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RESEARCH ARTICLE

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Automated streamflow measurements in high-elevation Alpine catchments

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Abstract

Salt dilution is a well-established streamflow measurement method in creeks, which works particularly well downstream of turbulent flow sections as the mixing of the salt tracer is enhanced. Usually, salt dilution measurements are performed manually, which considerably limits the observations of rare peak flow events. These events are particularly important for constructing robust rating curves and avoiding large uncertainties in the extrapolation of streamflow values. An additional challenge is the variability of the river cross section, especially after larger discharge events, leading to nonstationary rating curves. Therefore, discharge measurements well distributed over time are needed to construct a reliable streamflow–water level relationship and to detect changes caused by erosion and deposition processes. To overcome these two issues, we used an automated streamflow measuring systems at three different sites with contrasting hydrological and hydraulic characteristics in the Alps. This system allowed us to measure discharge at nearly maximum flow of the observation period (2020–2021) at all three sites and to detect abrupt changes in the rating curve by performing event-based salt injections. The uncertainty in the measurements was quantified, and the streamflow was compared with official gauging stations in the same catchment. Based on a very large dataset of almost 300 measurements, we were able to evaluate the reliability of the system and identify the primary sources of uncertainty in the experimental setup. One key aspect was the site selection for the downstream electrical conductivity sensors, as measurement location strongly controls the signal-to-noise ratio in the recorded breakthrough curves.

KEYWORDS
automated streamflow measurements, high-elevation Alpine catchments, rating curve, salt dilution

1 | INTRODUCTION

Measuring and recording water level and streamflow of rivers is essential for the dimensioning of water management facilities and for the rational management of water supply as well as for the simulation of hydrological processes with the help of models. While these are basic hydrological measurements, they come with additional challenges in Alpine settings: extremely dynamic fluctuations in streamflow combined with often unstable stream cross sections. Manual streamflow measurements are generally very limited in these catchments because they depend on the frequency of site visits, which are often sparse due to unfavorable weather and snow conditions. This is in direct conflict with the here especially pronounced need for high-resolution data resulting from the high variability of streamflow in space and time (Morgenschweis, 2018), the often short runoff concentration time (Mutzner et al., 2016; Simoni et al., 2011), and distinct seasonal characteristics (i.e., low flows in winter and high flows in summer) (Mutzner et al., 2015). Moreover, sub-daily discharge variations are typically caused by snow and glacier melt cycles in spring and summer (Mutzner et al., 2015; Weijs et al., 2013). Regular discharge measurements are further needed to frequently validate the correctness of the rating curve (i.e., the relation between river stage and streamflow) since rating curves are affected by changes in the river cross section caused by high sediment and coarse bedload transport of glacio-nival rivers (Comiti et al., 2019; Weijs et al., 2013). Morgenschweis (2018) recommended 10–12 discharge measurements per year for natural cross sections with loose sediments. Additionally, regular and high-quality streamflow measurements are particularly important to quantify the uncertainty in rating curves and to understand better how the uncertainty propagates from the measurement to the rating curve (Kiang et al., 2018).

Tracer-based methods (e.g., salt) have been used for the derivation of rating curves in Alpine rivers for many decades (Allen & Taylor, 1923; Moore, 2005; Østrem, 1964). Although a range of water-soluble hydrological tracers can be used (Leibundgut et al., 2011; Morgenschweis, 2018), food-grade table salt (NaCl) is preferred as it is generally nontoxic at the concentrations typically involved in stream gauging (Morgenschweis, 2018; Resources Information Standards Committee (RISC), 2018; Sentlinger et al., 2019). Moreover, the salt injection method is a reliable and relatively cheap technique for measuring discharge in small streams (Gottardi et al., 2006). Although tracer-based methods are simple and relatively easy to use, two main requirements have to be met (i.e., complete mixing of the tracer and mass conservation). Limitations can occur in the application, for example, due to absorption of salt tracer in river sections with a lot of aquatic vegetation, stream water exfiltration to the groundwater and riparian zone, or delay of the breakthrough curve due to pools in the river section (Clow & Fleming, 2008; Moore, 2005). A detailed summary of the method and the individual sources of uncertainty can be found in RISC (2018). If the main requirements are fulfilled, the salt dilution is very accurate with a measurement uncertainty of about 5% (Richardson, Moore, & Zimmermann, 2017; Richardson, Sentlinger, et al., 2017). Hauet (2020) developed a first complete framework for uncertainty quantification of salt dilution discharge measurements following the GUM (Guide to the Expression of Uncertainty in Measurement) method that takes into account all uncertainty sources. Another limitation of the salt dilution method is the measurement of discharges larger than 10 m^3/s since the required amount of salt (i.e., between 5 and 10 kg) can be difficult to be diluted and injected within the time of the event (Richardson, Sentlinger, et al., 2017).

While salt dilution is the discharge measurement method of choice for Alpine systems, we are still left with the challenge of monitoring a system with pronounced dynamics and fast responses under conditions of limited or difficult accessibility. Our proposed solution for this dilemma is the automatization of the salt dilution method. This would remove the need for continuous access to the field sites and would provide a much higher data density and, thus, lower uncertainty of the stage–discharge curve than would be possible with manual measurements.

In this work, we test an automatic salt dilution system for the derivation of robust rating curves in three Alpine catchments characterized by different background electrical conductivities, glaciated areas, streambed gradients, and ranges of discharge. This innovative measurement device allowed us to perform event-based salt injections to capture rare events and to detect abrupt changes in the rating curve. To the best of our knowledge, this is the only commercial automatic salt injection system available. Moreover, we discuss how uncertainties in the measurements can be quantified and reduced.

2 | MATERIALS AND METHODS

2.1 | Research areas and site descriptions

The research sites are located in three high-elevation Alpine catchments in Tyrol/Austria (Horlachtal and Kaunertal) and South Tyrol/Italy (Martelltal). In addition to the already existing stream gauges (triangles in Figure 1) operated by the Tiroler Wasserkraft AG (Kaunertal and Horlachtal) and the Hydrological Office of South Tyrol (Martelltal), we installed new gauges for estimating runoff contribution from side valleys (in the case of Kaunertal and Horlachtal) or at the outlet of the upper Martelltal (see Figure 1 for locations and setup). Each gauge consists of an OTT CTD probe inserted in a 2-in. aluminum pipe attached to larger boulders in the creek. The measurement sites were selected at river sections with cross sections that were assumed to be stable and not too turbulent flows to increase the accuracy of transducer readings. Pool location behind larger rock is ideal to protect the probe from turbulences and debris (U.S. Environmental Protection Agency [EPA], 2014). The sensors log mean values of water level (m), water temperature T (°C), and temperature-compensated electrical conductivity EC_T (μS/cm) to 25°C at 15-min resolution. The OTT CTD sensor accuracy of the actual electrical conductivity EC (μS/cm) is ±0.5%, ±0.1°C for temperature and ± 0.05% full scale (FS) for water level (OTT, 2023). We installed an automated salt injection system (AutoSalt, Fathom Scientific Ltd.) at the same location as the OTT CTDs in order to collect streamflow measurements at different water levels by an automatic event-based configuration of the device. The AutoSalt in Kaunertal was in operation for 1 year, while the other sites collected data for 2 years (Table 1). The AutoSalt in Horlachtal was moved to another sub-catchment (Grastal) in 2022 (Figure 1c), where it was partly destroyed by an extreme event.

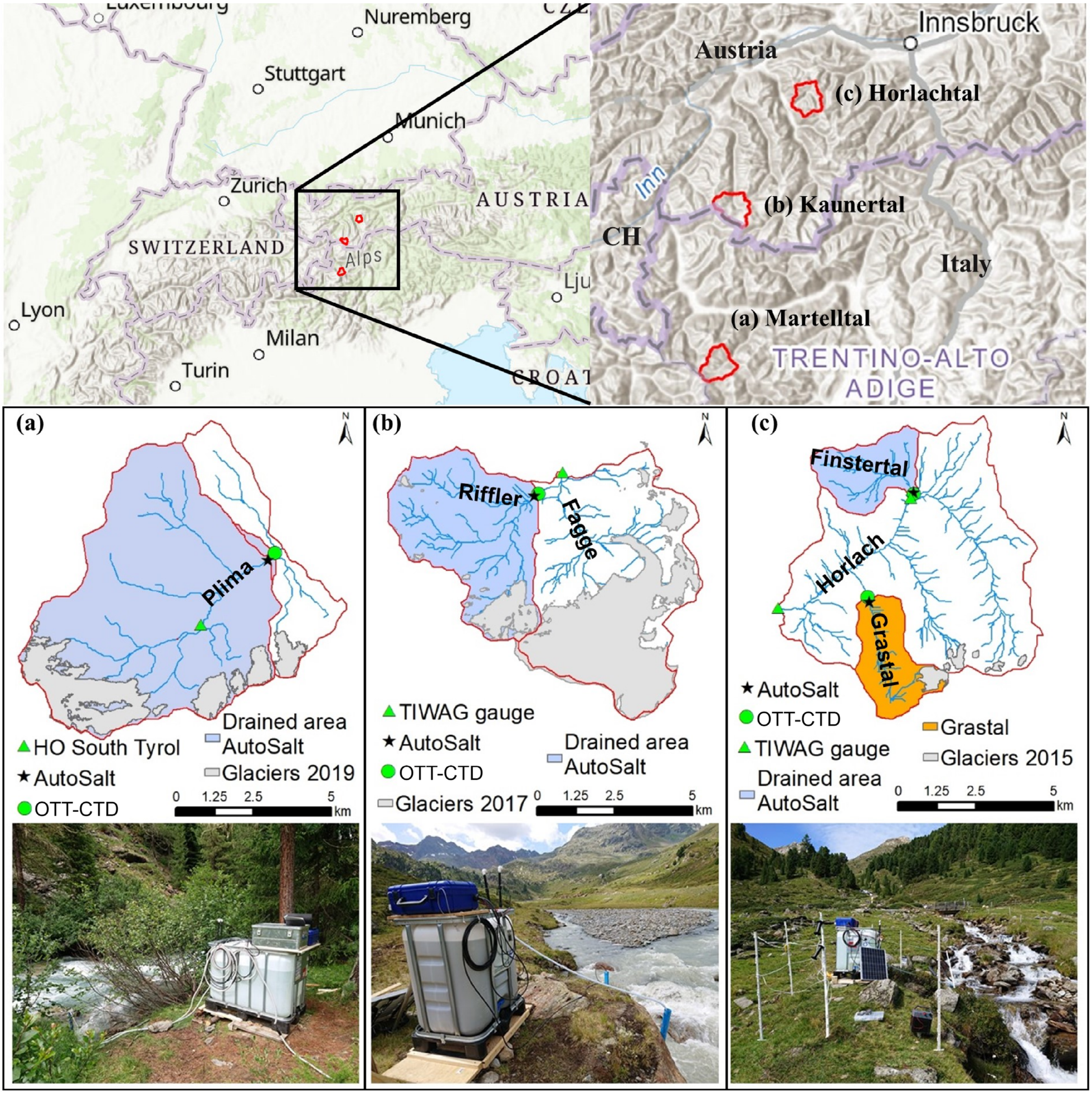

FIGURE 1 Overview maps of the three research areas, that is, (a) Martelltal, (b) Kaunertal, and (c) Horlachtal, with outer borders and delineation of the sub-catchments (red), as well as the drained area of the AutoSalt sites (blue). Green circles indicate locations of the OTT CTD probes, and the green triangles indicate the already existing stream gauges. Lower panel contains corresponding pictures of the AutoSalt system. The orange area in (c) Horlachtal delineates the Grastal catchment where the AutoSalt was moved to from Finstertal (blue area) in 2022. [Color figure can be viewed at wileyonlinelibrary.com]

The main differences between the three monitored catchments are the size of the drained area, the extent of the glaciated area (Buckel & Otto, 2018; Knoflach et al., 2021), the streambed slope, and the background EC_T (Table 1). While the drained area in Martelltal just before the inflow of the Plima into the Zufritt/Gioveretto reservoir is about 50 km^2, the site in Kaunertal at the Rifflerbach drains 20 km^2 and in Horlachtal is a very small side valley (Finstertal) that drains about 6 km^2. Since the mean discharge depends directly on the drained area, higher amounts of salt are needed for one discharge measurement at Rifflerbach and Plima than at Finstertalbach to achieve a noticeable increase in stream EC_T. The streambed gradient of the streambed along the mixing length ranges from 3.9% (Plima) to 4.5% (Rifflerbach) and finally to 18% (Finstertalbach). Further information about the site characteristics is listed in Table 1. The grading of

TABLE 1 Key features of the AutoSalt sites such as drained area (km^2); glaciated area (km^2); elevation of AutoSalt and mean elevation of basin (m a.s.l.); tank volume; distance between AutoSalt, EC_T, and OTT CTD probes; mean slope of the mixing reach; and mean background EC_T (also included are metadata of the measurements such as total number of measurements, highest peak event, proportion of grades [A, B, and C] according to RISC (2018), and dose of the salt tracer [g NaCl per m^3/s]).

Valley stream	Martelltal Plima	Kaunertal Rifflerbach	Horlachtal Finstertalbach
Drained area (km^2)	50.4	19.9	6.2
Glaciated area (km^2)	8.15 (2019)	2.45 (2017)	0.0 (2015)
Elevation of AutoSalt (m a.s.l.)	1917	2192	1982
Mean elevation of basin (m a.s.l.)	2837	2817	2512
Tank volume (l)	600	300	300
Distance between AutoSalt injection and EC_T sensors (m)	200 (right); 210 (left)	79 (right); 82 (left)	57 (right); 67 (left)
Distance between AutoSalt injection and OTT CTD probes (m)	181	51	41
Mean slope of the mixing reach (%)	3.9	4.5	18
Observation period AutoSalt	07.2020–10.2021	07.2021–10.2021	08.2020–10.2021
Mean background EC_T (μS/cm)	205	174	31
No. of Q measurements	78	40	180
Highest measured Q (m^3/s)	17.1	5.9	2
Lowest measured Q (m^3/s)	1.1	0.5	0.1
Share grade A ($\delta Q < 7\%$)	74.4%	95%	73.3%
Share grade B (>7% δQ <15%)	25.6%	5%	26.6%
Share grade C ($\delta Q > 15\%$)	0%	0%	0%
Dose (g NaCl per m^3/s)	400	200	400

streamflow measurements, as listed in Table 1, follows the RISC (2018) hydrometric standards for streamflow measurements. Grade A is for measurements with an uncertainty of smaller 7%, B for the range 7%–15%, and C for uncertainty larger than 15%.

2.2 | Salt dilution method

The salt dilution method is based on the point injection of a solution of NaCl and the measurement of the breakthrough curve of the electrical conductivity downstream (Moore, 2005). The method relies on two key assumptions: (i) mass conservation of the salt tracer and (ii) complete mixing of the salt tracer across the stream width at the location of the EC sensors. The stream discharge Q (m^3/s) can be computed with the following equation:

$$Q = \frac{M}{CF_T * A_{BC}}, \tag{1}$$

where M is the mass of salt injected (kg), CF_T (kg cm /m^3 μS) is a conversion factor, which is the slope of the relation between salt mass concentration in the calibration solution and EC_T (Richardson, Sentlinger, et al., 2017), used for calculating the Q from the EC_T, and A_{BC} (s μS/cm) is the area under the breakthrough curve commonly calculated as

$$A_{BC} = \Delta t \sum_{i=1}^{n} [EC(t) - EC_{BG}], \tag{2}$$

where Δt is the recording interval (s), $EC(t)$ is EC_T as a function of time recorded downstream of the point of salt injection (μS/cm), EC_{BG} is the background EC_T of the stream water, and the summation is carried out over the duration of salt breakthrough curve. Additional information about the salt dilution method is available in many references such as Leibundgut et al. (2011) or Moore (2004).

2.3 | AutoSalt system

The automated salt injection system (AutoSalt) is an autonomous flow measurement system providing discharge data in turbulent watercourses with high temporal resolution. The system usually consists of a control module, a brine tank and stand, a creek pressure transducer (sensor accuracy ±0.1% FS), two high-resolution electrical conductivity sensors (T-HRECS) one for each riverbank, and a salt injection system. EC and temperature (T) sensors downstream of the injection location log the EC, T, and the temperature-compensated EC_T to 25°C. The EC_T records of the T-HRECS sensors are stored on individual SD cards. The measurements are also transmitted wirelessly using LoRa radios to the AutoSalt control module and processed to calculate the streamflow Q and its uncertainty. The uncertainty analysis is

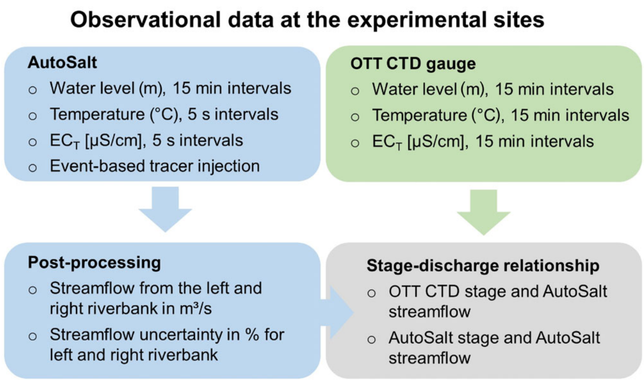

FIGURE 2 Overview of collected observational data, its post-processing, and analysis for each experimental site. The blue box represents the measurements collected with the AutoSalt, and the green box represents the measurements collected with the OTT CTD gauge. [Color figure can be viewed at wileyonlinelibrary.com]

based on the general framework of the GUM (JCGM, 2008) and is described in the supporting information. The detailed EC_T records (set to 5-s interval) are also stored in the SD card on the AutoSalt control module for more detailed quality assurance and quality control (QA/QC) analysis. The brine is delivered from the tank to the creek by a pump through rigid piping with a mechanical flow meter providing feedback on the rate and total amount of brine delivered. The AutoSalt is programmed to trigger salt injections on the falling limb of the hydrograph, as the stage is generally more stable on the falling limb than on the rising limb. The AutoSalt internally calculates Q in real time on the AutoSalt controller. This automated Q value is a good estimate of the measured discharge even though it does not have any QA/QC correcting, for example, for changing background EC_T or missing data. Therefore, external post-processing of the discharge data and its uncertainty quantification are required (Sentlinger et al., 2019). Further information about the AutoSalt system can be found in the latest user manual (Fathom Scientific Ltd., 2020).

The high sensitivity of the T-HRECS sensors (i.e., EC in 0.001 µS/cm and temperature in 0.001°C), the high temporal resolution (5 s), and accuracy (i.e., 0.01% of reading for both EC and temperature) allow us to achieve a high signal-to-noise ratio (SNR), thereby requiring less salt solution than for conventional sensors (Sentlinger et al., 2019). The uncertainty analysis of the AutoSalt system is based on standard equations for error propagation (Sentlinger et al., 2019). The internal grading system of the AutoSalt follows the RISC (2018) hydrometric standards for discharge measurements, which was already introduced. The computed uncertainty corresponds to the 95% confidence interval. Additionally, basic information about the uncertainty quantification of the AutoSalt and equations is provided in the supporting information.

Since we collected various observational data with different sensors at different temporal resolutions and experimental sites, it is beneficial to give an overview of the collected data before presenting the results (Figure 2). Moreover, the observation period of the various sensors differs. The AutoSalt was only in operation over the summer,

TABLE 2 Performed quality checks to test the reliability of the AutoSalt and quality of the collected automatic discharge measurement.

Quality checks	Implemented quality check measure
Test for incomplete mixing of salt tracer	Comparison of the measured values using two EC sensors on the left and right riverbanks
Test for change in the cross section	Rank correlation of the measured river stage values at two different cross sections within the mixing length
Test for noise in stage data caused by wave action	Rank correlation of the measured river stage values at two different cross sections within the mixing length
Test for noise in EC data caused by aeration	Comparison of the values measured using two EC sensors on the left and right riverbanks
	Use of a high-pass filter on the breakthrough curve
Plausibility check of discharge values	Rank correlation with official gauging stations
	Comparison with manual measurements
Assessment of peak events	Comparison between continuous OTT CTD river stage measurements and event-based AutoSalt recordings

Abbreviation: EC, electrical conductivity.

whereas the OTT CTD recorded throughout the year. We set up a stage–discharge relationship with stage data from the AutoSalt and OTT CTD. Thus, there are two stage–discharge relationships per experimental site. We estimated the uncertainty in the OTT and AutoSalt water level measurements by considering the sensor accuracy and the mean hourly *SD* of the water level measurement during steady flow periods. The equation for calculating the relative accuracy of the stage measurements is given in the Supporting information.

Table 2 lists the quality check measures we used to evaluate the reliability and quality of the AutoSalt's measurements. With the EC_T measurements from left and right riverbanks, we checked whether the salt tracer is completely mixed, which is one main prerequisite for a reliable salt tracer measurement. The equation to calculate the uncertainty due to incomplete mixing is given in the supporting information. Additionally, the comparison also allows for checking the influence of air bubbles (i.e., aeration) at the EC_T measurement sites. With an additional high-pass filter, it is possible to increase the SNR of the EC_T breakthrough curves. The redundant stage measurements allow us to quality check the water level measurements and to verify the stage–discharge relationships of each experimental site for possible inconsistencies, such as a change in the cross section. In addition, we performed a plausibility check with the measurements from the AutoSalt by comparing the discharge measurements with data from official gauging stations and performing manual measurements during each site visit. Based on the continuous OTT CTD stage measurements, we assess the recorded peak events with respect to their probability of occurrence.

3 | RESULTS

3.1 | Recorded events by the AutoSalt

The system performed 298 measurements in total, with discharges ranging from 0.1 to 17.1 m^3/s (see also Table 1 for more details). The largest amount of discharge measurements (180) were generated at Finstertalbach since it has the smallest drainage area with a mean discharge of 0.7 m^3/s and hence requires the smallest volume of brine injection. The AutoSalt system at Rifflerbach was only in operation in 2021 and collected 40 discharge measurements with a mean discharge of 2.6 m^3/s. The Martelltal AutoSalt collected 78 discharge measurements with a mean discharge of 4.8 m^3/s. The average relative uncertainty of Q, estimated by the aforementioned uncertainty quantification framework, is 6.2% at Plima, 4.1% at Rifflerbach, and 5.4% at Finstertalbach.

The default dose of the AutoSalt is 200 g per m^3/s. However, for a higher background EC_T or longer transient times, larger doses are recommended. For short transient times and lower background EC_T, the dose can be reduced. At Rifflerbach, we used the default dose of 200 g per m^3/s and increased the dose to 400 g per m^3/s at Finstertal and Plima. The increase in the dose at Plima was necessary due to the relatively long distance between injection and EC_T recording of about 200 m and the high mean background EC_T (205 μS/cm).

Despite the higher dose at Plima, the EC_T peaks were only about 10 μS/cm above the background EC_T as can be seen in Figure 3a. It was possible to derive discharge measurements with lower uncertainty during the peak flow event that occurred at the end of August 2020 due to the clear EC_T signal (i.e., high SNR). However, the EC_T signal shows several small spikes during the rising limb of the breakthrough curve and a slight increase in the background EC_T (Figure 3b). The AutoSalt system performed six discharge measurements during this particular peak event (Figure 3a).

At Rifflerbach, we were able to collect 11 measurements during a peak event, which occurred at the end of July 2021 (Figure 3c). Despite the lower dose of 200 g per m^3/s and a partly noisy background EC_T, the EC_T peaks are well recognizable. The mean EC_T at Rifflerbach was 174 μS/cm during the measurement period 2021. The snapshot shows a clear peak of about 30 μS/cm above the background EC_T with hardly any spikes in the signal (Figure 3d).

We can observe the highest relative change in EC_T (>70%) for injections at the Finstertal (Figure 3e) since the background EC_T is relatively low with 31 μS/cm (Figure 3f). Therefore, the EC_T peaks of the injections are clearly visible. However, the background EC_T signal starts to oscillate when the water level and discharge increase (Figure 3e). The EC_T peaks are still clearly visible, but the stronger oscillations make the processing of the measurements more difficult and lead to higher uncertainty. Therefore, we have decided to set the dose to 400 g per m^3/s at Finstertal.

At each experimental site, the AutoSalt pressure sensor at the site of the injection and the downstream OTT CTD sensor both record the water level at the same 15-min time interval. Depending on the length of the mixing section and flow velocity, there may be a deviation between injection and recording at the downstream sensors of up to 5 min, as in the example of the Plima. Each streamflow measurement of the AutoSalt can be linked with two stage observations, one performed with the OTT CTD sensor and the other with the AutoSalt sensor. We compared the relationship between the two stage measurements in the Supporting information (Figure S1), and we can observe that they are highly correlated (Kendall tau of 0.72 at Plima, 0.74 at Rifflerbach, and 0.81 at Finstertalbach). The Kendall rank coefficient is a nonparametric test and, hence, does not rely on any assumptions concerning the distributions (Kendall, 1938).

The left panel of Figure 4 shows the stage–discharge relationship at all three sites, including the measurement uncertainties of discharge and water level at the downstream OTT CTD river section and the right panel at the AutoSalt section. In addition to the different channel geometries, the stage–discharge relationship also differs because of the aforementioned timing of the measurements and the prevalence of turbulence or wave action at the measurement site, which can lead to noise in the stage signal. The OTT CTD pressure transducer is only located at the deepest point of the cross section at Finstertal. At the other sites, the sensor is not recording the lowest stages in winter. The AutoSalts were not in operation when performing some manual streamflow measurements. This is why a few manual streamflow measurements are only linked with the OTT CTD stage (left panel of Figure 4). Manual and automated measurements do not display particular anomalies and agree with each other. The uncertainty of water level and discharge increases during larger discharge events, especially at the Rifflerbach (Figure 4c). In addition, a jump in the stage–discharge relationship at the 0.3-m water level can be seen in the case of Rifflerbach due to cross section widening where the OTT CTD probe is located (Figure 4c). A change in the geometry of the control section where the OTT CTD probe is located between 2020 and 2021 is already visible at mean discharges at Plima (Figure 4a). The cross section at the AutoSalt is more stable and does not show a change (Figure 4b).

In order to assess at which discharge condition the AutoSalt recorded the most streamflow measurements, we analyzed the percentage of measurements during frequent water levels and discharges, which corresponds to the 25–75 percentile of the continuous stage observation recorded by OTT CTDs (Figure 5). At Plima, most measurements (55%) were collected during frequent water levels and discharges. Most measurements were collected during higher water levels at Rifflerbach (43%) and Finstertalbach (28%). Consequently, lower stages (<0.25 m) are underrepresented at Rifflerbach and Finstertalbach. The pronounced seasonality of runoff in high-elevation catchments is the reason for the underrepresentation of low flows as the AutoSalt is not in operation during the winter period. The percentile of the recorded peak event is 0.99 at Plima, 0.98 at Rifflerbach, and 0.99 at Finstertalbach. Accordingly, the recorded streamflow peaks are slightly lower than the recorded maximum stage peaks in the respective observation period.

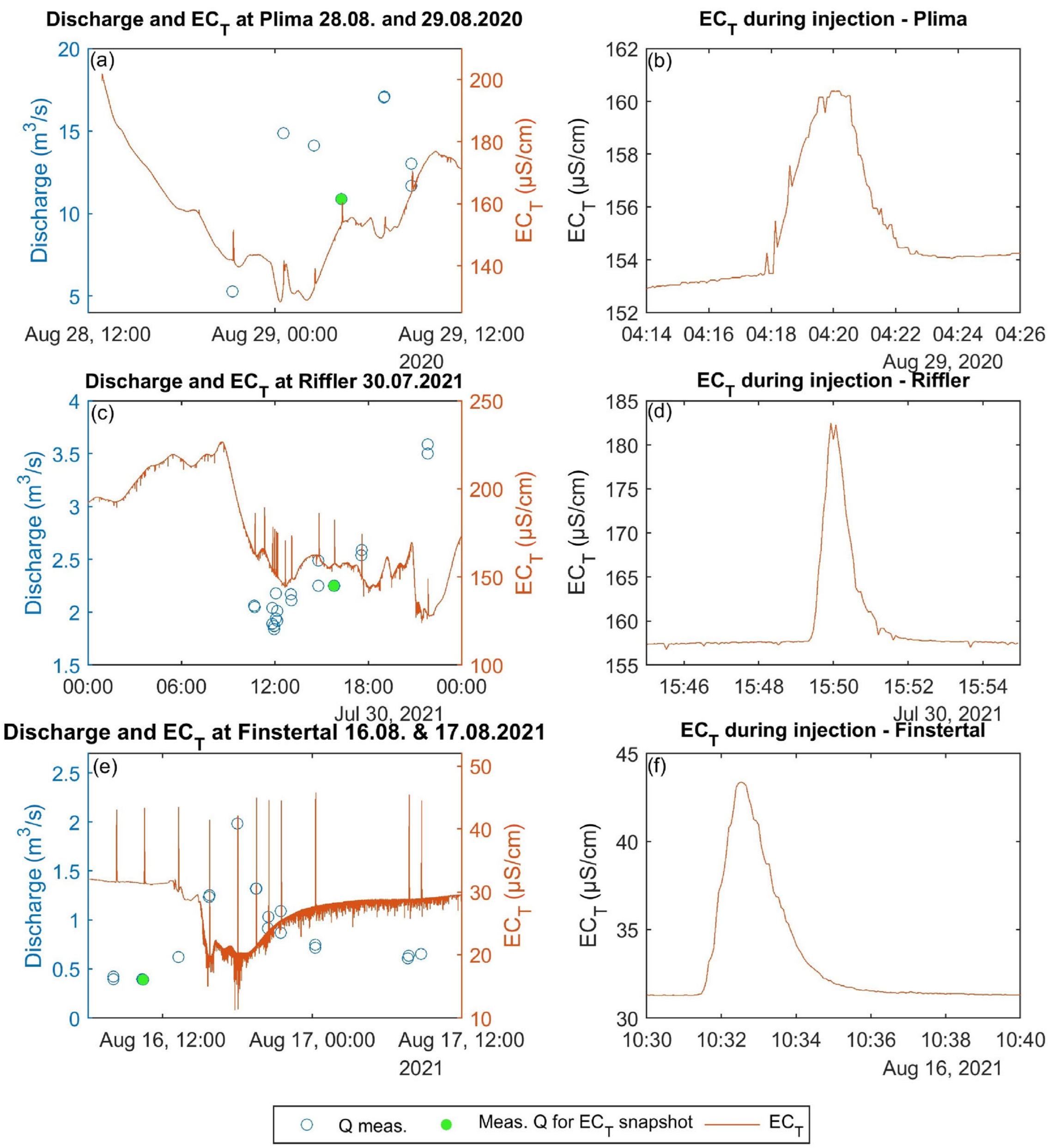

FIGURE 3 Snapshot of measured discharge (blue dots) and EC_T (orange line) at each site: (a) Plima, (c) Rifflerbach, and (e) Finstertalbach, as well as a detailed snapshot of an exemplary EC_T breakthrough curve (green dots) of the corresponding sites, i.e., (b) Plima, (d) Rifflerbach, and (f) Finstertal. [Color figure can be viewed at wileyonlinelibrary.com]

3.2 | Quality of the AutoSalt measurements

Since the measurement uncertainty is available for each riverbank in addition to streamflow, we examined whether there is a systematic correlation between streamflow magnitude and uncertainty or a difference between the left and right banks. The left panels of Figure 6 illustrate the dependence of discharge uncertainty on discharge magnitude for both stream banks separately (i.e., the right or left bank from orographic view). Generally, the uncertainty is mostly below 5%. Larger measurement uncertainty (>10%) occurs sporadically at certain discharges and not always on both riverbanks. There is no systematic correlation between discharge magnitude and uncertainty (i.e., Kendall tau of 0.36 at Plima, 0.24 at Riffler, and 0.07 at Finstertal). Rather, the SNR at different water levels and the presence of turbulences are decisive for a low measurement uncertainty. The right panels of Figure 6 show the observed discharge by the already existing stream gauges and the discharge recorded by the AutoSalt. The discharges of the already existing gauges are not based on simultaneous measurements but are extracted from the discharge time series available at 15-min resolution or 10-min resolution in the case of Plima. Since we do not have the rating curves of the existing gauges, we cannot make any statement about the uncertainty regarding the discharge time series. The highest agreement (Kendall tau of 0.86) was found for the official discharge observations at Horlach Fassung and AutoSalt at the Finstertal site (Figure 6f), which is located only about 65 m upstream of the Horlach Fassung gauge. For the

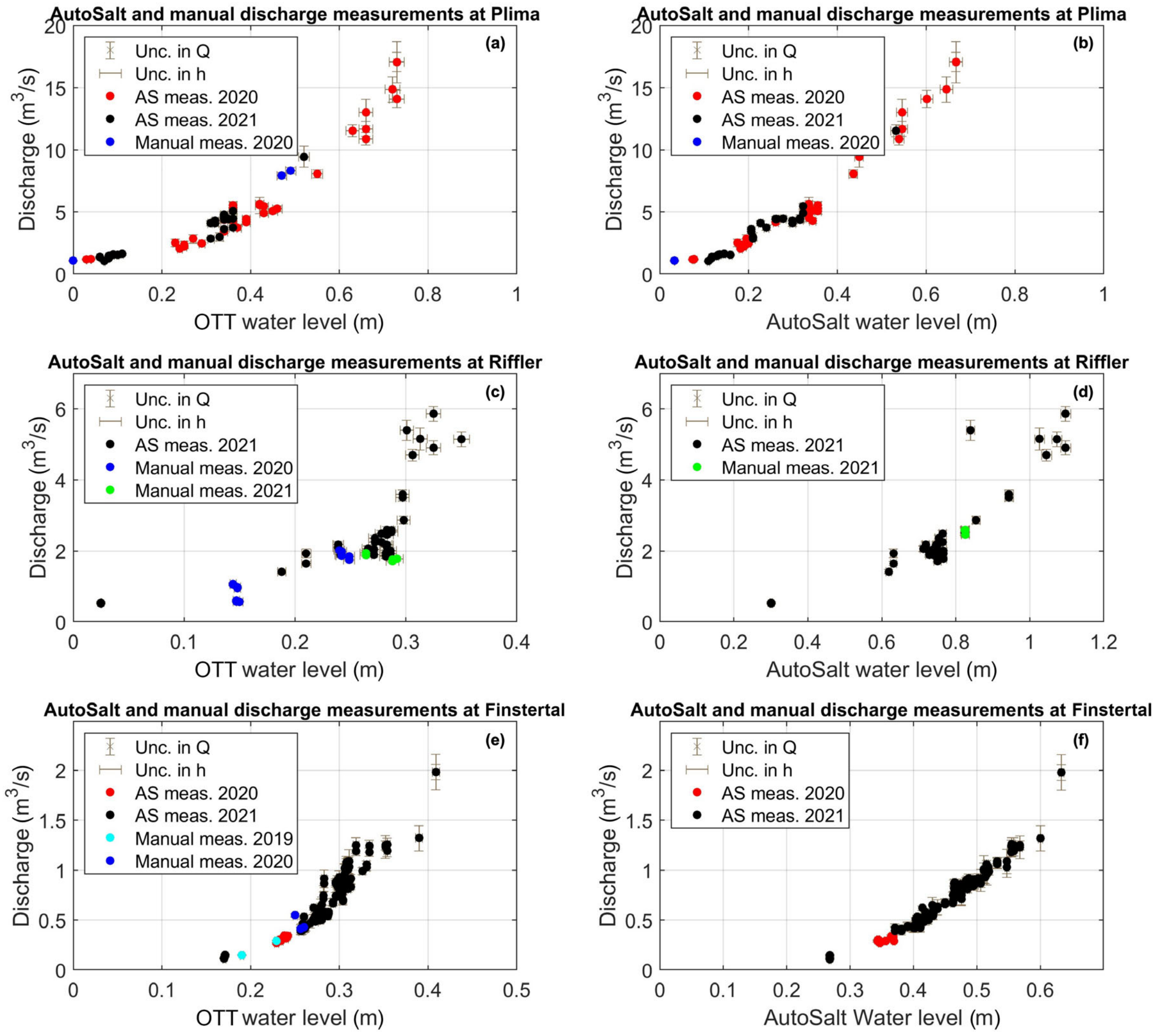

FIGURE 4 The left and right panels show the stage–discharge relationship of the salt dilution measurements with stage recorded by OTT CTD (AutoSalt stage), including the measurement uncertainties at the three sites (a and b) Plima, (c and d) Rifflerbach, and (e and f) Finstertalbach. AS, AutoSalt measurements. [Color figure can be viewed at wileyonlinelibrary.com]

Plima, the official stream gauge is about 3.8 km upstream of the AutoSalt injection site. There is predominantly only good agreement at lower and medium discharges (<7 m^3/s) (Figure 6b). At higher discharges, the scatter increases. Nevertheless, a Kendall tau correlation coefficient of 0.8 is achieved. At the Riffler stream, the distance between the two discharge observation sites is smaller (about 1.3 km) than at the Plima. However, the discharge magnitudes recorded at the Gepatschalm gauge and the AutoSalt injection site differ significantly (Figure 6d), which results in a Kendall tau of 0.76. The reason for the discrepancy is the larger share of the glaciated area at the Gepatschalm gauge compared to the AutoSalt site.

We moved the Finstertal AutoSalt to another sub-catchment (Grastal) of Horlachtal in order to collect discharge measurements to efficiently set up a stage–discharge relationship at Grastalbach in 2022. The Grastal is characterized by steep topography and a high activity of debris flows (Rom et al., 2023). The AutoSalt started to perform discharge measurements in the mid of July 2022 (Figure 7). About 1 week after installation, the system was partly destroyed by an extreme event. A storm event has not only triggered a fast flood wave but also activated debris flow, which transported debris into the creek. The highest observed peak in the stage of the downstream OTT CTD probe was reached in less than 2 h (i.e., time to peak). The AutoSalt made an injection at the highest peak, but at this point, the injection hose and the pressure transducer of the AutoSalt were torn away by the debris flow. Therefore, we cannot compute the discharge of the peak flow. Nonetheless, thanks to the continuous monitoring of the device, we can estimate the time of the change in the cross section and assume that the change occurred during the peak flow of the first event of July 19.

4 | DISCUSSION

4.1 | Recording of peak flow

The AutoSalt system recorded close to the peak discharges at all experimental sites in the observational period. However, it is unclear how reliably the AutoSalt works at discharges >20 m^3/s. The extreme

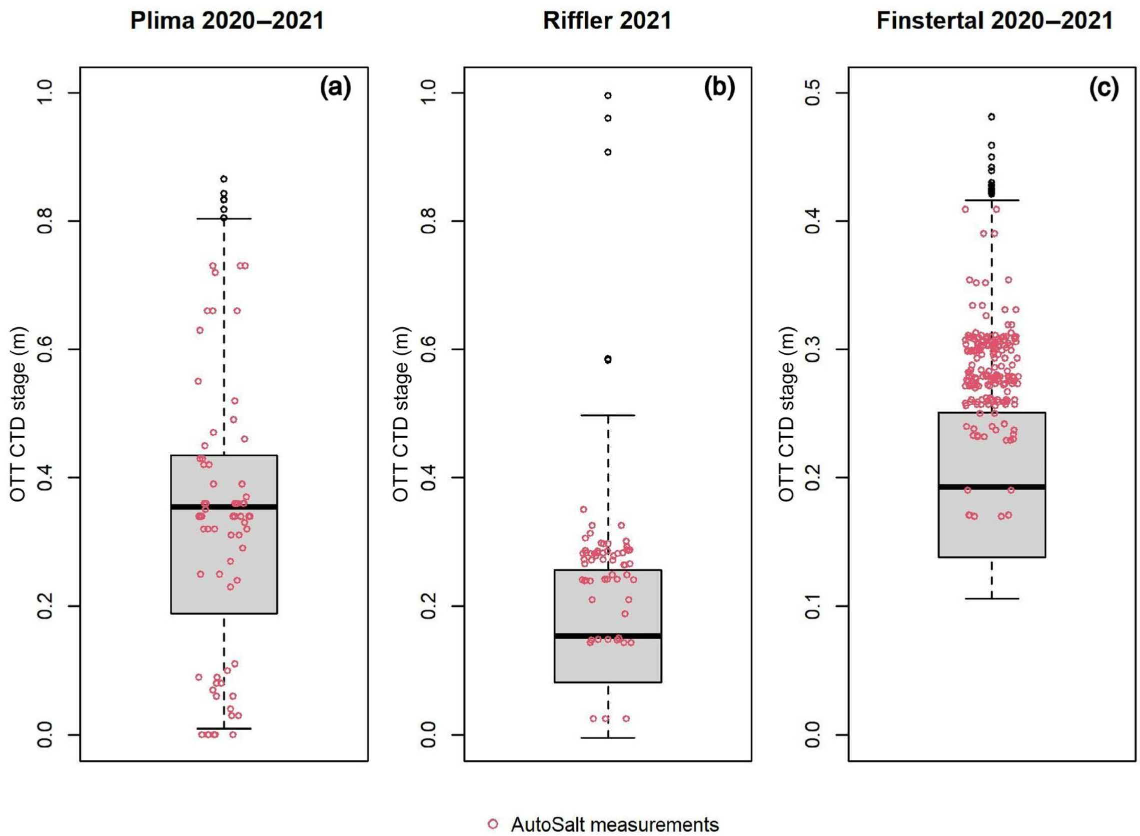

FIGURE 5 The boxplot shows the entire OTT CTD stage during the observation period and the stages at which AutoSalt measurements (red dots) were taken at each site: (a) Plima, (b) Rifflerbach, and (c) Finstertalbach. [Color figure can be viewed at wileyonlinelibrary.com]

case at the Grastalbach demonstrates the risk associated with these events, which would make the manual acquisition of any data impossible, while the AutoSalt system was able to retrieve some important information such as the rate of increase in the water level. The collected high-discharge events are especially important for the construction of robust rating curves. The highest discharge measurements were made slightly below peak water levels since the AutoSalt performs the measurements on the falling limb of the hydrograph. We observed some variability in the highest recorded discharge values at similar water levels, as seen, for example, at Rifflerbach (Figure 4c,d). In addition, the pronounced noise in the stage measurements at Finstertalbach (Figure S2) also leads to scatter in the stage–discharge relationship (Figure 4e,f). The reason for the noisy stage signal at Finstertalbach is the relatively high streambed gradient (i.e., 18%), which results in a highly turbulent flow with pronounced wave action at the measurement sites. The two other experimental sites have distinctive lower streambed gradients (i.e., 3.9% at Plima and 4.5% at Rifflerbach), which result in less turbulent flow (Figure S2).

Another important aspect of measuring peak flow events with the AutoSalt is the time interval between two injections. The default interval between two consecutive injections is 1.5 h, which ensures that the tracer measurements do not interfere with each other. Under good mixing conditions (e.g., high flow velocity and turbulence), the time interval can be reduced to allow a higher number of measurements during a peak flow event. At Rifflerbach, for instance, the breakthrough time was about 3 min, as shown in Figure 3d. Therefore, we reduced the interval to 0.5 h. Although the system is autonomous and can be operated remotely, site visits should be at least monthly to ensure reliable operation of the system by checking the system's functionality and calibrate the system (e.g., brine concentration, flow meter, and EC_T sensors) if necessary.

4.2 | Changes in cross section

The large number of discharge measurements recorded by the AutoSalt allows us to identify changes in the cross section from 1 year to another, as is the case at Plima (Figure 4a). This will enable us to quality check the rating curve and have a valid rating curve for each observational year or before and after each relevant hydrological event that can modify the river cross section. We could only observe the change in the cross section at the downstream river section, where the OTT CTD is located, and not at the injection site (Figure 4b), showing the possibility of very local effects that can lead to uncertain streamflow observations. Even after the complete change of a cross section, as was the case at Grastalbach, the AutoSalt systems enable a quick and efficient collection of discharge measurements for setting up a new stage–discharge relationship.

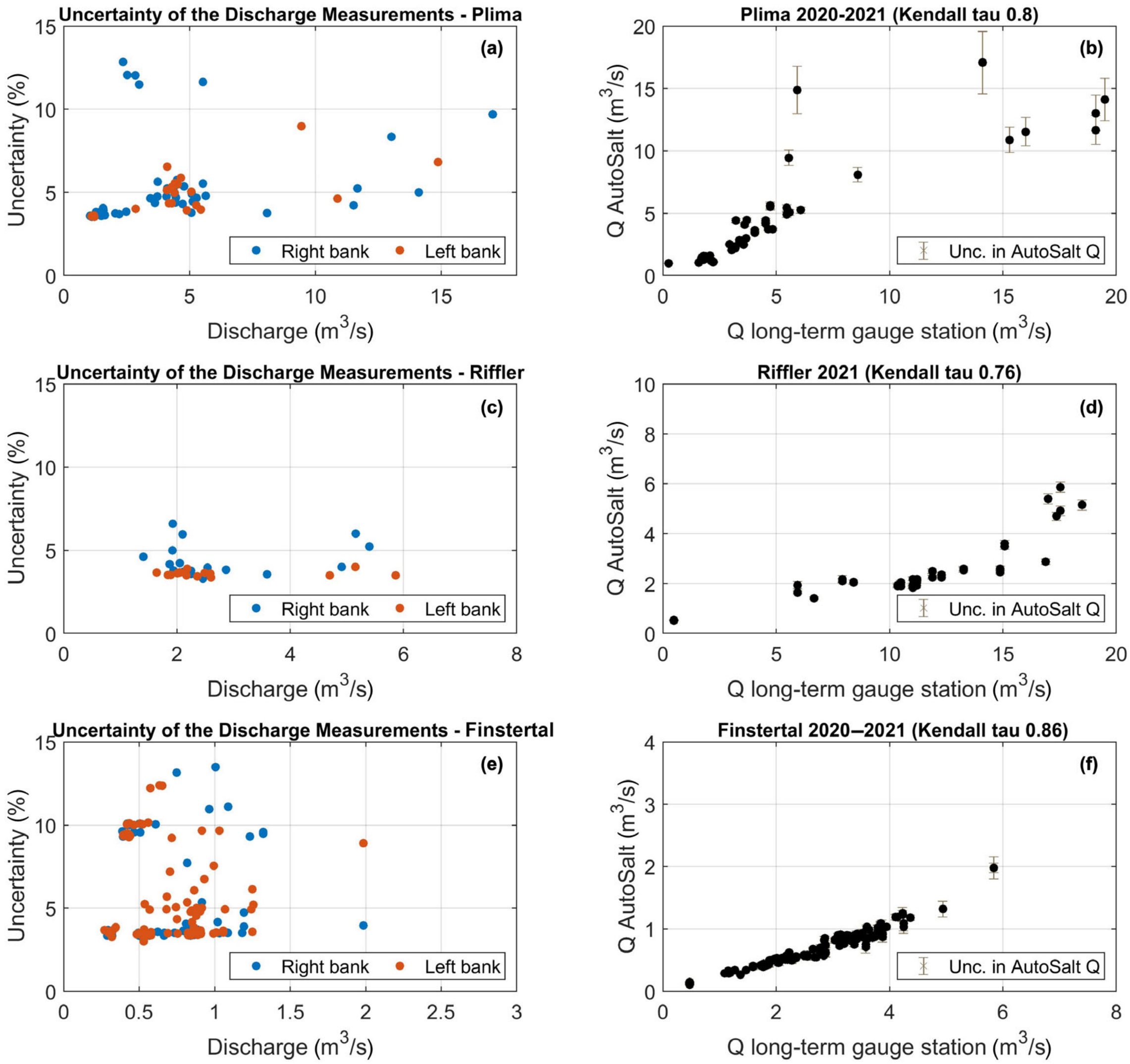

FIGURE 6 The left panels show the uncertainty of the discharge measurements of the AutoSalt observed at the right (blue dots) or left (red dots) bank at the respective experimental sites: (a) Plima, (c) Rifflerbach, and (e) Finstertalbach. The right panels show the observed discharge by the already existing stream gauges versus the discharge recorded by the AutoSalt at the respective sites and when the AutoSalt performed a measurement at (b) Plima, (d) Rifflerbach, and (f) Finstertalbach. [Color figure can be viewed at wileyonlinelibrary.com]

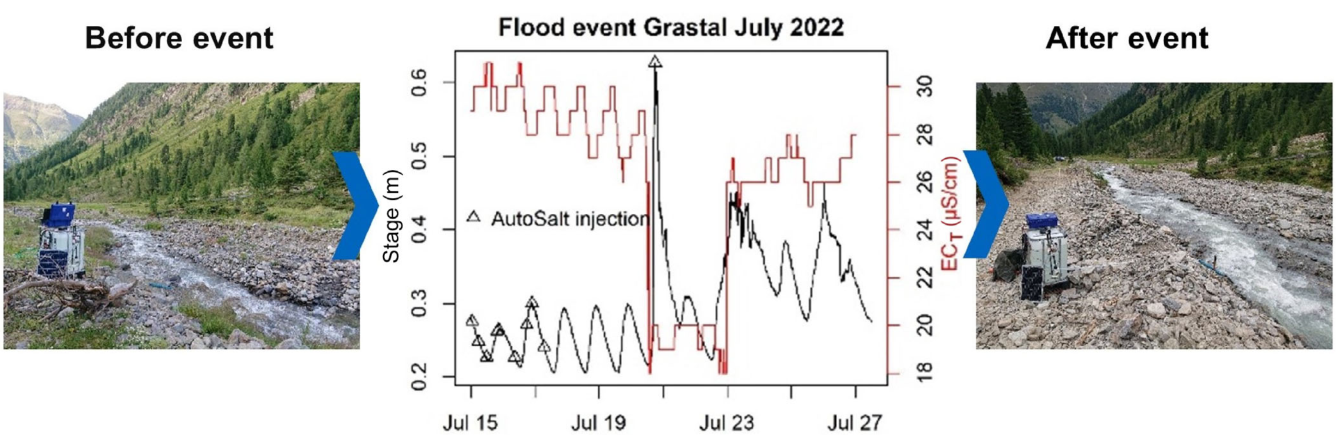

FIGURE 7 AutoSalt monitoring of a combined extreme event of flood and debris flow in a high-elevation catchment (Grastal) in July 2022. The graph shows the recorded downstream stage and EC_T of an OTT CTD probe as well as the salt injections performed by the AutoSalt. The change in the river channel as a result of this event can be seen by comparing the two photos. [Color figure can be viewed at wileyonlinelibrary.com]

Moreover, we can detect segments within the stage–discharge relationship between mean and high flow conditions, specifically for the Rifflerbach at about 0.3-m stage (Figure 4c). The segments can be considered in the construction of a three-segment rating curve with an optimal rating curve fit for low, mean, and high flow conditions (Horner et al., 2022).

4.3 | Contrasting experimental sites

We obtained good results with the AutoSalt at all three experimental sites, which differ strongly concerning discharge and stage ranges, glaciated area, channel geometry, and background EC_T. As mentioned, the injection quantity depends directly on the expected streamflow quantity, which in turn depends on the catchment size. Thus, the AutoSalt is well suited for smaller catchments (<10 km^2) since a larger number of measurements are possible with one reservoir filling (i.e., 300 L). However, it is also possible to upgrade the system (e.g., 600 L), as we did at the Plima in 2021. Accordingly, it is possible to perform about 60 injections with a dose of 400 g per m^3/s for a high-elevation catchment with 50 km^2 and a mean discharge of about 5 m^3/s. The range of collected discharge measurements was largest at Plima (from 1.1 to 17.1 m^3/s), followed by Riffler (from 0.5 to 5.9 m^3/s) and Finstertal (from 0.1 to 2 m^3/s).

It turned out that the selection of the sites for the EC_T sensors is essential for controlling the SNR and hence the measurement uncertainty, as shown in the left panels of Figure 3. We installed the sensors as close as possible to the riverbed (but ensured that there was no sediment accumulation inside the sensor casing) to reduce the influence of aeration and prevent the sensors from falling dry at low flows. Nevertheless, it cannot be ruled out that the flow behavior changes depending on the water level, resulting in increased turbulence and consequently introducing noise in the data due to waves and aeration, as was the case at the Finstertal site with the steepest streambed gradient (i.e., 18%). Depending on the background EC_T and turbulences at EC_T monitoring sites, the injection dose can be increased to achieve a higher SNR. In the end, the selection of the injection dose is a compromise between the efficient use of the salt brine and a sufficiently high SNR, which allows a relatively low measurement uncertainty (<7%). Since unstable background EC_T, as seen in Figure 3b, can lead to higher uncertainties in the discharge measurements, we have considered its uncertainty in the post-processing (i.e., the deviation between pre- and post-background EC_T). This is particularly relevant when a measurement extends over several minutes while the background EC_T changes quickly, like at Plima (Figure 3a).

While we performed regular manual measurements at each site visit, those were often under very similar streamflow conditions (Figure 4). Nevertheless, they are very helpful in verifying the automated measurements since they have less uncertainty in the injected mass. In some cases, the manual measurements can deviate from the stage–discharge relationship, as visible at Rifflerbach (Figure 4c). At low discharges with low turbulence, there may be deviations because of incomplete lateral mixing of the salt tracer.

It is noticeable how EC_T drops abruptly during larger precipitation events at all three measuring sites (Figure 3a). The natural background EC_T in streams as a predictor for discharge was already observed in previous studies (Cano-Paoli et al., 2019; Chang et al., 2022; Weijs et al., 2013), and therefore, the collected continuous EC_T values of the AutoSalt system and of the OTT CTD probe could be further used beyond the event-based observations to generate EC_T-based gauging station.

5 | CONCLUSION

By using the AutoSalt, it was possible to perform continuous and event-based streamflow measurements in high-elevation Alpine areas at very different locations. Rare peak discharges of almost 20 m^3/s were measured with the system. The mean measurement uncertainty of the almost 300 measurements is in the majority (81%) below 7%. Larger measurement uncertainties resulted from low SNR due to turbulence at the EC_T measurement sites. The low SNR occurred particularly at the experimental site with the largest streambed gradient (i.e., 18%), where turbulence and wave action affected EC_T and stage measurements independent of the discharge magnitude. In addition, the noise in the stage observations transfers to the stage–discharge relationship. Consequently, we could only find a correlation between the measurement quality and the streambed gradient as the only site-specific characteristic. Moreover, we could not find a systematic correlation between discharge magnitude and measurement uncertainty. Therefore, the sensor locations should be thoroughly selected in river sections with a high streambed gradient to establish a reliable stage–discharge relationship at creeks in high-elevation catchments. Another benefit of the collected measurements of the system was the detection of nonstationarity in the cross section, which is a particular challenge for establishing reliable stage–discharge relationships on creeks with natural cross section.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there may be a conflict of interest as Gabriel Sentlinger works for Fathom Scientific Ltd., which also develops and distributes the AutoSalt system.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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