where 10 % of the water goes to a unit hydrograph with a certain time lag (twice x_4 as fixed in the GR4J model of Perrin et al., 2003) representing direct runoff. The remaining 90 % of the water are distributed via

a unit hydrograph with a time lag of x_4 that finally passes through a non-linear routing store of maximum capacity x_3. The routing store is draining according to the maximum capacity and the water level in the reservoir at each time step (Figure 4). As mentioned before, the fixed split of 1:9 is an outcome of the GR4J model development (see Perrin et al., 2003 and references therein). Nevertheless, various other fixed splits have been tested (e.g. 2:8, 3:7 and 0:10). Moreover, this split has been introduced as an additional free to be calibrated parameter. These results support the findings of Perrin et al. (2003), as this fixed split of 1:9 yielded the best model fit. Model runs including the split as an additional free parameter resulted in splits close to 1:9 (e.g. 0.7:9.3 or 1.1:8.9). However the model fit did not improve substantially to justify this additional parameter (as reported in Perrin et al., 2003). Importantly, the calibration of this split gave similar x_1 and x_3 compared to the fixed split of 1:9. If other fixed splits are used (2:8 and 3:7), x_1 and x_3 are consequently also slightly different; but the overall conclusion related to the relative values of the routing and production stores of the individual catchments remains unchanged (not shown here). As such, within the examined range, the influence of this split has only a minor influence on the actual storage parameters of the model, which are the main focus of our analysis as discussed later.

The unit hydrographs are used to simulate a time lag between rainfall events and resulting streamflow peaks by spreading effective rainfall over successive time steps (Perrin et al., 2003). The time parameter (x_4 for UH1 and twice x_4 for UH2) defines the time period of the unit hydrographs, i.e. the number of days the water is distributed over time to simulate peak flows. The smallest integers exceeding x_4 and $2*x_4$ define the number of unit hydrograph inputs for UH1 and UH2, respectively. The ordinates of the unit hydrographs are then derived from cumulative proportions of the input with time (S-curve method), thereby influencing the shape of the unit hydrographs and affecting the proportion of water distributed over the time period (for details see eq. 9-17 in Perrin et al., 2003). The non-linear routing store based on a power law is able to simulate long streamflow recessions, as the outflow reduces to very low values as the reservoir content relative to its maximum capacity declines over time (see eq. 20 in Perrin et al., 2003).

Moreover, based on the water level in the routing store, a groundwater exchange term is computed based on a water exchange coefficient x_2 and the reservoir content. This groundwater exchange term is computed for both flow components, the direct runoff and the one via the routing store. The total stream (or spring) flow is the output of the routing store and the direct runoff including (or subtracting) the exchange components. All four parameters in the model (x_1-x_4) are real numbers, where x_1 and x_3 are positive [mm]; x_2 [mm] can be zero, negative (outflow) or positive (inflow) and x_4 is greater than 0.5 [day]. Obviously, allowing more parameters to be calibrated, a model might yield a better fit; however as Perrin et al. (2003) could show, a simple model structure has to

be favored in order to avoid overparametrization of the model while still getting valuable information from model parameters about the catchment and its physical characteristics (e.g. Mouelhi et al., 2006; Wagner et al., 2013).

4. Results

4.1 Local scale – SRGcatch

The SRGcatch is simulated (calibrated and validated) using GR4J+ and the discharge data at the SEQ gauging station. The model yields acceptable model fits, which is demonstrated in Figure 5 by comparing observed and simulated runoff (spring discharge). The $\overline{NSE}$ values are given in Table 2 for calibration and validation periods. The available time series (see Table 1) were split into two equal parts (excluding a warm-up period);

which were then used each for calibration and validation applying a simple split test according to Klemes (1986).

The GR4J+ and its optimal (based on $\overline{NSE}$) parameters found for the two input data sets (S-AWS and Schöner-ZAMG data sets) are compared to the median values of the study of Perrin et al. (2003) and discussed in the following (Table 3). First of all, the model allows observing the influence of solid precipitation in an alpine catchment. The model results of the snow accumulation and melt are compared to visual data available from a remote camera (S-RDC) that takes pictures of the catchment once a day. Although no quantitative information is possible, obvious snow cover changes correlate with changes in the snow accumulation of the snow module of the GR4J+ and support its functional efficiency (Figure 6). Subsequently, the storage of water from rainfall and/or snowmelt in the catchment is accomplished by a production and a routing store. Based on model calibration and validation, x_1 is rather small and seems to play a subordinate role, whereas x_3 is relatively large (especially compared to the median value from the study of Perrin et al. (2003)). Interestingly, x_4 is short and x_2 is positive, indicating that some additional water is necessary to satisfy the water balance. This deficit is especially noticeable when the S-AWS weather station data is used. This can likely be attributed to an underestimate of precipitation, especially during winter when wind and solid precipitation complicate the measurement in alpine catchments (e.g. Sevruk et al., 2009). Additional snow is deposited by the wind due to the northeast exposition of the cirque and a preferential western wind direction. Inflow into the catchment from a neighboring catchment can be excluded based on the geological settings. The short x_4 might be explained by a vadose zone that is passed rather quickly; which is consistent with the fast flow component identified by Winkler et al. (2016b). The small x_1 is related to the rather sparsely vegetated catchment with little to no soil. The rather

(a)

(b)
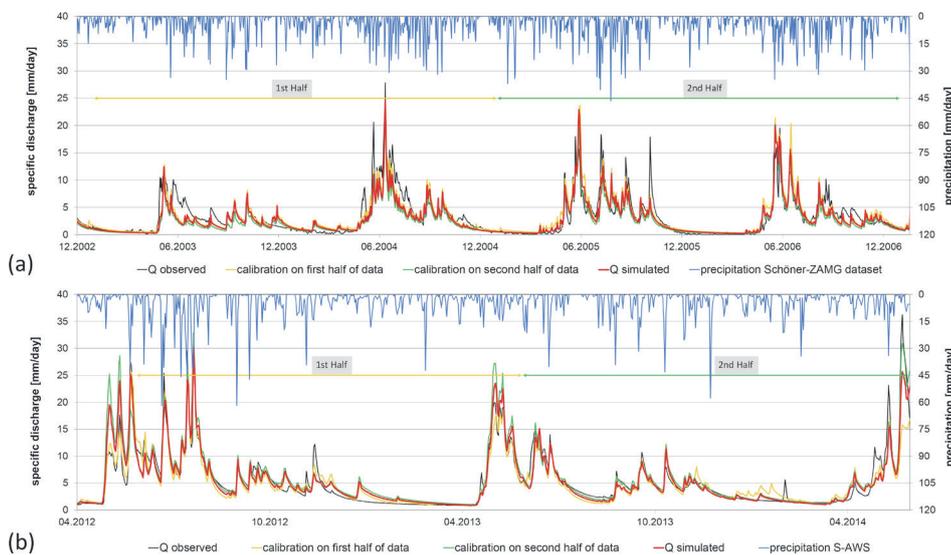
Figure 5: Comparison of observed and simulated runoff of SEQ using the GR4J+. Observed discharge is compared to simulated discharge based on calibration of different parts of the data (complete data set, first and second half) and the related validation is shown. For the time period 2002-2007, the forcing input (precipitation and air temperature) is based on the Schöner-ZAMG dataset (a); for the time period 2012-2014, the data from the S-AWS weather station is used (b).

efficiency criteria $\overline{NSE}$	complete time series		first half of data set		second half of data set	
	SchönerDS	S-AWS	SchönerDS	S-AWS	SchönerDS	S-AWS
calibration on total time series	**78.60**	**89.47**	75.89	90.73	80.05	87.41
calibration on first half of data set	74.36	84.81	**77.86**	**92.31**	71.23	73.02
calibration on second half of data set	76.20	87.50	68.82	86.02	**80.75**	**89.62**

Table 2: $\overline{NSE}$ values for calibration and validation of the first and second half of the data, respectively, and vice versa, as well as calibration of the whole time series (excluding a warm-up period; see Figure 5). Bold values are the calibration values, other values are related to the validation periods. For the time period 2002-2007, the forcing input (precipitation and airtemperature) is based on the Schöner-ZAMG dataset (SchönerDS); for the time period 2012-2014, the data directly from the S-AWS weather station is used.
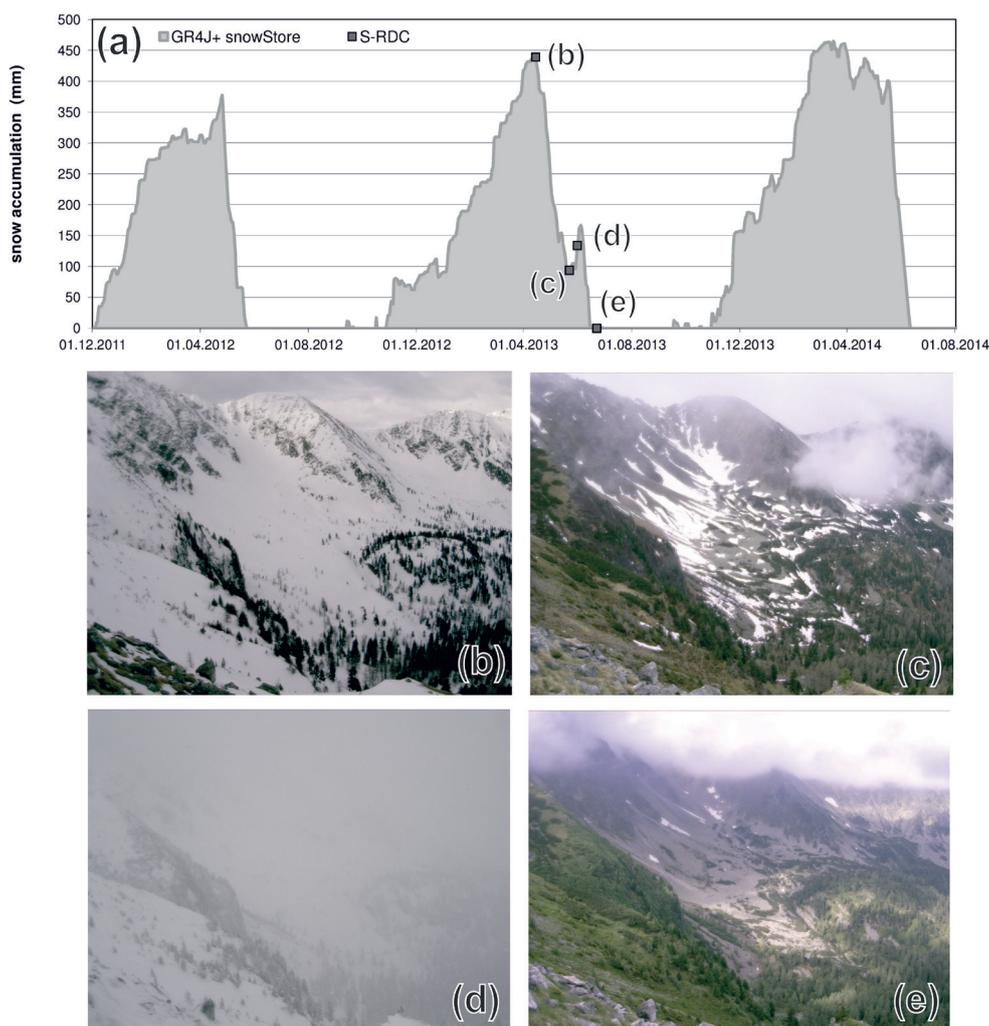
Figure 6: Comparison of snow model results and observed snow cover. (a) Modeled snow accumulation for the SRGcatch. Note the snow melt periods especially in May and June. (b-e) Extend of snow cover based on pictures of the S-RDC correlate well with the modelled snow accumulation and melt as indicated by exemplary photos related to certain time periods indicated in (a).

large x_3 indicates a substantial groundwater storage component. This is likely due to the debris accumulations of the relict rock glacier and the surrounding scree slopes, as there is not much storage in the fractured rock itself and a thick weathering zone is absent. Considering only these debris accumulations, the actual storage capacity can be assumed to be even higher, as the areal cover of the relict rock glacier makes up only 16.5 % of the total catchment while other debris accumulations cover 26.8 %. The actual volume of the sediment body representing the relict rock glacier is interestingly large with a maximum sediment thickness of more than 60 m (Winkler et al., 2016b). However, the actual storage is represented by the thickness of the saturated layer (e.g. Muir et al., 2011). Winkler et al. (2016b) suggested that the lowest 10 to 15 m are supposedly build up by finer grained sediments that act as the main aquifer. The overlaying layers seem to be

		S-AWS	Schöner/ZAMG dataset				Perrin et al. (2003)
		SRGcatch	SRGcatch	UW-fullyLump	UW-semiDistr	FL-fullyLump	FL-semiDistr	median (80 % conf. intervall)
efficiency criteria	$\overline{NSE}$ (%)	89.47	78.6	63.97	64.28	72.42	73.13	56.8
	$\overline{NSE}Q$ (%)	89.5	76.32	59.98	60.34	64.59	65.74	51
	$\overline{NSE}\sqrt{Q}$ (%)	90.1	81.41	64.7	64.98	74.42	74.89	61.9
	$\overline{NSE}\log Q$ (%)	88.79	78.07	67.24	67.53	78.26	78.74	57.5
	WB (%)	97.58	90.58	97.5	98.45	96.51	96.64	79
model parameters	x_1 (mm)	89.78	14.55	1317.37	1513.38	490.26	568.46	350 (100 to 1200)
	x_2 (mm)	9.4	2.3	-0.02	0.01	-0.65	-1.03	0 (-5 to 3)
	x_3 (mm)	302.82	487.78	314.12	343.53	673.63	503.74	90 (20 to 300)
	x_4 (days)	1.15	1.33	1.26	1.43	1.65	1.41	1.7 (1.1 to 2.9)
	T_s (°C)	2.56	1.05	1.59	1.75	1.95	1.54	-
	T_m (°C)	4.61	4.1	4.18	3.5	3.4	4.08	-
	C_m (mm/°C)	3.65	3.32	2.45	1.86	2.54	2.72	-

Table 3: Model parameters and efficiency criteria (average, classical, square root-transformed and log-transformed Nash-Sutcliffe efficiency criteria, WB = water balance criterion) of the GR4J+ of the SRGcatch using the S-AWS and the Schöner-ZAMG data sets as forcing input and published median values (and 80 % confidence intervals) of the study of Perrin et al. (2003). Moreover, the model parameters and efficiency criteria of the UWcatch and the FLcatch using the GR4J+ and the GR4J+sd are displayed. WB = sum of the modelled runoff divided by the sum of the observed runoff in percent; values below 100 % indicate an underestimation of the modelled runoff, values above 100 % an overestimation.

unsaturated based on geophysical surveys (seismic refraction and ground penetrating radar; Winkler et al., 2016a,b).

The rainfall-runoff model, however, does not allow for direct identification of storage components or any hydraulic parameters. Nevertheless, a comparison of different catchments and/or sub catchments allows drawing conclusions regarding the relative importance of individual components. Compared to average parameter values from the study of Perrin et al. (2003), it is noteworthy that x_3 is rather large and x_1 rather small (Table 3). How this translates to the UWcatch and the FLcatch and the effect of relict rock glacier-influenced headwaters will be discussed later.

For the SRGcatch, it can be concluded that the GR4J+ is able to reproduce the observed runoff using both the S-AWS weather station data as well as the Schöner-ZAMG data set. Moreover, the model aids in aquifer characterization (i.e. it supports the findings of Winkler et al., 2016b). In general, the SRGcatch indicates a relatively large routing store and a rather small production store, in combination with a rather short time lag (within the vadoze zone). This might be representative for an alpine setting where relict rock glaciers and related screes are dominant.

4.2 A more regional scale – the influence of rock glaciers on downstream river flow

For the regional analysis, the forcing input parameters are extracted from the Schöner-ZAMG dataset as no meteorological data are available for the investigated catchments (besides S-AWS). For the larger catchments (FLcatch and UWcatch) it was aimed to quantify the influence of the rock glaciers in the individual catchments. In other words, is the signal of the large routing store (high storage capacities) of the SRGcatch still observable in the catchments FLcatch and UWcatch? Moreover, what is the actual contribution of the relict rock glacier sub-catchments to the total runoff of the two catchments at discrete time steps?

Table 3 shows the efficiency criteria of the model for the three different gauging stations SEQ (considering SRGcatch), FL and UW. Moreover, the hydrographs of observed versus simulated discharge (calibration and validation) of FL (7.26 km²) and UW (Liesing creek, 44.1 km²) are presented in Figure 7.

Figure 8 shows an overview of the storage parameters x_1 and x_3 of the GR4J+ of the three catchments and the relation to the fraction of rock glacier area, rock glacier-influenced catchment area, and scree area. Moreover, the median values and the 80 % confidence interval from the study of Perrin et al. (2003) are displayed. For the SRGcatch, x_1 is almost not noticeable at this scale (for values see Table 3). x_3 for the SRGcatch is additionally shown as area-corrected values, where it is assumed that the possible storage is reduced to the area of the rock glacier itself or the area of the rock glacier and the adjacent scree deposits. Moreover, for the UWcatch and the FLcatch, the storage parameters are shown
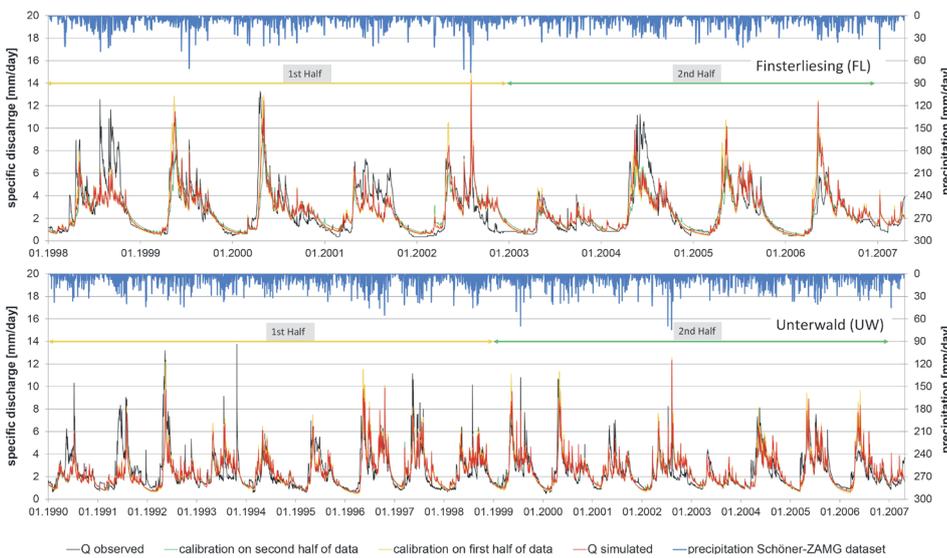
Figure 7: Observed and simulated runoffs of FL and UW using GR4J+. Observed discharge is compared to simulated discharge based on calibration on different parts of the data and the related validation is shown.
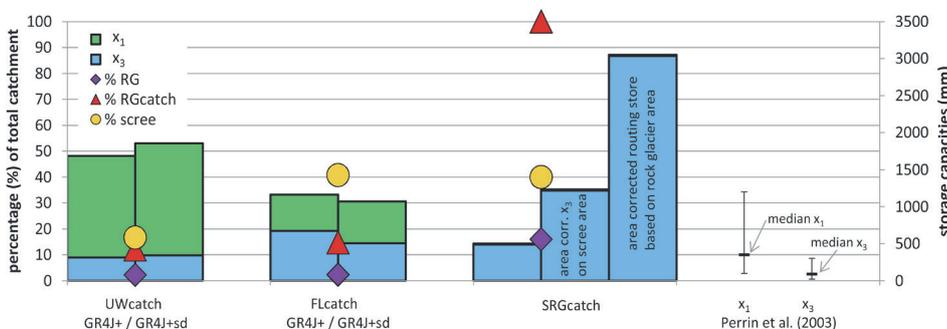
Figure 8: Graphical representation of the storage parameters x_1 and x_3 of the individual catchments considered in GR4J+ and GR4J+sd for the UWcatch and the FLcatch and in GR4J+ for the SRGcatch in comparison to the median parameters and the 80 % confidence interval from the study of Perrin et al. (2003). Moreover, SRGcatch additionally shows area-corrected values, with the possible storage reduced to the area of the rock glacier itself, and to the area of the rock glacier including the adjacent scree deposits (area corr. x_3 on scree area). Additionally, the fraction of rock glacier area (RG), rock glacier influenced catchment area (RGcatch), and scree area compared to the catchment area is displayed.

for the GR4J+ approach and for an extended semi-distributed approach (discussed in the next section).

Comparing model parameters of the GR4J+ approach with catchment characteristics shows that x_1 plays the most important role in the UWcatch. However, x_3 is also still above the median values of the study of Perrin et al. (2003) in this catchment. For the FLcatch, x_3 is more dominant than x_1, and both values are above the median of Perrin et al. (2003). For the SRGcatch, x_1 is almost negligible, while x_3 is relatively large. As much of the actual catchment is composed of bare rocks and steep cliffs, a more realistic area is used for the routing store by assuming that the contributing area where storage might take place is not the whole catchment area but is only related to the relict rock glacier area itself (area corrected routing store based on rock glacier area in Figure 8), or the area of the relict rock glacier and the adjacent scree deposits (area corr. x_3 on scree area in Figure 8). Because of the smaller considered area, the capacity of the store increases accordingly.

The simple internal model structure applied for the larger catchments is on the one hand suitable to simulate the runoff (operational mode: simulated flow acceptably agrees with observed data; Table 3), but might be too simple (not enough parameters/stores) to really reproduce the actual processes in the real catchment (principle of equifinality, e.g., Beven, 1993, 2006). However, the relatively large values of x_3 for the UWcatch and the FLcatch (Figure 8) indicate some storage component that might be related to the relict rock glacier-influenced sub-catchments (and/or other debris accumulations). However, based on these three catchments, increasing x_3 of the rainfall-runoff model seems to go hand in hand with increasing areal coverage of relict rock glaciers and/or debris accumulations within a catchment besides an obvious correlation of decreasing x_1 with increasing areal coverage of sparsely vegetated debris accumulations and bare rocks.

To elaborate on this, a semi-distributed approach was applied (GR4J+sd). The relict rock glacier-influenced parts of the UWcatch and the FLcatch are simulated separately and added to the UWcatch and the FLcatch as an external source

(after the production store; see Figure 4). Therefore, the forcing input parameters of the catchments are computed only for the areas that are not influenced by the relict rock glaciers (6.2 km² and 38.7 km² for the FLcatch and the UWcatch, respectively). Table 3 compares the model fits as well as the resulting parameter sets of the UWcatch and the FLcatch using the fully lumped and the semi-distributed approach. Figure 9 compares the simulated hydrographs based on these two approaches.

Interestingly, for the semi-distributed approach, a relatively large x_3 is still needed to simulate the observed discharge accordingly for both catchments, although the influence of the relict rock glaciers is considered separately. For the FLcatch, x_3 decreases while x_1 increases. The semi-distributed approach suggests a small increase in both storage parameters of the UWcatch. However, the explicit consideration of the relict rock glaciers using GR4J+sd does not really change the storage capacities of the individual stores for both catchments. This leads to the conclusion that although the relict rock glaciers play a role in deferring the runoff, other storage components are also active and important in the UWcatch and the FLcatch. These storages are likely to be related to moraine materials and other scree deposits present in the catchments. Unfortu-
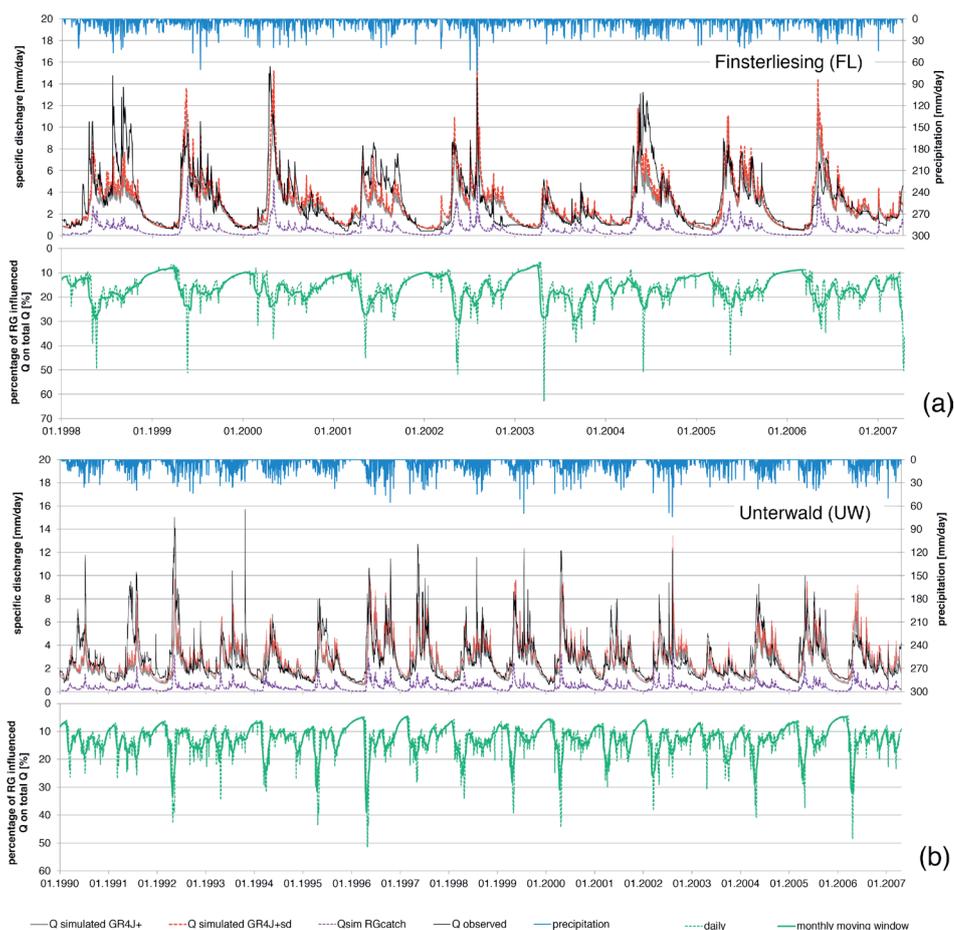
Figure 9: Observed and simulated runoff of Finsterliesing (FL) (a) and Unterwald (UW) (b) gauging stations. Simulated runoff based on the semi-distributed (GR4J+sd) and the fully lumped (GR4J+) approach and the simulated runoff from the respective rock glacier-influenced headwaters (Qsim RGcatch) is shown. In addition, the percentage of relict rock glacier (RG)-influenced headwater-runoff compared to the total runoff on a daily basis and using a one month moving window is displayed.
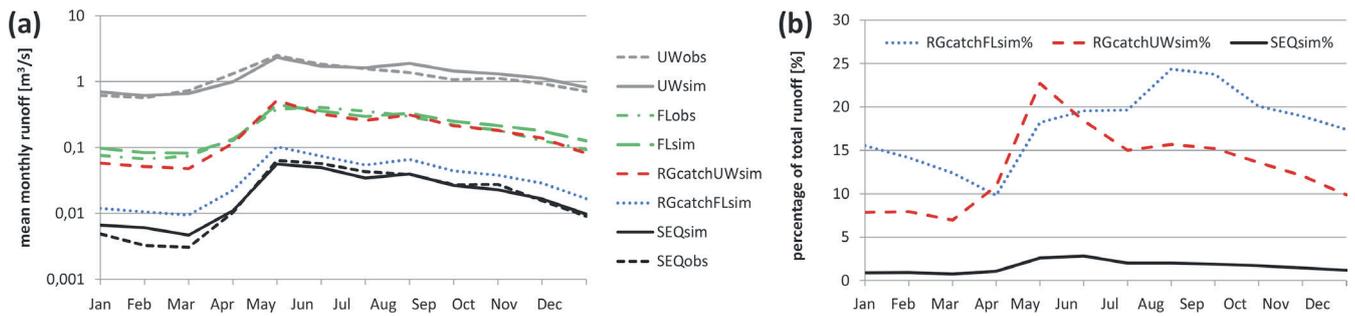
Figure10: Seasonal runoff contributions. (a) Seasonal mean monthly runoff for the time period 06/2002-04/2007 for the three gauging stations UW, FL and SEQ (observed = obs; simulated = sim), and the simulated runoff from the rock glacier-influenced headwaters within the FLcatch (RGcatchFLsim) and the UWcatch (RGcatchUWsim). (b) Percentage of simulated runoff from the relict rock glacier-influenced headwaters within the FLcatch (RGcatchFLsim %) and the UWcatch (RGcatchUWsim %) and the percentage of runoff from the SRGcatch at the SEQ gauging station within the UWcatch (SEQsim %).

nately, little is known about their storage capabilities in these particular catchments and further research is needed.

In addition to the contribution of rock glacier-influenced headwaters on the total runoff of the FLcatch and the UWcatch on a daily basis (Figure 9), Figure 10 shows the rock glacier-influenced headwater runoff versus the total runoff of the FLcatch and the UWcatch as monthly averages. Interestingly, the contribution of rock glacier influenced headwaters seems to play only a minor role during winter base flows. However, their contribution in the late snow melt period and during summer months is rather high. Based on these simulations, the average annual contribution of relict rock glacier-influenced headwaters on the FLcatch and the UWcatch is about 16 % and 13 %, respectively (note that this is slightly above the areal share, see Table 1). On a monthly average (see Figure 10b), the lowest values are in April for the FLcatch (10 %) and in March for the UWcatch (7 %) and the highest values in August (24 %) and May (23 %), respectively. On a daily basis (see Figure 9), the variation increases and ranges from about a quarter to more than four times of the areal share (runoff contribution of 6 % to 63 % for the FLcatch and 4 % to 52 % for the UWcatch compared to an areal share of 15 % and 12 %, respectively).

5. Discussion

Water resources studies in the 1990s already recognized the significance of relict rock glacier springs for the water supply for human consumption and the ecosystem in the Niedere Tauern Range (Untersweg and Schwendt 1995, 1996). The detailed understanding of the hydrogeological system/structure of relict rock glaciers such as the SRG is work in progress. Recent results are discussed by Winkler et al. (2016b). General aquifer and catchment characteristics of these alpine catchments can potentially be derived from rainfall-runoff models of different complexity. However, parsimonious models are to be favored for a more unique process-based interpretation in such alpine settings due to data limitations and the often limited information content of runoff time series (Jakeman and Hornberger, 1993). As aquifer (or catchment) characterization often leads to non-unique results (principle of equifinality; e.g. Beven, 1993, 2006), the mutual agreement of the conceptual model

of Winkler et al. (2016b) and the model approach applied herein reinforce each other. Moreover, it allows to test the rainfall-runoff model in terms of its physical relevance (Mouelhi et al., 2006; Wagner et al., 2013).

To be able to quantify the storage capabilities and the influence of relict rock glaciers on stream flow further downstream, outflow from relict rock glacier catchments is computed based on simulated runoff using GR4J+ and the parameter set of the SRGcatch (ungauged basin approach). This simple approach takes all the (ungauged) relict rock glacier-influenced headwaters within the catchment into account. The simulated discharge of the rock glacier-influenced headwaters cannot be verified at the moment, but within the study area, the similarity of the SRGcatch to the other relict rock glacier-influenced catchments seems to be justified, and this can be seen as a valuable first approximation. Comparing this simulated outflow to discharge at a gauging station further downstream allows a detailed description of the impact of these landforms. Interestingly, the temporal contribution of relict rock glacier-influenced headwaters on streamflow of the FLcatch and the UWcatch at their gauging stations based on this approach indicates that in the late snowmelt period and during summer months, the contribution is a multiple of its areal share (up to 52 % for UWcatch and 63 % for FLcatch in Figure 9 related to an areal share of 12 % and 15 %, respectively). This seems to be related to the replenishing of the depleted routing (and also production) store during the snow melt period and the following summer storm events. As such, the relatively high volume of water in the routing store (x_3, representing the aquifer component) leads to a higher outflow during this time period as the outflow is related to the actual fill level of the store. Although delayed snow melt, which is common in higher parts of alpine catchments, also plays a role in delaying runoff (e.g. Hood and Hayashi, 2015), the important role of the production store is emphasized here by the fact that these observations are also made during summer time when no snow is present in the catchments. This is also in agreement with the observation of a faster aquifer response in times when the water level increases and upper, more conductive aquifer layers are

activated (Winkler et al., 2016b). The fast flow component of the relict rock glacier-influenced headwaters becomes more dominant and the buffer capabilities are reduced. However, during winter base flows, the contribution actually decreases to about half of the areal share (see Figs. 9 and 10) as storages are increasingly depleted and the outflow is further reduced. For the catchments FLcatch and UWcatch, the production store has a higher importance than for the SRGcatch, likely due to the more extensive soil cover and subsequent larger storage capacity (Figure 8).

Moreover, the comparison of the storage components of GR4J+ and GR4J+sd applied to alpine catchments which are influenced by relict rock glaciers, shows that the relict rock glaciers do not have as much of an influence on runoff during base flow as expected from field experience (e.g. Untersweg and Schwendt, 1996). The parameter sets of both approaches are rather similar, especially compared to the respective other catchment (UWcatch for FLcatch). As Hill (2006) pointed out, the use of simple models with a limited number of parameters is generally preferable over very complex models. However, this result might indicate that using only streamflow data in a relatively complex catchment, some information about catchment complexity might remain hidden. An increasing production store (x_1, representing the soil moisture accounting store) from the SRGcatch via the FLcatch to the UWcatch correlates with an increase in soil and vegetation cover. The routing store x_3 of the UWcatch is the smallest compared to the other two, but the largest values are obtained for the FLcatch. It has to be noted that there are other storage components besides relict rock glaciers in the FLcatch (and also the UWcatch) that additionally delay/buffer runoff. The role of other debris accumulations and especially one of moraine deposits needs further attention (e.g. Roy and Hayashi, 2009; Langston et al., 2011). Moreover, ambiguities are to be expected due to the fact that different debris accumulations might have different (aquifer) thicknesses and subsequent storage volumes; the differences between areal coverage (applied in the approach herein) and actual volume of the debris accumulations needs to be further examined.

Nevertheless, the hydrological response of relict rock glaciers seems to be of importance for the transformation of precipitation to runoff in alpine catchments. On the one hand, the lumped-parameter model is able to reproduce the observed runoff behavior of the SRGcatch, and on the other hand, based on a recent hydrogeological (and geophysical) study at the SRGcatch (Winkler et al., 2016b), the model can further be used to aid in catchment/aquifer characterization. However, if parts of the model region (here the catchment and especially the rock glacier itself) become better understood or the model region becomes more complex, a more distributed model is required to account for this added knowledge, or more parameters/storages are needed to account for it. This will in turn increase model complexity. However, the necessary additional input data to justify a more complex model is usually unavailable.

6. Conclusions

A simple rainfall-runoff model was able to reproduce the observed runoff from a relict rock glacier spring catchment as well as the runoff in alpine catchments that are affected by relict rock glacier-influenced headwaters.

The parameter sets of the rainfall-runoff model can be related to catchment characteristics. The relict Schöneben Rock Glacier is associated with a high storage capacity of the routing store, which fits with the current conceptual understanding of the catchment/aquifer system. However, the results are more ambiguous when catchment characteristics become more complex. Other debris accumulations, such as moraine deposits and scree slopes, also seem to play an important role in the catchments with rock glacier influenced headwaters.

Applying a simple semi-distributed approach, the runoff drained from relict rock glaciers can explicitly be accounted for in catchments further downstream. These results suggest that a significant influence on downstream river flow is observed during the late snow melt period and summer time, that reaches a multiple (more than four times) of its areal share.

Finally, it needs to be pointed out that the applied model could potentially be used to apply climate projections (precipitation rate/intensity, temperature) to study the impact of relict rock glaciers or other sediment accumulations such as moraines or scree slopes in alpine catchments in a changing environment. As precipitation patterns change and increasing temperature alters the time and duration of solid precipitation, the impact of these relict rock glacier-influenced headwaters on stream flow further downstream might become (even) more important and are subject of future research.

References

Andréassian, V., Perrin, C. and Michel. C., 2004. Impact of imperfect potential evapotranspiration knowledge on the efficiency and parameters of watershed models. Journal of Hydrology, 286, 19-35. http://dx.doi.org/10.1016/j.jhydrol.2003.09.030

Barnett, T.P., Adam, J.C. and Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438, 303-309. http://

dx.doi.org/10.1038/nature04141

Barsch, D., 1996. Rockglaciers: Indicators for the present and former geoecology in high mountain environments. Springer Series in Physical Environment 16. Springer Verlag, Berlin, 331 pp.

Beven, K., 1993. Prophecy, reality and uncertainty in distributed hydrological modeling. Advances in Water Resources, 16, 41-51. http://dx.doi.org/10.1016/0309-1708(93)90028-E

Beven, K., 2006. A manifesto for the equifinality thesis. Journal of Hydrology 320, 18-36. http://dx.doi.org/10.1016/j.jhydrol.2005.07.007

Buttle, J.M., 1994. Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. Progress in Physical Geography 18, 16-41. http://dx.doi.org/10.1177/030913339401800102

Clow, D.W., Schrott, L., Wobb, R., Campell, D.H., Torizzo, A. and Dornblaser, M., 2003. Ground water occurrence and contributions to streamflow in an alpine catchment, Colorado Front Range. Ground Water, 41, 937-950. http://dx.doi.org/10.1111/j.1745-6584.2003.tb02436.x

Gasser, D., Gusterhuber, J., Krische, O., Puhr, B., Scheucher, L., Wagner. T. and Stüwe, K., 2009. Geology of Styria: An overview. Mitteilungen des naturwissenschaftlichen Vereins für Steiermark, 139, 5-36.

Gray, D. M., 1970. Handbook on the Principles of Hydrology. National Research Council of Canada, Secretariat, Canadian National Committee for the International Hydrological Decade, Ottawa, Canada, 625 pp.

Haeberli W., Hallet, B., Arenson, L., Elconin, R., Humulum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S. and VonderMühll, D., 2006. Permafrost creep and rock glacier dynamics. Permafrost and Periglacial Processes 17, 189-216. http://dx.doi.org/10.1002/ppp.561

Hausmann, H., Krainer, K., Brückl, E. and Ullrich, C., 2012. Internal structure, ice content and dynamics of Ölgrube and Kaiserberg rock glaciers (Ötztal Alps, Austria) determined from geophysical surveys. Austrian Journal of Earth Sciences 105/2, 12-31.

Hill, M.C., 2006. The practical use of simplicity in developing ground water models. Ground Water, 44/6, 775-781. http://dx.doi.org/10.1111/j.1745-6584.2006.00227.x

Hood, J.L. and Hayashi, M., 2015. Characterization of snowmelt flux and groundwater storage in an alpine headwater basin. http://dx.doi.org/10.1016/j.jhydrol.2014.12.041

Jakeman, A.J. and Hornberger, G.M., 1993. How much complexity is warranted in a rainfall-runoff model? Water Resources Research, 29/8, 2637-2649. http://dx.doi.org/10.1029/93WR00877

Kellerer-Pirklbauer, A., Lieb, G.K. and Kleinferchner, H., 2012. A new rock glacier inventory of the Eastern European Alps. Austrian Journal of Earth Sciences 105/2, 78-93.

Kirchner, J.W., 2003. A double paradox in catchment hydrology and geochemistry. Hydrological Processes 17, 871-874. http://dx.doi.org/10.1002/hyp.5108

Kirchner, J.W., 2006. Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. Water Resources Research, 42/3, W03S04. http://dx.doi.org/10.1029/2005WR004362

Klemes, V., 1986. Operational testing of hydrological simulation models. Hydrological Sciences Journal, 31/1, 13-24. http://dx.doi.org/10.1080/02626668609491024

Krainer, K. and Ribis, M., 2012. A Rock Glacier Inventory of the Tyrolean Alps (Austria). Austrian Journal of Earth Sciences 105/2, 32-47.

Krainer, K., Kellerer-Pirklbauer, A., Kaufmann, V., Lieb, G.K., Schrott, L. and Hausmann, H., 2012. Permafrost Research in Austria: History and recent advances. Austrian Journal of Earth Sciences 105/2, 2-11.

Krainer, K., Bressan, D., Dietre, B., Haas, J.N., Hajdas, I., Lang, K., Mair, V., Nickus, U., Reidl, D., Thies, H. and Tonidandel, D., 2015. A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy). Quaternary Research 83, 324-335. http://dx.doi.org/10.1016/j.yqres.2014.12.005

Langston, G., Bentley, L.R., Hayashi, M., McClymont, A.F. and Pidlisecky, A., 2011. Internal structure and hydrological functions of an alpine proglacial moraine. Hydrological Processes 25/19, 2967-2982. http://dx.doi.org/10.1002/hyp.8144

López-Moreno, J.I. and García-Ruiz, J.M., 2004. Influence of snow accumulation and snowmelt on streamflow in the central Spanish Pyrenees. Hydrological Sciences Journal 49/5, 787-802. http://dx.doi.org/10.1623/hysj.49.5.787.55135

Majone, B., Bertagnoli, A. and Bellin A., 2010. A non-linear runoff generation model in small Alpine catchments. Journal of Hydrology, 385, 300-312. http://dx.doi.org/10.1016/j.jhydrol.2010.02.033

Millar, C.I., Westfall, R.D. and Delany, D.L., 2013. Thermal and hydrologic attributes of rock glaciers and periglacial talus landforms: Sierra Nevada, California, USA. Quaternary International, 310, 169-180. http://dx.doi.org/10.1016/j.quaint.2012.07.019

Monnier, S., Camerlunck, C., Rejiba, F., Kinnard, C., Feuillet, T. and Dhemaied, A., 2011. Structure and genesis of the Thabor rock glacier (Northern French Alps) determined from morphological and ground-penetrating radar surveys. Geomorphology 134, 269-279. http://dx.doi.org/10.1016/j.geomorph.2011.07.004

Monnier, S. and Kinnard, C., 2015. Internal Structure and Composition of a Rock Glacier in the Dry Andes, Inferred from Ground-penetrating Radar Data and its Artefacts. Permafrost and Periglacial Processes. http://dx.doi.org/10.1002/ppp.1846

Mouelhi, S., Michel, C., Perrin, C. and Andréassian, V., 2006. Stepwise development of a two-parameter monthly water balance model. Journal of Hydrology, 318, 200-214. http://dx.doi.org/10.1016/j.jhydrol.2005.06.014

Muir, D.L., Hayashi, M. and McClymont, A.F., 2011. Hydrological storage and transmission characteristics of an alpine talus. Hydrological Processes 25, 2954-2966. http://dx.doi.org/10.1002/hyp.8060

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. http://dx.doi.org/10.1016/0022-1694(70)90255-6

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F. and Loumagne, C., 2005. Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2 – Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modeling. Journal of Hydrology, 303, 290-306. http://dx.doi.org/10.1016/j.hydrol.2004.08.026

Oudin, L., Andréassian, V., Perrin, C., Michel, C. and Le Moine, N., 2008. Spatial proximity, physical similarity, regression and ungaged catchments: A comparison of regionalization approaches based on 913 French catchments, Water Resources Research, 44/3, W03413, http://dx.doi.org/10.1029/2007WR006240.

Perrin, C., Michel, C. and Andréassian, V., 2003. Improvement of a parsimonious model for streamflow simulation. Journal of Hydrology, 279, 275-289. http://dx.doi.org/10.1016/S0022-1694%2803%2900225-7

Prettenthaler, F., Podesser, A. and Pilger, H. (eds.), 2010. Studien zum Klimawandel. Band IV: Klimaatlas Steiermark Periode 1971-2000. Eine anwenderorientierte Klimatographie. ÖAW, Vienna, 358 pp.

Roy, J.W. and Hayashi, M., 2009. Multiple, distinct groundwater flow systems of a single moraine-talus feature in alpine watershed. Journal of Hydrology, 373, 139-150. http://dx.doi.org/10.1016/j.jhydrol.2009.04.018

Schmid, S.M., Fügenschuh, B., Kissling, E. and Schuster, R., 2004. Tectonic map and overall architecture of the Alpine orogen. Eclogae Geologicae Helvetiae, 97/1, 93-117. http://dx.doi.org/10.1007/s00015-004-1113-x

Schöner, W. and Dos Santos Cardoso, E., 2004. Datenbereitstellung, Entwicklung von Regionalisierungstools und einer Schnittstelle zu den regionalen Klimamodellen (Arbeitsbericht für den Zeitraum 1.11.2003 bis 30.9.2004). Projektbericht für das Projektjahr 1, Projekt reclip:more (Research for Climate Protection: Model Run Evaluation). 44 pp, http://foresight.ait.ac.at/SE/projects/reclip/reports/report6_Regionalisierung_ZAMG.pdf

Sevruk, B., Ondráš, M. and Chvíla, B., 2009. The WMO precipitation measurement intercomparisons. Atmospheric Research, 92, 376-380. http://dx.doi.org/10.1016/j.atmosres.2009.01.016

Uhlenbrook, S., 2006. Catchment hydrology – a science in which all processes are preferential. Hydrological Processes 20/16, 3581-3585. http://dx.doi.org/10.1002/hyp.6564

Untersweg, T. and Schwendt, A., 1995. Die Quellen der Blockgletscher in den Niederen Tauern. Bericht der wasserwirtschaftlichen Planung Nr. 78, Graz, 76 pp.

Untersweg, T. and Schwendt, A., 1996. Blockgletscher und Quellen in den Niederen Tauern. Mitteilungen der Österreichischen Geologischen Gesellschaft, 87, 47-55.

Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H. and Birk, S., 2012. Auswirkungen des Klimawandels auf Abfluss und Wasserkrafterzeugung österreichischer Flüsse. Nieder-schlags-Abfluss-Modellierung basierend auf vier Klimaszenarien bis 2050. Wasserbau Symposium 2012 Tagungsband, Graz. ISBN 978-3-85125-230-9, pp. 1-8.

Wagner, T., Mayaud, C., Benischke, R. and Birk, S., 2013. Ein besseres Verständnis des Lurbach-Karstsystems durch ein konzeptionelles Niederschlags-Abfluss-Modell. Grundwasser, 18, 225-235. http://dx.doi.org/10.1007/s00767-013-0234-4

Weijs, S.V., Mutzner, R. and Parlange, M.B., 2013. Could electrical conductivity replace water level in rating curves for alpine streams? Water Resources Research 49/1, 343-351. http://dx.doi.org/10.1029/2012WR012181

Winkler, G., Pauritsch, M., Wagner, T. and Kellerer-Pirklbauer, A., 2016a. Reliktische Blockgletscher als Grundwasserspeicher in alpinen Einzugsgebieten der Niederen Tauern. Berichte der Wasserwirtschaftlichen Planung Steiermark, Band 87, 134 p.

Winkler, G., Wagner, T., Pauritsch, M., Birk, S., Kellerer-Pirklbauer, A., Benischke, R., Leis, A., Morawetz, R., Schreilechner, M.G. and Hergarten, S., 2016b. Identification and assessment of flow and storage components of the relict Schöneben Rock Glacier, Niedere Tauern Range, Eastern Alps (Austria). Hydrogeology Journal. http://dx.doi.org/10.1007/s10040-015-1348-9

Wolff, M.A., Isaksen, K., Petersen-Øverleir, A., Ødemark, K., Reitan, T. and Brækkan, R., 2015. Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: results of a Norwegian field study. Hydrology and Earth System Sciences, 19, 951-967. http://dx.doi.org/10.5194/hess-19-951-2015

Zurawek, R., 2002. Internal Structure of a Relict Rock Glacier, Sleza Massif, Southwest Poland. Permafrost and Periglacial Processes 13, 29-42. http://dx.doi.org/10.1002/ppp.403

Zurawek, R., 2003. The problem of the identification of relict rock glaciers on sedimentological evidence. Landform Analysis 4, 7-15.

Thomas WAGNER[1) *)], Marcus PAURITSCH[1)] & Gerfried WINKLER[1)]

Institute of Earth Sciences, NAWI Graz Geocenter, University of Graz, Heinrichstrasse 26, 8010 Graz, Austria;

*) Corresponding author: thomas.wagner@uni-graz.at