


**RESEARCH AND OBSERVATORY CATCHMENTS:
THE LEGACY AND THE FUTURE**

Brixenbach research catchment: Quantification of runoff process proportions in a small Alpine catchment depending on soil moisture states and precipitation characteristics

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Abstract

The Brixenbach valley is a small Alpine torrent catchment (9.2 km², 820–1950 m a.s.l., 47.45°, 12.26°) in Tyrol, Austria. Intensive hydrological research in the catchment since more than 12 years, including a hydrogeological survey, pedological and land use mapping, measurements of precipitation, runoff, soil moisture and infiltration as well as the conduction of rainfall simulations, has contributed to understand the hydrological response of the catchment, its subcatchments and specific sites. The paper presents a synthesis of the research in form of runoff process maps for different soil moisture states and precipitation characteristics, derived with the aid of a newly developed Soil-hydrological model. These maps clearly visualize the differing runoff reaction of different subcatchments. The pasture dominated areas produce high surface flow rates during short precipitation events (1 h, 86 mm) with high rainfall intensity, whilst the forested areas often develop shallow subsurface flow. Dry preconditions lead to a slight reduction of surface flow, long rainfall events (24 h, 170 mm) to a dominance of deep subsurface flow and percolation.

KEYWORDS

Alpine research catchment, rainfall characteristics, runoff processes, soil-hydrological model, system state

1 | INTRODUCTION

Alluvial fans at the exit of torrent catchments are preferred settlement sites in the Alps as they are protected from inundations taking place at the main valley bottom. However, they are threatened by floods and debris flows caused by the torrents of the tributary valleys which have formed the alluvial fans (e.g., Grelle et al., 2019). In these torrent catchments, rain and discharge gauges are sparse or missing. Additionally, flood events have very short lead times due to the short distance between the runoff generating areas and the

endangered objects. Thus, there the flood risk assessment is challenging.

The runoff reaction of small catchments is controlled by the sizes and positions of hydrological response units developing different runoff processes. Temporary or permanent infiltration hampering properties such as topsoil compaction, hydrophobic effects (= water repellency, for example, of dry organic layers or mat grass), silting or surface sealing produce infiltration excess overland flow (Hortonian overland flow, HOF; Scherrer & Naef, 2003) as soon as the precipitation intensity is larger than the infiltration rate. Infiltrated water

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subsequently percolates through the soil and the geological substrate. Percolation hampering horizons or layers with reduced hydraulic conductivity are responsible for subsurface flow (alias subsurface storm-flow, SSF; Weiler et al., 2005) if they are inclined and an effective system of lateral flow paths is present above them (Scherrer & Naef, 2003). If not, the site is saturated after a while and develops saturation overland flow (SOF; DWA, 2020). Sites without any infiltration and percolation obstruction show deep percolation (DP) of the water until the groundwater table is reached. Depending on the pore volume and size (and thus the degree of field capacity), water can also be stored within the soil against gravity (retention, RET, DWA, 2020). In Alpine torrent catchments, the runoff reaction to short rainfall events with high precipitation intensity is often dominated by fast overland flow processes. The longer the precipitation event, the more the slower subsurface flow processes may contribute to the runoff (for subsurface flow velocities see, e.g., Anderson et al., 2009).

The runoff reaction of small catchments (<10 km²), for example, Alpine torrent catchments, is strongly dependent on the catchments' general characteristics (topographical situation, connectivity, geological settings, soil, vegetation, land use), the seasonal characteristics and the current system state (e.g., antecedent soil moisture content, hydrophobic conditions, loss of vegetation due to grazing, trampling or mowing, accumulation of dead biomass on the surface resulting in different dominant runoff processes. Single characteristics, as for example, the proportion of saturated areas or the temporary development of hydrophobic properties, determine the velocity and intensity of a catchment's runoff reaction, whereas in larger catchments averaging effects may reduce the importance of specific site characteristics (Merz & Blöschl, 2009; Spreafico et al., 2003). This is why flood risk assessment for such small Alpine catchments has to be based on high-resolution spatial data and should account for possible changing system states (Meißl et al., 2017).

The Brixenbach catchment, being a typical small Alpine catchment of medium altitude, with typical land use (cattle grazing, forests, tourism) and partly less permeable geological underground is one of the few small Alpine catchments <10 km² with a rainfall and a runoff gauge (operated by the Hydrographic Service of Tyrol). Thus, it is an ideal research catchment for studying the runoff reaction at different system states. Since 2008, we have executed comprehensive investigations, including topographical-geomorphological analyses (Meißl et al., 2011), pedological mapping, soil analyses, and investigations of the earthworm abundance (Geitner et al., 2014; Geitner, Tusch, et al., 2011), infiltration measurements (Ruggenthaler et al., 2016) as well as rainfall simulations (Mayerhofer et al., 2017), partly conducted with dye tracers, soil moisture measurements (Meißl et al., 2020), snow cover modelling (Förster, Garvelmann, Meißl, & Strasser, 2018), modelling of the effect of climate (Meißl, Geitner, Tusch, Schöberl, & Stötter, 2017) and land use changes (Schermer et al., 2018; Strasser et al., 2019).

Here, we present a synthesis of the previous work in our research catchment aiming at answering the following questions:

- Which are the dominant runoff processes in the catchment and its subcatchments and which are the controlling site characteristics?
- Which hydrological response units (HRU) are sensitive to changing system states regarding their runoff reaction?

Being part of the special issue on Research and Observatory catchments, this paper

1. summarizes the results of our previous studies in the light of these research questions and
2. presents the application of a new soil-hydrological assessment tool (DWA, 2020; Soil-hydrological model, 2020) for estimating the water flux proportions of the runoff processes.

Soil-hydrological assessment tools may support the production of soil-hydrological maps such as dominant runoff process maps, maps of water flux proportions or retention capacity and thus provide input data for further hydrological modelling. Furthermore, such tools contribute to the standardization of soil profile recording and reveal the sensitivity of the runoff generation to different input parameters.

2 | MATERIALS AND METHODS

In the following, we describe the research catchment (Section 2.1), the data provided by the Hydrographic Service of Tyrol (Section 2.2.1), the methods used in 12 years of hydrological research in this catchment (Sections 2.2.2 and 2.2.3) and the new Soil-hydrological model (Section 2.2.4) applied in this study.

2.1 | Research catchment description

The Brixenbach catchment (Figure 1) is situated in the Kitzbühel Alps (Tyrol, Austria). The torrent Brixenbach is a headwater of the Brixentaler Ache, a tributary of the river Inn. The catchment covers an area of 9.2 km² with a mean elevation of 1370 m a.s.l. Its highest point (Gampenkogel) rises up to 1957 m a.s.l. The discharge gauge, installed in 2004 by the Hydrographic Service of Tyrol, is situated on the alluvial fan at the catchment's outlet (818 m a.s.l.). Geologically, the catchment is part of the Palaeozoic Greywacke Zone and thus dominated by porphyroids as well as shales (slightly metamorphic sand-, silt- and claystones), partly overlain by Mesozoic dolomites (Figure 1c). Nevertheless, most of the geological materials at the surface, and thus parent material for soil development, are unconsolidated Quaternary deposits, covering large areas of the bedrock, such as till, slope debris, talus deposits, fluvial and aeolian sediments. Depending on these parent materials in combination with vegetation type, water supply, and morphodynamics, the following soil types can be found (Figure 1b): Cambisols (widespread on different unconsolidated parent materials), Podzols (on deposits free from carbonates partly under coniferous forests and usually under dwarf-shrub heath), Gleysols (near the wider channels and in some areas dominated by slope water), Rendzic Leptosols (on dolomitic debris or bedrock), Regosols (on carbonate-silicate mixed loose material), Lithic Leptosols (on bedrock with different mineralogic

compositions), and Histosols (in wet depressions) (Meißl et al., 2020). In terms of land use, the catchment area is mainly characterized by cattle pastures (44%) and forests (35%, Figure 1a). Rock faces and talus slopes cover 14%, and only small areas are used as hay meadows, for settlements, ski-slopes and forest roads (Meißl et al., 2017). The forests are dominated by conifers, with spruce (*Picea abies*) being the predominant tree species. Silver firs (*Abies alba*), European larch (*Larix decidua*), Swiss stone pines (*Pinus cembra*), mountain pines (*Pinus mugo*), grey and green alders (*Alnus incana*, *Alnus viridis*) can be found in smaller proportions (Förster et al., 2018).

The catchment's slopes are quite steep with a mean slope of 30.5° (see Figure 2) with deeply incised brooks, which favour geomorphic and partly coupled hydrological processes. Deep-seated slope deformations cover parts of the western catchment. A smaller, active mass movement at the eastern slope necessitated a

relocation of a forest road. The weathered shales can easily be mobilized during short convective rainfall events with high precipitation intensities, especially when combined with hail. Resulting slope failures and high bedload transport then may form a threat to the settlements on the alluvial fan. Thus, the torrent control structures (debris retention basin, torrent dams) have been renewed recently.

2.2 | Data acquisition and modelling

2.2.1 | Precipitation data

The Hydrographic Service of Tyrol runs a precipitation gauge in the catchment (Talkaser, 1450 m a.s.l.) and one about 1.8 km west of

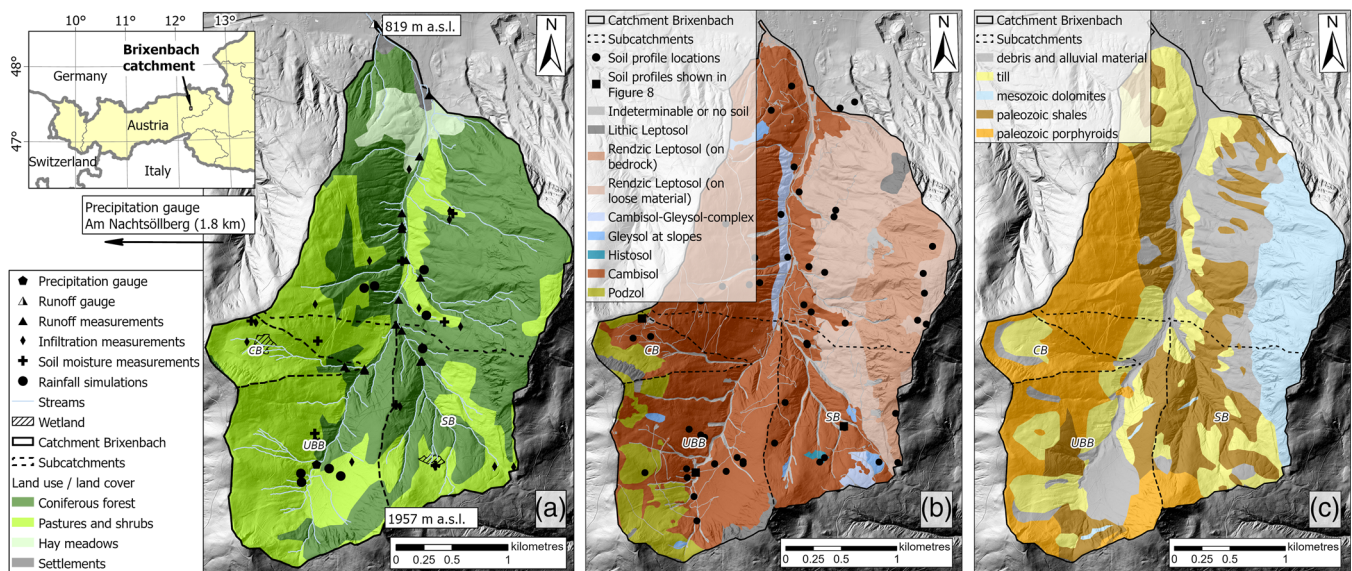


FIGURE 1 Research catchment Brixenbach: Land use and measurement sites (a), soil types (b), lithology (c). UBB Upper Brixenbach subcatchment, CB Choralmbach subcatchment, SB Schranbach subcatchment. The two elevations in map (a) indicate the highest and lowest point of the catchment, respectively. The map colours are slightly modified by the underlying hillshade. Data source: Lidar-DTM: Office of Tyrolean Government, land use/land cover: Corine land cover 2018 (modified), country borders: European Commission, Eurostat (ESTAT), GISCO, Geological map: GBA (2008)

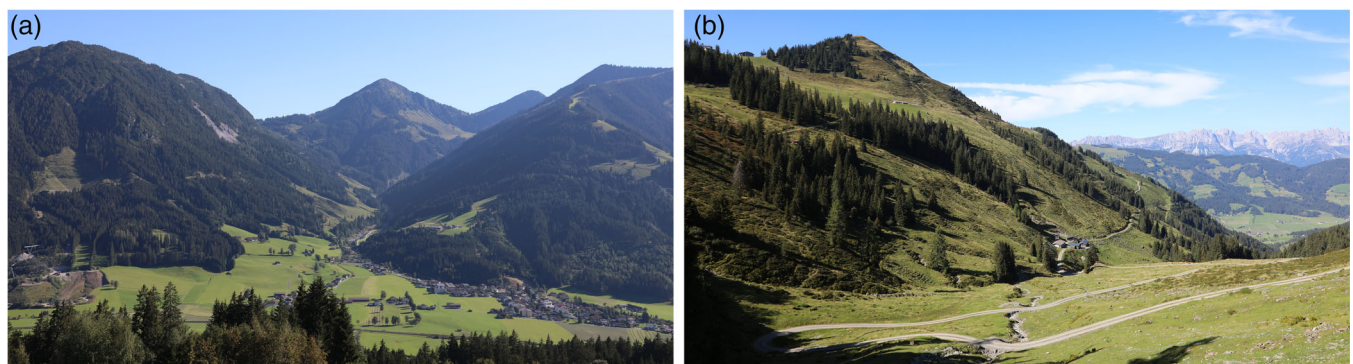


FIGURE 2 View from the counter slope into the Brixenbach catchment with the settlement on the alluvial fan at the catchment's outlet (a), Upper Brixenbach subcatchment (UBB) - this picture was taken from a position slightly south of the southernmost selected soil profile (black square in Figure 1) with viewing direction to the north (b) (Photographs: Gertraud Meißl)

the catchment (Am Nachtsöllberg, 990 m a.s.l.), registering precipitation sums with a temporal resolution of 15 min since 2009 and 2000, respectively (Figure 1a). Being situated near the north rim of the Alps, the annual precipitation sum is relatively high with 1550 mm (mean of 2010–2018, Talkaser, 1450 m a.s.l., data provided by the Hydrographic Service of Tyrol). The precipitation sum for a design event with a duration of 1 h and a return period of 100 years is between 86 mm (ehyd.gv.at: grid point 4426, west of the catchment) and 82.7 mm (grid point 4427, east of the catchment). The Kitzbühel Alps, to which the research catchment belongs, are known for quite high snow depths in winter. At the station Am Nachtsöllberg (990 m a.s.l.), a mean duration of the snow cover of 132 days and a mean snow depth of 81 cm with a standard deviation of 33 cm (1990–2010) were recorded.

2.2.2 | Caption of infiltration and runoff reaction for different site characteristics and system states

In order to determine the infiltration capacity and runoff reaction of the research catchment for different site characteristics and system states, we conducted (i) soil moisture measurements, (ii) double ring infiltration measurements, (iii) rainfall simulations, (iv) and runoff measurements with the salt dilution method at different times.

1. A soil moisture measurement network has been installed in July 2009 between 1000 and 1700 m a.s.l. (Meißl et al., 2020). It consists of four pairs of sites, thus eight sites altogether (Figure 1a), each of them equipped with three soil moisture sensors (Delta-T ThetaProbe ML2x frequency domain sensors) and one soil temperature sensor (Skye SKTS 200). All sensors have been installed 10 cm beneath soil surface within a perimeter of 10 m in maximum, aiming at understanding the soil moisture dynamics in the topsoil, which are highly relevant for the runoff generation, and also capturing the local variability of soil moisture. Soil moisture is recorded at 1 h-intervals from July to September and at 2 h-intervals from October to June. Six sites are situated on cattle pastures, two of them west faced, two east faced and two on relatively wet areas near the upper catchment borders. Two sites were covered by forests. However, due to timber harvesting and natural breakdown of the surrounding trees, both forest sites have developed more or less to clearing sites within the last years. This leads to a reduction of the interception storage at both sites, but the soil characteristics have remained more or less unchanged until now. The soil moisture data series is one of the rare long-duration data series in the Alps (Meißl et al., 2020).
2. At each of the soil moisture monitoring sites, we conducted infiltration measurements with a double ring infiltrometer at dry, medium, and wet conditions (Ruggenthaler et al., 2016). In order to guarantee that the measurements take place at exactly the same spot, we used split inner rings, of which the lower part was permanently installed in the soil over the entire investigation period (three spots at each site), the upper part was only mounted on the

lower part directly before the measurement, and removed afterwards. The dry run was performed at soil moisture conditions close to the permanent wilting point. The medium run was carried out 2–4 days after the last rainfall event, enabling the soil moisture to level out at field capacity. Wet conditions were produced with artificial sprinkling immediately before the infiltration experiment with a high rainfall intensity (60 min, 100 mm) in order to guarantee comparable conditions at all sites. Infiltration measurements with a dye tracer (brilliant blue) displayed matrix and macropore flow (Ruggenthaler et al., 2016).

3. Rainfall simulations were carried out at eight characteristic pasture and forest sites in the catchment using a transportable spray irrigation installation for large plots (for detailed description of the device see Markart et al., 2011; Mayerhofer et al., 2017). According to water availability and slope form, we used a plot size between 40 and 80 m². To assess the influence of antecedent soil moisture content on surface runoff, the simulations were repeated after a break of about 1 h at most of the pasture sites (Mayerhofer et al., 2017). Soil moisture content was measured at two profiles in about the middle of the experimental plot in four depths (5, 15, 25 and 40 cm) with TDR-probes. As the conduction of large-plot rainfall simulations is associated with a considerable effort, we used a small plot rainfall simulator (1 m × 1 m) to compare the results with the large-plot simulations (Mayerhofer et al., 2017) and to investigate the surface runoff at the soil moisture measurement sites (Ruggenthaler et al., 2016). At two sites, also the sprinkling water was dyed with brilliant blue (Mayerhofer et al., 2017; Schader, 2013). For all rainfall simulations, we applied 100 mm during 60 min.

In order to determine subsurface flow velocities, a long-term rainfall simulation was conducted during 5 days with an intensity of about 9 mm h⁻¹ on an even larger plot (600 m²) at a talus slope covered by dwarf-shrubs (*Rhododendron ferrugineum*) in the upper part of the catchment. On the third day, salt water was applied at 50 m² (2 h 22 min, 17 mm min⁻¹). The progress of the seepage front and subsurface flow velocities were observed by geoelectrical profile measurements (Markart et al., 2013). At the opposite slope a salt tracer solution (concentration: 6 mS cm⁻¹) was washed into a gleyic soil by use of water from a natural linear irrigation trench along the slope.

4. Additionally, we conducted discontinuous runoff measurements with the salt dilution method (Bronge & Openshaw, 1996) at different sections of the Brixenbach and at several tributary brooks (in total 15 locations) in order to capture the runoff reaction of the subcatchments at different system states (e.g., during rainfall events, after dry periods) about weekly in summer 2009 and irregularly in the following years. Continuous runoff data at the catchment outlet (818 m a.s.l., 47.45°, 12.26°) are provided by the Hydrographic Service of Tyrol, who has installed a contact-free runoff gauge (radar) in 2004 measuring with a temporal distribution of 15 min. Due to construction works – the trench regulating the torrent at the alluvial fan was completely rebuilt and widened – the runoff gauge was removed in September 2016 and re-

erected in May 2018. The new water-level/discharge relationship is currently being established.

2.2.3 | Acquisition of geological and soil information

Geological and soil information was acquired using the following data sets and accomplishing the following investigations, respectively:

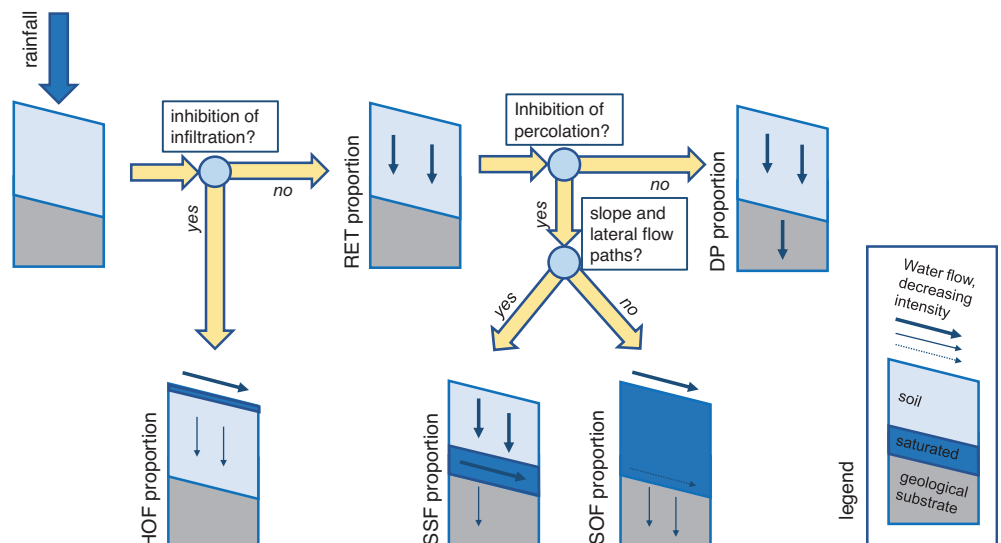
1. The geological map 1:50.000 of the Geological Survey of Austria (Geofast map No. 121) shows the lithological units of the area. More detailed information on geological substrate as parent material for soil development can be gained from the recently available geological substrate map of the Office of the Tyrolean Government (Simon et al., 2020). Among other aspects, its interpretation gives further information on soil texture. Pirkl (2012a) developed a map of the shallow and deep interflow in the catchment based on a hydrogeological mapping strategy as described in Pirkl and Sausgruber (2015).
2. Soil characteristics of the sites were recorded by soil profile description at 30 sites following Ad-hoc-Arbeitsgruppe Boden (2005) and Blume et al. (2010). For each horizon, core samples were collected in order to analyze soil texture, bulk density, and organic matter content. For the nine large-plot rainfall simulation sites, we additionally analyzed core samples of different soil-depth levels (0–10, 10–20, 20–30, 30–50 cm) to assess the above-mentioned characteristics as well as the distribution of the pore volume including high permeable coarse pores as well as the hydraulic conductivity. Earthworm extraction produced information on biomass and abundance of earthworms depending on the soil characteristics (Geitner et al., 2014) and helped to interpret the pore volume data. For this study, we recorded 13 new soil profiles according to the guidelines of DWA (2020). Thus, in total 52 soil profiles were analyzed.

2.2.4 | Assessing runoff processes

For each of the 52 soil profiles, we assessed the runoff processes by using a new Soil-hydrological model, which was developed complementing a code of practice for soil-hydrological mapping (DWA, 2020). It is implemented within Microsoft Excel and freely available (Soil-hydrological model, 2020). The Soil-hydrological model assesses the formation of dominant runoff processes by analyzing the key points of runoff formation. As shown in the flow-chart of Figure 3, it checks if the site characteristics and soil profile properties give a hint for (i) the existence of infiltration inhibition resulting in infiltration excess overland flow, (ii) the existence of percolation inhibition resulting in subsurface flow or saturation overland flow depending on the slope and the existence of lateral flow paths. In addition, the model assesses the storage potential, the velocity of runoff processes and the connectivity of the site by using qualitative rules and quantitative calculations. The indication of infiltration inhibition leading to infiltration excess overland flow, for example, is among others deduced by means of information on (i) the tendency for silting, (ii) anthropogenic influence like cattle grazing or the usage of heavy machines leading to top soil compaction, (iii) the bulk density of the top soil, (iv) the existence of roots and stones in the soil profile as well as their embedding and (v) texture and hydraulic conductivity of the top soil matrix. The applied rules are documented in the respective Excel sheets and in detail delineated and discussed in DWA (2020). In the present paper, the model results were verified using the data and measurement results described in Sections 2.2.1–2.2.3.

For each site, the Soil-hydrological model calculates the proportion of the four runoff process types infiltration excess overland flow, saturation overland flow, subsurface flow and deep percolation depending on (i) the antecedent soil moisture status: dry (available pore volume = air capacity and half of field capacity), moist (available pore volume = air capacity), saturated and (ii) the duration and intensity of the rainfall event. Based on a standard rainfall

FIGURE 3 Flow chart for the assessment of the runoff process proportions in the Soil-hydrological model. HOF Hortonian overland flow, SOF saturation overland flow, SSF subsurface flow, DP deep percolation, RET retention (modified after DWA, 2020, p. 24). Besides, the Soil-hydrological model also assesses the potential water storage volume and the draining velocity



intensity of 100 mm h^{-1} , the model adjusts the infiltration excess overland flow to the rainfall duration and rainfall sum defined by the user. Equation (1) shows the underlying adjustment function derived from a large number of rainfall experiments (Kohl et al., 2013).

$$\begin{aligned} \Psi_N &= (0.3 - \Psi_{100}^2 + 0.7 - \Psi_{100}) \\ &\quad - (1 - \text{EXP}(-0.03 - \text{EXP}((0.1 - \text{EXP}(3.3 - \Psi_{100}))) \\ &\quad i_N^{(-0.7 - \Psi_{100} + 1)})) + (-0.0035 - \Psi_{100} + 0.0035) - i_N \end{aligned} \quad (1)$$

Ψ_{100} Surface runoff coefficient at discharge constancy at a rainfall intensity of 100 mm h^{-1} .

Ψ_N Surface runoff coefficient at discharge constancy for the selected rainfall intensity $i_N \text{ mm h}^{-1}$.

i_N selected rainfall intensity $N \text{ mm h}^{-1}$.

Additionally, the model gives information on the process velocities and the connectivity.

For this study, we investigated rainfall events of two different durations, each with a return period of 100 years and used the Austrian design rainfall tables (ehyd.gv.at, grid point 4426). The 1 h-event has a rainfall sum of 86 mm and represents the short convective rainfall type. One hour is approximately the critical rainfall duration for maximum peak runoffs in the Brixenbach catchment. The 24 h-event representing the advective rainfall type has a rainfall sum of 170 mm (7.1 mm h^{-1}).

In order to derive area-wide maps for the runoff reaction in our research catchment, we regionalized the soil profile assessment. Depending on land use, soil and geological characteristics, we transferred the soil profile results to their surrounding area and to areas with comparable geological, pedological, land use properties and thus derived Hydrological Response Units (HRU) for the entire Brixenbach catchment.

3 | RESULTS

To quantify the runoff process proportions of the HRUs in the Brixenbach catchment, we first lay the basis by summarizing the findings of our previous studies (Sections 3.1 and 3.2), followed by presenting the new results of the application of the Soil-hydrological model (Sections 3.3 and 3.4).

3.1 | Runoff reaction of the catchment

Figure 4 displays the precipitation sum, discharge volume and mean temperature measured by the Hydrographic Service of Tyrol at the precipitation gauge Talkaser (1450 m a.s.l.) in the southern part of the Brixenbach catchment and the runoff gauge at the basin outlet, respectively. Being a small catchment ($<10 \text{ km}^2$), the Brixenbach shows its strongest runoff reaction during local convective rainfall events when thunderstorms with high precipitation intensities cover the whole catchment area. Therefore, our study mainly focusses on summer rainfall runoff processes.

The highest peak flow recorded by the runoff gauge (2004–2016) occurred on 03 August 2014 (Figure 5a). A short convective rainfall event with a duration of 1 h, a precipitation sum of 30.3 mm and a maximum intensity of $15 \text{ mm}/15 \text{ min}$ (return period of about 2 years, compared to ehyd.gv.at – grid point 4426) caused a peak flow of $17.5 \text{ m}^3 \text{ s}^{-1}$ with a steep ascent and descent of the hydrograph. The event was accompanied by hail (Jenner, 2015) and resulted in intensive erosion processes and voluminous bedload transport, destroying several torrent control structures and completely filling the retention basin at the top of the alluvial fan (Meißl et al., 2020).

Extraordinary advective rainfall events also produce high peak runoffs, but flatter runoff curves like between 01 and 03 June 2013, when a rainfall event occurred with a return period of >100 years for the 2- to 4-days precipitation sum during a so-called Vb weather situation (a low-pressure area on the path from the Adria to Poland; Seibert et al., 2007). It caused a significant peak flow at the runoff gauge Brixenbach (Figure 5b) as well as a flood event with a return period of about 40 years in the river Brixentaler Ache, the receiving stream of the Brixenbach torrent, and large inundations in neighbouring catchments (Hydrographic Service of Tyrol, 2013).

The runoff measurements with the salt dilution method helped to understand the differing reaction to rainfall events of the subcatchments. Figure 6 shows selected gauge data for the Brixenbach (BB) at the catchment outlet as well as the data of selected salt dilution runoff measurements for three selected subcatchments: (i) the upper Brixenbach catchment above the influx of Schranbach (UBB), mostly covered by grassland with compacted topsoils due to cattle pasture, (ii) the catchment of the southeastern tributary Schranbach (SB) with large forested areas with shallow soils on less permeable silt- and claystones, and (iii) the catchment of the Choralmbach (CB), a western tributary to the upper Brixenbach with an extended saturated area in relation to the catchment area (see Figure 1a). Table 1 gives information on the rainfall data of the measurement dates. On each measurement day, the discharge measurements with the salt dilution method were conducted within at most 4 h. Thus, especially during rainfall events, the comparability of the data may be limited depending on the shape of the hydrograph. However, discharge measured at the gauge during the salt dilution measurement period varied only within max. $\pm 10\%$, mostly even less.

The measurements showed that the proportions of the specific discharge of the subcatchments change depending on the weather conditions. The specific discharge on an early summer day without rainfall event (06 June 2009) of UBB was about double of the yields of CB, SB and BB (Figure 6). In parts of SB and the southeastern BB, fissured dolomite on rather impermeable shales enables the formation of a large groundwater reservoir with a spring tapped for the water supply of the municipality of Brixen im Thale. In late summer, after a longer dry period interrupted only by short thunderstorms (26 August 2009), the specific discharge of UBB, SB and BB were reduced to about 50% of the yields in early summer, while the reduction of the specific discharge of the CB was less, probably due to the continuous water supply of the extended saturated area and deep subsurface flow in a deep-seated mass movement. In case of long rainfall events

FIGURE 4 Monthly precipitation sum, discharge volume and mean temperature measured by the Hydrographic Service of Tyrol at the precipitation gauge Talkaser (1450 m a.s.l.) in the southern part of the Brixenbach catchment and the runoff gauge (819 m a.s.l.) at the basin outlet, respectively

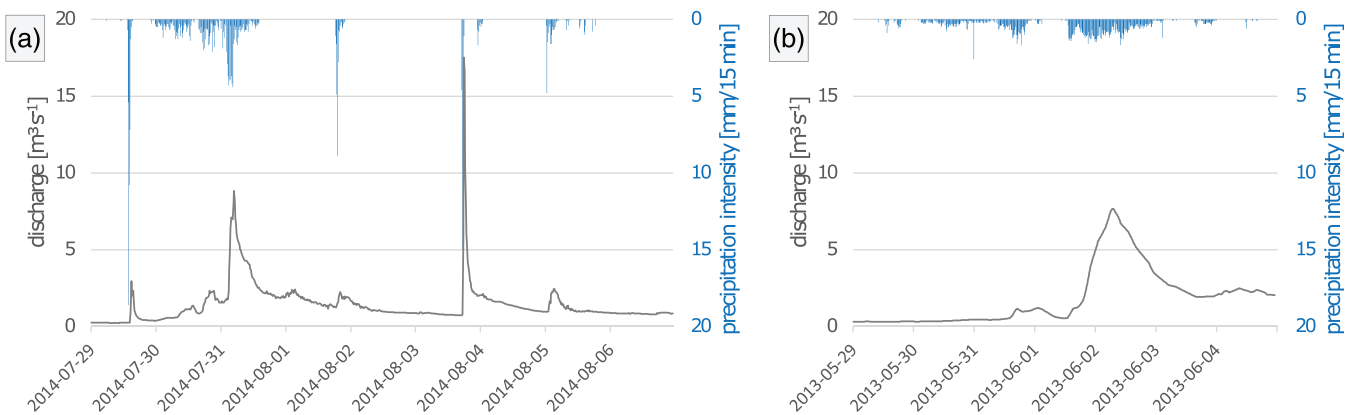
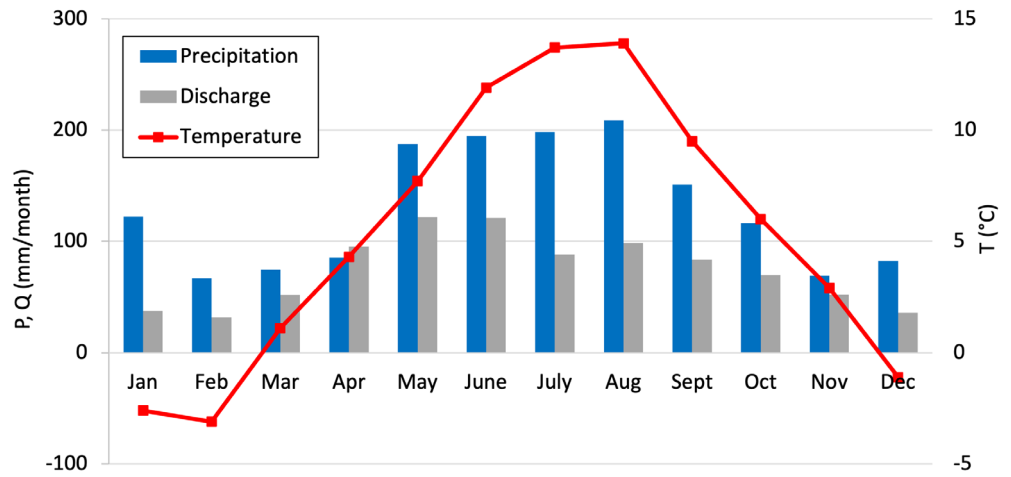


FIGURE 5 Rainfall and runoff data for convective precipitation events (a) and an advective precipitation event (Vb weather situation) (b). Data provided by the Hydrographic Service of Tyrol

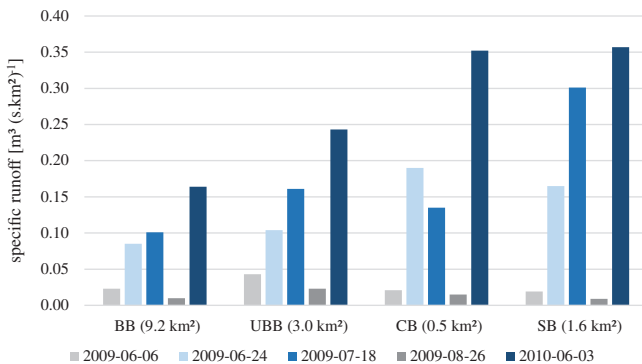


FIGURE 6 Specific runoff [$\text{m}^3 (\text{s.km}^2)^{-1}$], measured by the gauge of the Hydrographic Service of Tyrol (Brixenbach catchment BB) and with the salt dilution method (upper Brixenbach subcatchment UBB, Choralmbach subcatchment CB and Schranbach subcatchment SBB), for precipitation events (blue) and dry days (grey)

with quite high intensity, the specific discharge of the tributary catchments SB and CB significantly overruns the specific discharge of the UBB and BB. Then, in SB, intensive subsurface flow develops on the shallow soils on less permeable bedrock (see soil profile in

Section 3.3). Additionally, saturated areas presumably extend during these events, which is the case in upper SB and above all in CB. Specific discharge for short convective rainfall events cannot be determined, as due to logistical reasons (travel time, risk situation), no salt dilution measurements could be conducted during such events.

3.2 | Infiltration and runoff reaction at different system state conditions

Repeated rainfall simulations at pasture sites clearly show increasing surface runoff coefficients with increasing soil moisture at begin of the rainfall simulation (Figure 7, see also Klebinder et al., 2014; Mayerhofer et al., 2017). Accordingly, pasture sites showed decreased amounts of totally infiltrated water for decreasing soil moisture deficits at the double ring infiltrometer measurements. However, this is not the case for wetland areas, which always show low infiltration rates, and forests with different, but mostly high infiltration rates which overrun also high precipitation intensities (Ruggenthaler et al., 2016).

Date	Rainfall event	Rainfall duration [h]	Precipitation sum [mm]
2009-06-06	no	-	-
2009-06-24	yes	42.0	68.0
2009-07-18	yes	21.5	69.5
2009-08-26	no	-	-
2010-06-03	yes	62.0	54.8

TABLE 1 Rainfall data for selected salt dilution measurement days displayed in Figure 6

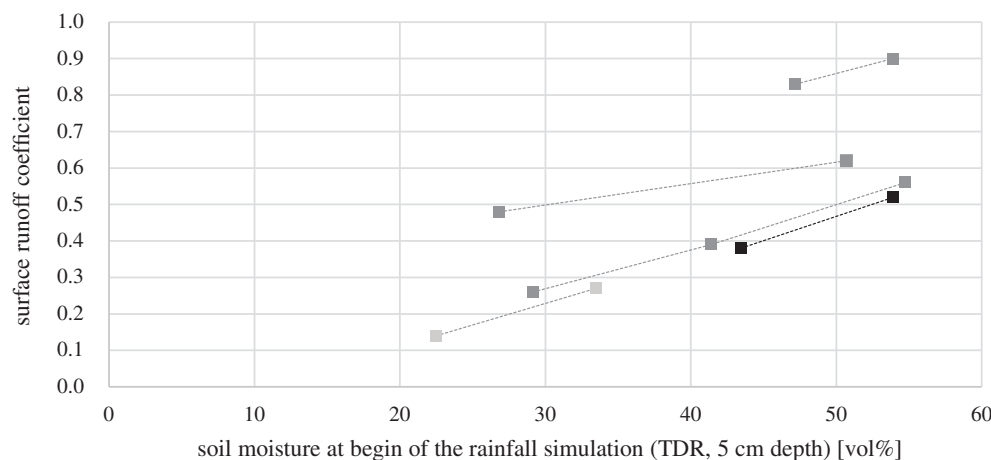


FIGURE 7 Relationship between soil moisture at begin of the rainfall simulation and surface runoff coefficient for repeated rainfall simulations on pasture sites with the large-plot simulator. Light grey: before grazing season, dark grey: during grazing season, black: after grazing season

For the Brixenbach catchment as a whole, the comparison of the data of our soil moisture measurement network and the runoff coefficients of rainfall-runoff events extracted from the precipitation and runoff data of the Hydrographic Service of Tyrol showed a clear threshold behaviour: runoff coefficients above 0.23 only occurred when the soil moisture spatial mean of the eight sites overruns 43.5 vol% (Meißl et al., 2020). This soil moisture threshold differs between the soil moisture measurement plots between 31 and 52 vol %, but exists at nearly all sites. Therefore, the exact level of the threshold depends on the number and (casual) location of the soil moisture sensors. Nevertheless, the existence of a threshold per se is an important characteristic of the catchment and describes the limited storage capacity. At moist conditions, event streamflow peaked prior to soil moisture, which can be explained by increased surface flow volumes at higher soil moisture as well as already initialized subsurface flow paths (Meißl et al., 2020).

Changing system conditions do not only refer to the antecedent soil moisture state of a rainfall-runoff event, but, for example, also to (seasonal) land use changes. Repeated rainfall simulations before the grazing season (May 2012, Figure 7, light grey squares) and after (September 2012, Figure 7, black squares) at the site Brixenbachalm showed a strong influence of grazing on the generation of surface runoff. The surface runoff coefficient increased significantly after the grazing season (+0.24 for medium soil moisture, +0.25 for saturated conditions). This can be explained by the reduction of the vegetation cover, the compacted top soil owing to mechanical impact by grazing livestock, and hydrophobic effects initiated by accumulated dead organic matter (Leighton-Boyce et al., 2007; Markart et al., 2011;

Mayerhofer et al., 2017; Sharrow, 2007). During the non-grazing season, a recovering process of the soil (decreasing of bulk density, increasing of macroporosity and hydraulic conductivity) occurs as a consequence of a number of processes including shrinkage and swelling, earthworms burrowing and root penetration (Courmane et al., 2011; Mayerhofer et al., 2017; Unger, 1991).

Subsurface flow velocity was measured at a talus slope with dwarf-shrubs on the west-faced slope in upper UBB. The site showed a medium subsurface flow velocity of 3.2 m h^{-1} in the upper layer of the substrate (5–10 m depth). At the east-faced slope a salt tracer solution (concentration: 6 mS cm^{-1}) was injected into a gleyic soil by use of water from a linear irrigation trench along the slope. Large proportions of the water formed overland flow within the first 10 m of the flow section. The infiltrated water showed a subsurface flow velocity of 2.4 m h^{-1} for the uppermost combined layer of soil and substrate (until 2 m depth) (Markart et al., 2013). Studies on flow velocities in near-surface subsurface are rare. However, the flow velocities measured in UBB are at a comparable level to those measured by other studies on slope debris (Kirnbauer et al., 2009; S. Tilch, Uhlenbrook, et al., 2006) and till material (Laine-Kaulio, 2011; Markart et al., 2013).

3.3 | Dominant runoff processes on the plot

Out of the 52 soil profiles for which we conducted field and laboratory analysis in order to parameterize the Soil-hydrological model, we exemplarily present three profiles, typical for the Schranbach (SB),

upper Brixenbach (UBB) and Choralmbach (CB) subcatchment, respectively (Figure 8, Table 2). Two soils are Cambisols, however with different characteristics, one soil is a Podzol. The Cambisol at SB is situated in a forest clearing, but still shows the characteristics of a forest soil with organic layers, low bulk density and a high number of macropores (Figure 8a). It is developed in till above less permeable weathered paleozoic shales resulting in a subsoil with water logging conditions and thus redoximorphic features (coarse, diffuse, grey blotches). These soil profile conditions indicate subsurface flow within the upper 3 or 4 dm.

On the contrary, for the Cambisol profile in UBB at a pasture site, the dominant features with respect to hydrological behaviour are the lack of organic layers due to land use and the compacted topsoil as a result of cattle grazing, which leads to infiltration excess overland flow at high precipitation intensities (Figure 8b).

As already mentioned, a quite large area of the CB subcatchment is covered by a saturated area with peat soils. Towards the upper catchment rim, Podzols with quite thick organic layers developed under dwarf-shrubs (mainly *R. ferrugineum*) (Figure 8c). This humus form is called Rohhumus and its thick organic layers can serve, as observed under wet conditions, as a pathway for subsurface flow (N. Tilch, Zillgens, et al., 2006).

Depending on the permeability of the geological substrate, the soil texture, the stone content and organic matter, the bulk density, the macropore abundance, possible hydrophobicity, and land use

effects, the rule system of the Soil-hydrological model (see Section 2.2.4) calculates a large amount (50%) of subsurface flow for the SB soil profile for short duration rainfalls (1 h) with a return period of 100 years at saturated conditions (Figure 9). At dry conditions with an estimated available pore volume comprising the air capacity and half of the field capacity, the soil profile is supposed to be able to absorb the whole precipitation sum (100% retention). For a 24 h-rainfall event with a return period of 100 years, the model assumes that the permeability of the geological substrate is high enough in order to enable deep percolation for saturated conditions.

According to the compacted topsoil of the soil profile at UBB, there the 1 h-rainfall produces a high amount of Hortonian overland flow (61%) at saturated and dry conditions according to the Soil-hydrological model. At dry conditions a large part of the rainfall amount can be stored in the profile (retention), deep percolation dominates at saturated conditions for the 24 h 100 years-event. Despite the different soil, the runoff process assessment of the CB soil profile is similar to that of UBB.

The exact proportions of the runoff processes may be subject of discussion. However, the general assessment of the Soil-hydrological model corresponds with field evidence, as can be shown by a large-plot rainfall simulation (100 mm h^{-1} , Figure 10) conducted at the site of the UBB soil profile which shows a surface runoff coefficient up to >60% and thus confirms the Soil-hydrological model results. A small-plot rainfall simulation with a dye tracer (brilliant blue) at the same site

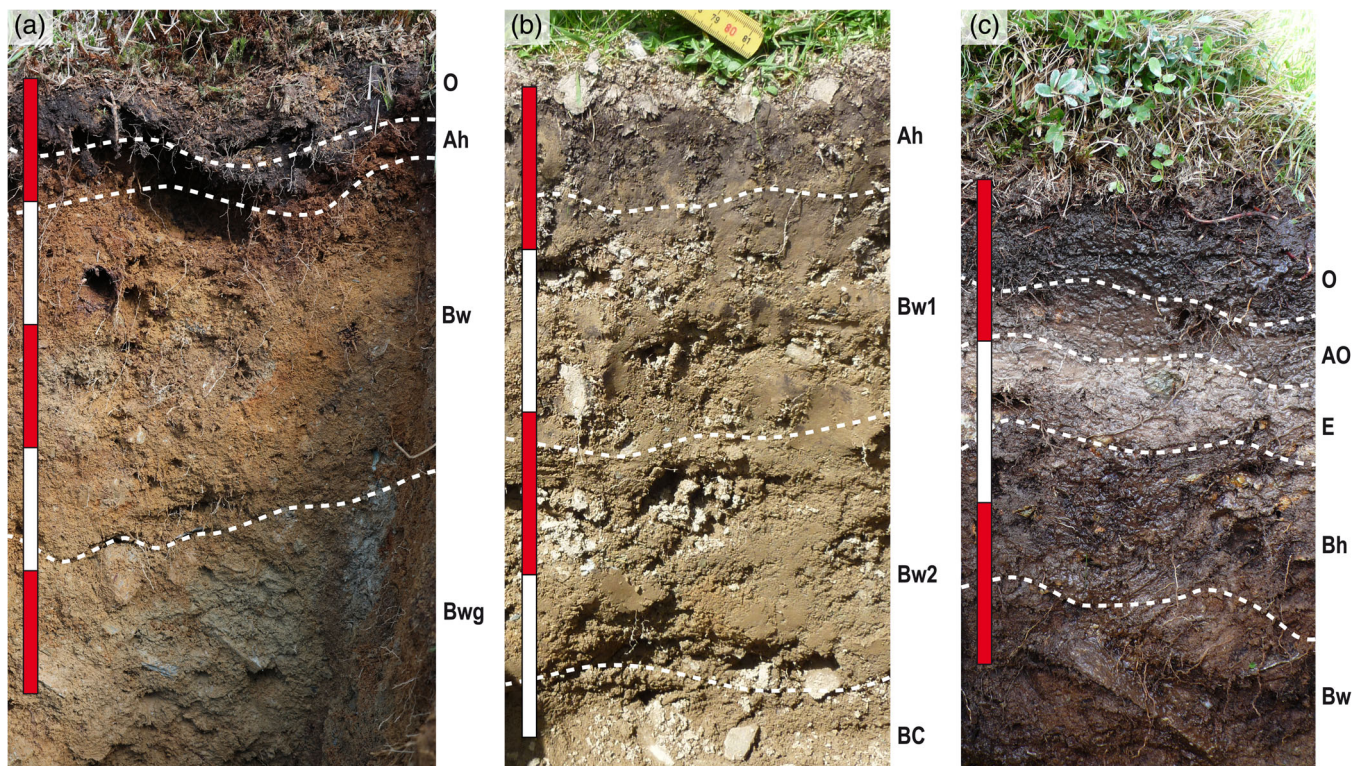
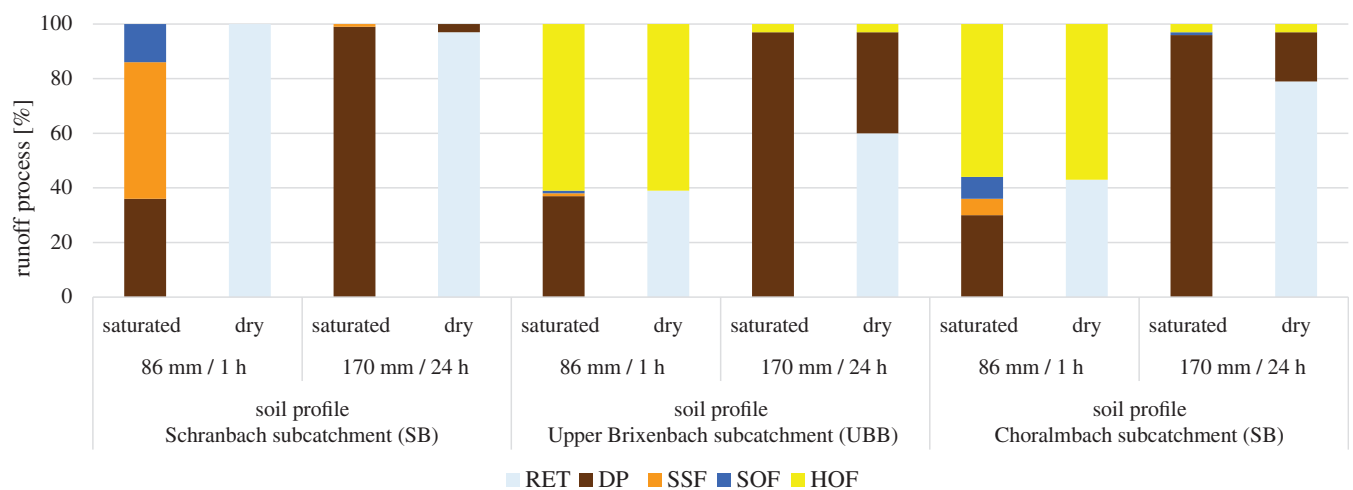


FIGURE 8 Typical soil profiles with relevant soil horizons and their designations according to FAO (2006) in the Schranbach subcatchment (SB) (a), upper Brixenbach subcatchment (UBB) (b) and Choralmbach subcatchment (CB) (c), each red and white bar indicates 10 cm, slight distortion due to oblique photograph (for more detailed information see Table 2). Their positions are marked by squares in the soil map of Figure 1 (Photographs: Clemens Geitner, Klaus Klebinder)

TABLE 2 Soil characteristics of the profiles shown in Figure 8, described according to DWA (2020), soil texture partly analysed in the laboratory, all other parameters estimated in the field

Site	Soil (IUSS working group, 2015)	Horizon	Depth [cm]	Stone content ($\varnothing > 2$ mm) [%]	Stone embedding type	Soil texture (FAO, 2006)	Bulk density of fine earth	Organic matter content	Macropore presence
SB	Dystric Skeletic Stagnic Cambisol (Loamic)	O	0–6	-	-	-	nd	nd	nd
		Ah	6–12	20	3	Loam	very low / low	h4 (4–<8%)	visible
		Bw	12–36	20	3	Loam	very low / low	h2 (1–<2%)	visible
		Bwg	36–86	70	3	Loam	very low / low	h1 (>0–<1%)	visible
		BC	86–126	70	3	Loam	very low / low	h1 (>0–<1%)	visible
		C	126–136+	80	3	Loam	medium	h0 (0%)	visible
UBB	Dystric Cambisol (Loamic)	Ah	0–6	0	2	Sandy loam	very high / high	h5 (8–<15%)	likely
		Bw1	6–20	40	2	Sandy loam	medium	h4 (4–<8%)	no indications
		Bw2	20–36	30	2	Sandy loam	medium	h3 (2–<4%)	no indications
		BC	36–61+	50	2	Sandy loam	medium	h3 (2–<4%)	no indications
CB	Skeletic Albic Podzol (Loamic)	O	0–6	-	-	-	nd	nd	nd
		AO	6–10	5	2	Silt loam	medium	h4 (4–<8%)	likely
		E	10–18	15	3	Silt loam	medium	h1 (>0–<1%)	likely
		Bh	18–26	50	3	Loam	medium	h3 (2–<4%)	likely
		Bw	26–60	50	3	Sandy loam	medium	h2 (1–<2%)	likely
		BC	60–100+	60	4	Sandy loam	medium	h0 (0%)	no indications

Note: Stone embedding type: 1 loosely, 2 embedded, but without accurately fitting cavity, 3 with accurately fitting cavity, 4 layered. nd, not defined.

**FIGURE 9** Runoff processes for the soil profiles shown in Figure 6 calculated by the soil-hydrological model for the precipitation events with a return period of 100 years and a duration of 1 and 24 h for saturated and dry system status conditions. RET retention, DP deep percolation, SSF subsurface flow, SOF saturation overland flow, HOF Hortonian overland flow (infiltration excess overland flow)

shows the low matrix permeability and limited macropore flow (Figure 11).

Macropore presence is among others related to soil fauna. The activity of earth worms, especially of certain ecological groups, can considerably alter the soil structure and thus increase percolation and storage capacities (Ruedisser et al., 2021). Geitner et al. (2014) investigated the number of earthworm species, their biomass and abundance at 15 alpine pasture and hay meadow sites in the Brixenbach catchment between 910 m and 1735 m a.s.l. They found in total 13 species that show major spatial differences of the mean site values in both biomass (1–69 g/m², with clearly higher values on meadow sites) and abundance (3–338 ind./m², see also Geitner et al., 2011). In general, the presence of earth worms proved to be highly variable on a very small-scale level, depending on organic matter, pH value and the kind of nutrient input.

3.4 | Surface and subsurface runoff maps of the Brixenbach catchment

The regionalization of the soil profile assessments depending on land use, soil and geological characteristics resulted in area-wide runoff process maps for the whole Brixenbach catchment. Figure 12 shows the proportion of surface runoff, subsurface flow and deep percolation for the 1 h-event (86 mm). The different characteristics of the southern subcatchments clearly appear: UBB and CB are dominated by high proportions of surface flow due to cattle grazing, while in SB,

subsurface flow plays an important role in the shallow soils on relatively impermeable geological substrate. Details have been discussed in Section 3.3.

The relative high proportion of subsurface flow at the eastern rim of the catchment is due to the steep slopes with so-called Tangel humus on dolomitic bedrock. This specific humus form with organic layers up to 100 cm preferentially occurs over solid or coarse carbonate rocks with low residual clay contents in the montane up to the subalpine zone in the Alps, mostly associated with coniferous trees, *P. mugo* shrubs and plants of the heath family (Kolb & Kohlpaintner, 2018). The hydrological effect of the Tangel humus form is not well enough investigated. The unsaturated peat-like organic matter can uptake high amounts of water. Nevertheless, during dry periods, water repellent effects can occur. In order to hydrologically differentiate Tangel humus effects, both the thickness of organic layers as well as the structure of underlying geological substrate should be considered.

Compared to surface runoff at saturated conditions (for the 1 h-event; Figure 13a), dry conditions lead to a reduction of surface runoff in some areas (Figure 13b). However, the difference of the estimated specific surface runoff between saturated and dry conditions is mostly smaller than 10% and thus only partly visible in the classified maps.

As surface runoff at pasture sites is dominated by infiltration excess (see Figure 9), the reduced rainfall intensity of the 24 h-event leads to reduced surface runoff proportions comparing to the 1 h-event (Figure 13c) and a dominance of deep subsurface flow and percolation.

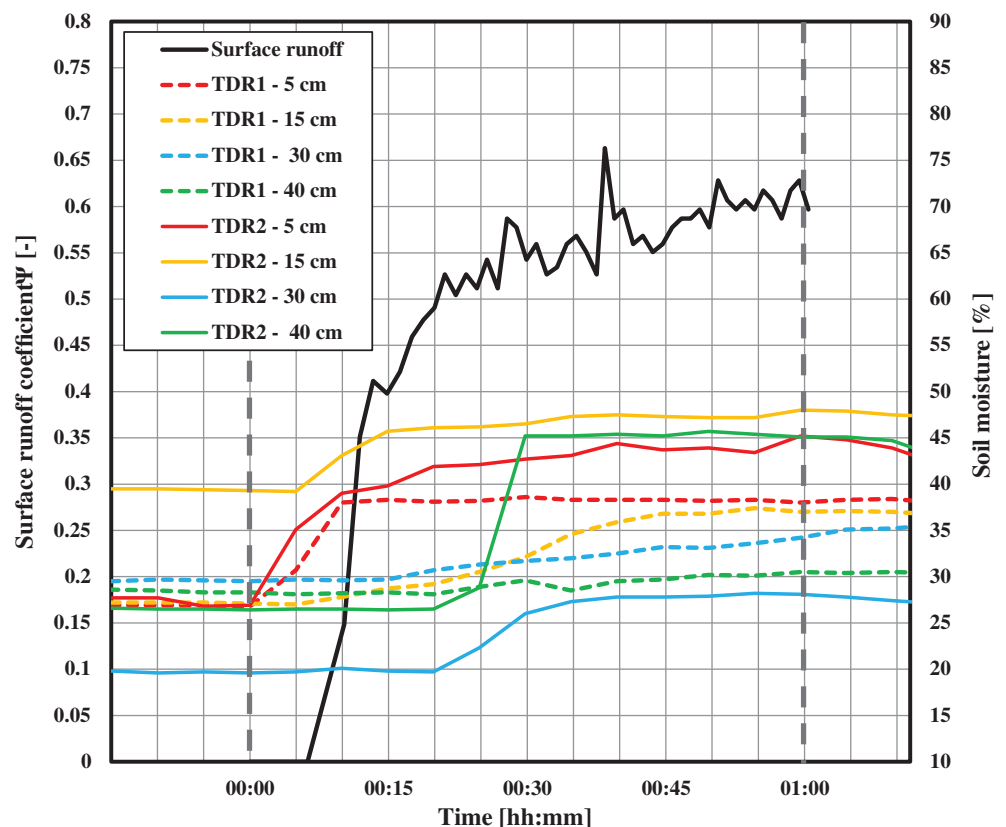


FIGURE 10 Results of the rainfall simulation at UBB at the large-plot and soil moisture measured with TDR-probes at two profiles in the centre of the plot. The vertical dashed lines indicate begin and end of the rainfall simulation

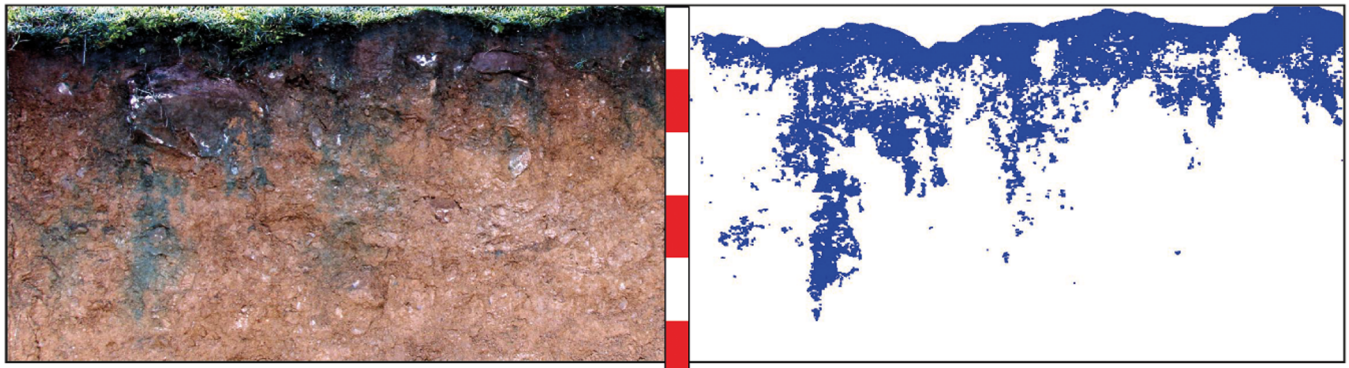


FIGURE 11 Rainfall simulation at UBB at the small plot with dye tracers (each red and white bar indicates 10 cm). Left: Photograph, right: Image interpretation (Schader, 2013, p. 57). Water charged with a dye tracer (brilliant blue) was applied by a 1 m² rainfall simulator. On the following day, the soil profile was dug up, cleaned and photographically documented. The blue patterns show matrix flow in the topsoil, indicated by a nearly continuous colour, and macropore flow with concentrated colour spots/pattern below (Photograph and image interpretation: René Schader)

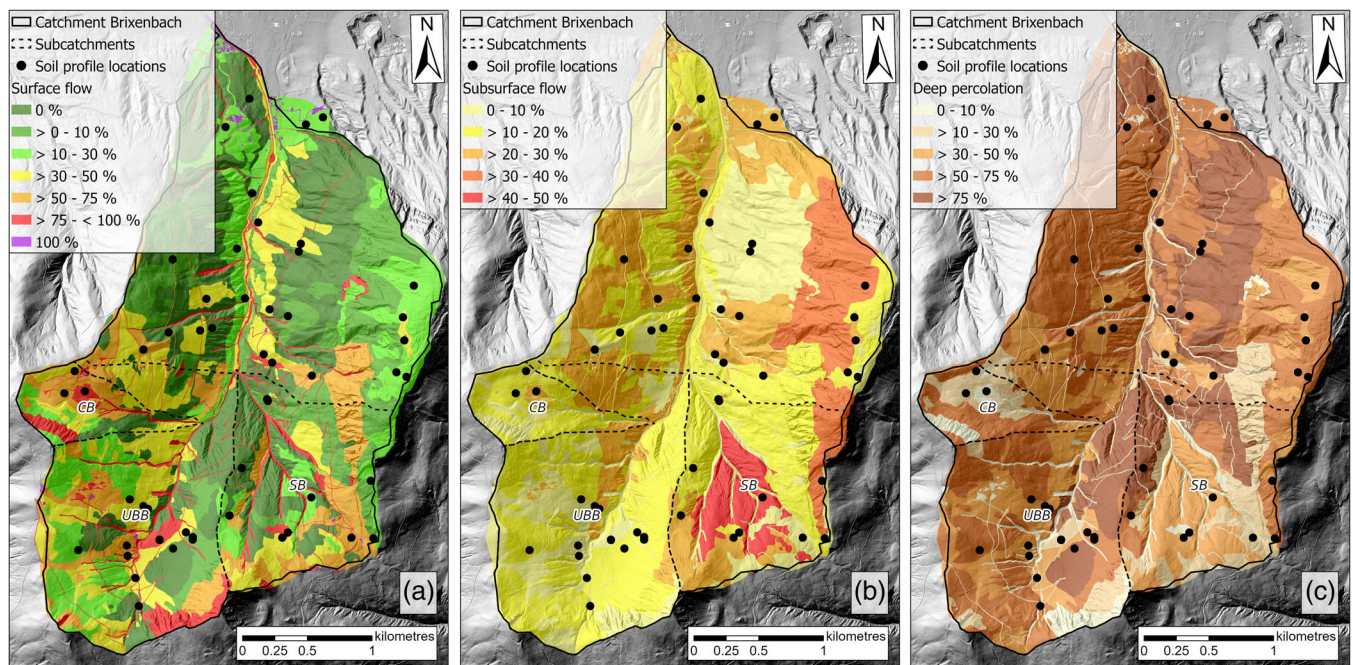


FIGURE 12 Proportions of surface runoff (a), subsurface flow (b) and deep percolation (c) assessed by the soil-hydrological model for the Brixenbach catchment for 1 h-rainfall event (86 mm, return period 100 years), saturated conditions. Surface runoff classes according to Markart et al. (2011). Data source of the background map: Lidar-DTM: Office of the Tyrolean government

4 | DISCUSSION

According to Schmocker-Fackel et al. (2007), soil-hydrological maps can be developed using top-down or bottom-up approaches. Different top-down approaches were introduced, for example, in Great Britain (Boorman et al., 1995; Tetzlaff et al., 2007), Germany (Behrens et al., 2005; Müller et al., 2009; Peschke et al., 1999; Steinbrich et al., 2016; Uhlenbrook, 2003), Switzerland (Dobmann, 2009; Schmocker-Fackel et al., 2007), Austria (Kleibinder et al., 2012; Pirk, 2012b; Tilch et al., 2006) and Canada (Rosin, 2010). They identify homogenous landscape units based on area-wide available data and

provide valuable information on the investigated catchments. However, their application is restricted by the availability of high-resolution input data and/or the transferability of the approaches to other catchments with different process characteristics.

The method we used in this study is a bottom-up approach. They are characterized by the investigation of the runoff generation characteristics on the plot scale and the successive delineation of the surrounding area to which the resulting assessments are transferred (Schmocker-Fackel et al., 2007). Previously published bottom-up approaches, which have been widely used in Alpine and other catchments, are restricted to the assessment of surface flow coefficients

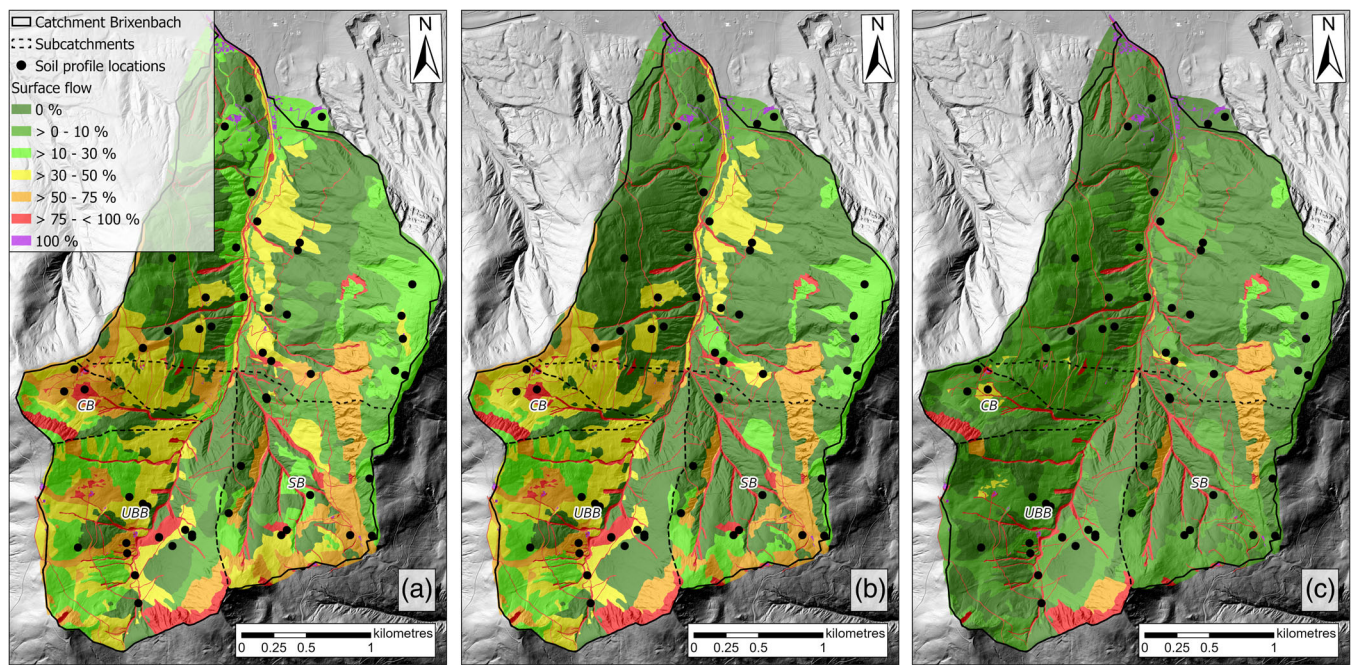


FIGURE 13 Proportions of surface runoff assessed by the soil-hydrological model for the Brixenbach catchment for the 1 h-rainfall event (86 mm) at saturated conditions (a) and dry conditions (b) as well as for the 24 h-rainfall event (170 mm) at saturated conditions (c). Surface runoff classification according to Markart et al. (2011). Data source of the background map: Lidar-DTM: Office of the Tyrolean government

(Markart et al., 2011) or dominant runoff processes on limited land use types (meadows and pastures, farmland, vineyards, forests, Scherrer & Naef, 2003; Scherrer, 2006). The code of practice (DWA, 2020) and the complementary Soil-hydrological model are based on these preceding approaches and extend their applicability to various land use types, different soil moisture conditions and rainfall characteristics.

Here, we reported on one of the first applications of this new Soil-hydrological model (DWA, 2020; Soil-hydrological model, 2020) on 52 soil profiles collected in the catchment. The model helped us to systematically verify our understanding of the hydrological processes in the research catchment Brixenbach. The stated proportion of surface runoff, subsurface flow and deep percolation is the result of different rules developed on the basis of the above mentioned publications and intensive discussions in the expert working group who developed this code of practice (DWA, 2020). Depending on the weighting of rule parameters, the exact value of the runoff process proportion may be subject of discussion. However, the results of the Soil-hydrological model agree well with our process understanding gained in the research catchment from 12 years of field work and data analysis.

Regarding the proportion of subsurface flow, it has to be noted that the Soil-hydrological model is applied on soil profile data and thus calculates the amount of subsurface flow if the percolation is hampered within the soil profile. If the soil shows cross-linked lateral macropores, lateral flow of the retained water can develop (Kienzler & Naef, 2008; Weiler et al., 2005). As the investigated soil profiles usually have a maximum depth of 1 m (due to the high stone content it is

mostly impossible to dig deeper), the proportion of subsurface flow assessed by the Soil-hydrological model refers to a very shallow process. Additionally, a proportion of water which the Soil-hydrological model assigns to deep percolation may in reality form subsurface flow in deeper layers. Nevertheless, for small Alpine catchments (<10 km²) dominated by pastures, which show their maximum peak runoffs during short convective rainfall events, this deeper and thus slower subsurface flow component is of subordinate importance for flood events. However, it may be of high relevance for catchments with large storage capacities in deep-seated mass movements or thick sediment covers which can store large amounts of water, but may overflow during extensive rainfall and therefore react in a threshold manner (e.g., Pirkel & Sausgruber, 2015; Smoorenburg, 2015).

In order to gain area-wide maps, the soil-hydrological assessment of the soil profiles had to be transferred to hydrological response units. The quality of this regionalization depends on the representativity of the investigated soil profile for the HRU to which the assessment of the soil profile is transferred (DWA, 2020). Long-term runoff process observation in our research catchment strongly supported the regionalization procedure. Although we had a large data base containing 52 soil profiles and a high number of measurement dates, still some HRU delineations, especially in hardly accessible parts of the catchment (steep rock slopes), are afflicted with a certain amount of insecurity.

The presented soil-hydrological maps show runoff process proportions for the different HRUs. Such maps help to identify areas producing high runoff yields within a catchment. Comparing runoff process maps of different catchments may classify those catchments

into fast and slowly responding basins. However, it has to be kept in mind that the maps presented here show runoff generation in the HRUs. They do not aim at displaying the modification of the runoff processes along the slope. For example, in the southwestern valley head of UBB south of the precipitation gauge (see Figure 1a), the torrent Brixenbach is flowing in debris flow sediments. There, the torrent is water-bearing only during snow-melt periods and rainfall events. In rainless periods, water of the small brooks from the valley sides infiltrates into the torrent bed due to the coarse debris. Then, only delayed subsurface flow originates from the valley head, which is superficially disconnected from the rest of the catchment. Therefore, in order to assess and display whether, for example, surface runoff infiltrates or subsurface flow exfiltrates on its way downslope, Scherrer (2006) suggests evaluating slope catenae in a next step.

The Soil-hydrological model can be used to display the proportions of surface and subsurface runoff processes at different soil moisture states. In the case of the Brixenbach catchment, the difference between dry and saturated conditions, here shown for surface runoff proportions, is visible, but not very large. Reasons for this are the position of the catchment near the north rim of the Alps and the relatively high altitude resulting in relatively high annual precipitation sums and moderate temperatures, both leading to a low probability for the development of hydrophobic effects due to drying up of organic layers. Vegetation with more or less permanent hydrophobic characteristics such as, for example, dense cover of matgrass (*Nardus stricta*, L.) or organic layers in spruce forests without undergrowth (*Piceetum nudum*) play a subordinate role in the Brixenbach catchment.

As also the runoff reaction to different rainfall durations and intensities can be assessed, the model allows to account for climate-change determined increases of precipitation intensity as reported, for example, by Bürger et al. (2014) and Formayer and Fritz (2016). Different seasonal conditions can be reproduced by using seasonally adapted input parameters (such as degree of soil coverage by vegetation, top soil bulk density for instance due to grazing activity).

However, for the application of the Soil-hydrological model labours, detailed soil surveys and additional measurements (e.g., rainfall simulations) are indispensable implicating higher effort than, for example, for the use of the approach of Markart et al. (2011). In our case, we used an extensive database gained in 12 years of research. Nevertheless, the adaptation of the soil-profile data, gained in different projects with differing survey foci proved to be challenging.

Vereecken et al. (2015: 2628) “are convinced that an improved description of local-scale processes related to soil hydrological fluxes are key to reducing the large uncertainties that are still present in large-scale models used to predict these fluxes”. The Soil-hydrological model exactly meets this demand. For the implementation of the resulting improved process understanding into rainfall-runoff models, a blueprint has to be developed in future. Especially the transfer from the map information into physically-based models is not trivial. Models of the type of the conceptual event model ZEMOKOST (Kohl, 2011; Rogger et al., 2012) show some potential in this respect.

5 | CONCLUSION

The research catchment Brixenbach is a typical small Alpine torrent catchment. 12 years of research have helped to gain detailed knowledge on the runoff processes in the catchment:

- The highest runoff peaks are caused by short convective cells with high rainfall intensity. Maximum runoff measured by the runoff gauge at the catchment's outlet was $17.5 \text{ m}^3 \text{ s}^{-1}$ (specific discharge $1.9 \text{ m}^3 [\text{s.km}^2]^{-1}$).
- Discharge measurements with the salt dilution method during advective rainfall events displayed that the specific discharge of the subcatchments CB (dominated by a relatively large, saturated area) and SB (dominated by forest with shallow soils on rather impermeable geological substrate) increase stronger than the specific discharge of the subcatchment UBB (dominated by pasture sites with compacted topsoils) and the entire catchment BB, to which an extended area with fissured dolomites belongs.
- Surface runoff coefficients gained by repeated rainfall simulations with high precipitation intensity (60 min, 100 mm) significantly raised with increased soil moisture. Infiltration measurements showed the same patterns for pasture sites (Ruggenthaler et al., 2016).
- The catchment shows a threshold behaviour: runoff coefficients above 0.23 only occurred when the soil moisture spatial mean of the eight sites overruns 43.5 vol% (Meißl et al., 2020).
- The application of a new Soil-hydrological model (2020; DWA, 2020) to 52 soil profiles in the catchment and the regionalization of the results to HRUs allowed us to create area-wide maps for surface and shallow subsurface flow proportions and the proportion of deep percolation depending on the soil moisture status (dry, saturated) and rainfall duration and intensity. Selected maps are shown in this paper.
- For the 1 h-event with a return period of 100 years (86 mm), these maps show high surface runoff proportions in UBB and CB (mainly HOF due to cattle grazing) and high shallow subsurface flow proportions in SB. For the 24 h-event with the same return period (170 mm), surface flow plays a subordinate role.
- Subsurface flow velocities measured at a talus slope with dwarf-shrubs were in the range from 2.4 to 3.2 m h^{-1} (Markart et al., 2013).
- The new Soil-hydrological model is a valuable tool to synthesize and verify our long-term results. Its assessment accords well with our field measurements, for example, rainfall simulations. Based on our experiences, the model application in further catchments seems to be promising, but needs extensive field survey. Such further studies might show if and how the rules of the Soil-hydrological model need to be adapted to special soil profiles.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the authors upon reasonable request. Parts of the data that support the findings of this study are available from the Hydrographic Service of Tyrol.

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