University of Zurich[UZH]

# Seasonal and event-based changes in the flowing stream network of temporary rivers in the Reppisch catchment: Comparison of manual mapping and data from sensors.

GEO 511 Master's Thesis

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## Abstract

Temporary streams are streams and rivers that lack surface flow during certain periods of the year. They are present all over the world and their occurrence is predicted to increase in the future. However, their importance for hydrological and ecosystem functions has only recently been investigated.

As temporary streams start to flow, the flowing stream network expands and as they dry up the stream network contracts. This thesis aims to understand flowing stream network expansion and contraction for two neighbouring catchments, the Diebis and Bleiki in the Reppischtal in the Canton of Zurich, Switzerland. The study used two methods: field mapping in both catchments, during which the sections of the stream network were classified according to flow type, and automatic data collection with a monitoring system in the streams of the Diebis. These methods were applied for two timescales, seasonally, with regular mapping and measurements over an 11-week period, and after single-events to determine the suitability of these methods for the study of temporary streams.

The behaviour of the flowing stream density and the patterns of expansion of the two catchments differed on a seasonal scale. This difference can be explained by the topographic characteristics and by the difference in the levels of human disturbance of the two catchments. The analyses for single-events could not be performed as planned because of problems due to the malfunctioning of the flow sensors and the reduced functioning of the electrical resistance sensors from the monitoring system. However, the study highlights the large differences in stream network expansion and contraction for neighbouring catchments. Thus, it is necessary to conduct studies in multiple catchments to come to a robust understanding of the hydrologic behaviour of temporary streams in a region.

The methods used are complementary and suitable if they work as planned. The field mapping has a good spatial resolution which helps in particular for the seasonal analysis but is not suitable for the analysis of single-events. For this, the high temporal resolution of the monitoring system is very useful. However, the uncertainties of these two methods have to be considered as well. In particular, the subjectivity of the determination of the flow type and the variability of the conditions during the field mapping sessions have to be considered. Regarding the sensors, the largest uncertainties are due to the need for spatial interpolation because the data are recorded only at specific locations and due to external disturbances of the registration of data because of sediments or other changes in the stream conditions.

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# 1. Introduction

## 1.1. Temporary streams: definition and role

Temporary streams are rivers that lack surface flow for a certain period of the year and are therefore characterized by periods of drying and wetting. These characteristics set them between fully aquatic and fully terrestrial ecosystems (Mc Donough et al., 2011). The flow duration is the main element differentiating temporary from perennial streams (Hansen, 2001). This is influenced by more factors than the precipitation events over a certain area, such as the soil composition, the geology, the land cover type of a certain area and the human disturbance.

Temporary streams in humid climates are generally small headwater streams. An estimate by Downing et al. (2012) indicates that around 75% of the total global length of streams is composed of rivers with a width smaller than 1.8m. Larned et al. (2010) add that at least 60% of the total river length in the conterminous United States are temporary rivers. At least 43% of the rivers in Greece (Tzoraki & Nikolaidis, 2007) and large proportions of long rivers in Italy (Doering et al., 2007) are temporary rivers. Also, Lohse et al. (2020) confirm that in dryland regions, temporary streams are the dominant flow regimes. Even if these values are not perfectly measurable, they are still indicating that temporary streams are largely present on a global scale. A recent study by Messager et al. (2021) suggests that 51-60% of the length of all the streams in the world are temporary streams. In the future, the number of temporary streams is expected to increase due to climate change and water withdrawals. Döll & Müller Schmied (2012) investigate how climate change influence flow regime patterns during the coming years. They find that a shift from perennial to temporary streams or in the other direction will happen in several areas of the world. An opposite trend towards more perennial streams in the cold areas occurs because of the reduced time of frozen water. Therefore, it can be expected that these areas may come back to a temporary stream status in the future if the warming continue causing even more aridity also in these areas.

The abundance of temporary streams is not the only important factor about them. In fact, the mixture of ecosystem characteristics in temporary streams implicates that they are habitats of terrestrial and aquatic plants and animals. Additionally, they are biogeochemical hot spots allowing the processing of materials and connecting with perennial streams (McDonough et al., 2011). The communities in these types of rivers are usually generalists, but depending on the phase of flow intermittence, specialists may be present. In case of strong evolution, they may even enhance the biodiversity. However, when the flowing phase is strongly variable, the diversity of the community is lower than for the perennial streams; it is at a similar level, or even higher because of habitat heterogeneity, where the flowing phases are long-lasting (Stubbington et al., 2017). According to Acuña et al. (2017) there are therefore four biodiversity elements that are enhanced by temporary streams, they 1) harbour aquatic organisms that gain adaption capacities to drying periods; 2) harbour terrestrial organisms that use dry riverbeds for refuge and foraging are attracted; 3) are used as corridors by terrestrial biota; and 4) harbour fauna that needs higher moisture and vegetation presence.

The value of temporary streams is not only given by their biological role. In fact, they are important for the integrity of the whole network as they allow for the lateral exchange of nutrients and organisms between the channel and the areas with vegetation beside it (Acuña et al. 2017). Wohl (2017) adds that temporary streams, as typical headwater streams, cover various important aspects of the functioning of the whole river network. They are a source of water, solutes, mineral sediment, and particulate organic matter. Also, their water chemistry is important because of being strongly influenced by the upland flow paths which are reacting rapidly to changes in land cover or atmospheric inputs. In addition, headwaters are the first defence against contaminants such as excess of fine sediment or nutrients. Finally, headwaters are important for the connectivity between different parts of a drainage basin, in particular, considering the fluxes of water, sediment, and dissolved solutes.

The importance of temporary streams is very high, but the protection that they should receive is still debated (Acuña et al., 2017; Wohl, 2017) as they are difficult to define (and map) because of their varying conditions. It is recognized that the number of temporary rivers is expected to increase because of climate change and the extraction of water by humans. However, policies, protection and management plans are applied differently in every country because of the differences in their definitions (Wohl, 2017). Additionally, the management and understanding of temporary streams are poor as they are often treated as perennial streams (Acuña et al., 2017).

Although the importance and abundance of temporary streams have been recognized for a long time, their study has often been neglected. Only in recent years the interest of ecologists and hydrologists in temporary streams increased (Larned et al., 2010). To improve the surveillance and inventory of temporary streams, the available methods and new methods have to be implemented (Larned et al., 2010; Acuña et al., 2017). The typical methods used for specific areas, such as mapping based on topographic maps, aerial images or field surveys, are time intensive and often subjective so that they are not suitable for large areas (González-Ferreras & Barquín, 2017). For this reason, modelling techniques are being developed. However, they require large networks of monitoring systems, which are often not placed at temporary streams because of the low interest in their dry phases (González-Ferreras & Barquín, 2017; van Meerveld et al., 2020).

## 1.2. Definition of intermittent, ephemeral and episodic streams

Temporary streams are distinguished from perennial streams because of the absence of flow during certain periods of the year. It is possible to make a more detailed differentiation of streams in this category: intermittent, ephemeral and episodic streams.

McDonough et al. (2011) define intermittent and ephemeral streams as follow: "*Intermittent streams flow seasonally in response to snowmelt and/or elevated groundwater tables resulting from increased periods of precipitation and/or decreased evapotranspiration*" and ephemeral streams as: "*those that only flow during and in immediate response to precipitation events*". The difference between these two categories is not large. Figure 1 highlights an important element of differentiation, the groundwater table. It is for parts of the year above the bed of intermittent streams, while it is below the bed for the entire year for ephemeral streams.

Finally, episodic streams flow only in response to extreme precipitation events and may not flow for several years (Uys & O'Keeffe, 1997). For this reason, episodic and ephemeral streams are quite similar in the conditions of the groundwater table being below the bed. Additionally, they do not only have sporadic surface flow, but also sporadic surface water presence.

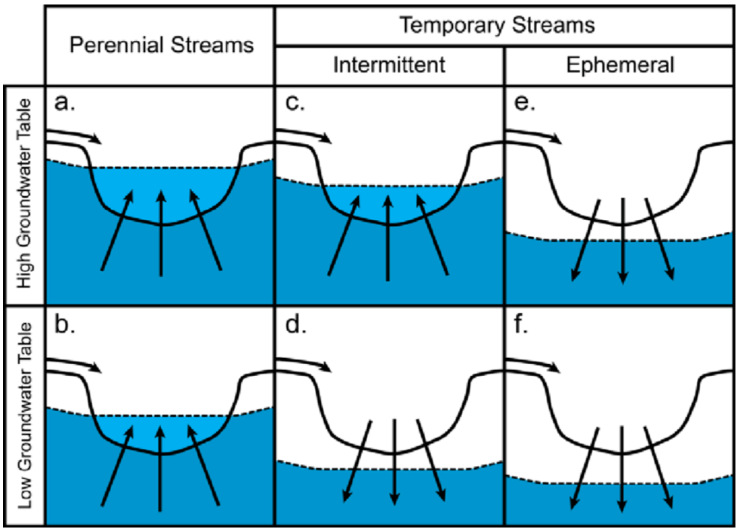



***Figure 1*** *Groundwater table characteristics for perennial, intermittent and ephemeral streams during wet periods (top) and dry periods (bottom) (Source: McDonough et al., 2011).*

## 1.3. Streams dynamic: expansion and contraction

The dependence of flow in temporary streams on precipitation events and seasonal changes in groundwater levels implicates strong stream dynamics (Godsey & Kirchner, 2014). This results often in a fast expansion and contraction of the stream network, which vary spatially depending on the type of precipitation event and on the conditions prior to this event (Peirce & Lindsay, 2014). For example, snowfall events or snowmelt are important factors in pre-alpine and alpine areas (Stähli et al., 2021; Paillex et al., 2020). In particular, the vegetation type and the cover of the areas have a direct influence on the snow conditions (Stähli et al., 2021). The variability of expansion between stream networks is often given by the geological and topographic characteristics of the catchment, where the type of soil or the steepness play fundamental roles (van Meerveld et al., 2019; Ward et al., 2018). Finally, the land cover of the catchment influences also the streamflow of the network and thus its expansion and contraction (Jensen et al., 2017).

There are several factors influencing the dynamics of the stream network and their effects result generally in three patterns of expansion and contraction (Figure 2) (Bahmjee & Lindsay, 2011; Peirce & Lindsay, 2014): “bottom-up” (Bahmjee & Lindsay, 2011; Peirce & Lindsay, 2014; Goulsbra et al., 2014), “top-down” (Bahmjee & Lindsay, 2011; Peirce & Lindsay, 2014; Goulsbra et al., 2014; Day, 1978) and “coalescence (or disjointed)” (Bahmjee & Lindsay, 2011; Peirce & Lindsay, 2014; Day, 1978). The three patterns are often observed for the expansion process of the stream network, while for the contraction the “bottom-up” pattern is not visible (Peirce & Lindsay, 2014).

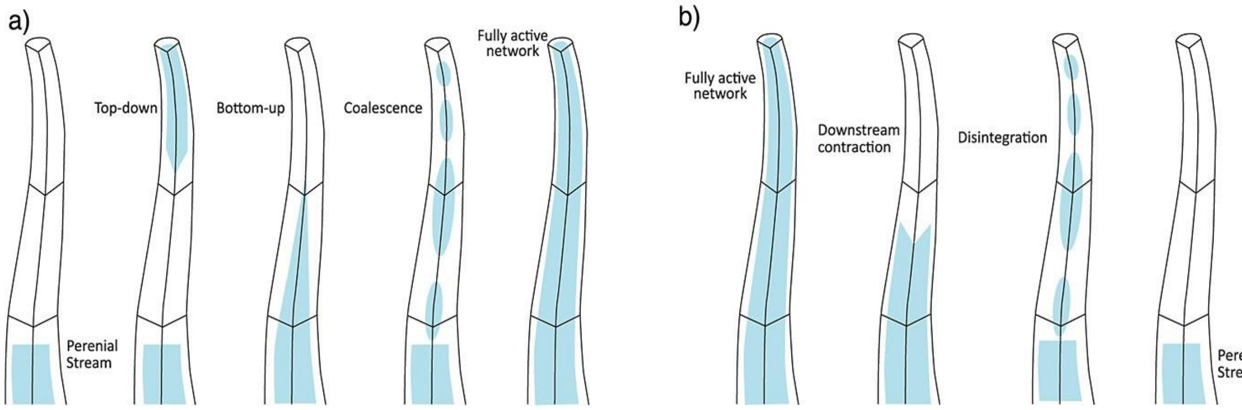



***Figure 2*** *Stream network patterns for a) expansion and b) contraction (Source: Peirce & Lindsay, 2014).*

The “Bottom-up” expansion pattern describes the filling of the streams of the network starting from the lowest parts of the network and expanding towards the top when the channel bed becomes saturated (Peirce & Lindsay, 2014). This pattern often results from the groundwater table rising and the point where the groundwater table intersects the surface progressively moving upslope (Goulsbra et al., 2014). This pattern is mostly related to the seasonal changes in wetness conditions.

The “top-down” expansion is the opposite and happens when the water from the saturated hillslopes converges into a temporary stream, and consequently flows downstream until reaching the perennial parts of the network at lower elevations (Peirce & Lindsay, 2014; Goulsbra et al., 2014). In this case, the pattern is often observed on the occasions of precipitation of high intensity or in catchments whose terrain has a low infiltration capacity (Peirce & Lindsay, 2014). The contraction pattern of stream networks often follows a downstream direction, therefore a “top-down” pattern, because the groundwater level and consequently the saturation of the terrain decrease.

The last pattern is “coalescence (or disjointed)” and takes place when several pools along the stream connect to one another, expanding the segments of the stream having surface flow. This expansion can continue in an upstream and/ or downstream direction. The reason for this pattern is related to the physical characteristics of the area, for example, saturated hillslopes or depressions at some locations of the stream can create pools and can allow their connection. The contraction of the network happens for the same physical reasons with a disjointed pattern. Parts of the terrain of the network are less saturated earlier than others (Peirce & Lindsay, 2014; Goulsbra et al., 2014) or because of permanent groundwater inflows in parts of the catchment.

The three patterns depend on spatially variable factors, such as the geology, topography, and land cover, and can occur at different time scales (e.g., bottom-up pattern due to seasonal changes in wetness conditions and a top-down pattern for single events). For this reason, every catchment is characterized by different patterns depending on the combination of the factors influencing them.

## 1.4. Monitoring of temporary streams: sensors and mapping

The monitoring of temporary streams and the collection of data on them is very limited as the methods that are used are difficult to apply on large scale and on strongly varying streams. Gauging stations are often placed at perennial streams or are covering temporary streams only seasonally (Peters et al, 2012). The sensors often does not indicate all the characteristics of the streamflow or the water presence to completely understand temporary streams (van Meerveld et al., 2020; Zimmer et al., 2020). An alternative approach is the mapping of these streams through satellite imagery and modelling them based on field mapping of the catchments. However, field mapping only gives partial information on all the characteristics of streams and is often subjective (Jensen et al., 2018). Day (1978) and Blyth & Rodda (1973) already measured the expansion and contraction of streams with the help of simple methods. These allowed for only a low temporal and spatial resolution because of the limited possibilities of the observer to be in the field. Finally, an additional approach is the collection of data from crowdsourcing or citizen science. The collection of data from crowdsourcing or citizen science offers a large amount of direct visual observations. However, the quality of the observations still has to be better evaluated (van Meerveld et al., 2020; Acuña et al., 2017).

Bhamjee & Lindsay (2011) explain that a comparison of the value of the different methods should be done based on the purpose of the study and looking at the spatial and temporal resolution of the data. In the case of measuring the stream network, the spatial resolution is related to the density of detectable changes in an area. The limitations are given by the cost of the survey (e.g. material, travel, etc.) and by the practicality, which means that it is not possible to gain more useful information by investing more in the method used. The temporal resolution refers to the shortest event that can be measured. This is limited by the type of data logger used or by the reachability of a certain area for a fast enough field mapping survey.

### 1.4.1. Sensors

Temporary streams are rarely monitored with gauging stations (van Meerveld et al., 2020). Gauging stations which measure the water level continuously and convert it to streamflow based on a rating curve are not suitable for temporary streams. They are not suitable for temporary streams because of the high sediment load which causes the rating curve to change. Furthermore, gauging stations are not designed to differentiate between flowing water and standing water. Therefore, they are not suitable for temporary steams since temporary streams usually have a low level of streamflow and often form pools of water (Bhamjee & Lindsay, 2011; van Meerveld et al., 2020). Portable current meters or repeated salt dilution gauging may be more suitable for these types of streams. However, they require the presence of a person, which reduces the spatial and temporal resolution of the data. The costs are an additional problem.

The water level can also be measured with pressure transducers or optical and acoustic sensors that send a light or a sound towards the water surface. The main problem for this type of measurements is the presence of debris and sediments below the sensors, which results in wrong depth values. Also, erosion during storms leads to the same problem, so that a regular new determination of the "level zero" has to be done.

Floats are an alternative method usually used within stilling wells. They are also helpful to measure the stage in temporary rivers. Unfortunately, floats also present several problems. Firstly, they are complex to be installed. Secondly, their functioning with a vertical movement and the stabilization at the maximum height requires the direct observation by a person which reduces the temporal resolution and the spatial resolution. Still, the spatial resolution can be higher than for other sensors (Bhamjee & Lindsay, 2011).

The development of inexpensive electronic devices in the 1990s enabled the creation of new sensors that allow for higher spatial resolution because of the lower costs and higher temporal resolution from the automated functioning (Bhamjee & Lindsay, 2011). Among these devices, there are temperature sensors and electric resistance sensors (Bhamjee & Lindsay, 2011; van Meerveld et al., 2020). The temperature sensors placed below the channel bed allow the researcher to determine the presence or the absence of water according to the temperature. However, sudden variations in air temperature make the data highly variable and difficult to analyse. This method was improved by the electric resistance sensors as the difference in conductivity between wet and dry streambeds is significantly higher than the temperature difference. In particular, placing them above the surface allows for a better determination of the state of the stream (Bhamjee & Lindsay, 2011).

The multi-sensor system developed by Assendelft & van Meerveld (2019) tries to combine several of the existing sensors, allowing for the differentiation between standing water and flowing water. The initial tests of these sensors have shown promising results, even if a broad use has still to be developed because of the investment needed for the development and maintenance of the sensors (van Meerveld et al., 2020). The specific components of this multi-sensor system are four low-cost sensors: the electric resistance sensor, the temperature sensor, the float switch sensor and the flow sensor. These sensors are connected to a microcontroller board with a data logger shield to register the data in the terrain (Assendelft & van Meerveld, 2019).

### 1.4.2. Mapping

Several studies on specific areas have used topographic maps, aerial images, and field surveys to map the distribution of temporary rivers (González-Ferreras & Barquín, 2017). The field surveys imply long walks along the stream network to map all the streams (Godsey & Kirchner, 2014; Jensen et al., 2017). This methodology of mapping temporary streams is therefore not suitable for large areas (González-Ferreras & Barquín, 2017) and the time resolution is low (Kaplan et al., 2019). In fact, it is labour-intensive and subjective. The time resolution is limited by studies being often conducted only seasonally or in uneven intervals during dry periods or after precipitation events (González-Ferreras & Barquín, 2017; Kaplan et al., 2019).

Although field surveys are not considered an optimal method for mapping temporary streams, it remains one of the most accurate. The recent development of geospatial data and analysis of aerial images is still not sufficient to compensate for the limitations of this methodology. In fact, aerial images are often giving a timely limited indication of the temporary streams, as they are taken at a single moment. In addition to that, the vegetation cover is often a limiting factor to determine the wetness of the soil and these better-performing methods are often expensive (Jensen et al., 2018).

In recent years, a different approach to compensate for the subjectivity and the difficulty to map large areas has been applied more widely. With the help of modelling techniques, there is a combination of data from sensors and standard mapping techniques. Many of the statistical modelling methods are now conducted with data from gauging stations (González-Ferreras & Barquín, 2017). An alternative approach in this field is the automatic extraction of streams from the digital elevation models (DEMs). However, this does not lead to consistent identification of smaller streams. The logistic regression determining the probability of the presence of a stream has been more successful, but mostly for perennial streams and less for temporary streams (Jensen et al., 2018).

### 1.4.3. Comparison sensors and mapping

The two methodologies to collect information about temporary streams have several advantages and disadvantages. None of the methods has the capacity to guarantee a complete image of the characteristics of temporary streams. The temporal and spatial resolutions are often a limiting factor combined with resource problems and output completeness (Figure 3; Bhamjee & Lindsay, 2011). For this reason, the methods are often combined to obtain the best results given the specific scope of the research.

| Sensor | Spatial res. | Temporal res. | Cost | Calibration time | Data processing | Output |
|---|---|---|---|---|---|---|
| Current meter[1] | Very low | Very high | Very high | High | Low | Velocity |
| Wading rod[1] | Low | Low | High | High | Low | Velocity |
| Observation[2] | Low | Low | Low-high | Low | High | Flow state |
| Press. transducer[3] | Low | High | High | High | Low | Stage |
| Optical/audio[3] | High | High | Low | Low | Med | Stage |
| Floats (stilling well)[3] | Very low | High | High | Low | Low | Stage |
| Floats (modified) | High | Very Low | Low | Low | Low | Stage |
| Temp. sensor[4] | Very high | Low-high | Low | High | High | Flow state |
| ER sensor[5] | Very high | Low-high | Low | Low | Low-high | Flow state |

***Figure 3*** *Characteristics of methods used to collect data about temporary streams (Source: Bhamjee & Lindsay, 2011).*

## 1.5. Research questions and hypotheses

This thesis aims to better understand the variability of stream network dynamics within a single catchment and between two neighbouring headwater catchments in the Reppischtal near Zurich in Switzerland. Additionally, I try to evaluate the two methods of data collection: manual mapping during field surveys conducted seasonally and after single-event precipitations, and the automatic multi-sensors system (Assendelft & van Meerveld, 2019) installed in one of the two studied catchments. I compare the patterns of stream network expansion and contraction for the two catchments to evaluate the factors influencing the dynamics of the stream networks.

The specific research questions are:

1. How variable are the flowing stream density and the pattern of stream network expansion and contraction across two headwater catchments in the Reppischtal? And can the differences in stream network dynamics between the headwater catchments be explained by land cover, topography, or other spatial characteristics?
2. Is the pattern of stream network expansion similar at the seasonal and single-event time scale?
3. How much of the variation in stream network density can be captured by repeated mapping in comparison to the collection of data by automatic sensors?

My hypotheses for the three research questions are the following:

1. The stream network dynamics differ and are related to the degree of human disturbance (e.g., the road network and drainage) and the topography in the catchments.
2. The seasonal flowing stream network expansion follows mostly the bottom-up pattern, while event-based stream network expansion resembles the top-down pattern more (Godsey & Kirchner, 2014; Goulsbra et al., 2014; Peirce & Lindsay, 2014). The contraction patterns are in both cases mostly top-down.
3. The derived two flowing stream densities are different for the two methods and this difference is largest for the precipitation events.

# 2. Material and methods

## 2.1. Study area

### 2.1.1. Location

The two studied catchments are located in the municipality of Stallikon ZH on the southwest-facing slope of the Uetliberg in the west of Zurich in Switzerland. The northern catchment is called the Diebis and the southern is called the Bleiki. Both streams drain small catchments, eventually flowing into the Reppisch, the main river of the Reppischtal where the two catchments are located. The Diebis catchment is located between 513 m asl and 839 m asl, while the Bleiki catchment is between 537 m asl and 801 m asl. Both catchments contain areas which are part of the forest reserves in Switzerland. They have the goal of developing the biodiversity with specific human interventions such as the cutting of trees, which allows a renewal of forests, or specific studies in the terrain by universities and by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) (BAFU, 2020).

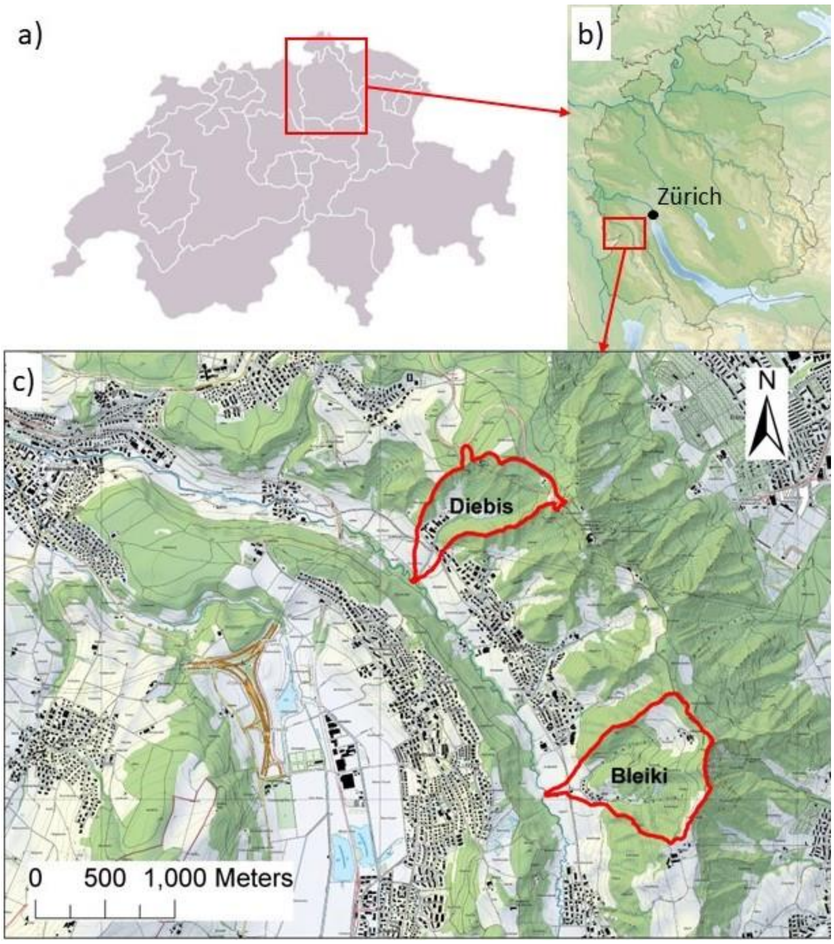



***Figure 4*** *Location of the two studied catchments Diebis and Bleiki (Basemap from the Map viewer map.geo.admin.ch of the Federal Office of Topography swisstopo).*

### 2.1.2. Climate

The climate of the area is estimated according to the newest climate diagrams and normals from the period 1991-2022 for the measuring station of Fluntern, which is located ca. 7–8km east of the two catchments as the crow flies. The climate is temperate with a yearly average air temperature of 9.8°C, varying between 0.9–1.8°C during the coldest winter months (December-February) and 17.1–19.0°C during the warmer summer months (June-August). During the period of data collection for this thesis, the climate normals of the mean temperature start from 10.0°C in October, descend during the winter months, and increase to 9.6°C in April. The yearly mean precipitation is 1108mm, which is below the general estimated Swiss mean of 1500mm. From May until August a higher precipitation amount is varying between 120–128 mm/month, while the winter months are much drier, in particular January and February with 63 mm/month and 60 mm/month respectively. During the period of data collection, the precipitation is expected to start from 85 mm/month in October, descend in January and February and rise to 80 mm/month in April (Federal Office of Meteorology and Climatology MeteoSwiss, 2022). Regarding the snow precipitation during the winter, which influences the stream conditions of the area during the data collection period, it is difficult to interpret it from the data of the Federal Office of Meteorology and Climatology Meteoswiss. The area presents strong variation because of the elevation being often at the edge between the change from rain to snow. Even on a small spatial scale, as it is the distance between the catchments and the measuring station, it is not possible to assume that those values perfectly describe the conditions in the catchments. According to the Federal Office of Meteorology and Climatology MeteoSwiss (2022), in Fluntern there is normally 72 cm of new snow per year concentrated between October and April.

***Table 1** Summary of the most relevant climatic normals for the Diebis catchment, measured at the weather station of Meteoswiss in Fluntern (Source: Federal Office of Meteorology and Climatology MeteoSwiss, 2022).*

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T [°C] | 0.9 | 1.8 | 5.8 | 9.6 | 13.6 | 17.1 | 19.0 | 18.6 | 14.4 | 10.0 | 4.9 | 1.7 | 9.8 |
| Max T [°C] | 3.5 | 5.2 | 10.2 | 14.8 | 8.8 | 22.4 | 24.3 | 23.9 | 19.1 | 13.8 | 7.6 | 4.0 | 14.0 |
| Min T [°C] | -1.4 | -1.2 | 1.9 | 5.1 | 9.0 | 12.6 | 14.4 | 14.3 | 10.7 | 7.1 | 2.5 | -0.5 | 6.2 |
| Sum P [mm] | 63 | 60 | 71 | 80 | 128 | 128 | 126 | 119 | 87 | 85 | 76 | 83 | 1108 |
| New snow [cm] | 14 | 18 | 10 | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 7 | 19 | 72 |

### 2.1.3. Vegetation and land cover

The two catchments present several land cover types which are relatively similarly distributed in the two studied regions.

In the upper part, there is a mixed deciduous forest in both areas, which also contains mixed coniferous trees in some parts. The types of trees influence the vegetation on the soil and the smaller trees which are more developed in the deciduous areas. In the forested areas, human presence is relatively low, especially in the Diebis where there are only a few small hiking paths and even smaller traces. In the Bleiki, on the other hand, there are a few larger paths which can be used by vehicles.

Both catchments present several open meadows, the ones in the middle of the forests are generally quite wet. In the Bleiki, there is at the highest point a big open area with a farm and meadows used for the activities of the farm. In the lower part of the catchments, the open meadows are larger and often used for pasture of the neighbouring farms. Along the streams that reach the Reppisch there are small lines of forest.

In the middle part of the catchments between the large areas of forest and the big open meadows at the bottom, the streams are more exposed than the other areas to human activities and are even partly canalized, or in the Bleiki partly buried. In this part, there are industrial buildings in the Diebis catchment while the Bleiki presents a small residential area. These buildings are connected with asphalted streets which start from the main road going along the Reppischtal and cutting transversely both catchments. Finally, the highest border of the Diebis catchment is determined by the road and by the railway reaching the station of the Uetliberg.

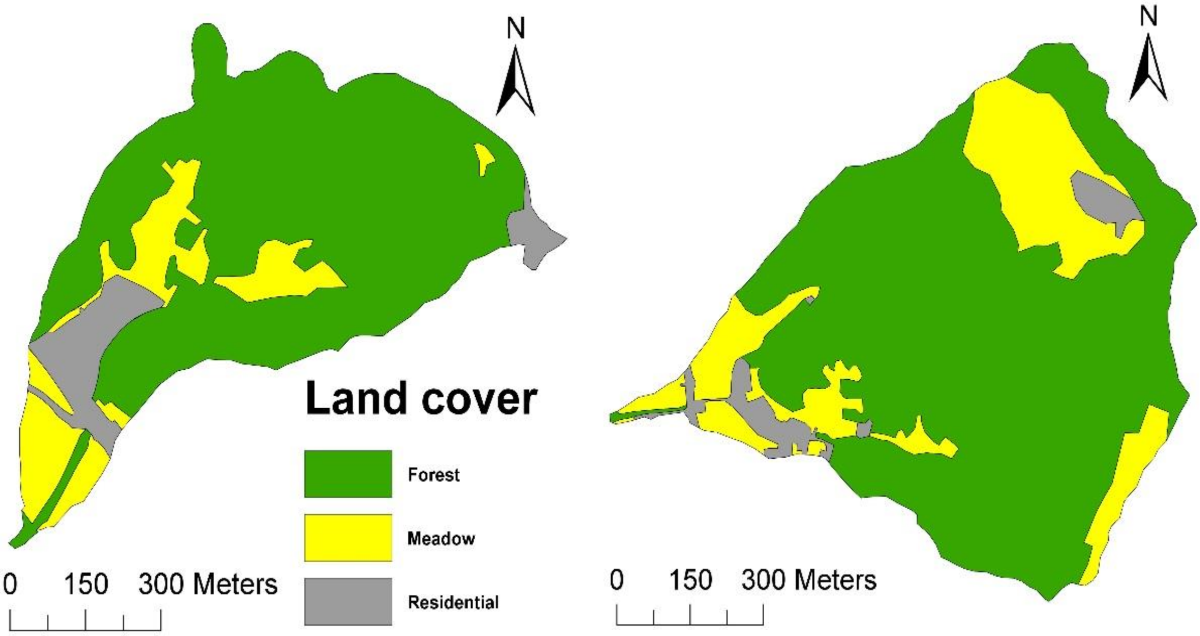



***Figure 5*** *Land cover type of the two studied catchments Diebis (left) and Bleiki (right). Land cover derived from SWISSIMAGE (2015) of the Federal Office of Topography swisstopo.*

### 2.1.4. Geology, soil and topography

The area around Zurich, and thus the Reppischtal, consists mainly of rocks of the upper freshwater molasse. The Reppisch has eroded up to 100m of rock soils in the molasse with the melting water during the last ice age. The valley is filled with loam washed away from the slopes of the Uetliberg. At the bottom of the slopes, there are screes with fine-grained material coming from gullies eroded in the upper parts of the slopes. Looking in more detail at the parts of the catchments, the ridges are composed of marl and marl sandstones with carbon-rich sandstones and conglomerate. Inside the valleys, there is the loam from the slopes mixed with the material deposits falling from the slopes. In the zones below the main street, there is loam and alluvial material. In the highest zones of both catchments, there are areas of moraine and landslide (Pavoni et al., 2015).

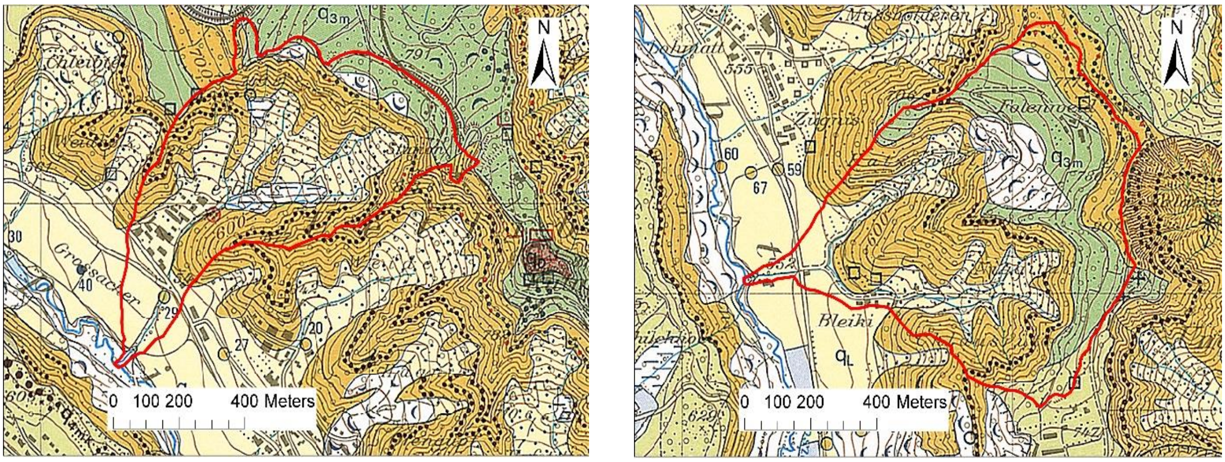



***Figure 6*** *Geology of the two studied catchments Diebis (left) and Bleiki (right). Orange: marl and marl sandstones; green: moraine; yellow: slope loam; white with dashed lines: marsh, white with curved lines: landslide (Source: Federal Office of Topography swisstopo, Geological Atlas of Switzerland 1:25'000).*

The geology of the two catchments reflects several characteristics of the topography. In Table 2 it is shown that the mean slope inclination is quite high with 24.6° for the Diebis and 22.2° for the Bleiki. This high inclination explains the large quantities of material that are transported from the slopes and deposited on the flatter areas close to the Reppisch river in both catchments. The main topographical difference between the two catchments is the presence of two steep valleys in the Bleiki, while the Diebis is characterized by one main valley which is wider than those in the Bleiki. The highest part of both catchments, on the other hand, is similar and less steep, partially with clear changes of steepness from where the valleys start. In Figure 7 it is additionally shown that there is a slight difference between the distribution of slope steepness between 0°–20° for the two catchments. The Diebis has a bit more areas with around 5°, while the parts with 10° are scarce compared to the Bleiki. However, the Diebis has slightly more areas with a high steepness than the Bleiki.

***Table 2*** *Summary of the physical characteristics of the two studied catchments Diebis and Bleiki.*

| | | Catchment | |
|---|---|---|---|
| | | Diebis | Bleiki |
| Area [ha] | | 46.5 | 67.4 |
| Land cover [%] | Forest | 76 | 75 |
| | Meadow | 16 | 21 |
| | Residential | 9 | 4 |
| Elevation [m asl] | Mean | 657 | 686 |
| | Min | 513 | 537 |
| | Max | 839 | 801 |
| | Difference | 326 | 264 |
| Slope [°] | Mean | 25 | 22 |
| | Max | 81 | 78 |

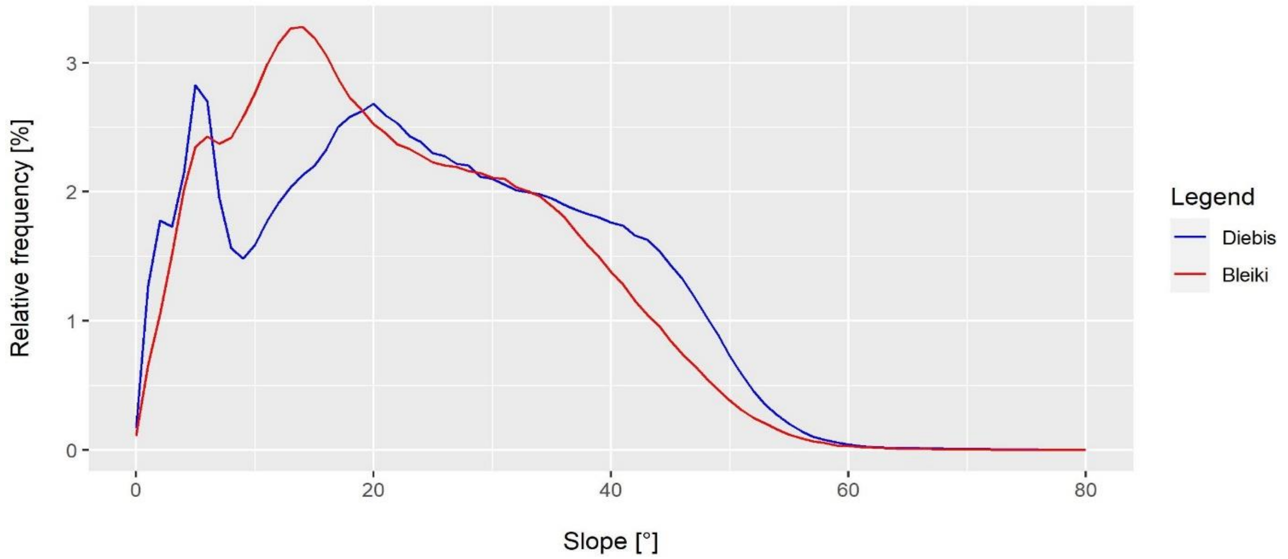



***Figure 7*** *Relative frequency of the slope inclination in the two studied catchments Diebis and Bleiki.*

## 2.2. Fieldwork

The collection of data for this thesis was done using two methods, field mapping and sensor measurements. The work was started at the beginning of October with a visit of the four possible catchments in the Reppischtal to have an overview of the area. The Diebis catchment with the installed sensors and the Bleiki catchment were chosen because of being close to each other and to have the possibility to cover both areas during my fieldwork campaigns. The Obertal and the Tagerest catchments were therefore excluded from the work. After the first recognition of the catchments, a more detailed schedule for the fieldwork was defined. Between October and April, I did 18 days of fieldwork, which started with the cleaning and restarting of the sensors. I continued with field mapping, maintenance of the sensors and collection of data from the sensors. To conclude the fieldwork, I spent a day removing the sensors from the Diebis catchment.

### 2.2.1. Field mapping

The field mapping was conducted to analyse the changes in water presence and streamflow in the two catchments. The work was started with a base map of the streams from a previous study of the area of Ander Oses Orbegozo (2015). During my first mapping of the water presence, I also updated the presence and the shape of the streams. To help with a more precise mapping I worked with a topographic background map from the Federal Office of Topography swisstopo and with the 2m contour features from the previous study. The first mappings were characterized by dry conditions and high ground vegetation so that the update of the previous map was not feasible everywhere. In addition to that, in the Diebis catchment, it was decided to focus on the southern network, where the sensors were still installed. Additionally, on the northern excluded side, agricultural work had been done in the meadows which partly changed the natural flowing of the streams.

The effective mapping was done following the single streams because of the topography of the areas. The steep slopes and the vegetation did not allow to follow “zig-zag” routes as was used in previous similar studies in the Alpthal (Sølberg, 2021; Sjöberg, 2016). Following “zig-zag” routes was only possible for a few passages where the slopes did not present continuous small valleys and gullies. The most efficient line to connect the mapping of all the streams was optimized during the first field surveys. In the Diebis catchment, it was additionally better to follow the streams in their entirety to combine the management of the sensors in a more efficient way.

The mapping of the streams was done using a classification scheme with six classes (Table 3) estimating the streamflow as the previous studies in the Alpthal (Sølberg, 2021; Sjöberg, 2016).

***Table 3*** *Classes for the classification of the streamflow during the field mapping.*

| Streamflow level | Estimated streamflow (L/min) |
|---|---|
| Flowing | >5 |
| Weakly flowing | 2-5 |
| Trickling | 1-2 |
| Weakly trickling | <1 |
| Wet | 0 |
| Dry | 0 |

The classification in the terrain was done with an own estimation of the streamflow. To learn how to recognize the right classes I used a small bottle during my first field surveys to measure how much water was flowing.

The aim of the fieldwork was to collect data at two temporary scales, seasonally and after single-events of precipitation. The seasonal mapping was distributed over 11 weeks between mid-October and mid-December during which I mapped the Diebis catchment once per week (11x) and the Bleiki catchment was mapped every two weeks (5x). The single-events mapping was done at the beginning of February (2x), and it covered both catchments on the same day. The initial plan was to visit the field four times after precipitation events, but during the period I had planned to do it, there were no big events, especially in March. The travelling distance to the catchment and the weather forecasts allowed me to reach the areas only a few hours after the precipitation events, there was therefore no mapping exactly during an event.

### 2.2.2. Digital maps

The maps with the notes from the field were digitalized using the software ArcGIS. I updated a stream map created by Ander Oses Orbegozo (2015) and from this new base map, I classified the stream sections with numerical categories and then I colour-coded them. The colours were chosen according to the flow types. The two categories “dry” and “wet” were coloured in red and orange to show the absence of flow, while the other four categories were coloured using a scale of blue colours to show the increasing amount of flow.

In addition to the flow maps, I used the software ArcGIS to create maps representing the characteristics of the catchments and to visualize some analysis of the flow type. To describe the catchments, I designed the land cover maps, the geological maps and I calculated the elevation and slope values. The analysis performed with ArcGIS regarded the flowing stream density and the seasonal rank of the segments.

### 2.2.3. Sensors

In the Diebis catchment, I used different sensors to measure specific hydrological parameters. The sensors were already installed in the area during previous studies, and they were covering the catchment as indicated in Figure 8. In the slope on the northwest there have been sensors in precedent studies, but because of human intervention in the area, which partially changed the natural conditions, the sensors were removed. Therefore, I did not focus on that area. During the first weeks of fieldwork in October, I proceeded to the restoration and the restart of the sensors.

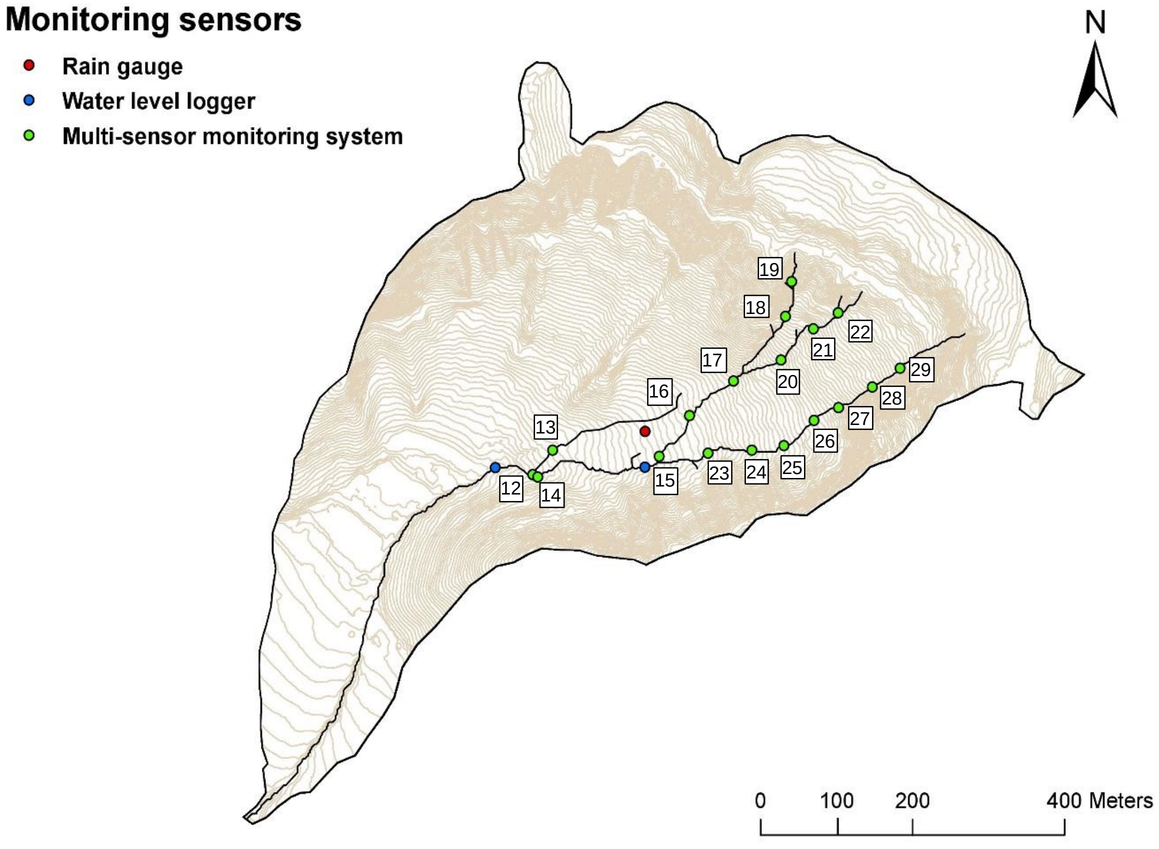



***Figure 8*** *Location of the measuring sensors in the Diebis catchment.*

The two water level loggers (Keller DXC-22 CTD Data Logger), paired with a barometric logger, allowed me to determine the water level at the two locations “Outlet”, the logger most on the west, and “Lehrwald”, the logger most on the east (Figure 8). The data from these loggers had to be downloaded every 2 months to avoid them being overwritten because of missing memory space. To calculate the water level in cm at the two locations I used the following formula (Fileccia, 2011):

$$Water\ level\ [cm]\ = \frac{Water\ pressure\ - (Air\ pressure\ -\ a)}{(\rho * g)} * 10$$

where:

- water pressure is measured by the water logger [mbar].
- air pressure is measured by the barometric logger [mbar].
- a is the correcting factor for the pressure at different elevations (0 [mbar] for the location “Outlet” and 4.8 [mbar] for the location “Lehrwald” (According to Dohmen et al. (2020) the barometric decreases by 12 hPa per 100m elevation and the location “Lehrwald” is 40m higher than the location “Outlet”)).
- ρ is the water density assumed to be 1000 kg/m$^3$.
- g is the gravity constant assumed to be 9.81 m/s$^2$.
- 10 is the multiplying factor to transform the water level in cm.

The rain gauge (Odyssey Tipping Bucket Rain Gauge Logger) was placed on an open field in the middle of the catchment, as Figure 9 shows. The logger registered the data every 10 minutes by counting the number of tips. I was able to retrieve the data for the first month of measurements. Afterwards, I had problems connecting the logger to the laptop to download the data and I was not able to retrieve them anymore. For this reason, I used the rain data from a weather station in Wettswil maintained by Prof. Dr. Jan Seibert. This weather station is located ca. 1.4km from the rain gauge in the Diebis (Figure 10) as the crow flies, at an elevation of 595 m asl, which is similar to the Diebis. There are no large hills in between, which could vary significantly the local weather conditions.

***Figure 9** Rain gauge in the Diebis catchment.*


***Figure 10** Location of the weather station in Wettswil (red point) and of the rain gauge in the Diebis catchment (blue point) (Basemap from the Map viewer map.geo.admin.ch of the Federal Office of Topography swisstopo).*

I compared the data available from the Diebis with those of Wettswil during the same period. The data are similar enough to allow the description of what happened during precipitation events in the Diebis catchment with the data from Wettswil. In Figure 11, the comparison of the hourly data shows that there is some scattering of the values. However, looking at the daily values in Figure 12, the two datasets are similar. Therefore, the total amount of rain per day is similar at both locations, only the hourly distribution is slightly different during certain events. This must be taken into consideration during the analysis, but the general picture of the events is precise enough.

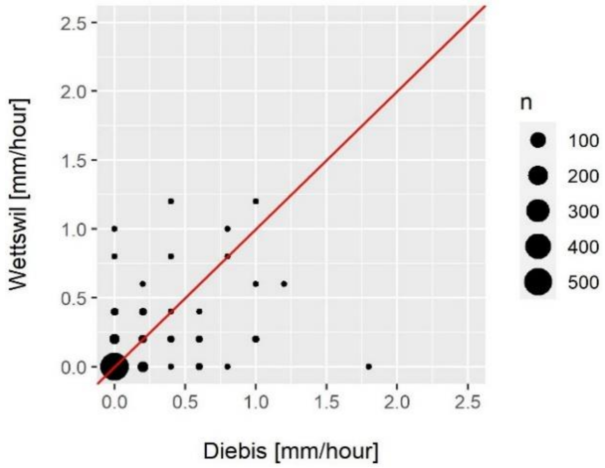



***Figure 11*** *Comparison of the hourly values of rain in the Diebis and in Wettswil during the same period. The value "n" indicates how often the combinations appear.*

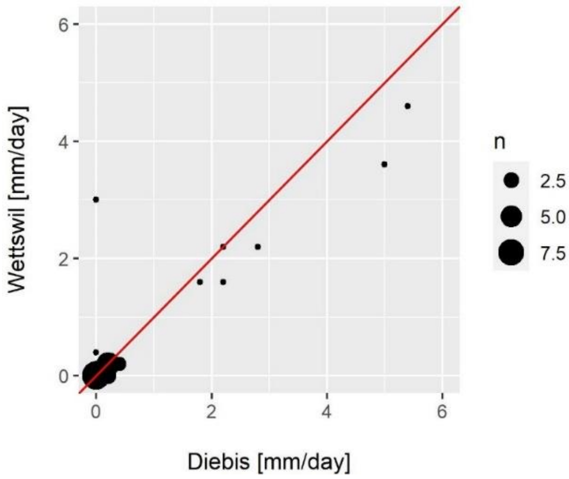



***Figure 12*** *Comparison of the daily values of rain in the Diebis and in Wettswil during the same period. The value "n" indicates how often the combinations appear.*

The single precipitation events were determined by looking at the hourly data of Wettswil and extracting the periods when the precipitation reached at least 4mm without any break of at least 12 hours. The threshold for defining the precipitation events was taken arbitrarily to have a sufficient number of events with changes in the ER-values and to exclude most of the small events when there were not any changes in the ER-values.

The measurements in the streams were done with the multi-sensor system of Assendelft & van Meerveld (2019). In Figure 13, an example of the setting of one sensor during an older field campaign is shown. In the catchment, there were 18 multi-sensors installed. During the first weeks of my work in October and at the beginning of November I spent some time restarting these sensors which had not been used for about one year. I had to clean the sensors from the sediments that were deposited on the channel bed where the ER sensor does the measurement (Figure 13 (d)) and where the water flow through the flow sensor (Figure 13 (e)). During the period of field measurements, I was collecting the data (from an SD-card insert in the Arduino Pro Mini microcontroller board (Figure 13 (c))) and I did maintenance one or two times per month.

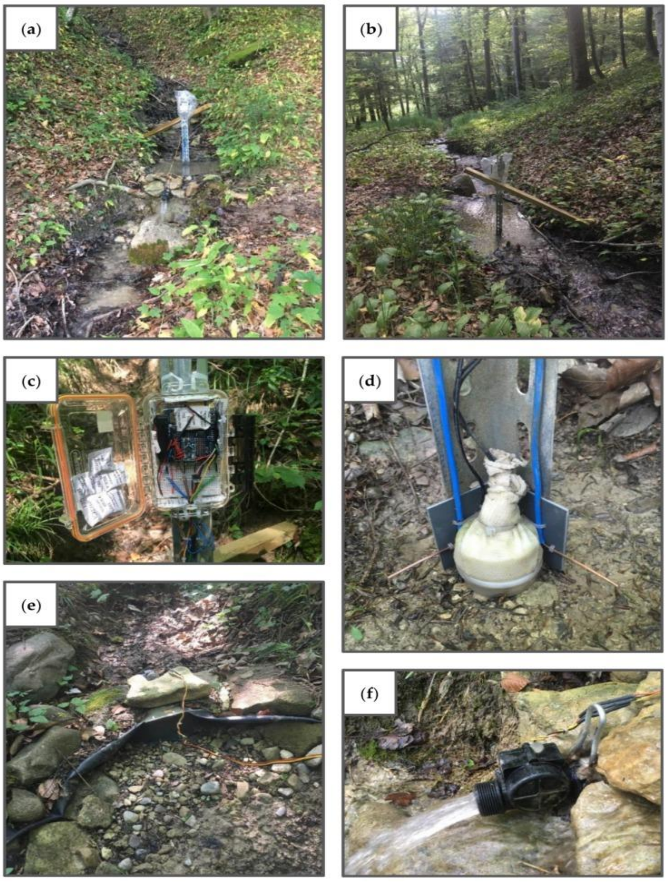


***Figure 13*** *Field setup of the multi-sensor monitoring system (2017 field season): (a) upstream view of the monitoring system in a flowing stream, (b) downstream view of the monitoring system in a flowing stream, (c) the waterproof box, containing the microcontroller board and data logger shield combination, battery pack and MOSFET, attached to the top of the angle bar, (d) the ER sensor, float switch sensor (wrapped in a filter sock) and temperature sensor (in a sheltered pocket behind the float switch sensor) attached to the angle bar (using an angled PVC sheet) at streambed level, in a dry stream (e) downstream view of the flow sensor setup in a dry stream, including the tarp buried into the channel bed and bank (f) the flow sensor during a flow event, and the double legged peg that secures the funnel neck to the channel bed. (Source: Assendelft & van Meerveld, 2019)*

My plan was to work with the data from the flow sensor and from the ER sensor. After several tries, it was not possible to repair all the flow sensors and I had not any usable data on the flow, therefore I had to focus on the electric resistance (ER) sensor of the functioning multi-sensors which were finally 11 (n° 12, 13, 16, 17, 20, 22, 23, 24, 25, 26, 27, see Figure 8), of which 4 (n° 12, 13, 23, 24) also had periods of time during which they were not working properly. The ER values allowed me to determine the presence or the absence of water in the stream. In fact, the fast drop of electric resistance shows the wetting of the stream (Assendelft & van Meerveld, 2019).

Finally, the values of the air temperature were taken from the weather stations of the "Amt für Abfall, Wasser, Energie und Luft" of the Canton of Zurich installed on the Altuetliberg at 774 m asl and in Eichbühl at 443 m asl. The Altuetliberg station is located just above the two catchments. Eichbühl is situated on the other (northwest) side of the Uetliberg in comparison to the catchments, but at a similar elevation as the lower parts of the catchments. The temperature from the two locations allowed me to determine the expected type (rain or snow) of precipitation during the events. The different elevations of the stations allowed me to better estimate which parts of the catchments could have snowfall instead of rainfall.

### 2.2.4. Flowing stream density

The flowing stream density (FSD) was calculated following the idea of the drainage density (D) defined by Horton as: $D = \frac{L}{A}\ [m/m^2]$ , where L is the total length of the streams in area A (Dingman, 1978). For my analysis, I was interested in seeing where there was at least a first stage of flowing. Therefore, I calculated the length of the streams for each mapping session using all the segments that on that day were in the categories “weakly trickling”, “trickling”, “weakly flowing” or “flowing”. For the Bleiki catchment, I divided the values by the total area of the catchment, while for the Diebis catchment I had to make adjustments because the north-western part (violet part in Figure 14) had not been mapped. Therefore, I calculated the flowing stream density of the green part, and I assumed it was representative enough for the violet part which has similar physical characteristics. Then, I divided the flowing stream density of the green part by the area of the violet part, so, I obtained the estimated length of the flowing streams in the violet part. Finally, I summed the length of the flowing streams of the mapped sections (green and lowest part of the catchment) with the estimated length of the violet part and I divided the value by the total area of the catchment.

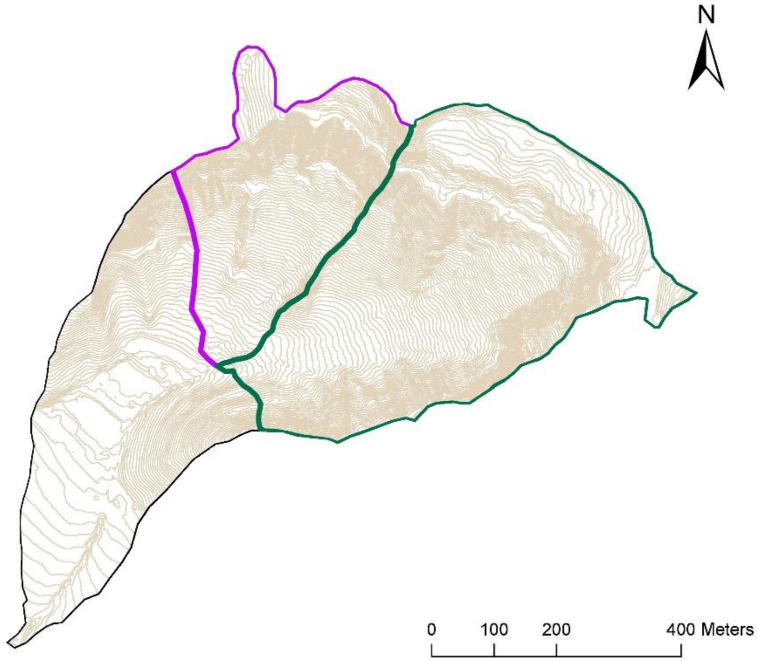



***Figure 14*** *The Diebis catchment divided into three parts to estimate the flowing stream density in the non-mapped violet part.*

I planned to determine the flowing stream density of the single-events in the Diebis catchment by assigning the segments of the river network to the sensors that are most representative of them. During the precipitation events, according to the ER-values, I should have determined if there was water at the location of the sensors and if the segments assigned to them could be assumed to be flowing. Even if the water presence is not a clear indication of flow, I would have tried to make this assumption because of the missing data on the flow from the sensors. The flowing stream density would have been finally calculated using the segments’ lengths and the areas of the parts of the catchment. In the analysis of the single-events, it resulted that the differences between the events were not large enough to observe significant changes in the flowing stream density calculated with this procedure. Therefore, this method was discarded. However, I calculated the Pearson correlation between the percentage of sensors that indicated the presence of water and the flowing stream density for each monitoring date to check if the two methods provide similar information about the dynamics of stream network expansion. I determined which sensors indicated the water presence based on the figures in Appendix 7.2. In the analysis, I only considered the mapping day from the 31 October 2021 because the sensors were either not functioning or they were only partially functioning during the first three mapping sessions. To decide if there was water presence, I took a threshold for the electrical resistance of 750 ohm based on the conditions of the sensors 17 and 20, which indicated flow during almost the whole season according to the field mapping. Sensor 26 was not considered because of the unstable behaviour during the whole measurement period.

### 2.2.5. Ranking

To determine the pattern of extension of the flowing stream network at seasonal and at single-event scales, I planned to rank the stream segments in the order that they start to flow and compare them for the two types of datasets.

The seasonal development was approached with the maps. For the Diebis catchment, I ordered the maps according to increasing water level, which was only slightly different from the temporal order (Figure 15). For the Bleiki catchment, I did not have sensor data and only mapped the streams every two weeks, and therefore used the temporal order. The temporal order was representative for increasing wetness conditions, as I observed in the Diebis catchment. The next step was to rank all the segments that were classified with a category indicating flow (“weakly trickling”, “trickling”, “weakly flowing” or “flowing”) in the first map. These segments were assigned a rank of 1. Rank 2 was assigned to the segments changing from a category of no flow (“dry” or “wet”) to a category indicating flow in the second map. I continued in this way, assigning the last rank (9 for the Diebis and 5 for the Bleiki) to all the segments that were never observed to flow.

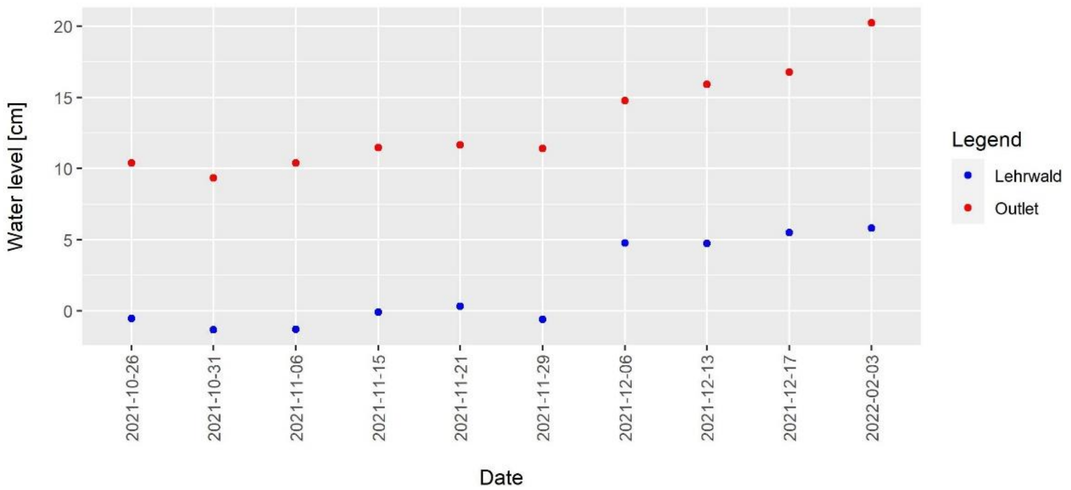



***Figure 15*** *Mean water level at the locations “Outlet” and “Lehrwald” during the hours of field mapping.*

The ranking of the single-events should have been determined by the ER-values of the sensors. The analysis of the ER-values was done by looking at the period some hours before and after the precipitation events to have an overview of the behaviour of the data prior to the start of precipitation.

The sensors would have been ranked according to the moment that they started to indicate water presence (i.e., a decrease of the ER-value). Finally, I would have compared the ranking of the single events with the seasonal ranking at that location using the Spearman correlation. However, this method had to be discarded because of the low variability of the ER-values during the events, which would not have shown any large difference in ranks for the different sections.

Pearson correlations were calculated following Kassambara (2020) and R-squared values with the summary of the function “lm: Fitting Linear Models” (Chambers, 1992; Wilkinson & Rogers, 1973). All figures were made with ggplot in R Studio (version R 4.0.2). All maps were made in ArcGIS (version ArcGIS 10.6.1).

# 3. Results

## 3.1. General stream network and events description in the Reppischtal

The effects of the weather conditions during the seasonal mapping until mid-December were mostly visible in the hydrological behaviour of the Diebis catchment. In fact, the flowing stream density of the Bleiki stayed quite stable for the whole period and it can not be used to describe what happened during that period. In fact, it can only indicate that there were some precipitations to keep the wetness and therefore the flowing stream density stable.

The first two weeks of fieldwork between mid-October and the end of October were quite dry without any large and long precipitation events. As Figure 16 shows, the flowing stream density and the water level in the Diebis were quite constant. At the beginning of November, there was a first large precipitation event which increased the water level and the flowing stream density in the Diebis. After this event, the month of November was characterized by few small precipitation events that only slightly increased the flowing stream density in the Diebis. The water level was also only shortly influenced by the precipitation events without showing an increase over the period. The end of November started a period characterized by several precipitation events, often quite large and partially in the form of snow, depending on the elevation. These events had a clear influence on the water level which increased its base level constantly over this period. Additionally, the flowing stream density of the Diebis increased strongly reaching the level of the Bleiki.

After the seasonal mapping, the precipitation at the end of December had a direct impact on the water level of the Diebis which showed a strong increase. From that moment, excluding the precipitation at the beginning of January, the base level decreased slowly because of the missing precipitation in January and because part of it was in the form of snow. At the beginning of February, when I mapped the catchments twice after precipitation events, the flowing stream density in both catchments had increased from the last stand in mid-December. Additionally, the water level showed a reaction directly after the event.

In the representation of the water level two observations are needed. Firstly, the water level at the location “Lehrwald” presented negative values for a long period, even if there was water in the terrain. The pattern that it followed was similar to the pattern of the location “Outlet”, it is therefore possible that the correction of the difference in elevation in comparison to the barometric logger is not sufficient. Even if the absolute values are not sure, the pattern in relation to the precipitation events can be used to have a confirmation of what happened at the location “Outlet”. Secondly, there are two periods represented with a straight line (mid-November and mid-December). On these occasions, the sensors were not in the field to download the data and the values were therefore deleted and interpolated linearly to allow for better visualisation. It is also interesting to observe that before the second data collection in mid-December there was a quite high noise in the data, or eventually an offset between the data of the barometric and water pressure logger. In contrast to that, the data of the water level showed less noise or a better alignment of the two loggers.

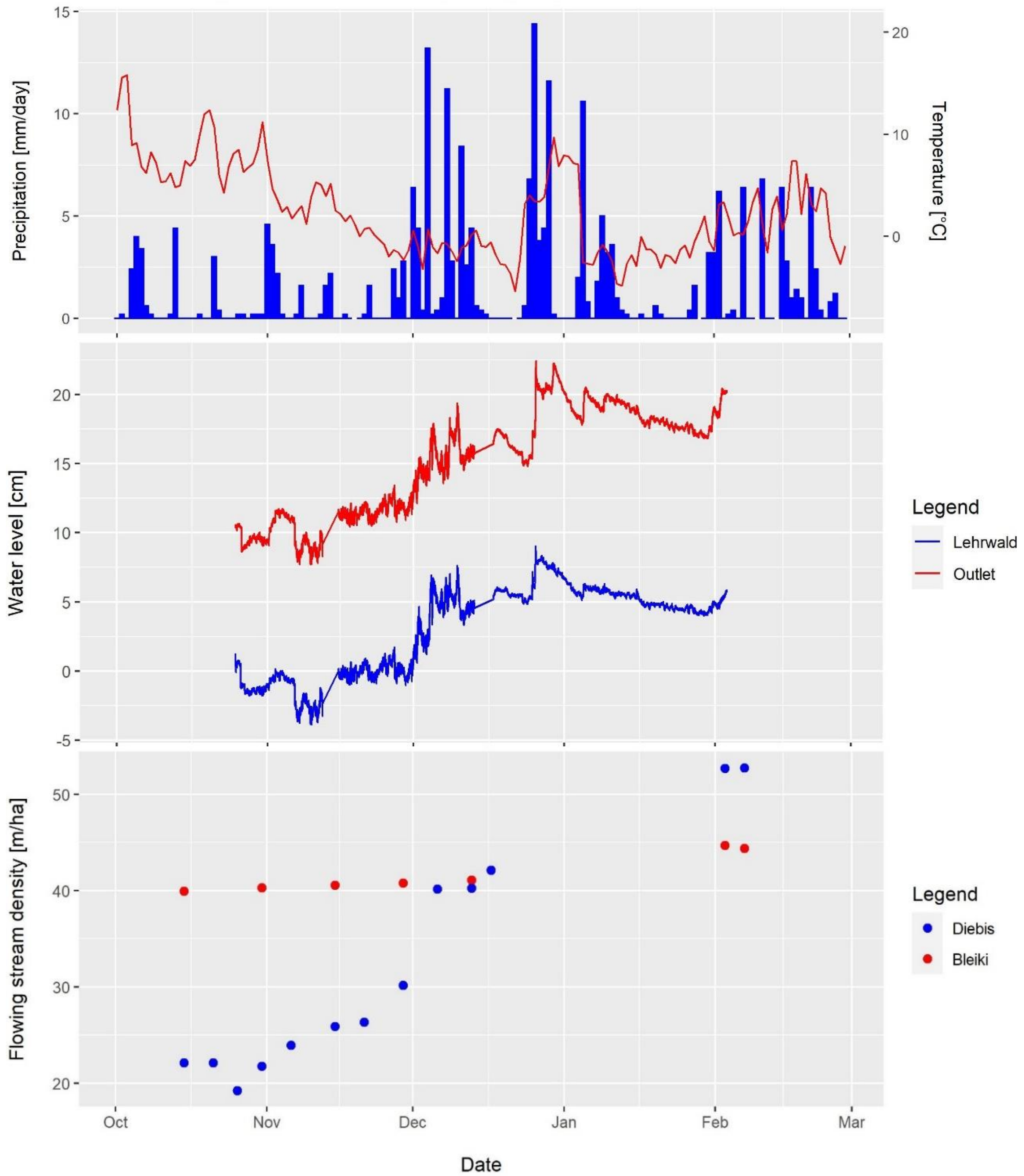



*__Figure 16__ On the plot on the top the precipitation per day in Wettswil (blue columns) and the temperature on the Altuetliberg (red line) are represented. On the middle plot, the water level at the two locations "Outlet" and "Lehrwald" in the Diebis catchment is shown. On the lowest plot, the flowing stream density on the mapping days in the two catchments Diebis and Bleiki is shown. All the values are represented from the 01.10.2021–28.02.2022. 21–28.02.2022.*

## 3.2. Dynamics of the of the flowing stream variability

During the mapping period, the proportion of stream length per flow category varied mostly in the Diebis (Figure 17). During the dry period in October (W1-W3), in the Diebis catchment, the flowing stream length reduced from 35% to 31% of the stream network, but after this period, the flowing stream density increased gradually until December, when it reached 67% (Figure 17). In particular, it took a long time for the two highest flowing categories (5 and 6) to increase significantly. In W9, in December, 38% of the stream length was in these categories, while one week earlier it was only 11%. In February, the proportion of the flowing stream categories had increased up to 82%. There were no further changes for the mapping that was done after precipitation events. In the Bleiki, 88% of the network was already flowing in mid-October. The amount increased only slightly during the seasonal measurements up to 91%. During the two mapping days in February, the Bleiki had reached an almost complete flowing status (98% of the network), and none of the sections were dry.

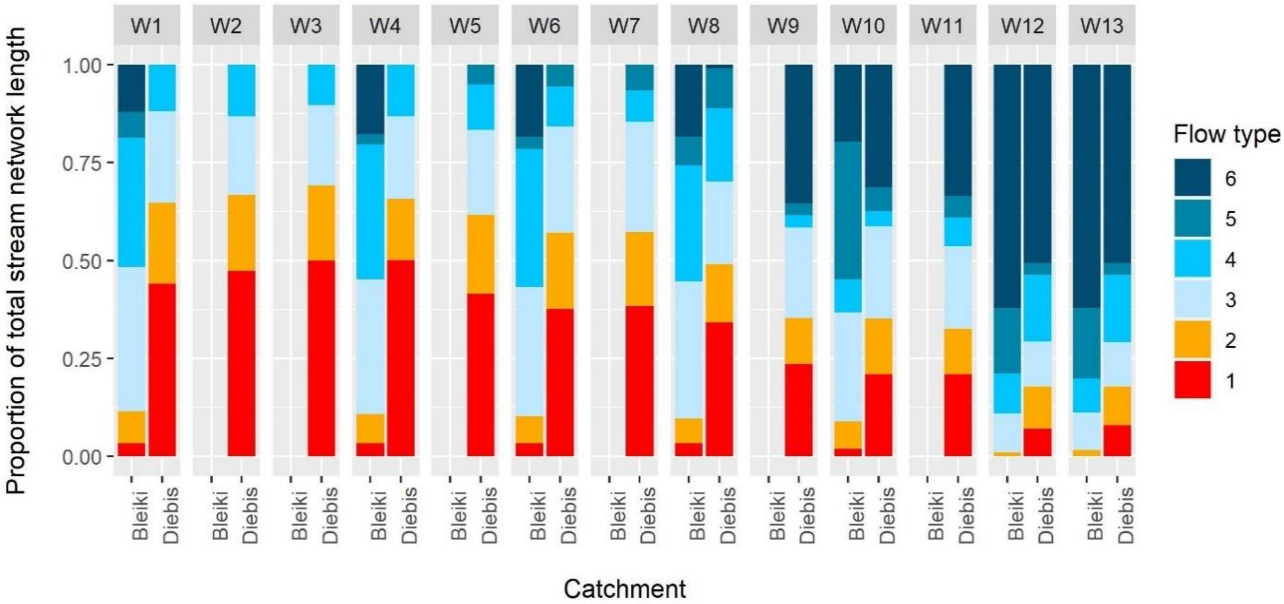



***Figure 17*** *Proportion of stream length per flow type category (1 = Dry; 2 = Wet; 3 = Weakly trickling; 4 = Trickling; 5 = Weakly flowing; 6 = Flowing) over the whole stream network length during the mapping days (W1 = 15.10.2021; W2 = 21.10.2021; W3 = 26.10.2021; W4 = 31.10.2021; W5 = 06.11.2021; W6 = 15.11.2021; W7 = 21.11.2021; W8 = 29.11.2021; W9 = 06.12.2021; W10 = 13.12.2021; W11 = 17.12.2021; W12 = 03.02.2022; W13 = 07.02.2022).*

Figure 18 shows the relation between the flowing stream density in the Diebis and the water level at the two locations in the catchment in more detail. Both graphs show a linear regression with an increasing flowing stream density paired with an increasing water level. The R-squared values for the location “Outlet” and the location “Lehrwald” are 0.96 and 0.87, respectively. Thus, the water level at both locations describes the flowing stream density well. Furthermore, the relation between the water level and the flowing stream density at the location “Outlet” is particularly strong. At this location the values of the water level were calculated with less uncertainty than those at the location “Lehrwald” because the barometric data did not have to be corrected for the elevation difference from the measuring sensor. This increases the reliability of the relationship between water level and flowing stream density.

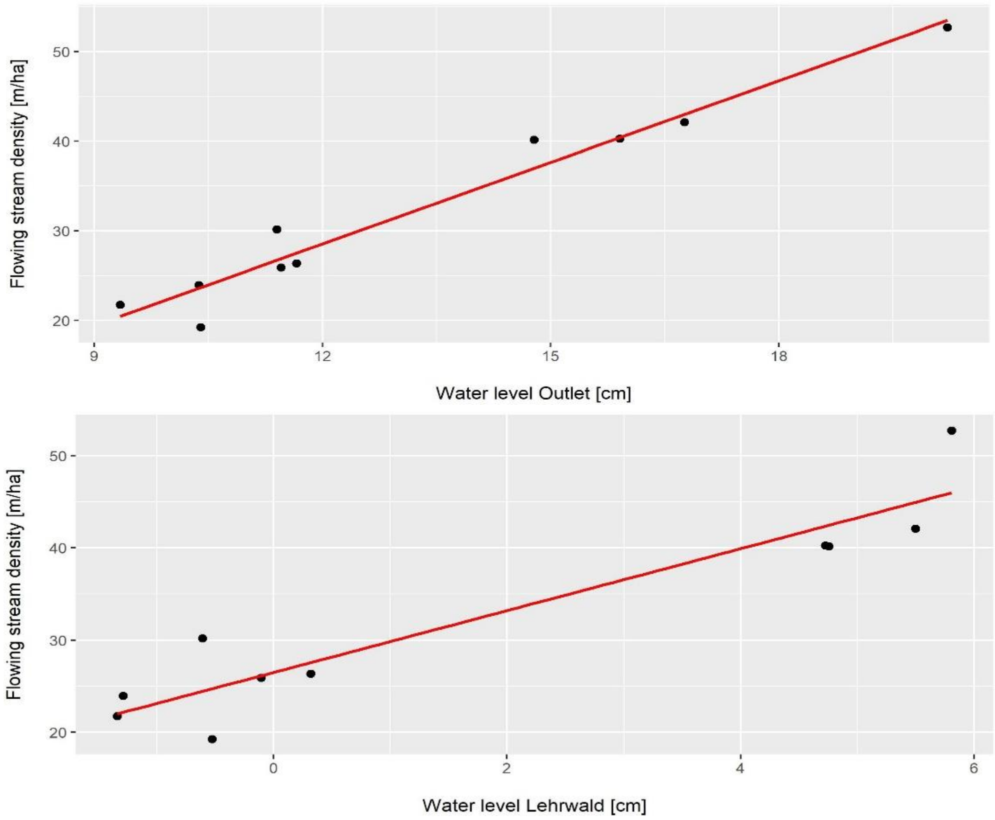



***Figure 18*** *Flowing stream density in the Diebis catchment during the mapping days in relation to the mean water level during the mapping hours at the location “Outlet” (plot on the top) and at the location “Lehrwald” (plot on the bottom). The red line indicates the linear regression.*

Figure 19 illustrates the relation between the flowing stream density in the Bleiki and in the Diebis on the same mapping days. The linear regression (red line) that describes this relation has a slope of 0.14. The strong relation given by the linear regression (based on the Pearson correlation value of 0.95 and p-value of 0.0001), however, shows that the dynamics in stream density are similar (i.e., when it went up in one catchment, it also did this in the other). However, the much smaller slope than 1 means that the magnitude of the change in flowing stream density was very different: there is a larger increase of flowing stream density for the Diebis than for the Bleiki.

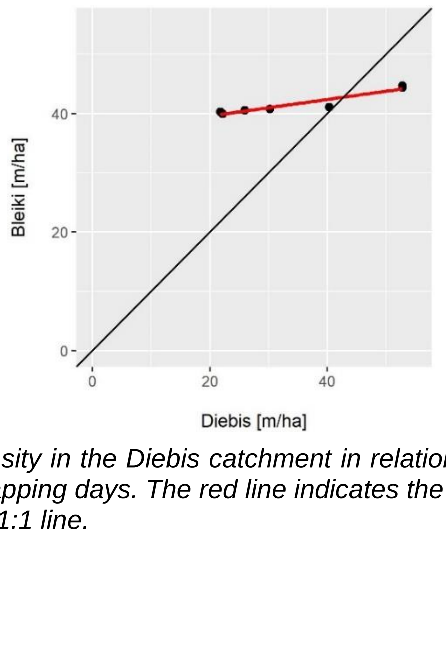



***Figure 19*** *Flowing stream density in the Diebis catchment in relation to the flowing stream density in the Bleiki catchment during the mapping days. The red line indicates the linear regression with a slope of 0.14 while the black line shows the 1:1 line.*

Figure 20 shows the relation between the flowing stream density in the Diebis and the percentage of sensors indicating water presence during the mapping days from the 31 October 2021. The linear regression (red line) that describes this relation has a slope of 1.33 and the strong relation given by the linear regression (based on the Pearson correlation value of 0.93 and p-value of 0.00009) shows that the two variables behave similarly. When the flowing stream density increases, the percentage of sensors indicating water presence also increases with a similar magnitude.

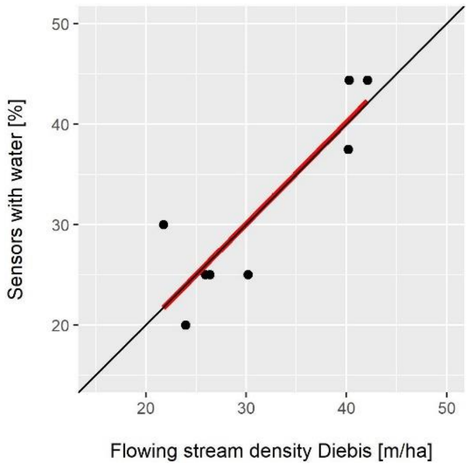



***Figure 20*** *Flowing stream density in the Diebis catchment in relation to the percentage of sensors indicating water presence based on the electrical resistance during the mapping days. The red line indicates the linear regression with a slope of 1.33 while the black line shows the 1:1 line.*

## 3.3. Seasonal streams dynamics

Figure 21 shows the ranking of the order in which the different segments of the stream network in the Diebis started to flow during the mapping period. The ranking is based on an increasing water level, which means that a higher ranking represents a start of the flow with a higher water level.

The lowest section of the stream, in a small section of forest surrounded by meadows, was ranked 2 or 3, which means that a higher water level was necessary to allow the start of flow in this section than in some other sections of the stream. Further up the stream, there is a long section of the stream beside a meadow, before it passes through the forest and then flows along a residential area, that was flowing already at the lowest water level (and thus had a rank of 1).

In the upper part of the catchment, the stream splits into three tributaries with different seasonal stream dynamics. The tributary furthest to the west started flowing in its lowest part, which is mostly covered by the forest, only in February and has a rank of 7 or 8. The highest part of the western tributary, which lies in a meadow, however, was already flowing earlier and has a rank of 4. The tributary in the middle in the meadow started flowing late as well (rank of 5 or 6), while its central part in the forest was already flowing earlier (rank of 2 or 3). The highest and steepest part of the tributary in the middle, which is also in the forest, only partially started to flow in February (rank 7). Finally, the tributary furthest to the east started flowing very late and was assigned mostly very high ranks.

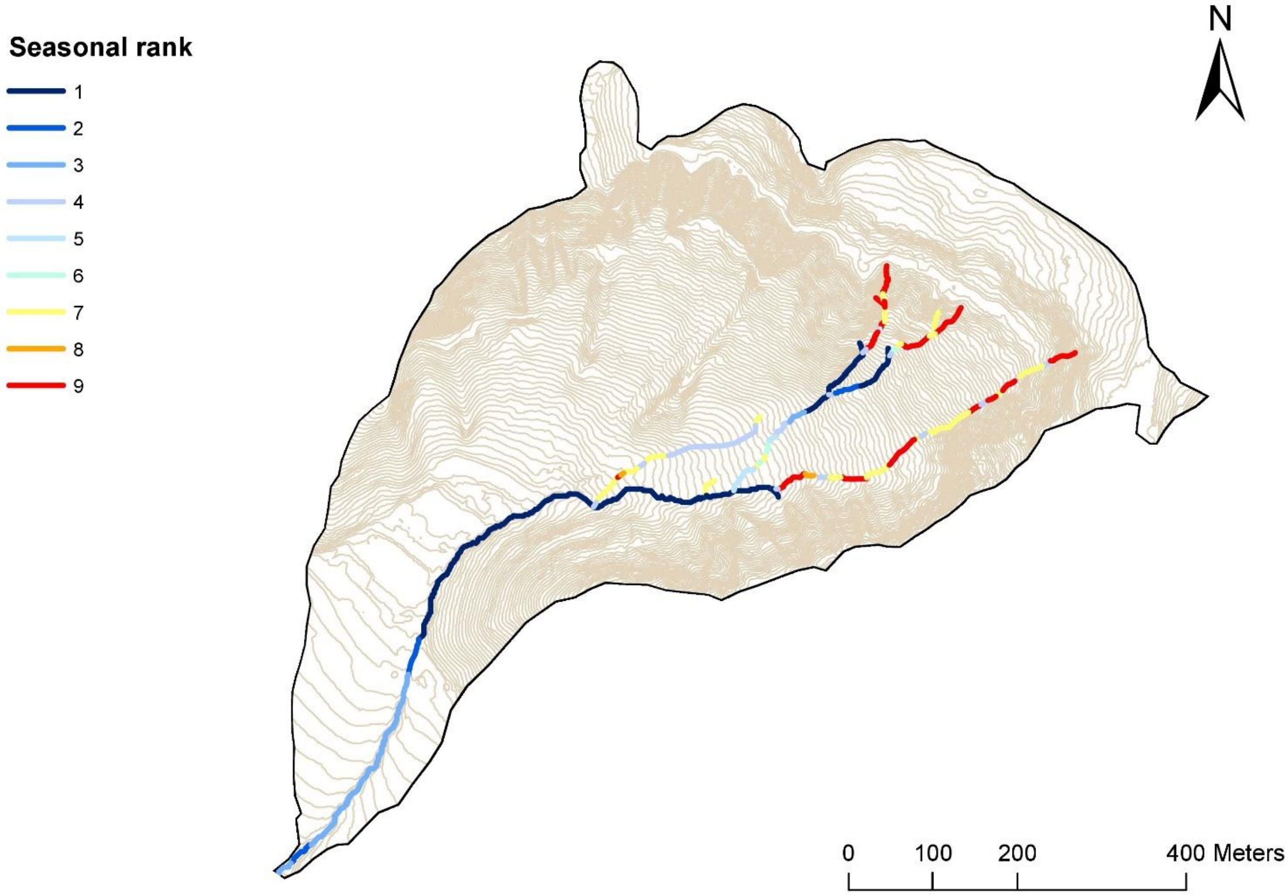



***Figure 21*** *Seasonal ranking of the segments of the stream network in the Diebis catchment. A lower rank means that the segment has started flowing (flow type 3-6) earlier than a higher rank. Each rank is assigned to a day of field mapping. The rankings in yellow and orange are the days in February, which were temporally separated from the other mapping days finishing in December. The rank 9 is assigned to segments which never started flowing.*

Figure 22 shows the same system of ranking as Figure 21, but for the Bleiki catchment. Figure 22 shows clearly that most of the network was flowing already on the first day of mapping. These sections were located in all the areas of the catchment with forest, meadow and residential areas, both in the flatter and the steeper sections. There are only few small segments, mostly at the top of the tributaries, that started flowing later. In most of the cases this happened only in February. Only one small segment in the east never had flowing water during the mapping days.

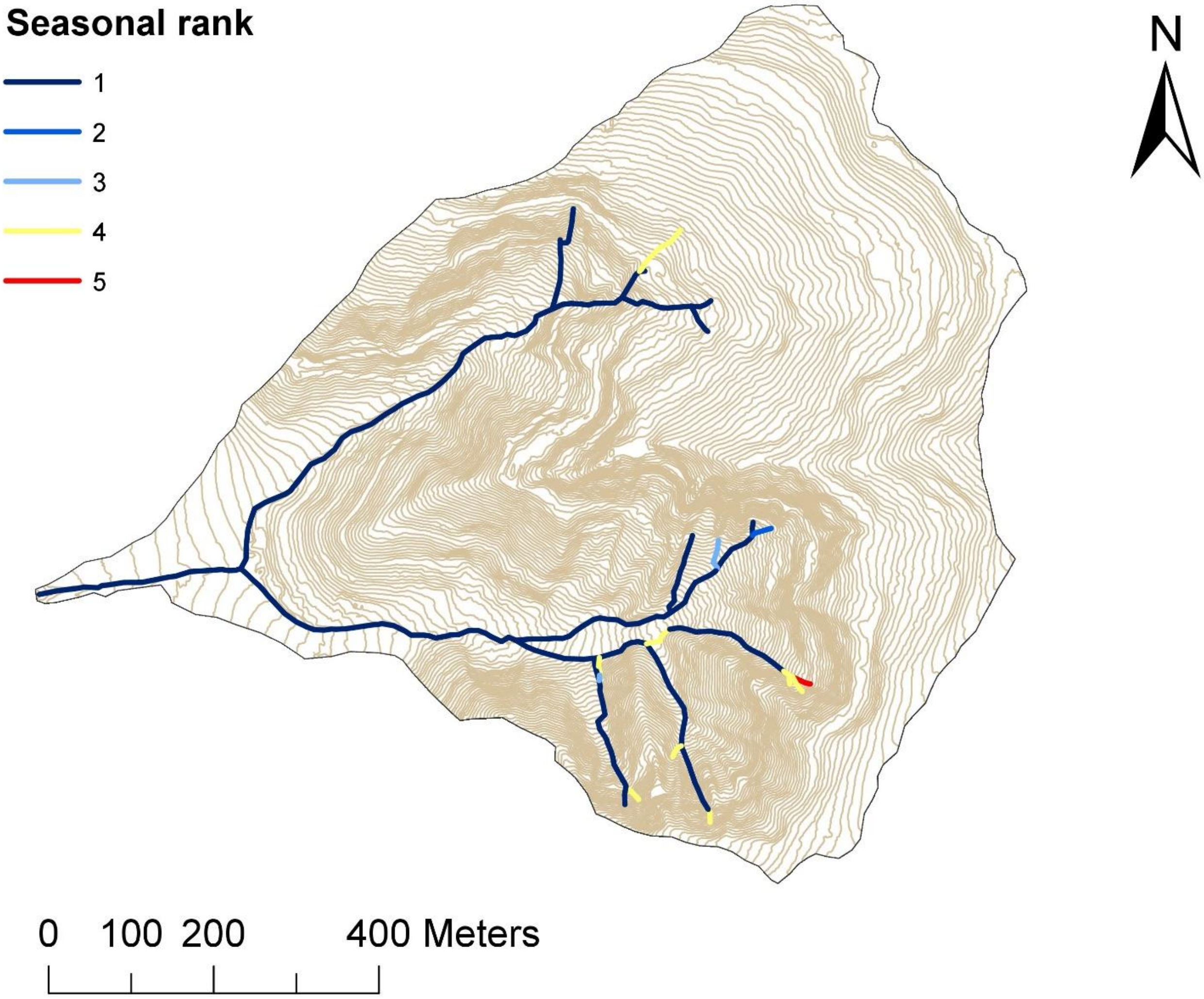
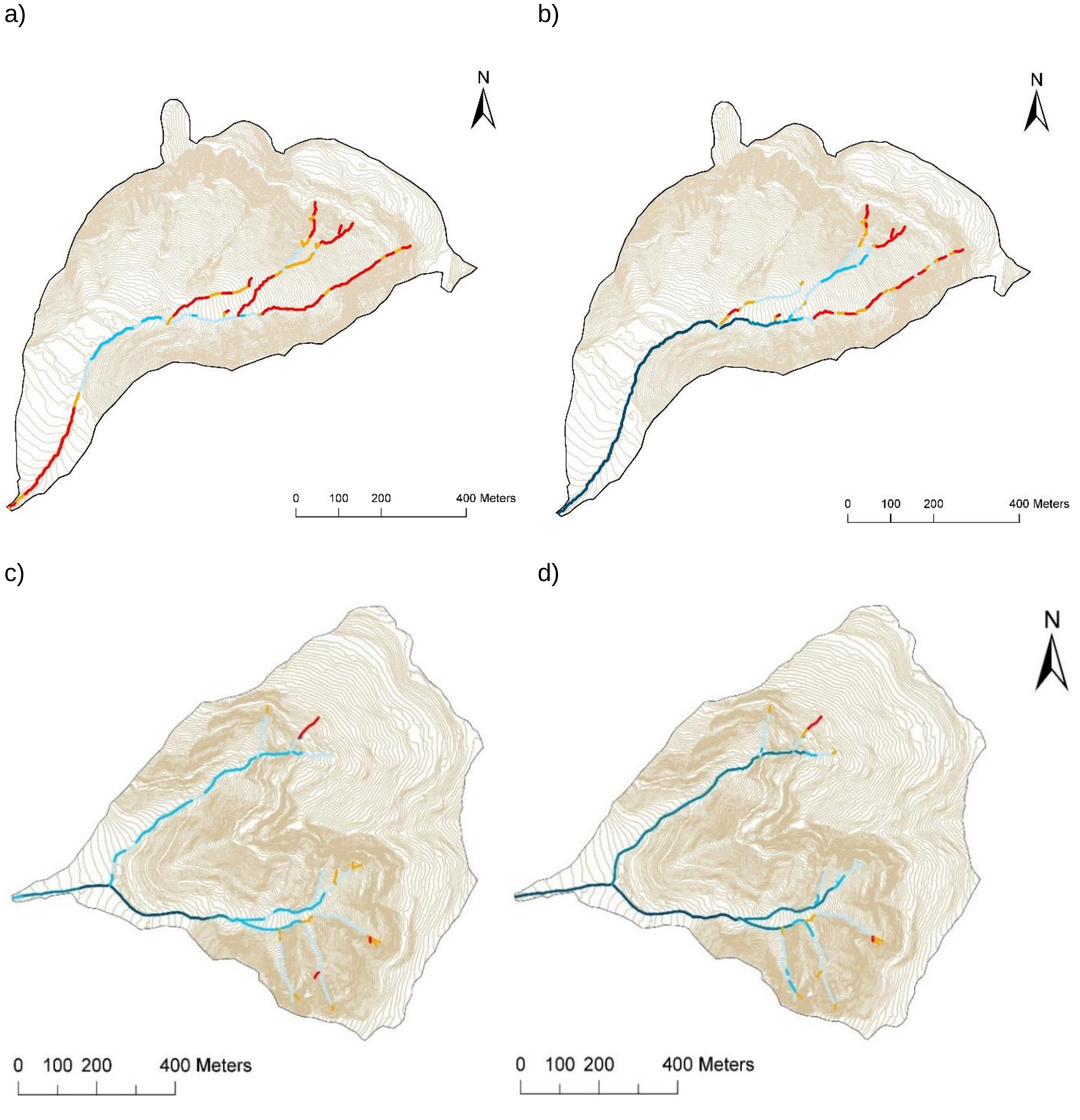



***Figure 22*** *Seasonal ranking of the segments of the stream network in the Bleiki catchment. A lower rank means that the segment has started flowing (flow type 3-6) earlier than a higher rank. Each rank is assigned to a day of field mapping. The ranking in yellow represents a start of the flow in February, which was temporally separated from the other mapping days finishing in December. The rank 5 is assigned to segments which never started flowing.*

A direct comparison of the flowing conditions of the stream networks in the Diebis and the Bleiki during a dry and a wet period of the season is visible in Figure 23. Similarly to the maps of the seasonal ranking, it is visible that in the Diebis, the central part of the stream network was flowing also during the dry period, while the lowest part was dry and only a small part of the middle branch was flowing slightly. In December, after several precipitation events and some snow melt, the network reached almost the maximum flowing length registered during the mapping days. On the other hand, in the Bleiki, most of the network was flowing also during the dry period and the difference in flowing streams with the wetter conditions in December was not so large. The largest difference was that the flow increased in the northern main tributary reaching the second highest flow category (weakly flowing). The same increase in flow category was visible in some parts of the southern main tributary. The conditions at the top of the tributaries, however, remained quite similar to the dry conditions.



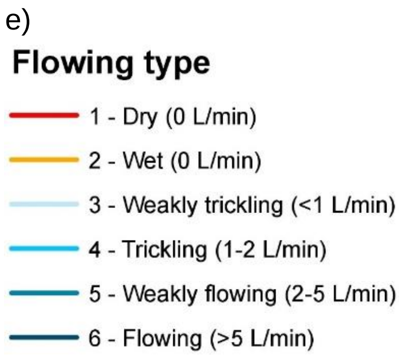




***Figure 23*** *Mapping of the flowing type in the Diebis catchment a) during a dry period of the season (26.10.2021), b) during a wet period of the season (17.12.2021), and in the Bleiki catchment c) during a dry period of the season (15.10.2021), d) during a wet period of the season (13.12.2021). (e) shows the legend of the flow type categories in the catchments. the flow type categories in the catchments.*

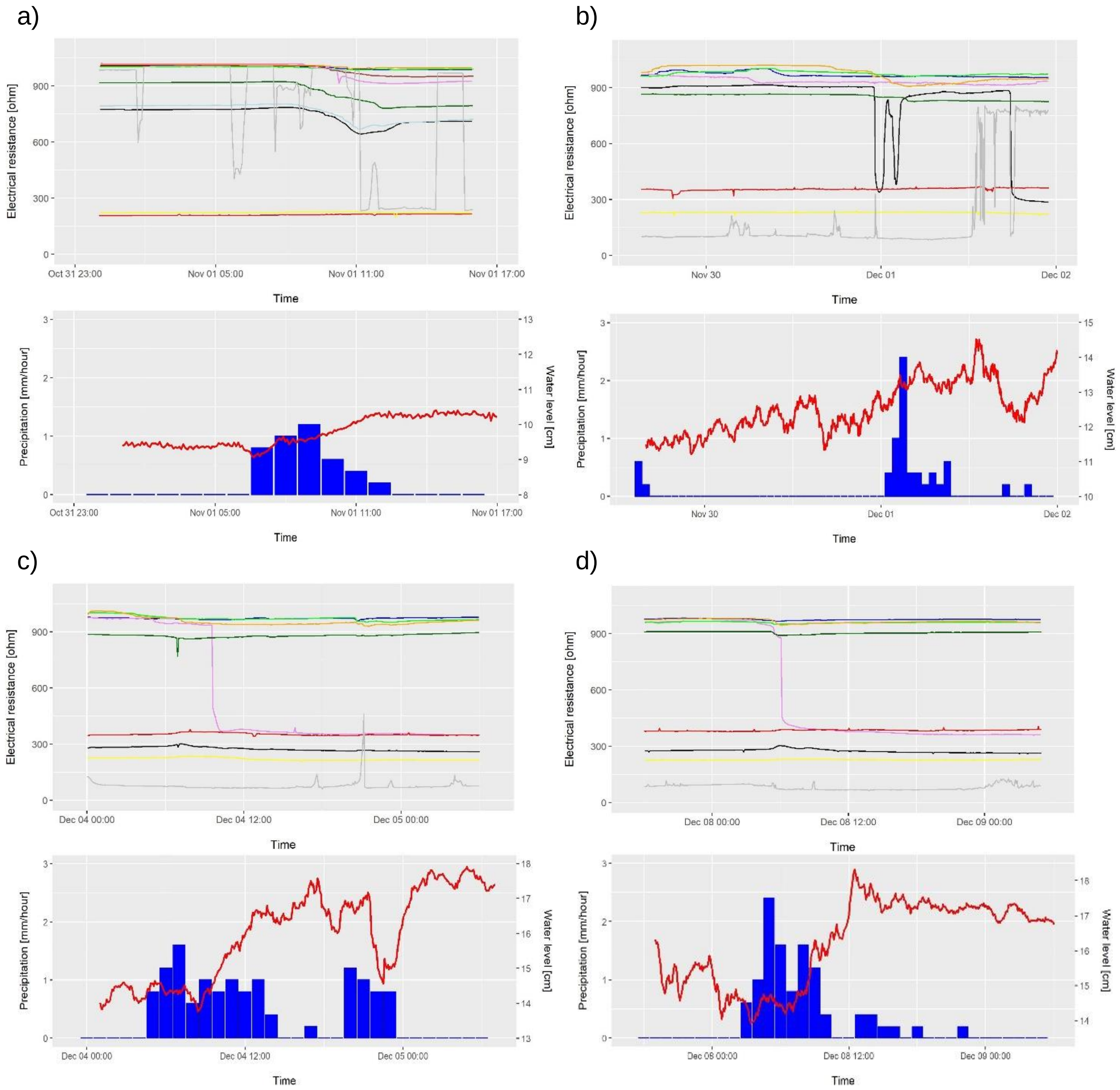
## 3.4. Single-events streams dynamics

Figure 24 illustrates the behaviour of the stream network at the locations of the multi-sensors monitoring system during the single precipitation events. In general, there was often only one sensor or no sensors (Figure 24 (i), (k), (l), (m), (n)) showing a change of electrical resistance and therefore the presence or absence of water in comparison to the situation prior to the event. In particular, sensor 16 was the only one getting wet during three events in December (Figure 24 (c), (d), (f)) with varying intensity and duration. It even showed the disappearance of water during another event in December (Figure 24 (e)). Sensor 12 showed repeated changes in the presence and absence of water at the precipitation event of 1 December 2021 without following the intensity of the precipitation (Figure 24). Sensor 22 also registered various changes from dry to wet on 5 January 2022 (Figure 24 (h)) but followed the intensity of the precipitation with wet conditions during the highest intensity. Sensor 27 showed the presence of water in the event between 1 February 2022 and 3 February 2022 (Figure 24 (j)) from the first peak of rain and remained wet also with small amounts of precipitation during the following hours.

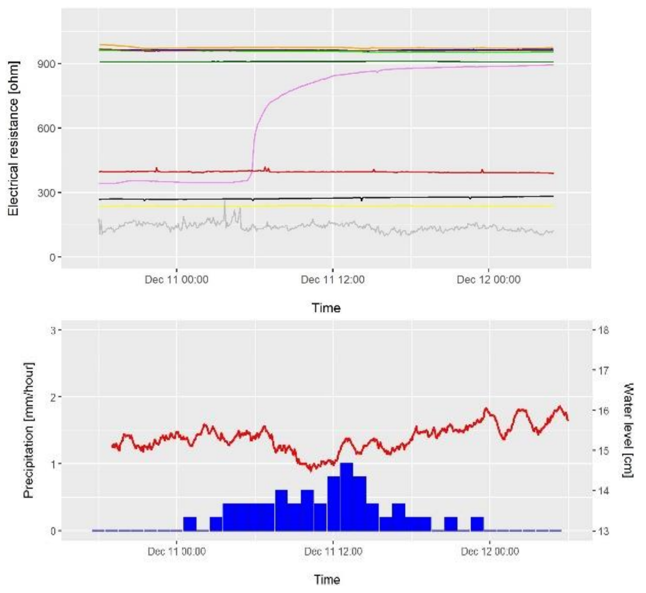
There are two examples of events causing more changes to the sensors and these are the first larger event on 1 November 2021 (Figure 24 (a)) and the large event lasting almost 5 days at the end of December (Figure 24 (g)). In the first event, sensors 12, 16, 23, 24 and 25 showed the presence of water from around the middle of the precipitation event. In the second event, only sensor 16 was reacting during the first precipitation peak at around 12.00 on 5 December 2021, showing a decrease in the electrical resistance. Sensors 22, 25 and 27 registered the decrease within a short period of time with the second peak, while sensor 23 reacted some hours later with the third peak. However, at the end of the third peak, sensor 25 showed again the absence of water, before registering a decrease in electrical resistance during the last long and large peak on 29 December 2022. Sensor 23 showed a short period of dryness during the fifth peak on 28 December 2022.

Overall, there are only the sensors 12, 17 and 20 which were wet during most of the precipitation events. Sensor 16 which lies in the middle of the catchment and close to the end of the forest and at the beginning of the meadow was reacting regularly during the precipitation events. The sensors at the highest elevation and those in the branch most on the east showed the wetting of the stream segments only irregularly. Finally, sensor 26 showed an irregular pattern which seems to indicate a misfunctioning in the measurements during all the events.

The water level normally grew after at least half of the precipitation duration. The intensity of the increase varied during the events, in certain cases, a low precipitation intensity caused a slight constant increase in water level, as shown in Figure 24 (a) or (e). In other situations, the increase was rapid despite low-intensity precipitation, as illustrated in Figure 24 (i). Generally, the increase was strong when the intensity of the precipitation was high, as shown in Figure 24 (f) or (g). Often, especially during intense precipitation events, the strong increase in water level happened at the same time as the sensors started to show the presence of water, but this was not the case for every change in electrical resistance.

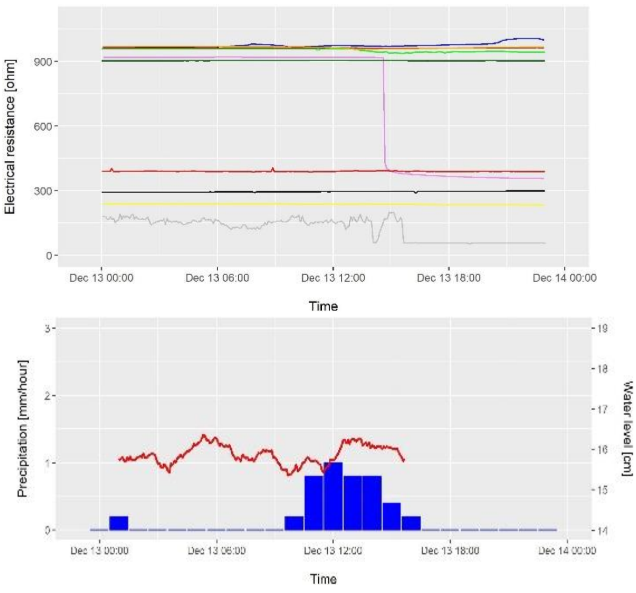


e)



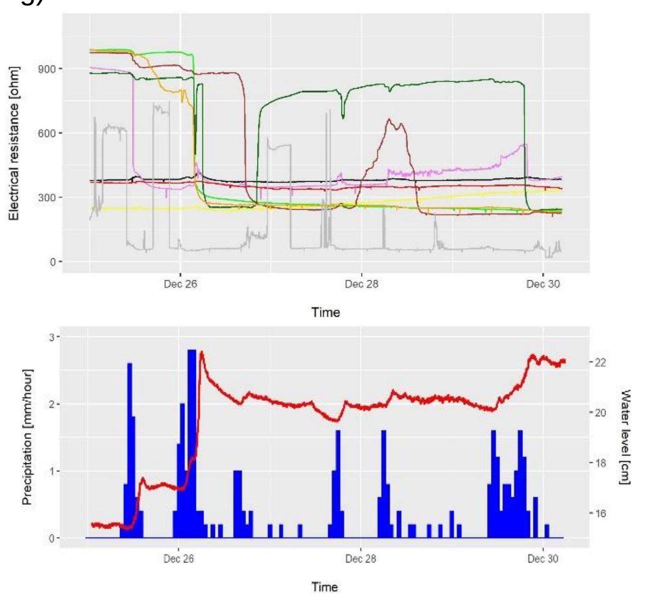
Electrical resistance [ohm]
Dec 11 00:00
Dec 11 12:00
Dec 12 00:00
Time
Precipitation [mm/hour]
Water level [cm]
Time


f)



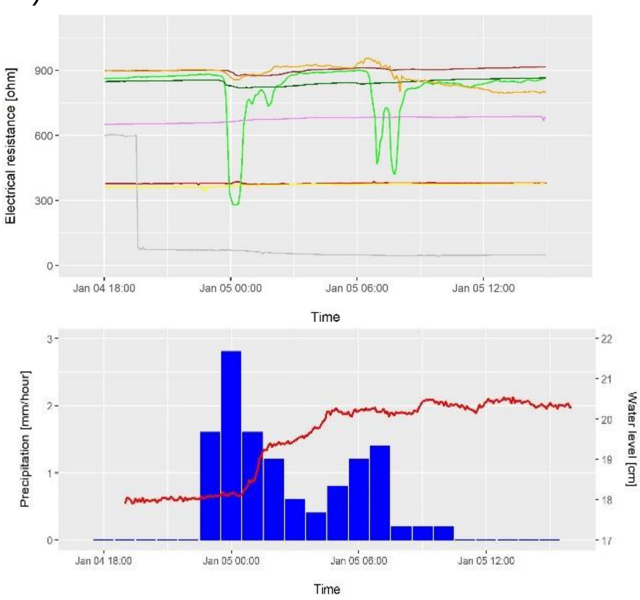
Electrical resistance [ohm]
Dec 13 00:00
Dec 13 06:00
Dec 13 12:00
Dec 13 18:00
Dec 14 00:00
Time
Precipitation [mm/hour]
Water level [cm]
Time


g)



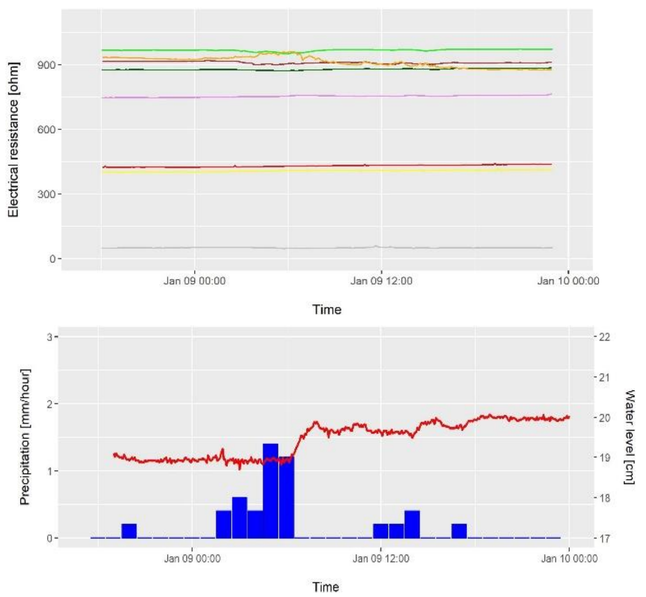
Electrical resistance [ohm]
Dec 26
Dec 28
Dec 30
Time
Precipitation [mm/hour]
Water level [cm]
Time


h)



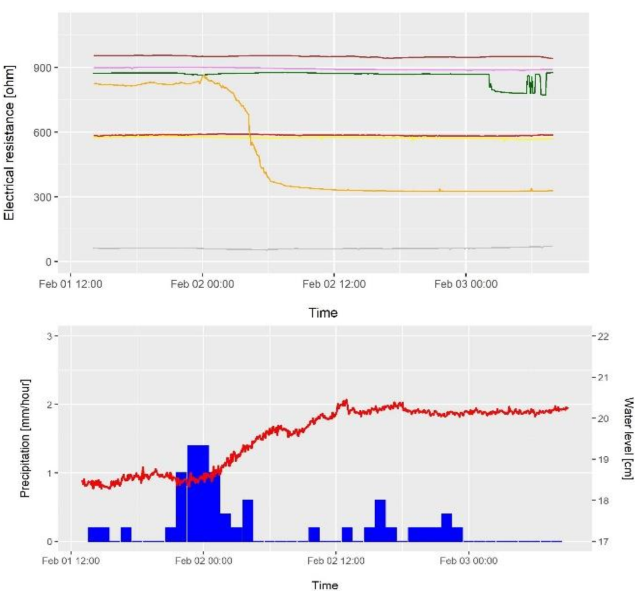
Electrical resistance [ohm]
Jan 04 18:00
Jan 05 00:00
Jan 05 06:00
Jan 05 12:00
Time
Precipitation [mm/hour]
Water level [cm]
Time


i)

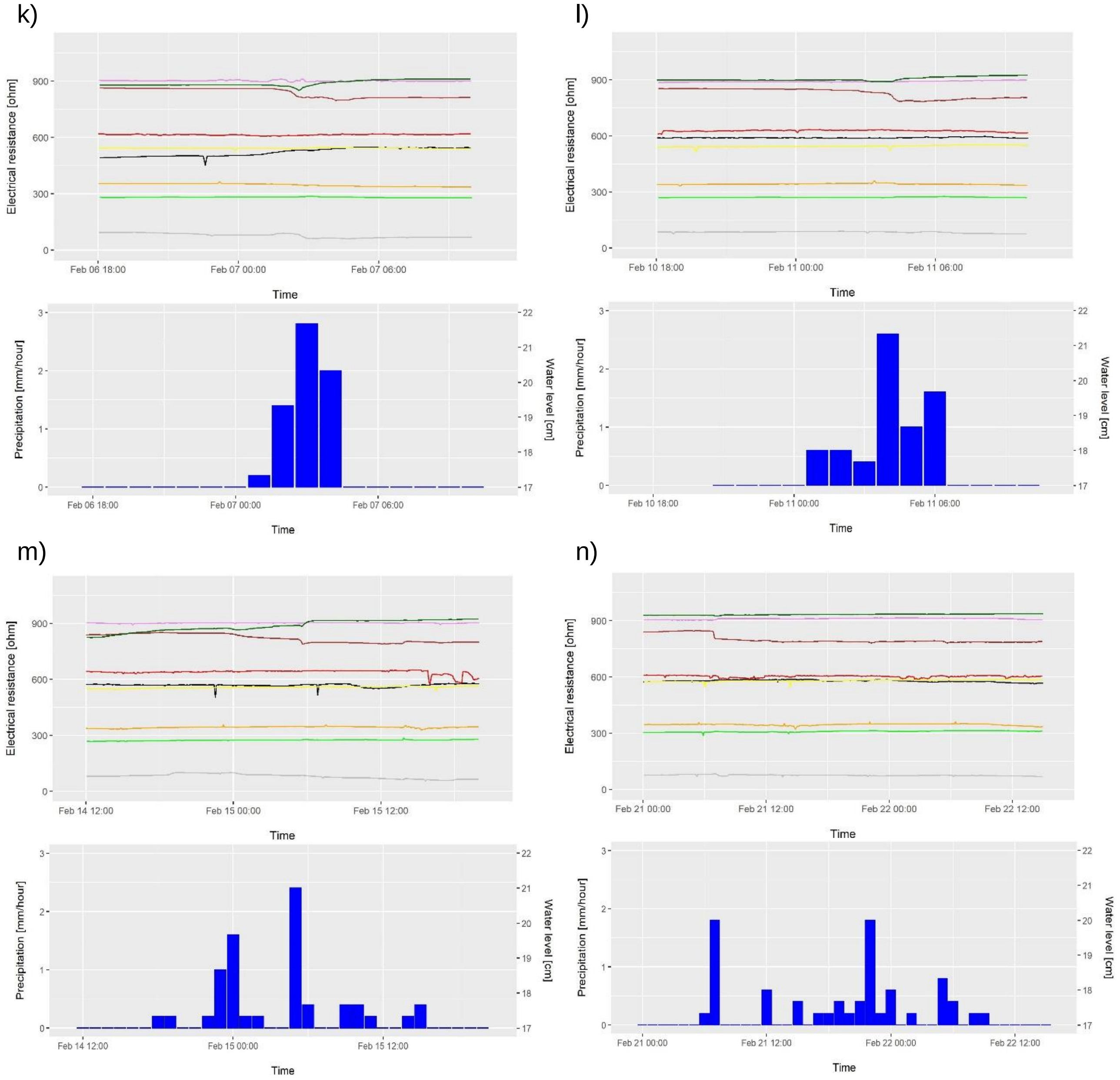


Electrical resistance [ohm]
Jan 09 00:00
Jan 09 12:00
Jan 10 00:00
Time
Precipitation [mm/hour]
Water level [cm]
Time


j)



Electrical resistance [ohm]
Feb 01 12:00
Feb 02 00:00
Feb 02 12:00
Feb 03 00:00
Time
Precipitation [mm/hour]
Water level [cm]
Time



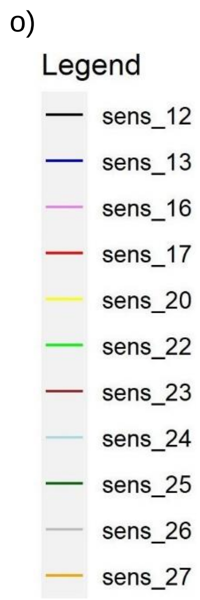




***Figure 24** Representation of electrical resistance (plot on the top) and precipitation and water level (plot on the bottom) for the major precipitation events extracted from the Wettswil data. The y-scale is the same for all the plots except for the precipitation/water level plot in (g) because of the larger water level changes. The water level for the last four events (k), (l), (m), (n) was not available. (o) shows the legend of colours for the sensors. The precipitation events were on:*
*(a) 01.11.2021 07:00 – 01.11.2021 12:00*
*(b) 01.12.2021 01:00 – 01.12.2021 09:00*
*(c) 04.12.2021 05:00 – 04.12.2021 23:00*
*(d) 08.12.2021 03:00 – 08.12.2021 22:00*
*(e) 11.12.2021 01:00 – 11.12.2021 23:00*
*(f) 13.12.2021 10:00 – 13.12.2021 16:00*
*(g) 25.12.2021 09:00 – 30.12.2021 01:00*
*(h) 04.01.2022 23:00 – 05.01.2022 10:00*
*(i) 09.01.2022 02:00 – 09.01.2022 17:00*
*(j) 01.02.2022 21:00 – 02.02.2021 23:00*
*(k) 07.02.2022 01:00 – 07.02.2022 04:00*
*(l) 11.02.2022 01:00 – 11.02.2022 06:00*
*(m) 14.02.2022 18:00 – 15.02.2022 15:00*
*(n) 21.02.2022 06:00 – 22.02.2022 09:00*

# 4. Discussion

## 4.1. Dynamics of the stream network in the catchments in the Reppischtal

### 4.1.1. Flowing stream density

The two neighbouring catchments Diebis and Bleiki in the Reppischtal differ in flowing stream density dynamics (Figure 17 and Figure 19). The Bleiki had a constantly high flowing stream density, while the Diebis reacted at the beginning of the precipitation events and took several months of precipitation to reach a similar flowing stream density as the Bleiki. In fact, only after the snow-melt events in December and in January, did the flowing stream density in the Diebis significantly increase. It increased especially in the categories 5–6 (weakly flowing and flowing), which indicate a clearly larger flow. Therefore, the weather conditions indicate that it was mostly a seasonal process that led to the increase of flowing density in the Diebis, rather than the direct effects of single-events. The snow falling and melting over two months allowed the soil moisture to increase. Furthermore, the precipitation events between November and January gave the additional input for a higher discharge due to the wetter antecedent conditions.

The physical characteristics of the two catchments seem to have an even larger influence on the flowing stream density than the weather conditions. The topography of the two areas probably plays a major role. Although the mean and maximum slope inclinations are slightly higher for the Diebis catchment (Table 2), it is characterized by a larger slope and not by narrow valleys as the Bleiki. These topographical forms in the Bleiki are possibly conducting the water more directly into the streams causing a higher saturation of the terrain where the streams are and recharging them continuously. On the other hand, in the Diebis, the water may get more dispersed over the whole slope with an overall higher saturation, but not high enough to allow the start of the flow.

The land cover of the two catchments is similar (Table 2) with the only major difference being the presence of a large meadow on the top of one of the two valleys of the Bleiki catchment. Considering that also the other valley shows a similar behaviour without being influenced by the meadow, this difference in land cover does not seem to be a factor that explains the differences in flowing stream density between the two catchments. Human intervention on the streams of the two catchments is mostly visible in the residential and agricultural areas. In the residential and agricultural areas, the course of the streams is partially modified due to roads, building and pasture lands. In the forested areas, on the other hand, all streams are natural streams. Thus, the flowing stream density is punctually influenced by human intervention.

The geological characteristics of the two catchments (Figure 6) are largely similar. However, there are some differences. The Bleiki has a larger moraine and landslide area at the upper part of the catchment, in particular to the north. These areas could perhaps provide a more constant source of streamflow, which would lead to differences in flow stream density in the two catchments, but it is necessary to conduct more surveys in other catchments to determine the effect of the geology on this type of streams.

### 4.1.2. Patterns of expansion and contraction in the catchments

During the studied period, I mainly observed the expansion patterns as the conditions of the catchments changed from dry in October to wet during the winter. Therefore, there were not any dry periods that could indicate a specific pattern of contraction of the stream network.

In general, the expansion pattern observed in the Bleiki was of the type "bottom-up" (Bahmjee & Lindsay, 2011; Peirce & Lindsay, 2014; Goulsbra et al., 2014). Most of the network was already flowing from the first mapping day. The segments, which started to flow later, were mostly at the extremities of the network (Figure 22). Additionally, the intensity of the flow shown by the categories of flow type in Appendix 7.1 indicates that it was increasing mostly in a "bottom-up" direction which could reflect also the expansion in the catchment starting from dry conditions.

For the Diebis catchment, the pattern of expansion is not as clear. Looking at the seasonal rank in Figure 21, there seems to be a "coalescence (or disjointed)" pattern (Bahmjee & Lindsay, 2011; Peirce & Lindsay, 2014; Day, 1978). There were two distinct sections flowing from the time with the lowest level of water level, while the lowest section of the catchment and other sections in-between started flowing only later. Also, for the most eastern section, where the flow started only late or never, the "coalescence" pattern is visible. However, most of the segments in the whole catchment, which start to flow late or never start, are located in the highest part of the stream network. Considering this point and looking at the behaviour of the single flowing categories in Appendix 7.1, it seems that once the network starts to have a baseflow in most of the segments, the tendency of increasing flow is "bottom-up".

The differences in expansion patterns between the two neighbouring catchments can be explained by similar factors as the behaviour of the flowing stream density. In particular, the topography of the two catchments influences them in a way that the water in the Bleiki is conducted more strongly to the streams at the bottom of the valleys. In the Diebis, where the slope extends over a wide area, the saturation of certain locations, which are not necessarily close to each other, is promoted.

Additionally, comparing the two lowest sections of the catchments, where all the streams converge, there is a clear difference. In the Diebis, there was no flow for a long time, while the Bleiki was flowing early. Generally, I expected these sections to always have flow because of the accumulation of water from the upper streams. However, in these cases, human intervention plays a role. In the Bleiki, the lower section on the south is canalised for a long distance through the residential area with the flow not being dispersed in the neighbouring terrain. On the other hand, in the Diebis, the stream is not so strongly canalised through the residential area. Furthermore, the strongest human intervention is short and close to the large transversal street. At that point, the flow was generally already lower than in the segments above, so that the channel below the street does not direct so much water to the lowest section of the network, while there may be a distribution to the meadow beside it.

## 4.2. Patterns of expansion and contraction seasonally and for single-events

In the previous chapter, the seasonal patterns of expansion and contraction for the two catchments were discussed. I planned to compare the seasonal behaviour with the behaviour during single-events. However, the information collected with the sensors and the mapping after the precipitation events was not sufficient for a complete analysis of the single-events. Assuming that the presence of water indicated by the ER-sensor is also an indicator of flow, a tendency to a coalescence pattern during the single-events is visible. The sensors that changed their status during precipitation events, were not close to each other (Figure 24). This indicates that there was not a progressive start of the flow upwards or downwards the stream network. This coalescence pattern in the Diebis is similar to what was observed on a seasonal scale.

The mapping after the precipitation events did not allow me to draw conclusions on the patterns for single-events because the two mapping sessions at the beginning of February showed steady conditions in both catchments. Thus, it is not possible to compare the seasonal and the single-events condition for the Bleiki.

## 4.3. Variation in the stream network captured by mapping and sensors

The variation in the stream network on a seasonal scale was described by the field mapping with relatively good quality. The data collected with this method allowed me to calculate the flowing stream density of the two catchments (Figure 16) and the proportion per flow category type (Figure 17). On a seasonal scale, important data were also collected with some of the sensors. In fact, precipitation, temperature and water level were important factors for describing the behaviour of the stream network. The direct measurement of the stream network with the monitoring system did not work properly. Therefore, only the electrical resistance was measured at several locations, while the flow data were missing. The data from the ER sensors showed a similar behaviour during the mapping days over the whole season as the flowing stream variability (Figure 20). The percentage of sensors indicating the presence of water increases and decreases with a similar magnitude as the flowing stream variability. This indicates that these sensors offer complementary information to the data collected with the field mapping. However, it is important to consider that the percentage of sensors is based on a low number of functioning sensors. Additionally, not all sensors were functioning properly on all of the days. This causes a large false variation in the results, in particular when a sensor indicating water presence was not functioning properly the following week.

## 4.4. Evaluation of the methods and possible future improvements

The methods planned for this thesis were in theory sufficient to obtain answers to the research questions. The combination of the mapping in the field with the monitoring system was supposed to allow for a good understanding of the changes in flowing stream density at various temporal and spatial scales. However, the difficulties and problems that arose in practice were significant. In fact, not all of the analysis could be performed as planned. In particular, the data collection from the monitoring system did not work properly. The malfunctioning of various sensors did not allow for the registration of the flow, which was crucial to compare the two methods properly. On one hand, to analyse the conditions during single-events. On the other hand, to avoid assumptions of flow based on the presence or absence of water indicated by the ER-sensors. To solve this problem, it would have been necessary to have more time to acquire the knowledge to repair all the sensors properly before the start of the measurements. Additionally, the use of cameras may have helped in this situation to have clearer images of the behaviour of the streams during single-events. However, for the analysis of a large number of videos, it would have been necessary to implement a program that is able to detect the presence of water or flow in the streams. Finally, there are important uncertainties related to the monitoring system. Firstly, the available data collected with the sensors are influenced by external environmental factors. For example, the rapid accumulation of sediments in the streams influences the ER-readings. Secondly, the data are collected at single specific locations, which makes it necessary to implement a spatial interpolation to assign the values to the neighbouring stream segments.

The mapping of the streams also has several uncertainties. The conditions during the season made it complicated to observe the whole catchment properly. The abundant vegetation and the snow were further obstacles. These conditions combined with the scale of the flow states lead to a large subjectivity in the assignation of the flow type. I tried to be consistent by training my eyes during the first field days with the measurements of the flow with the help of a small bottle. The small differences in the categories of flow type were not easy to recognize and it must be well considered how many categories are actually necessary and recognizable. To improve the subjective evaluation, it could be useful to do a measurement of the flow, for example, with the salt method during the first day of fieldwork to have a base to work on. At the same time, even with this method it is difficult to recognize the small differences between the categories properly.

An additional problem with the mapping was posed by the single-events. The first point that has to be clarified is which moment of the precipitation event has to be mapped, generally this is either during or just after the end of the event. Planning to be present during the precipitation event is a difficult task. Additionally, the conditions within the catchment vary during the mapping hours. Therefore, the mapped values of the single segments are not representative of the same time, making it difficult to compare the maps of the events. Mapping after the event does not show the complete picture of the behaviour of the streams during the events. In fact, at least a mapping campaign just before the event is necessary for comparison and to understand the changes during the event. Based on these problems, the best approach to the study of single-events is the use of a monitoring system which can describe the changes in the streams at every time step. Otherwise, it is necessary to reach the catchments in a very short time, but even this does not solve all the problems.

The combination of the methods that I used, together with an in-depth field analysis of the soil and geology composition of the catchments, may be helpful to better understand the reasons behind the different behaviours. Additionally, the use of analysis tools for the topographic surface may allow for a better comparison between the expected behaviour of the streams according to the topographic characteristics of the catchments and the results obtained with the methods of monitoring and mapping.

# 5. Conclusions

The work for this thesis in the Diebis and the Bleiki catchments confirmed that temporary streams are highly variable ecosystems. However, there were clear differences in the changes in the flowing stream density at the seasonal timescale for the two catchments. The close proximity of two catchments is thus not sufficient to draw general conclusions about the hydrological behaviour of this type of ecosystem. The main factor that can explain the differences between the two catchments is the topography and human disturbance, as the land cover is similar in both areas.

The increasing wet conditions during the studied period allowed me to observe the stream network expansion pattern for the two catchments but not the contraction. In the Bleiki, the observed seasonal flowing stream network expansion reflected the expected “bottom-up” pattern, but it was not possible to define a specific pattern for the single-events with the method I used. In the Diebis, a “coalescence” pattern describes the stream network expansion best. During the single-events, a similar pattern of “coalescence” could be observed for in the Diebis, even if the methodology used had large uncertainties.

The methods used could not be implemented completely as planned. The mapping was particularly helpful in the analysis of the seasonal processes because it allowed obtaining data from the whole stream network without the spatial interpolation. However, the analysis of the single-events was complicated. It is necessary to do repeated mapping shortly before, during and shortly after a precipitation event to be able to observe the variation in the stream network during events. Thus, a monitoring system is necessary. In general, both methods presented several uncertainties which are reduced by their complementary use. In particular, the field mapping has a better spatial resolution, while the monitoring system has a better temporal resolution.

To conclude, the study of temporal streams needs complementary methods to be able to observe the variability in the presence of flowing (or dry) stream segments. The large differences between catchments close to each other highlights that one cannot draw conclusions about temporary streams in a region based on observations in a small catchment.

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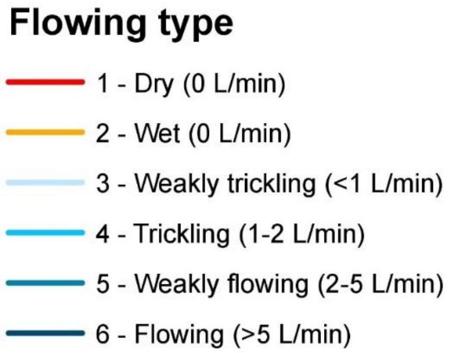
# 7. Appendix

## 7.1. Field mapping flowing type

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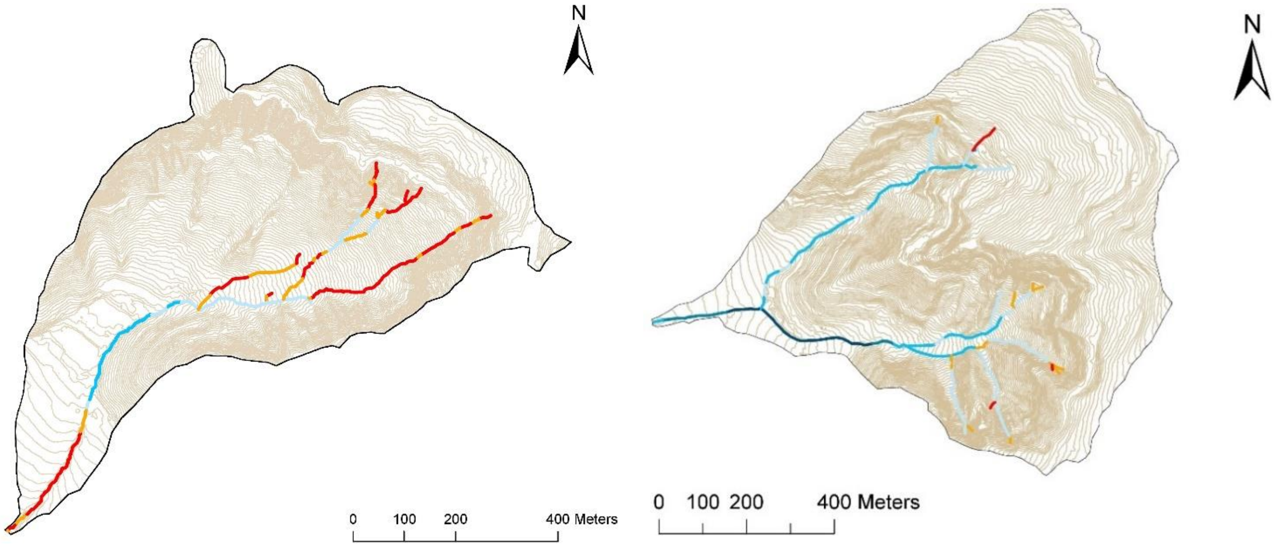


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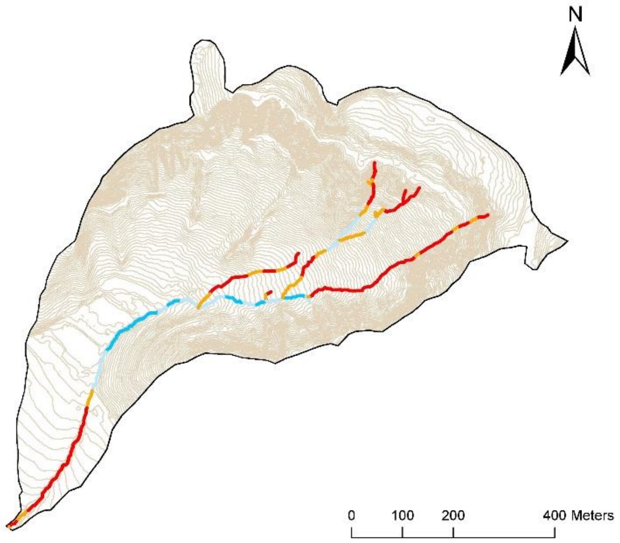

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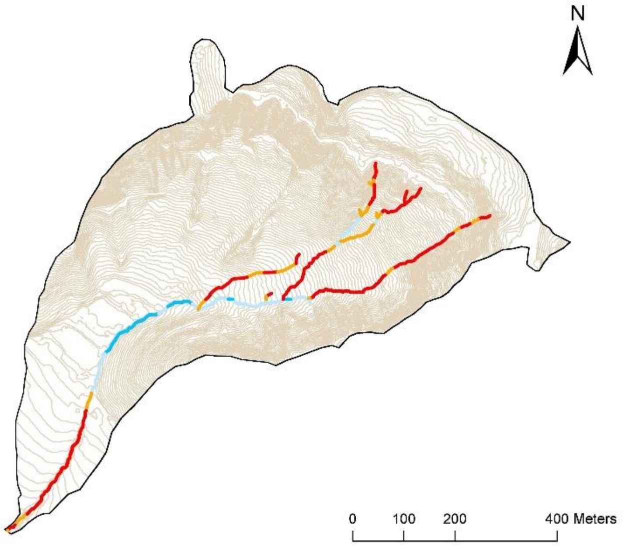


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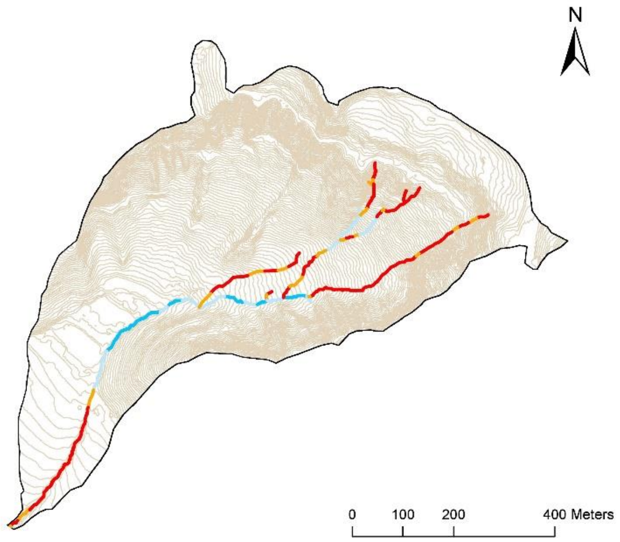


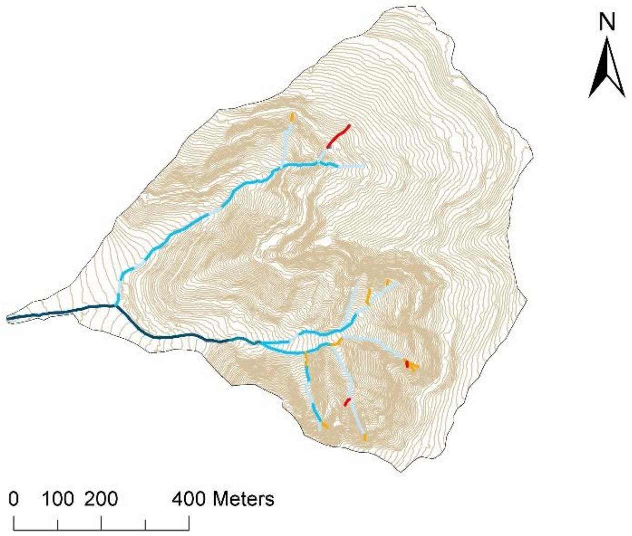


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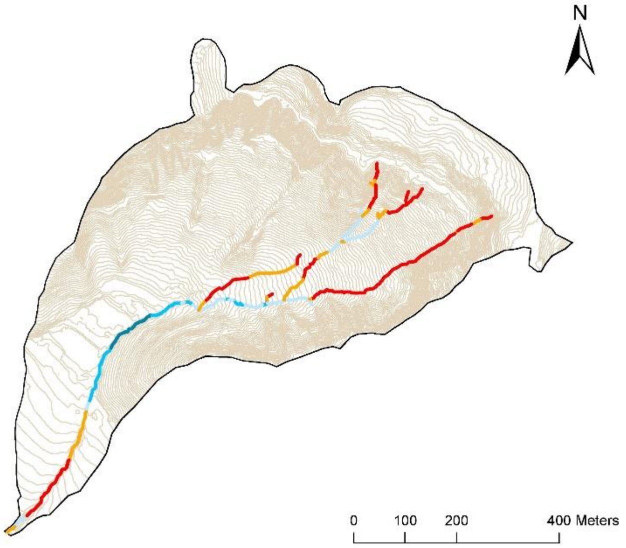

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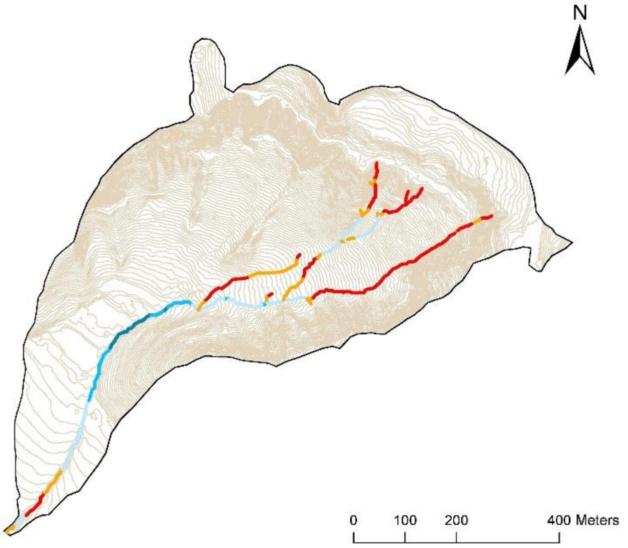


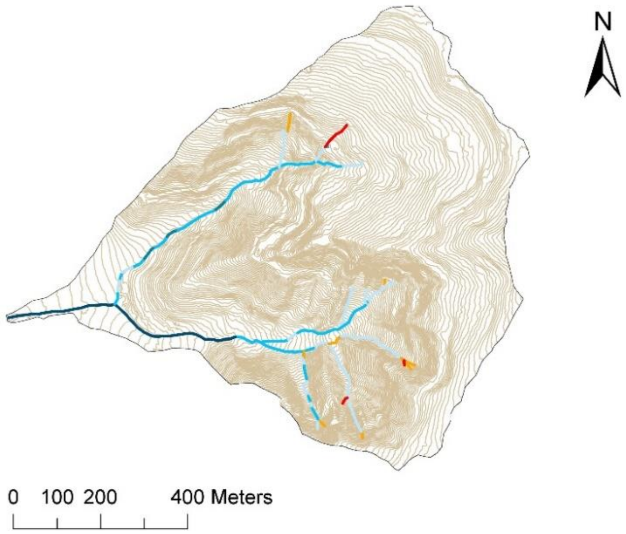


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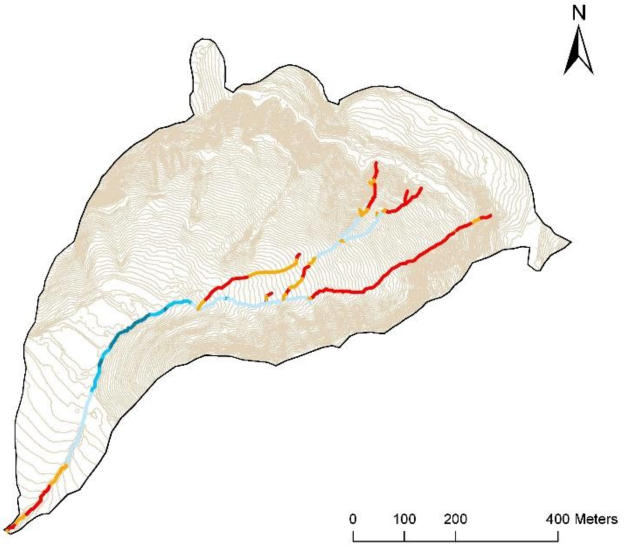


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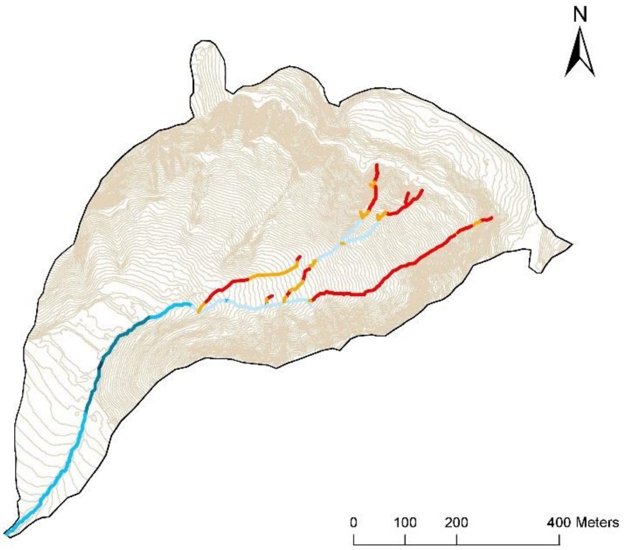


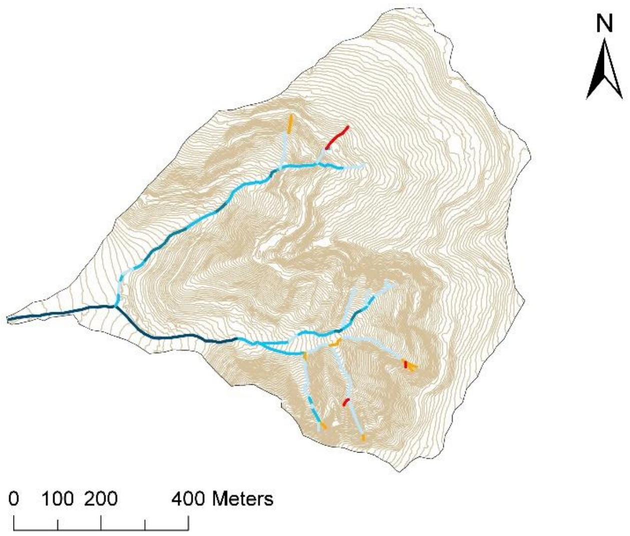

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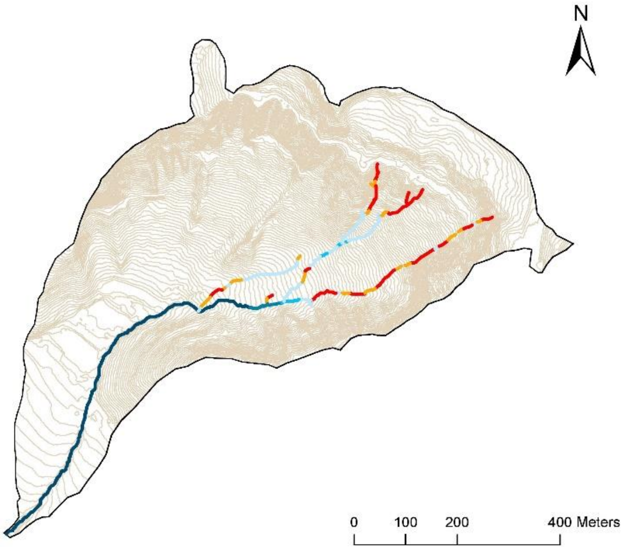


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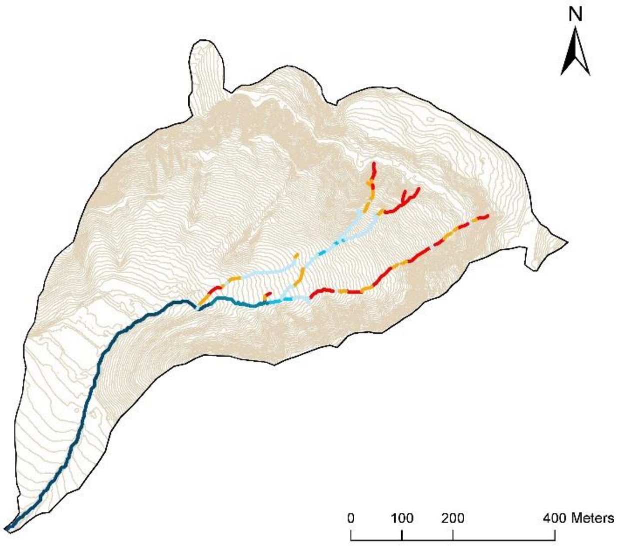


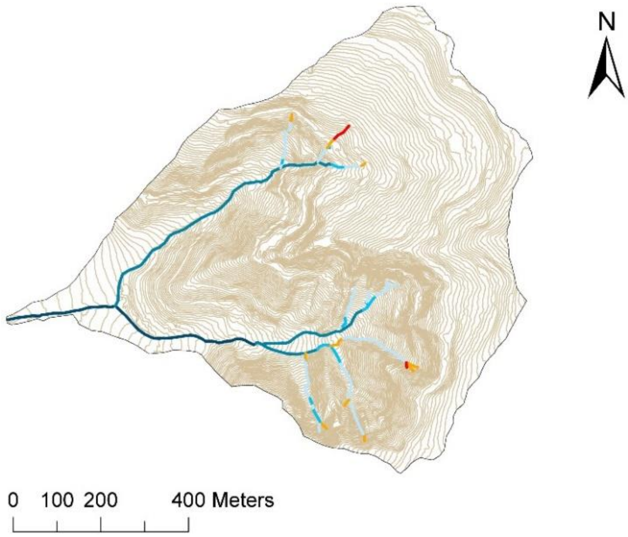


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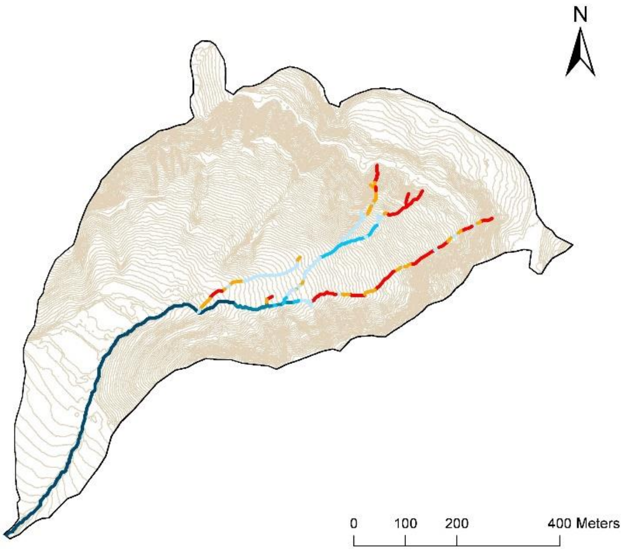

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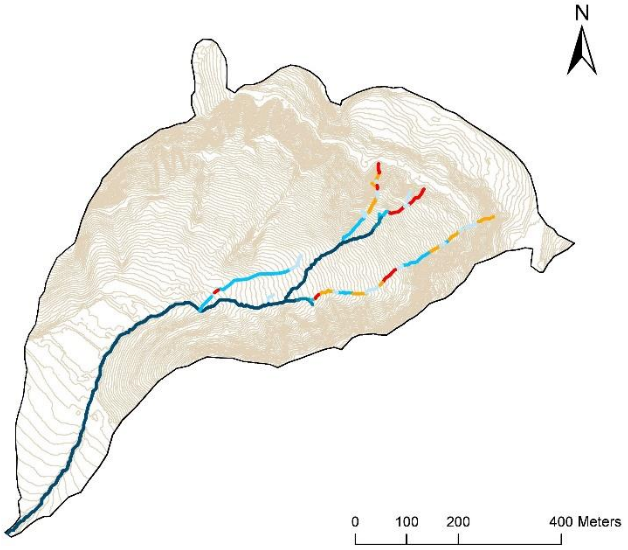


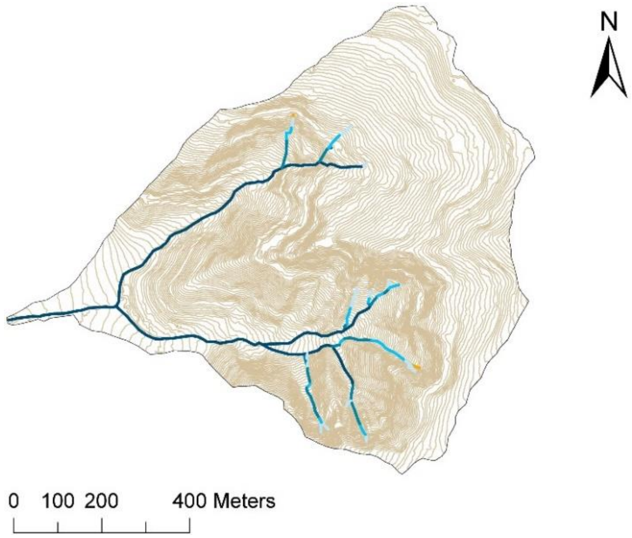


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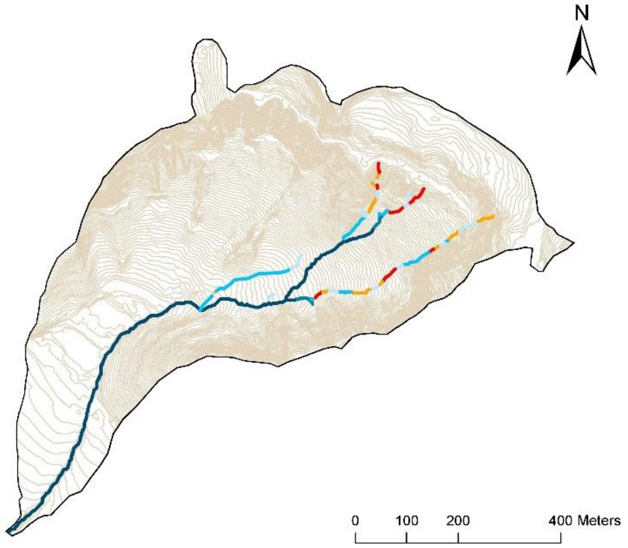


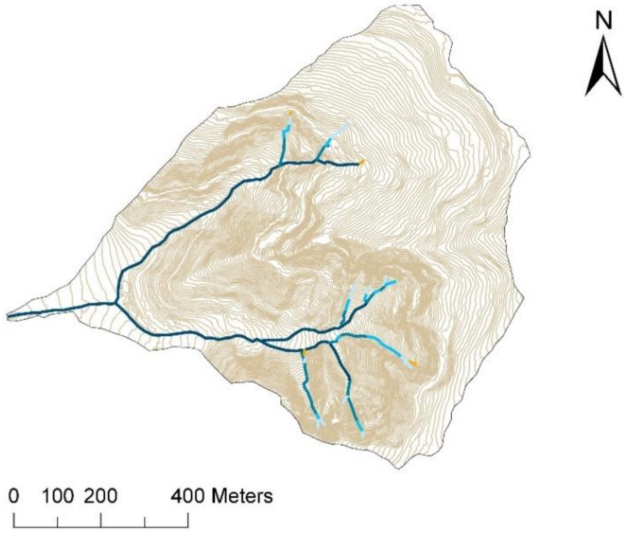


## 7.2. Electrical resistance during the mapping days from the 26 October 2021

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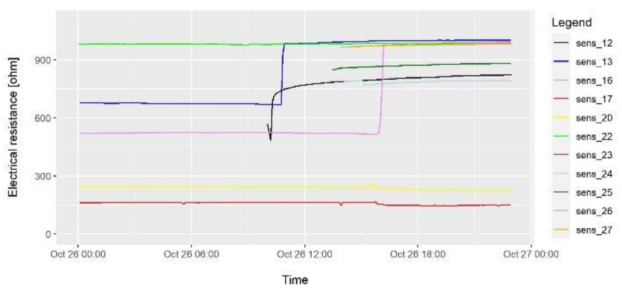


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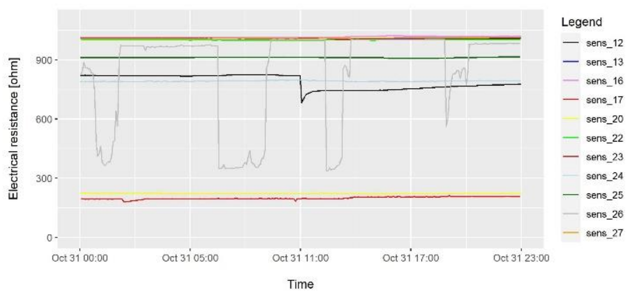

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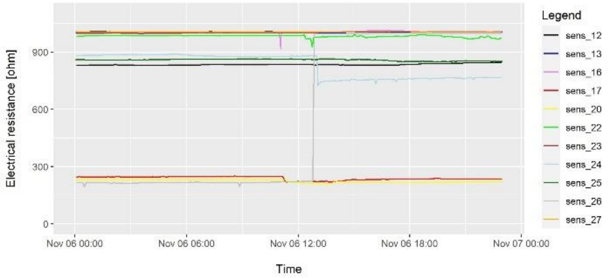


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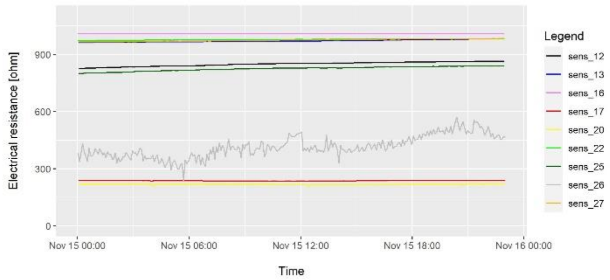


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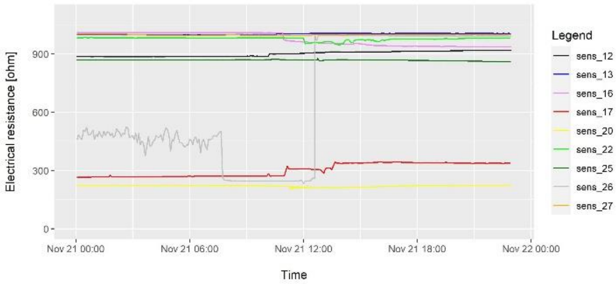


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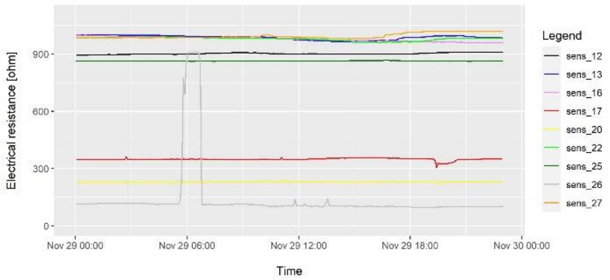


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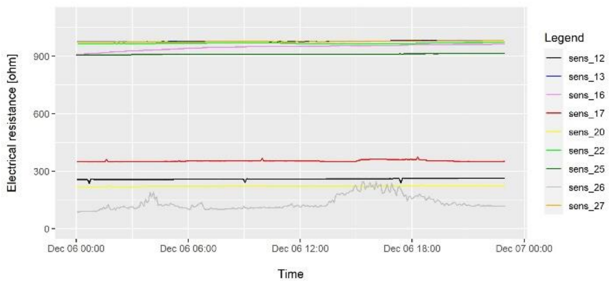


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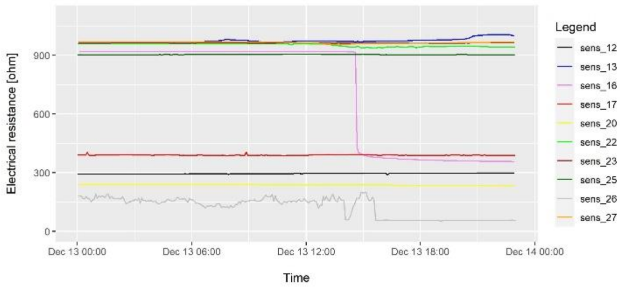


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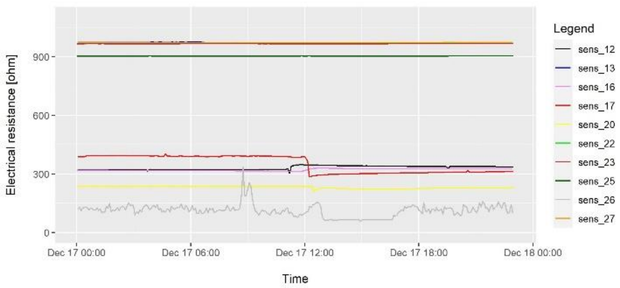


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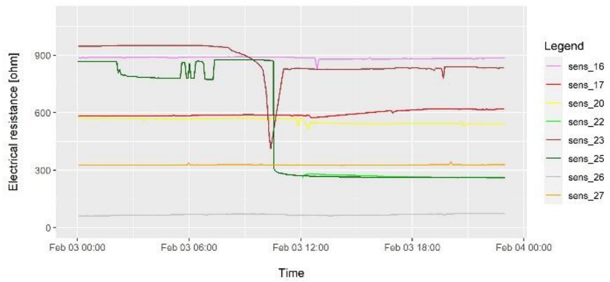


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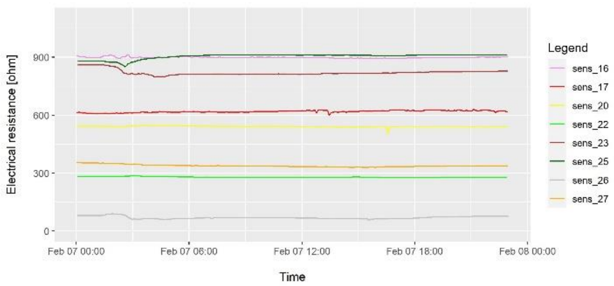

## Personal declaration

I hereby declare that the submitted Thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the Thesis.

Pontresina, 26 August 2022

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