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Dynamics of streamflow and stream chemistry in a Swiss pre-Alpine headwater catchment

A fine scale investigation of flow occurrence and electrical conductivity in the temporary streams in the lower Studibach catchment

Elise Baumann
Hanna Berglund

Abstract

Dynamics of streamflow and steam chemistry in a Swiss pre-Alpine headwater catchment - a fine scale investigation of flow occurrence and electrical conductivity in the temporary streams in the lower Studibach catchment.

Hanna Berglund & Elise Baumann

Temporary streams and their dynamics have often been largely overseen in hydrological research and there is relatively little knowledge about how the occurrence of flow in these streams varies temporally and spatially. Temporary streams are important from a hydrological perspective because they affect water quantity and quality in downstream perennial reaches, and from an ecological perspective because they provide habitat to unique species. In order to gain knowledge about these important streams, this maser thesis was conducted, within the Msc program in Water and Environmental Engineering at Uppsala University and the Swedish University of Agricultural Sciences, in collaboration with the Hydrology and Climate group at the University of Zurich. In this study, the temporal and spatial variation of the temporary streams in a small pre-Alpine catchment in Switzerland were investigated, both in terms of the presence of flowing water and stream chemistry. The 20 ha Studibach catchment is typical for the pre-Alpine area, with frequent precipitation. The streams in the lower part of the Studibach catchment were mapped in the field during September 2020. The temporal and spatial variations of the presence of flow and stream chemistry within the stream network was investigated in September and October 2020 during varying weather conditions. During ten field campaigns the flow state of the streams was classified and the Electrical Conductivity (EC) of the streams was measured approximately every 20 meter. The findings from the field campaigns were related to topographic indices, in particular the Topographic Wetness Index (TWI) and Upslope Accumulated Area (A), in order to see how topography influenced the presence of streamflow and stream EC. The results show a high temporal and spatial variation in both stream chemistry and streamflow. The active network length expanded by a factor of two in response to precipitation events. The stream EC also had a large spatial variation, and the streams in the southeast part of the catchment had a higher EC than the other streams. This spatial variation is expected to reflect the large variability in groundwater EC within the catchment. The spatial variation of the streamflow demonstrated a difference between the north-middle and the south part of the catchment, where the south part responded quicker to events and drained and retracted faster after the event. The findings also indicate that topographic indices can predict the occurrence of flow in the stream network, with sites with higher topographic index values having a higher probability of flowing water in the stream. Topography also influences the stream chemistry. The variation in stream chemistry was smaller for sites with higher values for the topographic indices, something that can be explained by the Representative Elementary Area (REA) concept, because sites with higher topographic index values are located further downstream and water at these locations is a mixture of the smaller streams that feed these streams.

Keywords: *Temporary Streams, Pre-Alpine Catchment, Streamflow, Stream Chemistry, Fine Scale Investigation, Electrical-conductivity, Stream Mapping*

Department of Earth Sciences. Program for Air, Water and Landscape Science, Uppsala University. Villavägen 16, SE-752 36, UPPSALA, ISSN 1401-5765

Referat

Dynamiken hos bäckflöden och bäckkemi i ett Schweiziskt pre-Alpint avrinningsområde av första ordningen - en finskalig undersökning av förekomsten av vattenflöde och elektrisk konduktivitet i temporära bäckar i den nedre delen av avrinningsområdet Studibach

Hanna Berglund & Elise Baumann

Temporära bäckar och dess dynamik har länge varit förbisedda inom hydrologisk forskning, och en djupgående kunskap rörande temporära och rumsliga variationer saknas. Temporära bäckar är viktiga utifrån ett hydrologisk perspektiv eftersom de påverkar både kvantitet och kvalitet på vattnet nedströms, och från ett ekologiskt perspektiv eftersom de bidrar med habitat till unika arter. Detta examensarbete har genomförts för att öka kunskapen kring dynamiken i dessa temporära nätverk. Examensarbetet genomfördes inom Civilingenjörsprogrammet i Miljö och Vattenteknik vid Uppsala Universitet och Sveriges Lantbruksuniversitet, i ett samarbete med Hydrologi- och Klimatgruppen vid University of Zurich. Studien har undersökt temporära och rumsliga variationer i ett temporärt bäcknätverk med avseende på flöden och kemin i vattnet, i ett mindre pre-alpint avrinningsområde i centrala Schweiz. Bäckarna i den nedre delen av avrinningsområdet Studibach karterades i fält för hand med karta och kompass under september 2020. Avrinningsområdet är på 20 ha och räknas som typiskt för ett pre-Alpint område, med frekvent nederbörd. Tio fältkampanjer genomfördes där temporära och rumsliga variationer undersöktes genom klassificering av flöden och mätningar av Elektrisk Konduktivitet (EC) i bäckarna ungefär var 20e meter, under september och oktober 2020 i varierande väderförhållanden. Resultaten från fältkampanjerna relaterades till de topografiska indexen Topographic Wetness Index (TWI) och Upslope Accumulated Area (A) för att undersöka hur topografin påverkar flöden och bäckkemin. Studien kom fram till att bäckarna i den nedre delen av Studibach visar både en temporär och en rumslig variation för både flöde och bäckkemi. De aktiva bäckarna i nätverket visade på en expansion med en faktor två som svar på nederbörd. En rumslig variation för flödet påträffades även mellan den södra och nord-centrala delen av nätverket där den södra svarade snabbare mot event och även drogs ihop snabbare. Kemin i bäckvattnet visade på en stor rumslig variation, med högt EC i den sydöstra delen av avrinningsområdet, vilket förmodas bero på den stora rumsliga variationen av EC i grundvattnet. Resultaten visar även på att topografiska index kan till viss del förutspå flöden i bäckarna, där platser med högre topografiska index har högre sannolikhet att det flödar i bäcken. Topografin påverkar även bäckkemin. Variationen i bäckkemin var mindre för platser med högre topografiska index, vilket kan förklaras med Representative Elementary Area (REA) konceptet, eftersom platser med högre topogragiska index värden återfinns längre nedströms och vattnet på dessa platser är en blandning av de mindre bäckarna som tillför vattnet till de större.

Nyckelord: *Temporära bäckar, Pre-Alpina avrinningsområden, Bäckflöden, Vattenkemi, Finskalig undersökning, Elektrisk konduktivitet, Bäck-kartering*

Institutionen för geovetenskaper, Luft-, vatten-, och landskapslära, Uppsala universitet
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Preface

This Master Thesis (30 ETCS) was conducted within the Msc program in Environmental and Water engineering at Uppsala University and the Swedish University of Agricultural Sciences. The thesis was carried out within the Hydrology and Climate (H2K) group at Department of Geography at the University of Zürich in Switzerland.

This work would not have been possible without the support and help from our fantastic supervisor Ilja van Meerveld, at University of Zürich. Thank you for answering all our questions, no matter how big or small, and for guiding us in the world of science and hydrology. Especially thank you for giving us the trust to investigate the streams in Alptal the way we wanted to. You are a true role model in the world of science.

Thank you Jan Seibert, at University of Zürich, for believing in us and giving us this opportunity. We are truly grateful for this experience. We will miss our Swedish talks during fika, and we look forward to seeing you again in Sweden.

Thank you to the H2K who invited us to be a part of the group and made us feel like home in Zurich. Thanks to you, this time became something special and memorable despite the circumstances during the fall of 2020. A special thanks to Marc Vis in H2K for your kindness and invaluable help with WhiteBox and other questions that we had.

A big thank you to WSL and the whole Alptal family, who made us feel like home in the beautiful Studibach catchment and provided us with data. It has been a pleasure to learn from your expertise.

Thomas Grabs, thank you for being our subject reader, providing us with great feedback and your enthusiasm for the project.

Lastly, thanks to our friends and family for always believing in us and supporting us to follow our dreams.

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Populärvetenskaplig Sammanfattning

Överallt omkring dig finns vatten i olika former, i haven, i sjöar och i bäckar. Kanske har du någon gång badat i en sjö och funderat på varifrån vattnet du badar i egentligen kommer? Och kanske har du någon gång använt uttrycket "många bäckar små", och även om det är ett uttryck så är det även så det fungerar i verkligheten. Alla större floder du sett består av många mindre bäckar som tillsammans bidrar med vatten till den större floden. En del av dessa mindre bäckar kallas *temporära bäckar* och de fyller en viktig funktion. Att de kallas temporära beror på att de ibland upplever perioder då de är helt torrlagda och det inte finns något vatten i bäcken alls, för att efter ett regn fyllas på och flöda friskt. Detta fenomen att bäcken torkar ut och fylls på är viktigt ur flera synpunkter. Det finns till exempel många djur och växter som har sitt hem i dessa temporära bäckar, då de är beroende av att bo på ett ställe där det är varierande blött och torrt. De temporära bäckarna påverkar även hur mycket vatten som transporteras till nedströms regioner och vilken kvalitet det vattnet har. Framtida klimatförändingar kan även komma att både öka och minska antalet temporära bäckar vilket ökar behovet av mer kunskap för att förstå hur de fungerar. Det är lätt att tro att bäckar är ett statiskt fenomen, då det ofta är så de framställs i kartor, men faktum är att bäckar är dynamiska och expanderar och kontraherar. En torr dag kan bäcken börja långt ned i avrinningsområdet för att efter ett regn sträcka sig långt upp mot avrinningsområdets kanter.

För att få mer kunskap om dynamiken hos temporära bäckar och förstå hur de kontraherar och expanderar och hur detta påverkar kemin i vattnet har detta examensarbete genomförts. I denna studie har vi undersökt hur dynamiken hos ett temporärt bäcknätverk i avrinningsområdet *Studibach* i centrala Schweiz ser ut, och hur det skiljer sig inom olika delar av avrinningsområdet och i olika väder med avseende på flöde och kemisk sammansättning av vattnet. För att kunna undersöka dynamiken hos de temporära bäckarna i Studibach gjordes en kartering av bäckarna. Denna kartering genomfördes genom att två personer gick genom området med karta och kompass och ritade ut alla de bäckar som påträffades på en karta. Då temporära bäckar ofta är små och svåra att se är detta ofta den bästa metoden för att kunna rita ut dem på en karta, då de är svåra eller inte går att se alls på flygfoton. Efter att en karta framställts med alla bäckar i området så genomfördes tio fält-kampanjer där flödet i bäckarna noterades och den elektriska konduktiviteten uppmättes. Den elektriska konduktiviteten är ett mått på hur många joner som finns i vattnet, och ett lågt värde indikerar att bäcken innehåller regnvatten medan ett högt värde indikerar att bäcken innehåller mycket grundvatten, då grundvatten innehåller fler joner som kommer från berggrunden. Flödet uppskattades på en skala från våt bäckfåra till flödande.

Data från de tio fältkampanjerna sammanställdes och det visade sig att både flödet och kemin i bäcken ändrades i olika väder. Det visade sig att bäckarna expanderade mycket under de blötaste dagarna, och att bäck-nätverket var nästan dubbelt så långt under en blöt dag jämfört med en torr dag. Det samma gällde den kemiska sammansättningen av vattnet, där den elektriska konduktiviteten visade sig vara nästan dubbelt så hög under torra dagar jämfört med blöta dagar, något som indikerar att det är mer regnvatten i bäcken en blöt dag jämfört med en torr.

Avrinningsområdet som undersöktes i denna studie var litet, men trots det så hittades stora variationer i flöde och bäckkemi inom området. Det gick inte att se ett samband med att ett visst flöde skulle ge en viss kemisk sammansättning, utan i Studibach verkar det vara mer avgörande för kemiska sammansättningen var i området bäcken ligger snarare än hur ofta bäcken flödar.

I denna studie undersöktes även hur topografin påverkar flöde och bäckkemi, hur flödet och kemin ser ut beroende på hur djupt eller högt bäcken är belägen, samt hur stor area uppströms som bidrar till flödet. Det visade på att topografin har en inverkan på var det flödar och även hur mycket. Det visade en liten inverkan på den kemiska sammansattningen av vattnet och att detta troligtvis beror på att det spelar större roll var i området bäcken ligger, än hur topografin där bäcken ligger ser ut.

Genom denna studie har mer kunskap om temporära bäckars dynamik tagits fram samtidigt som arbetet bidragit med detaljerade data samt en karta över ett avrinningsområde i centrala Schweiz. Detta kan i ett större sammanhang användas för att öka förståelsen över hur viktiga temporära bäckar är och vara en viktig del i att ge dem ökat skydd i lagar och bestämmelser.

View from the Studibach catchment area

Contributions

This master thesis was performed and written in a collaboration between Hanna Berglund and Elise Baumann. The field work was performed together. In the writing and analysis, Hanna Berglund focused on the *Stream Chemistry*, including the background section on the chemical composition of streamwater, the results and calculations regarding the EC, and discussions concerning the stream chemistry. Elise Baumann focused on the *Streamflow*, including the dynamics of temporary streams in the background section, the results and calculations regarding the length of the network and different flow classes, and discussion regarding the dynamics of the streamflow.

Abbreviations

A Upslope Accumulated Area [m^2].

DEM Digital Elevation Model.

EC Electrical Conductivity [μS/cm].

MRD Mean Relative Difference.

P Precipitation [mm/day].

Q Discharge [l/s].

RD Relative Difference.
REA Representative Elementary Area.

TWI Topographic Wetness Index.

Contents

1 Introduction

1.1 Temporary Streams and Stream Dynamics

Stream networks are, unlike depicted on maps, not static but dynamic and their length changes over time (Ågren et al. 2015; Godsey & Kirchner 2014; van Meerveld et al. 2019). This expansion and contraction of the active stream network affects streamflow in downstream reaches, stream chemistry and stream biodiversity (Meyer et al. 2007). Therefore, it is interesting and relevant to know how dynamic streams are and what affects their flow in order to ensure water quality in downstream reaches and legal protection (Meyer et al. 2003) .

Temporary streams do, unlike perennial streams, not have flow at all times, but experience periods without surface flow. The importance of the temporary streams has been overlooked in hydrologic research, which has long been focused on perennial streams (Acuña et al. 2014; Larned et al. 2010; McDonough et al. 2011). Temporary streams, however, are very important both from a hydrological and ecological viewpoint and deserve more attention and research focus. They have shown to be of high importance regarding nutrient dynamics (Meyer et al. 2007) and sediment transport (Dieterich & Anderson 1998). They are also crucial areas for biodiversity, providing habitat to unique species of fish, macroinvertebrates and amphibians (Meyer et al. 2007). Temporary streams thus are an important part of freshwater ecosystems (Larned et al. 2010) and more research about their dynamics are needed (Wohl 2017). Furthermore, the onset of flow in temporary streams affects water quantity and quality in downstream perennial streams. Understanding of their dynamics is thus also needed for better understanding runoff responses in perennial streams (Acuña et al. 2014; Foody et al. 2004; Gomi et al. 2002; Larned et al. 2010; Meyer et al. 2003; Wohl 2017).

In many places, temporary streams make up the majority of the stream network length(Acuña et al. 2014; Fritz et al. 2013; McDonough et al. 2011; Meyer et al. 2003; Nadeau & Rains 2007) but temporary streams are often underrepresented in current maps and stream models (Ågren et al. 2015), and the mapped network does not reach as far up in the catchment as in reality, see Figure 1. This can be problematic when these maps are used to design water quality monitoring (Fritz et al. 2013), hydrological models (Stoll & Weiler 2010) or when implementing legal protection or regulations of streams (Meyer et al. 2003).

However, it appears that people do not seem to realize the importance of headwaters in the same way as they value other rivers and stream segments (Wohl 2017) and in many countries headwaters do not have the same legal protection in terms of streamflow or water quality as perennial streams have (Meyer et al. 2003). These facts make Wohl (2017) also highlight the importance of gaining public awareness of the important ecosystem services and the important role temporary streams have in the bigger river network.

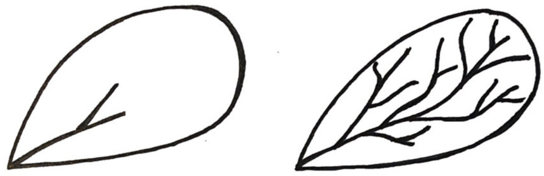


Figure 1: *Sketch of a catchment with streams as depicted on common maps (left) and what would be a more correct representation of the network (right).*

Wohl (2017) highlights mapping of small streams, techniques to measure spatial and temporal variations and data sets of such measurements, as one of the main focus areas for further research. This would increase the knowledge of the spatial distribution and cumulative length of small streams, which could be of importance for their ecological or physical function (Meyer et al. 2007).

Research has indicated that with climate change, more streams will become temporary. Signs of decreasing runoff are seen from large areas over the world, indicating that some streams that are perennial today will experience dry periods and become temporary (Larned et al. 2010). Jaeger et al. (2014) showed that with a predicted increase of zero-flow days, dry and disconnected sections of streams will likely increase during mid and late century, affecting the fish and fauna. These streams will therefore be an even more important part of the stream network and for understanding and predicting streamflow responses to rainfall and snow melt. This makes temporary streams interesting to study (Lowe & Likens 2005; Meyer et al. 2007).

1.1.1 What is a Stream?

A stream is by Cambridge Dictionary (n.d.) defined as *"water that flows naturally along a fixed route formed by a channel cut into rock or ground, usually at ground level"*. Streams originate when water is flowing over a surface or or when groundwater flow exceeds the maximum transmissivity of the soil. The magnitude of the flow might create channels when sediment is moved and erosion occurs (Costigan et al. 2016). In steep terrain and mountain regions channels are often created from shallow landslides due to groundwater discharge and geotechnical processes (Doyle & Bernhardt 2011). A small dry streambed, like the left one in Figure 2, might not be the first thing that comes to mind based on the definition of a stream, but all big rivers consist of many smaller rivers.

Figure 2: *Two temporary streams in the Studibach, Alptal Switzerland. Can you see them?*

The small streams that are the sources of the bigger streams are usually referred to as headwater streams. Headwater streams are usually defined as the upper part of the stream network and can be both perennial or temporary (Lowe & Likens 2005). Headwater streams make up around 70-80% of the total length of all rivers but have not received as much attention as the larger streams (Datry et al. 2014; Lowe & Likens 2005; Wohl 2017). Headwater streams may not always have the same clear channel or streambed as a perennial stream, and can vary a lot in their appearance. Some of these headwater streams do not flow all the time, but experience time when the streambed is dry (Datry et al. 2014).

The headwater streams that experience times of no flow are called temporary streams, and even though they do not always fit into the conventional definition of a stream they are important fractions of the stream network (Lowe & Likens 2005; Meyer et al. 2003). There is no clear definition of what can be counted as a stream channel in terms of depth and width of the channel. In temporary streams this can sometimes be a vague area since the streams are not always flowing in distinct clear channels but rather on top of the surface or in small rills. When water flows over the land surface outside a geomorphic channel, either diffuse over the area or as concentrated flow in small rills, it is defined as overland flow (Robinson & Ward 2017). However, overland flow that is concentrated in flowing rills can be included in the term temporary streams. If water from the overland flow reaches a stream channel this is part of the surface runoff contributing to the stream.

1.1.2 Intermittent, Ephemeral and Episodic streams

Temporary streams include *intermittent*, *ephemeral* or *episodic* streams. For intermittent streams the groundwater table is below the stream bed during certain times of the year but in other times located above it. This results in a flowing stream when the groundwater table is high and causes the flow to stop during very dry periods. An intermittent stream can be dry and return to flow multiple times during a year; it may dry up in some parts of the stream channel and have continuous flow in other parts (Uys & O'Keeffe 1997). Ephemeral streams have a groundwater table that is below the streambed, meaning the stream is not fed by groundwater; the streams only flow in direct response to a precipitation event (Buttle et al. 2012; McDonough et al. 2011). Episodic streams flow rarely and can be activated only once in a few years during extreme rainfall events (Uys & O'Keeffe 1997). All these three stream types are included in the term temporary streams.

1.1.3 Dynamics of Stream Networks

Stream networks are not static and their length and extent change over time (ibid.). This creates a dynamic that is not completely understood, but nonetheless important for predicting runoff and streamflow response. This can change both from catchment to catchment, as well as small scale within a catchment or even along a stream segment. The temporal variation in stream network dynamics aims to describe the changes in the sections of the network with flowing water over time, or from dry to wet periods. The spatial variation of stream networks describes the variation in the (frequency of the) presence of flowing water at different locations in the network. It is important to distinguish the flowing or *active* stream network from the full stream network, since these are usually not the same. An active stream means the stream that have flowing water in the channel. The active stream network will contract and expand whereas the full stream network refers to all potential waterways.

The active stream network expands and contracts during the year (Wigington et al. 2005) and during events (Ågren et al. 2015; Godsey & Kirchner 2014; van Meerveld et al. 2019). The pattern of expansion can be *Bottom-Up*, *Top-Down* or *Disjointed* (Goulsbra et al. 2014). Bottom-Up occurs when the water table rises, causing flow to occur first in the downstream reaches. This causes the stream head to move upstream and the active stream network to expand, as was shown by Morgan (1972) for a catchment in Malaysia. In the Top-Down pattern, the expansion of the active network instead occurs from the upper parts. This occurs when the soil infiltration capacity is exceeded, or the soil in the upper reaches become saturated, causing overland flow and water to move into the stream channels (Day 1978). Disjointed patterns occur in segments where water can be collected in pools, and connects to the network when the pools are filled and spill over (Bhamjee & Lindsay 2011). It is relevant to understand the dynamics and the changes in the stream network since it will affect how the network responds to precipitation events.

Headwater stream networks have been shown to not always be connected to the downstream waters (Assendelft & van Meerveld 2020b; Godsey & Kirchner 2014; Jensen et al. 2017; Nadeau & Rains 2007; van Meerveld et al. 2015). Rather the networks experience periods of disconnections where the upper streams or hillslopes are not connected (i.e. are missing visible surface flow) to the downslope stream. In some catchments, disconnection is the most common state and connection only appear during high intensity precipitation events (van Meerveld et al. 2015). This will also affect the expansion and contraction of the active stream network over time.

The term connectivity has been used differently in different studies but is defined by Leibowitz et al. (2018) as the "*degree to which components of a system are connected and interact through various transport mechanisms*". Connectivity and the variability of streams are included in the River Continuum Concept, RCC developed by Vannote et al. (2011). Connectivity varies over time and is highly influenced by the surrounding landscape. This is also suggested by Leibowitz et al. (2018) and Ward (1989), who highlights the need for a broad spatiotemporal perspective to fully be able to examine the changes in stream dynamics and connectivity and disconnections, and the interactions with the surrounding areas. The connectivity and disconnections can have large impacts on the produced discharge and is therefore an important part of understanding the stream dynamics and the effect downstream (Nadeau & Rains 2007). The smaller streams tend to be more disconnected from the main network, however since the number of smaller temporary streams is large the cumulative effect on the discharge can be large (Leibowitz et al. 2018).

Godsey & Kirchner (2014) examined four headwater catchments in California and showed that all of them dynamically expanded and contracted seasonally. The stream networks became disconnected during the field surveys. They furthermore showed that the active network length and drainage density decreased by a factor of two to three during the seasonal dry down. The scaling factor, β, i.e., the slope of the log-log plot of the flowing stream length and discharge, was in the range of 0.18 to 0.4.

1.1.4 Monitoring and Mapping of Temporary Streams

Mapping the location of temporary streams and the spatiotemporal variation of flow in them is not a simple task. Headwater temporary streams are often located in remote and not well accessible locations, and the extent of the large network is therefore difficult to map and monitor. However, field mapping is the most common and accurate method that has been used so far. This was for example done by Jensen et al. (2017) for four headwater catchments in the Appalachian mountains in the USA. They walked along the stream channel, from the outlet to the origin of the stream, and showed high variation in stream length in different weather conditions, as well as regional differences. Godsey & Kirchner (2014) similarly examined the expansion and contraction of the active stream network by walking the entire stream length multiple times. They also indicated difficulties of mapping by hand, in particular a low temporal resolution and that the precipitation events are hard to capture during one field campaign.

Sensors have been used to monitor and map stream dynamics as well (Assendelft & van Meerveld 2019; Bhamjee & Lindsay 2011; Goulsbra et al. 2014). Bhamjee & Lindsay (2011) examined different stream sensors and used ER sensors to examine when ephemeral streams were flowing or dry. The sensors were inexpensive and could be used during long periods. One limitation is that the sensors only measure the stream as dry or flowing (ibid.). To map the activation of streams Gelmini et al. (2018) used low-cost cameras. These where installed in three different streams and could in a easy way be used to determine when the streams were activated, when the peak flow occurred and the disconnection. They also discovered that the three streams were activated during different weather conditions. Kaplan et al. (2019) used both sensors (measuring electric conductivity and water level) as well as time-lapse cameras to determine presence of streamflow.

In the Alptal, Switzerland, mapping has previously been done by Sjöberg (2015) and van Meerveld et al. (2019). Assendelft & van Meerveld (2019) installed several monitoring sensors to examine the flow regime at a number of stream locations. The multi-sensor system could determine the hydrological state of the stream: as dry, standing water or flowing water. This presented the opportunity to capture events and changes in the hydrological state at a high spatiotemporal resolution at a low cost.

1.2 The Chemical Composition of Streamwater

The chemical composition of streamwater is influenced by several temporal and spatial factors, such as geology, soil, vegetation and land-use (Likens & Buso 2006). Precipitation and flowpaths are other factors that can influence the stream chemistry. During a rain event, runoff processes will increase the flow in the stream and changes the chemical composition in the stream. Several studies have examined the composition of streamwater during rain events to find out what water that contributes to the stream (Cano-Paoli et al. 2019; Fischer et al. 2017; McDonnell et al. 1991; Pinder & Jones 1969; Sklash & Farvolden 1979). Headwater streams are of high importance when it comes to water quality in downstream reaches (Meyer et al. 2007), and it is therefore interesting to examine the chemical composition of streamwater in temporary streams.

1.2.1 Temporal Variation in Stream Chemistry

The flow in a stream can be visualised in a hydrograph. A hydrograph is a plot of the flow in the stream against time. In a graphical hydrograph separation the groundwater recession curve is graphically separated from the streamflow in the hydrograph (McDonnell et al. 1991). This allows to determine how much water that is direct runoff or baseflow. Where baseflow is the flow in the stream between precipitation events, which can be fed by (deep) groundwater as well as delayed shallow subsurface water (Robinson & Ward 2017). Since direct runoff could be both event water and pre-event water, graphical hydrograph separation does not allow to determine if it is groundwater or event water that contributes to the streamflow. A tracer-based hydrograph separation can be used to determine the sources of the water that contribute to streamflow during an event.

Tracers can both be added to the stream (artificial tracers) or naturally occur in the stream (environmental tracers) (Leibundgut & Seibert 2011). Environmental tracers are natural components of the streamwater that can be tracked or monitored along the stream. Some natural tracers that are common in hydrological studies are stable isotopes, such as ^{18}O, radioactive isotopes, noble gases, or physio chemical parameters such as electrical conductivity or temperature (ibid.).

Stable isotopes are commonly used as a tracer in tracer-based hydrograph separation . In the last years, the analysis of stable isotopes has become faster and cheaper. Using stable isotopes as tracers allows to gain deeper knowledge of temporal and spatial variations in stream chemistry as well as residence time, flow paths and sources of the streamflow (Sklash & Farvolden 1979).

Streamwater can in a simple way be described as the mixture of old, pre-event water (i.e. groundwater) and new, event water (i.e. rainwater). The chemical composition of the water in the stream during dry conditions is more similar to the chemical composition in the groundwater (Grip & Rodhe 2016). During a rain event the proportion of new water in the stream increases, due to the precipitation falling on the stream and saturated areas (Spellman & Webster 2020) but also due to other fast runoff processes. In small to medium sized catchments in humid temperature climates, groundwater is the main contributor to the baseflow (Buttle 1994; Klaus & McDonnell 2013). Hydrograph separation studies have shown that during rain events, groundwater is the main contributor to the peakflow as well (Buttle 1994; Grip & Rodhe 2016; Sklash & Farvolden 1979). In other words pre-event water is the main contributor to streamflow during most stages in the hydrograph.

Fischer et al. (2017) analyzed the chemical composition of streamwater during 13 rain events in Alptal, Switzerland, by looking at the stable isotopes and found that increasing precipitation led to more event water in the streamflow. In many previous studies End Member Mixing Analysis (Christophersen et al. 1992) has been used to infer the different sources of streamflow (e.g., precipitation, soil water and groundwater) based on the stream chemistry. The method assumes that the spatial variation of the stream chemistry within the catchment does not vary significantly, and that water from different sources are well mixed to create the composition of stream water (Asano et al. 2009; Burns et al. 2001). While this in some cases might be true, Zimmer et al. (2013) emphasize the need of fine scale investigations of small headwater streams in order to see how different hillslope and landscape features affects the water chemistry in the stream.

1.2.2 Spatial Variation in Stream Chemistry

Research on streamwater chemistry has to a large extent been focused on the spatial variation in stream chemistry across catchments based on "snapshot" sampling campaigns (Fischer et al. 2015; Fröhlich et al. 2008). Few studies have sampled the water with a higher resolution along the stream, as Zimmer et al. (2013) who sampled a stream every 50 meters or Singh et al. (2016), who sampled the stream every 25 meters. Singh et al. (ibid.) analyzed the temporal and spatial variation in the stable isotope ^{18}O on a fine scale of 25 meters, and found both temporal and spatial variation along the streams. Grunder (2016) analyzed the spatial variation in stream chemistry in two sub catchments in the Studibach and found a large spatial variation in the stream chemistry even on a small scale.

The sampling scale will affect the understanding of the relationship between the chemical composition in the water and site specific chemical, physical and biological features (Gustafson 1998). Sampling the stream at a higher resolution also allows one to investigate how topography affects the stream chemistry at a finer scale (Zimmer et al. 2013).

The representative elementary area (REA) concept describes the phenomenon of a smaller variation when a larger area is sampled. It also describes the smaller variation in stream chemistry for larger streams (Wood et al. 1988). When smaller streams join together their water is mixed, leading to less variation in stream chemistry with a larger catchment area than for the individual smaller streams that contribute to it. In a study by Temnerud et al. (2007) it was shown that the chemical composition of the stream water in a boreal catchment in Sweden stabilized and was less variable for streams with a catchment area larger than 5 km^2.

1.2.3 Electrical Conductivity (EC)

A good first indicator of the chemical composition of the streamwater can be determined by studying the Electrical Conductivity (EC). The EC describes the capacity of the water to conduct a current and depends on the number of the dissolved ions in the water, which are the conductors. The EC thus reflects the total amount of ions in the water and is therefore an easy and especially fast measure that reflects the stream chemistry (Pellerin et al. 2008). The changes in streamwater EC during an event can indicate if the water is old or new. Groundwater generally has higher concentrations of solutes due to the weathering of the bedrock (Burns et al. 1998) compared to rainwater, and therefore pre-event water in the stream will generally have a higher EC than the the event water (Grip & Rodhe 2016).

It has been shown that the EC in the stream generally decreases during rainfall events, which indicates that the proportion of rainwater with a lower EC increases during an event (Cano-Paoli et al. 2019; Grip & Rodhe 2016). This is generally true, but Grip & Rodhe (2016) point out that the decrease in EC can not directly be assumed to be due to an increased proportion of event water, since the proportion of shallow groundwater with a lower EC-value might increase during the event, which could give the impression of the stream containing more rainwater than it actually does. Despite this issue, Cano-Paoli et al. (2019) concluded that EC could work better as an environmental tracer to determine which water contributes to streamflow than other standard methods, such as stable isotopes.

1.3 Topographic Indices

Topography affects the flow of water on the surface and in the subsurface and has been identified as a valuable descriptor for understanding and predicting hydrological processes (Beven & Kirkby 1979; Grip & Rodhe 2016). It could also be used to predict the chemical composition of streamwater, since topography influences the inflow of groundwater in lower elevated areas in a catchment (Grip & Rodhe 2016). Topographic features are therefore often included in hydrological models, as a way to predict runoff response.

1.3.1 Digital Elevation Model, DEM

A digital elevation model (DEM) is a 3D representation of the landscape. It is used to describe, explain as well as predict processes in many scientific fields, such as hydrology, geology, geomorphology and ecology. The elevation input data for DEMs can be derived from field surveys, photogrammetic methods (space or air photos) or other remote sensing methods. In recent years Light Detection and Ranging, LiDAR, has become a common way to derive elevation data. DEMs derived from high resolution LiDAR data include small scale landscape features (Hopkinson et al. 2009; Murphy et al. 2008).

In hydrological modelling, gridded DEMs are often used, where the elevation is represented as two-dimensional grid cells. Flow algorithms using the local surface gradient and the elevation changes in the DEM model can be used to determine the flow direction and the likely locations of streams (O'Callaghan & Mark 1984). Modifications to the DEM may need to be made to insure better performance, for example algorithms that fill sinks and depressions in the landscape (Jenson & Domingue 1988). A common way is to use a single-direction flow algorithm, which assumes the water only flows in one way, often creating straight lines in the network (Erskine et al. 2006). This can be especially problematic when dealing with small catchments and temporary streams, that do not always follow the steepest slope. Meaning the streams sometimes take other routes depending on geology or other obstacles, making the streams follow different paths than the steepest slope. Therefore multiple-direction algorithms can preform better, such as the MD-infinity algorithm by Seibert & McGlynn (2007).

To be able to use topographic data from a DEM together with a mapped stream network, stream burning may be necessary to represent the network correctly. Since the streams often take different routes than in the DEM using the DEM to extract topographic data would provide inaccurate data for the flow accumulation. Stream burning can either be done by lowering the grid cells at the locations of the streams or by instead raising the cells of the area around the streams (Lindsay 2016). The DEM can then be used to extract topographic indices as needed, with the data of the mapped stream network.

1.3.2 Upslope Accumulated Area, A

The upslope accumulated area, also known as upslope area, local contributing area (Seibert & McGlynn 2007), upslope contributing area (Erskine et al. 2006) or accumulation of hillslope area (Jencso et al. 2010), of a point in the landscape is the area that could potentially contribute to discharge at that point. It is commonly used as a topographic index (Erskine et al. 2006), and as a first order control on hillslope connectivity and runoff (Jencso et al. 2009). The Upslope Accumulated Area was found to partly explain flow occurrence in both the Upper North Grain catchment, South Pennines, UK (Goulsbra et al. 2014) and the Krycklan catchment in Sweden (Gassman 2018). Assendelft & van Meerveld (2020a) also found Upslope Accumulated Area to be related to flow permanence in the upper Studibach catchment in Switzerland. The upslope accumulated area can be estimated from a DEM using flow algorithms. Erskine et al. (2006) found that for smaller grid sizes of the DEM, multiple-direction algorithms worked best.

1.3.3 Topographic Wetness Index, TWI

The topographic wetness index (TWI) is commonly used to describe how hydrological processes are controlled by topography. It was first formulated by Beven & Kirkby (1979), as a part of the runoff model TOPMODEL. It is defined as equation 1. Where α refers to the area drained per unit contour length at a certain point, and β is the local slope angle.

$$TWI = ln(\frac{\alpha}{tan\beta}) \tag{1}$$

A high TWI-value corresponds to a location that has a large upslope area and/or a very low slope. These are generally wet areas with a higher availability of water that drain slowly. A low TWI-value indicates instead a smaller upslope area and/or a steeper slope. These are relatively dry sites.

The TWI can be calculated from a DEM and has been shown to be sensitive to the resolution of the DEM grid (Wolock & Price 1994), indicating a need for small grid cells. Some assumptions are made when using the TWI in hydrological models, which include that the groundwater follows the topography and that the hydraulic conductivity and the precipitation are the same at every point in the catchment (Sørensen et al. 2006). Rinderer et al. (2014) showed that in low-permeability soils, the TWI assumptions works best when there is a slow change in groundwater levels. Shortly after the peak flow, when the change in groundwater levels are fast, the correlation between TWI and groundwater level was lowest. Rinderer et al. (2016) suggested that in catchments with low-permeability soils the groundwater response timing was more affected by the topography than in soils that are more transmissive. Sjöberg (2015) found that TWI to some extent described flow occurrence in the Alptal area in Switzerland.

1.4 Aim of the Study

The aim of this study was to gain deeper knowledge into the dynamics of streams in a pre-Alpine catchment and to investigate how the spatiotemporal variations in the occurrence of streamflow and stream EC were related to groundwater inflows and topography. By examining the relation between these parameters the source of water that contributes to the stream during different weather conditions can be determined.

More specifically this was obtained by mapping presence of flowing water and the EC in the whole extent of the stream network during varying weather conditions. Fine scale measurements and classifications of streamflow were used to understand how the active stream network and the stream chemistry along the streams varies between dry and wet conditions. This fine scale sampling and classification enabled the investigation of how the topography can predict the permanence of streamflow and the variation of stream chemistry along the stream.

This study focused on answering the following research questions.

- How does the active stream network vary between different weather conditions, and how much does the active stream network expand from a dry to a wet day?
- How does the stream chemistry vary along the stream network and how does this change during rainfall events?
- Can topography predict the permanence of streamflow and the variation in stream chemistry?
- Are streams with a similar flow occurrence characterized by a similar EC?

This study will provide more knowledge about temporary streams. This study is important because more research about the dynamics of temporary streams is needed in order to obtain legal protection of these streams and to protect the unique flora and fauna of temporary streams. More knowledge about temporary streams is also needed in order to better understand variations in water quantity and quality in downstream perennial streams.

2 Study Area and Methods

2.1 Study Area

The study took place in the lower part of Studibach, a 20-hectares pre-Alpine headwater catchment in the Alptal (N47.038, E8.723), in the canton of Schwyz in central Switzerland (Figure 3). The Studibach drains to the Zwäckentobel, which drains into the Alp that drains into the river of Sihl, which flows through the city of Zürich before flowing into the Limmat, ultimately draining into the Rhine.

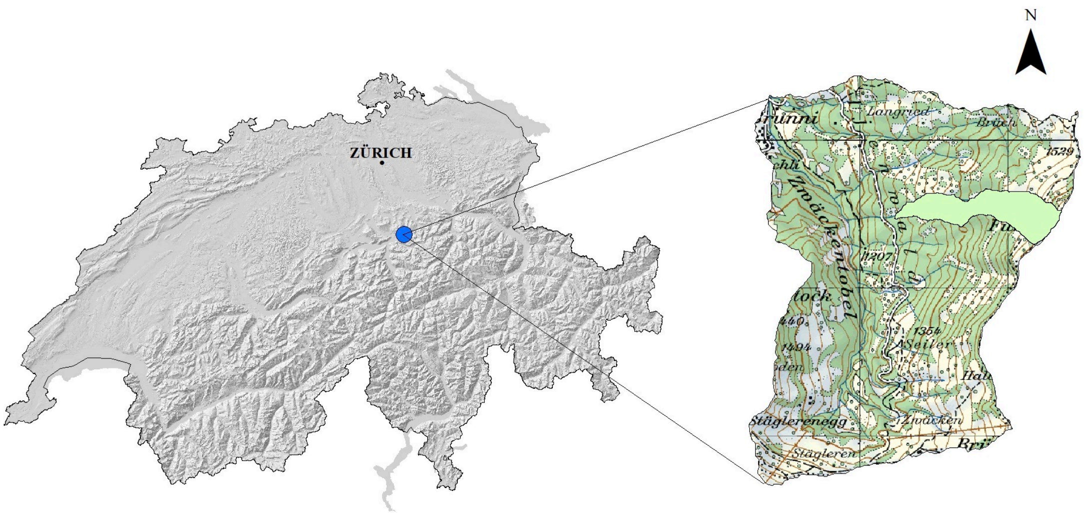


Figure 3: *Map of Switzerland, the Zwäckentobel catchment and the Studibach marked as a green polygon within the Zwäckentobel. Data Source: swissRELIEF; PK10; 1:10'000 (Federal Office of Topography Swisstopo, Bern).*

The Alptal area has been a site for hydrological research for 50 years (Stähli 2018). Research has been conducted in the Studibach catchment since 2010 (van Meerveld et al. 2017). Mapping of the upper area of the catchment has been done previously by researchers at University of Zürich (Assendelft & van Meerveld 2020b; Sjöberg 2015; van Meerveld et al. 2019). However, the lower part is less investigated in terms of mapping and the mapped stream network is therefore less dense, see Figure 4. Only one stream connects the upper part of the Studibach catchment to the lower part.

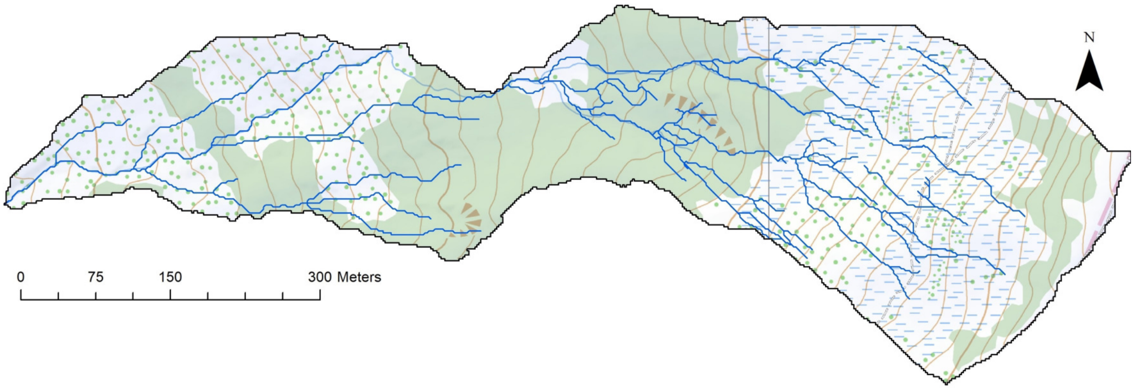


Figure 4: *Studibach catchment and the stream network. There is only one stream that connects the upper part and the lower part. Notice that the stream network in the lower part is less dense than in the upper part. The streams in the upper part has previously been mapped, whereas the streams in lower part are derived from the DEM. Data Source for the background image: PK10; 1:10'000; (Federal Office of Topography Swisstopo, Bern)*

The Studibach is divided into seven nested sub-catchments that are gauged (Figure 5). In total, 51 groundwater wells have been installed; their location was based on the TWI within each sub-catchment to capture both dry and wet sites (Rinderer et al. 2014). In the lower part of the catchment, there are two v-notch weirs and a flume with loggers that measure the water level; a logger at the outlet of the catchment measures the water level as well (Figure 5). The v-notch weirs are shown in Figure 6.

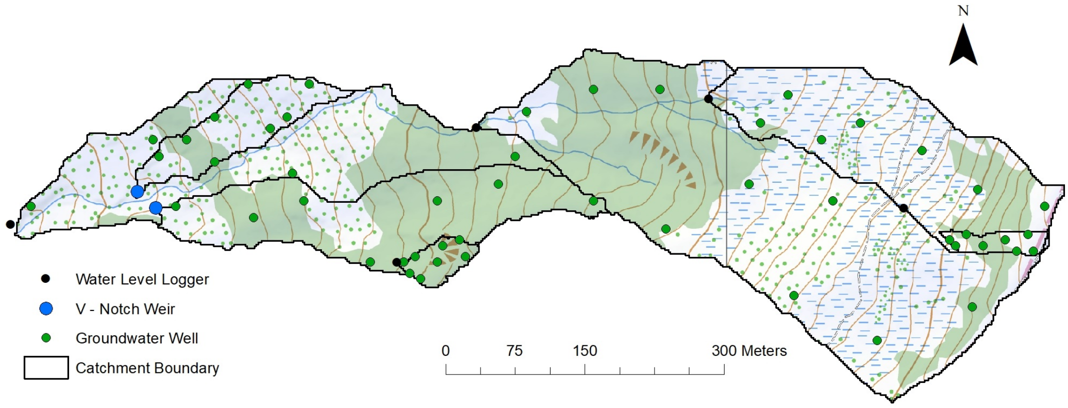


Figure 5: *Studibach with the location of the seven nested sub-catchments and the 51 groundwater wells. Data Source for the background image: PK10; 1:10'000; (Federal Office of Topography Swisstopo, Bern))*

(a) *Outlet sub-catchment 21.*

(b) *Outlet sub-catchment 31.*

Figure 6: *Photos of the v-notch weirs in the lower part of the Studibach Catchment*

The climate is typical for the Swiss pre-Alpine region (van Meerveld et al. 2017). Precipitation is frequent and the conditions are wet and cool, with a mean annual air temperature of 6°C (Schleppi et al. 1998). The mean annual precipitation in the nearby Erlenbach catchment is 2300 mm/year (Turowski et al. 2009). Around one-third of the precipitation falls as snow (Stähli & Gustafsson 2006). June to October is the snow-free season and during this time it rains on average every second day (van Meerveld et al. 2017). There is a weather station measuring precipitation in close proximity to the catchment, see Figure 7. The EC of the rainwater was measured by Kiewiet et al. (2019) during 2016 and 2017; the mean EC of the rainfall was 6.69 μS/cm.

Figure 7: *Weather station run by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL. Located in the Erlenbach catchment, just below Studibach*

Pre-Alpine catchments respond quickly to rainfall. Streamflow in the Studibach can increase several orders of magnitude during and shortly after a rain event, and generally returns to baseflow within 1-2 days after the event (Fischer et al. 2017). As in many catchments, the stormflow is mostly pre-event water (Buttle 1994). However Freyberg et al. (2018) showed that in the nearby Erlenbach catchment, a few rain events were dominated by event water. Small events appear to consist of more pre-event water than larger events for which the peak can be be dominated by event water (Fischer et al. 2015).

The lower part of Studibach, where this study is focused, is characterized by forest covered areas and steep terrain, with steep slopes over 35° (van Meerveld et al. 2017), and an average slope of 20° (Rinderer et al. 2014). Mapping of streams in this area is therefore a challenging task. The landscape is affected by landslides and soil creep and is characterized by a sequence of steep and flat areas, see figure 8. The elevation ranges from 1200 to 1400 meters above sea level. The northern part of the lower catchment receives water from the upper part of the Studibach whereas the southern parts does not connect to the upper parts.

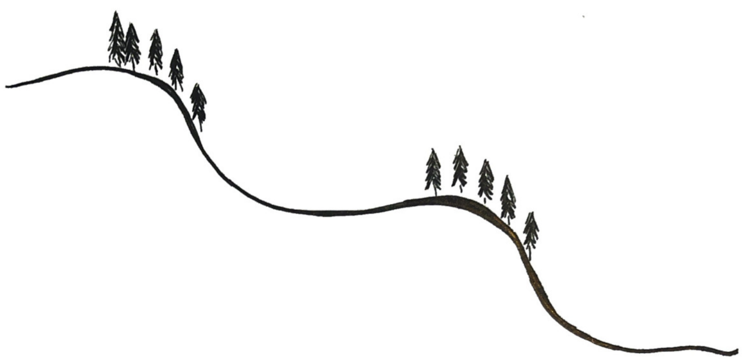


Figure 8: *Cross section sketch of the landscape in the area, showing the flatter and steeper parts.*

The Studibach is, similar to many pre-Alpine catchments, characterized by low permeability soils (van Meerveld et al. 2017) and a shallow groundwater table close to the surface (Rinderer et al. 2014). The soil in the area consist mainly of Gleysols, and the main bedrock in the area consist of flysch (Schleppi et al. 1998). Within the Studibach there are three different types of flysch (Kiewiet et al. 2019). The bedrock is clay rich and is considered relatively impermeable (Mohn et al. 2000).

Kiewiet et al. (2019) found that the groundwater chemistry in the Studibach is highly variable and that the spatial variability in the concentrations is larger than the temporal variations. In the southeastern part in the lower part of the catchment, the EC of the groundwater was higher than in the rest of the catchment.

2.2 Field Work

To examine the temporal and spatial variations of the state of the streams and the stream chemistry in the lower part of the Studibach catchment, several field campaigns took place during September and October 2020. The field work consisted of stream mapping, classification of state of the streams, EC-measurements and flow measurements. In addition, time lapse cameras were installed to monitor some streams for which flowing water was never observed to capture their response to larger storm events. The conditions throughout the study varied from dry to very wet, which allowed data collection during varying flow conditions. During some periods during the study, the area was snow covered, see Appendix Figure 38.

2.2.1 Mapping of the Streams

To map the streams in the field a compass and the basemap were used. A GPS was used to determine the approximate distances to known locations, such as the groundwater wells. Using the GPS as a tool alone to map the streams was considered to lead to too much uncertainty since the GPS had an offset of up to eight meters, and some streams were as close as two meters from each other. This method of mapping the streams had previously been evaluated as adequate for mapping the streams in the area by Sjöberg (2015). He also used aerial-photos to map the upper part of the catchment. Since the lower part of the catchment is mainly located in forest, the aerial-photos were not useful for navigating in the field.

The basemap was generated in ArcGIS. This basemap consisted of one meter contour lines, along with the locations of the main streams, groundwater wells and sub-catchments. A Swiss topographic map (swissALTI3D; (Federal Office of Topography Swisstopo, Bern) based on a DEM derived from LiDAR Data, with 2 meter spatial resolution was used to create the contour lines in ArcGIS. Contour lines extended beyond the catchment to navigate more easily around the boundaries. See Figure 9 for the used map.

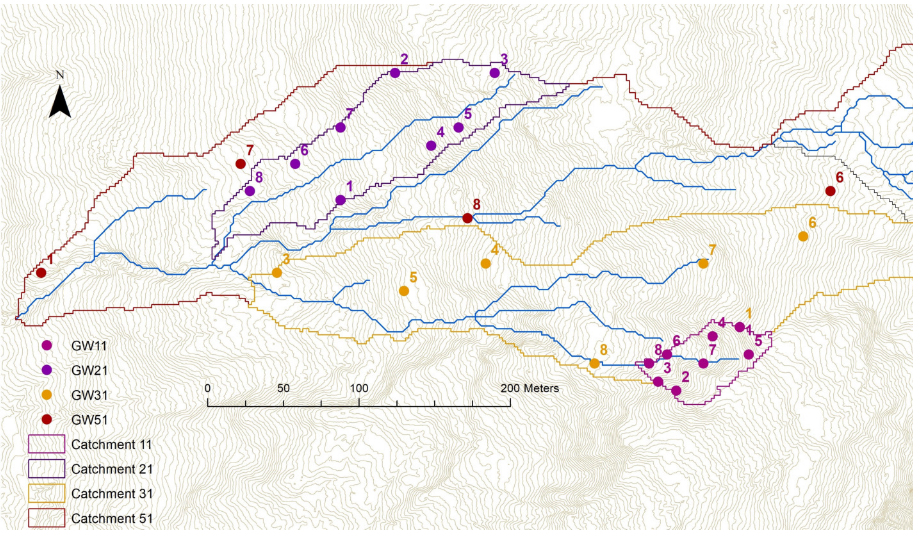


Figure 9: *Map of the lower Studibach that was used for the mapping of the stream, showing the main streams, groundwater wells (GW), sub-catchments, and contour lines .*

The streams were mapped by following one stream from the outlet to the origin. When branches of the stream were found the branches were followed from the main stream to the origin of the branch. This gave a first draft of a stream map. During rain events more streams were found, which were consequently added to the map. To not miss any stream during the study, the area was searched during varying events by walking around in the area, not only following streams.

The first mapping was performed in mid September 2020 during dry conditions. The map was later updated as new streams were found during wetter conditions. During these dry conditions, the bigger streams were flowing, while the smaller streams were mainly dry or contained segments with water in small pools or simply a wet stream bed. After the first field sessions, a draft of the temporary stream network was added to the map in ArcGIS as polylines. The stream network was updated throughout the project when new streams were discovered.

2.2.2 Field Campaigns

The field campaigns were performed on ten separate occasions throughout the study period (September-October 2020) during varying weather conditions, from dry to very wet, and at some occasions snow interfered the study. During the field campaigns the streams were classified based on the scale shown in table 3 and the EC was measured approximately every 20 meter in streams with enough water. The campaigns usually took around 5 hours to complete, from 9 am to 2 pm. The dates and conditions for each of the ten field campaigns are shown in table 2.

Table 2: *The different conditions for the ten field campaigns. Precipitation, P on the day of the campaign as measured at the Erlenbach climate station (data from WSL) and discharge, Q, at the outlet. Discharge is the mean daily discharge and precipitation as sum of the precipitation during the day of the campaign. Min and Max Q are the minimum and maximum discharge values during the campaign, from 9 am to 2 pm.*

Campaign	Date	Conditions	P [mm/day]	Q [l/s]	Min Q [l/s]	Max Q [l/s]
C1	18/9	Dry	0	26	23	29
C2	23/9	Dry	0.9	23	20	26
C3*	25/9	Very Wet	46.5	118	103	213
C4	28/9	Wet**	1.8	84	69	79
C5	1/10	Wet	0.6	60	53	63
C6	5/10	Wet	11.8	78	70	83
C7	7/10	Very Wet	24	144	119	161
C8*	9/10	Wet	0	62	55	67
C9	20/10	Wet	0	57	50	60
C10	30/10	Wet	0.3	92	84	97

*= Only streamflow was mapped
**=Snow in the catchment

The hydrograph and hyetograph for the field period is shown in Figure 10, highlighting the low discharge and no precipitation in the days leading up to the first campaign. As the arrows show, the campaigns captured a wide range of different weather conditions.

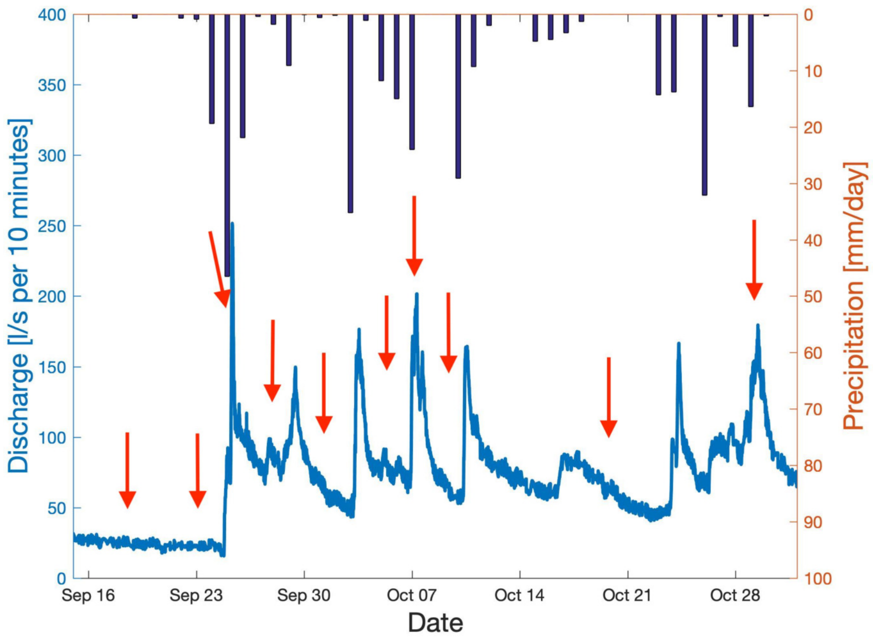


Figure 10: *Precipitation and discharge during the study period. With sum of precipitation for each 24 hour day, and mean daily discharge. The red arrows showing the campaigns.*

2.2.3 Classification of the State of the Streams

The state of the stream was classified by using a scale with six grades, ranging from dry to flowing, see Table 3. A similar classification system was used by Sjöberg (2015) when describing the streams in the upper part of the catchment in 2015. A similar scale for the mapping was used in the lower catchment in order to have similar classification system within the whole catchment. In the Studibach, as well as in many other pre-Alpine catchments, there is no clear difference between fully flowing and dry streams, but rather a range of conditions between them, which is why the classification system was developed. The classification system allows representation of different flows within the catchment. When classifying the flow, the flow was not measured but rather visually estimated. At occasions when the flow was hard to estimate and when possible, it was simply measured by testing how many liters of water could be collected within one minute. This test was difficult to perform when the flow was extremely low or when the stream bed was very wide, which is why the streamflow was mainly visually estimated.

Table 3: *Classification of streamflow*

Type	Estimated Flow [l/min]	State
Wet Stream bed [WS]	0	Inactive
Pools [P]	0	Inactive
Weakly Trickling [WT]	<1	Active
Trickling [T]	1-2	Active
Weakly Flowing [WF]	2-5	Active
Flowing [F]	>5	Active

The flow classes that include a movement of water, Flowing, Weakly Flowing, Trickling and Weakly Trickling are considered as active. The catchment is very wet year around, which is why the term wet streambed was used instead of dry.

2.2.4 EC-Measurements

To examine how the stream chemistry varied within the catchment during different weather events the Electrical Conductivity (EC) was measured along the streams. The EC in the Studibach catchment is largely determined by the concentration of calcium ions (Fischer et al. 2015). Measuring the EC in surface water as an indication of how the stream chemistry varies is a fast and inexpensive method that allows data collection for a large number of locations (Pellerin et al. 2008).

The EC was measured directly in the stream, approximately every 20 meters using a WTW portable conducitivity meter with a TetraCon measuring cell. Because the area is large, the EC was not measured in the exact same location during all campaigns, but was rather measured in every stream approximately every 20 meters where there was a sufficient amount of water. In some places, where there was very little flow, the water was collected in a cup to be able to measure the EC. If the streambed was dry or there was not enough water, even to sample in a cup, the EC was not measured during that field campaign.

To measure the EC-values during an event, *EC-traps* were installed. The EC-trap is a small jar with two pipes on the top, see Figure 11. When the water level in the stream rises the jar is filled with water through one hole and the air will exit through the other. Once the jar is completely filled no new water will enter the jar. The filled jar is collected during the next field campaign, usually one or two days after the event.

Figure 11: *An EC-trap installed in a stream.*

The EC-traps were installed in the smaller streams which usually were classified as a wet streambed or weakly trickling. The traps were mainly installed to examine what kind of water contributes to the first flush of the stream during an event. The EC-traps were installed at the locations shown in Figure 12 and sampled during three field campaigns C5, C7 and C9, which are described in section 2.2.2.

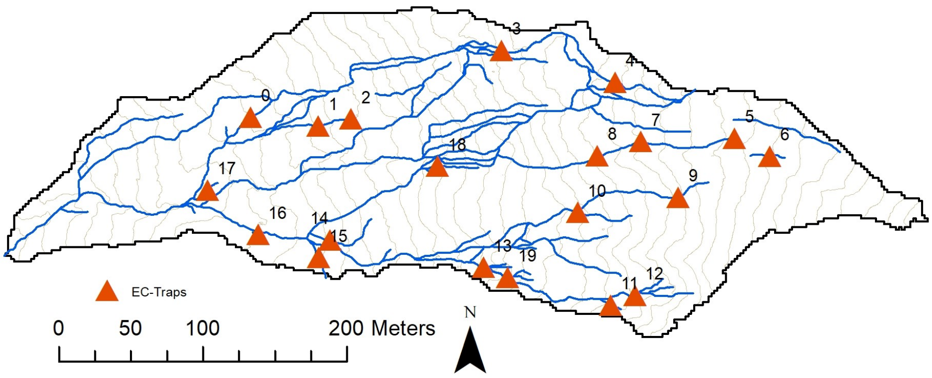


Figure 12: *Map showing the locations of the installed EC-traps.*

2.2.5 Camera Monitoring

During the mapping and classification, some streams were always classified as "Wet Streambed" or "Pools", and never as flowing. In order to see if these streams became active for short periods during the study, 12 time-lapse cameras (Figure 13) were installed around the catchment (Figure 14). Some cameras were also placed in streams with very low flow that were hypothesised to receive high flows during precipitation events.

(a) *Camera 3* ***(b)*** *Camera 12*

Figure 13: *Field set-up of two time-lapse cameras.*

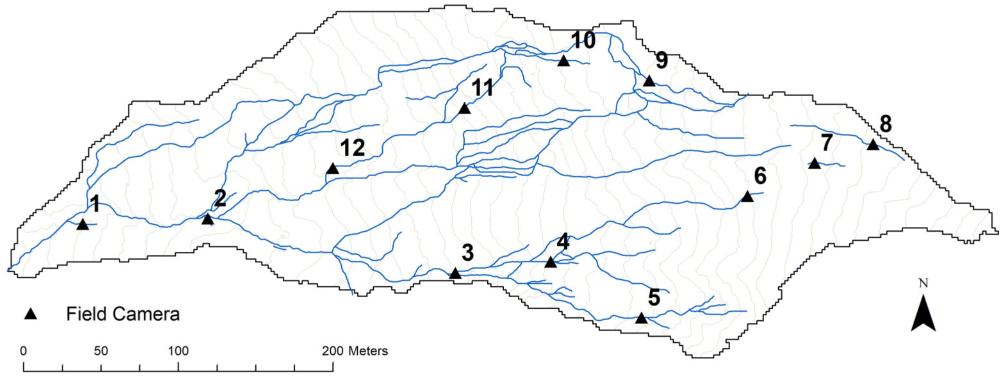


Figure 14: *Map showing the location of the 12 time-lapse cameras that were installed.*

Camera 3, 4, 5, 9 and 12 were installed in the beginning of October; Camera 1, 2, 6, 7, 8, 10 and 11 were installed on the 14th of October. All cameras remained in the field until the 6th of November.

2.2.6 Flow Measurements

Discharge from the Studibach outlet was derived from the water level, measured with a Keller DCX-22-CTD pressure transducer and a rating curve. The air pressure to relate the measured pressure to water level was measured at the Erlenbach weather station. The rating curve for the Studibach outlet, see equation 2, was based on previous salt dilution test (personal communication Leonie Kiewiet). Discharge was also determined for the two v-notch weirs at the bottom of the south and the north catchment. Both sides respond quickly to precipitation events, with the south side responding more and slightly faster, but flow also receding much quicker than for the north side, see appendix A.11.

$$Q = 0.3844 \cdot WL^2 - 5.382 \cdot WL + 21.02 \tag{2}$$

To ensure the rating curve was still relevant, three salt dilution test were performed at the outlet of the catchment: on the 26th of October, 28th of October and 6th of November.

2.2.7 Groundwater

At the 29 groundwater wells in the lower Studibach water level was measured every 5 minutes with either Keller DCX-22-CTD, Keller DCX-22 or Oddyssey water level loggers (Rinderer et al. 2016). For the wells with Keller DCX-22 and Keller-DCX-22-CTD pressure transducers the temperature and EC was measured as well. Near the end of the study, on 18th of October, some sensors were removed to prepare for the winter. In order to still obtain data for these sites the groundwater EC in the lower catchment was measured manually on the 28th of October using EC-meter and measurement tape with a light sensor. The wells were purged two days before the sampling to ensure that the groundwater was new.

2.3 Data Analysis

2.3.1 Maps and Visualizations

To present the different EC-values and the flow states in the map created in ArcGIS, the streams were divided into segments of approximately 20 meters. In total, the stream network consisted of 221 stream segments. Some segments were longer and some were shorter, depending on the variation in the flow state and EC along the stream observed during the different campaigns. In most cases, the measurement point of the EC was in the middle of the segment. This was, however, not the case for all segments because the EC was not measured exactly every 20 meters and not in the same exact locations every campaign. In these cases, the EC that was measured at the edge of the segment, was assigned to the whole segment. The observed flow states were inserted for each segment as attributes. Usually the flow state was the same for stretches longer than 20 meters and could be included in multiple segments. In some cases some adjustments had to be made for the flow state to correlate with the segments for the EC. The adjustments for both EC points and flow state classes were small and are unlikely to alter the results. Each stream segment was given both an EC and flow state attribute for all the campaigns; if some segment were not observed in some field campaigns these were given NA as attribute. The EC values that originally were taken as point values were this way set to represent the whole segment.

2.3.2 Treatment of Stream States

For analysing the expansion and contraction of the active stream network, the length of the network was calculated in ArcGIS based on the length of each segment and the flow state. All segments with at least weakly trickling water were considered to be active. The maximum values for the topographic indices within a segment were used for the analysis. If a stream segment had not been classified in more than 50 % of the campaigns the segment was not included in the analysis.

2.3.3 Ranking of EC-values

To compare the EC for different segments despite large differences in EC-values between the campaigns, the relative difference (*RD*) was calculated using Equation 3, where i represents a specific stream segment and *j* represent a specific campaign. x_{ij} represents the specific measurement value for location i and day *j*. μ_j is the mean value of all the measured values for the specific day, σ_j is the standard deviation of the measured values for the specific day. The R_{Dij} indicates how many standard deviations away from the mean value the specific score is.

$$R_{Dij} = \frac{x_{ij} - \mu_j}{\sigma_j} \tag{3}$$

For each stream segment the mean relative difference (MRD), was calculated using Equation 4. In Equation 4 the n_c represent the number of campaigns.

$$M_{RDi} = \frac{1}{n_c} \sum_{j=1}^{n_c} R_{Dij} \quad (4)$$

The stream segments were ranked by M_{RDi} where the segment with the highest M_{RDi} received rank 199 and the segment with the lowest M_{RDi} received rank 0; segments that did not have any recorded EC measurements were not included in the ranking and noted as NA (i.e., the ranking does not extend to 221, because 22 segments were notes as NA for all campaigns).

2.3.4 Stream Burning

In order to analyze how topography affects streamflow and stream chemistry, the Topographic Wetness Index (TWI) and the Upslope Accumulated Area (A) were used. Some of the streams did not appear in the DEM, because they were very shallow. In order to still represent these streams in the map and for a more correct representation of the flow directions and flow accumulation stream burning was used. More specifically, the grid cells in the DEM of these streams were lowered to ensure that the water enters these cells and flow can accumulate. To obtain a correct flow accumulation, the DEM of the whole Studibach catchment was used, with the mapped lower part and the previously mapped upper part merged to one single stream network.

The stream burning was done in Whitebox. Before executing the stream burning, the sinks in the DEM were filled using the Fill Depressions tool in order to minimize the risk of water accumulating in small sinks. The burning was done using the Burn Stream tool with the filled DEM and the stream network as input. The z-value, describing by how much the cells will be lowered in the burning, was set to 0.5, which made streams previously not visible appear in the new DEM. The distance decay coefficient, describing the gradient toward the stream, was set to 2. After the burning the sinks were filled again and the new DEM was imported to ArcGIS.

The tool MD-infinity (Seibert & McGlynn 2007) was used to determine the flow accumulation. MD-infinity allows water to enter more than one cell, which is a big advantage when modeling temporary streams that split and joins together again. The procedure of the stream burning and flow accumulation was repeated several times, and parts of the map that did not seem to correspond well with the flow accumulation map were changed by editing the polylines of the stream network. This minimized errors from the mapping by hand, where some streams may have been a few meters off. However, some segments were still not completely represented on the DEM after the stream burning, and therefore some had very low values for the flow accumulation. This was not further corrected (as a deeper burning of the DEM would lead to unrealistic results) but taken into account in the results.

2.3.5 Calculations of the Topographic Indices

For each grid cell, the value of the Upslope Accumulated Area A were obtained directly from the flow accumulation. The TWI-values could be calculated from the flow accumulation and local slope according to equation 1. The local slope was calculated with the

Spatial Analyst tool Slope in ArcGIS, with the original DEM as input. The local slope and the flow accumulation were then used as inputs for the TWI calculations, which were performed with the Spatial Analyst tool Raster Calculator in ArcGIS.

The maximum TWI and A values for each segment were used to represent the TWI and A value for the whole segment and used in the correlation analyses. The maximum value was used because this value is the least influenced by small discrepancies between the mapped stream segments and the burned streams in the DEM.

2.3.6 Correlation Between Flow State, EC and Topographic Indices

In order to determine the correlations between flow state, EC and the topographic indices in this study, the Spearman rank correlation was used. The Spearman rank correlation is a statistical measurement of the strength and direction of the relation of two variables. It is preferred when a monotonic relationship between two variables is expected, i.e., when one variable increases with the other, or when one variable decreases when the other increases. This test is preferred over a linear correlation because it does not assume a linear trend (Dodge 2008).

The Spearman correlation coefficient ρ varies between -1 and +1, where +1 indicates a perfect positive correlation and -1 indicates a perfect negative correlation. A value of 0 indicates no correlation; the closer to zero the ρ is the weaker is the relation (Fowler et al. 1998).

The p-value is the probability of obtaining the results if the null hypothesis is correct. It thus provides an indication of whether or not the null hypothesis can be rejected. A smaller p-value indicates a lower likelihood that the null hypothesis is correct, and that a correlation between the investigated parameters is probable. The smaller the p-value, the higher is the significance of the correlation (Dodge 2008). In this study a p-value <0.05 was considered to indicate a significant correlation.

3 Results

3.1 Stream Network

The mapping of the streams resulted in a much denser stream network than shown in previous maps of the area. Figure 15 shows the full extent of the stream network in the Studibach catchment, including both the previously mapped upper part as well as the newly mapped lower part. Notice the difference compared to Figure 4, where fewer streams are shown for the lower part. The mapped network also includes streams that were not active during the field visits but are assumed to be a part of the full network during large rainfall events. See Appendix A.2 for a map of only the lower part.

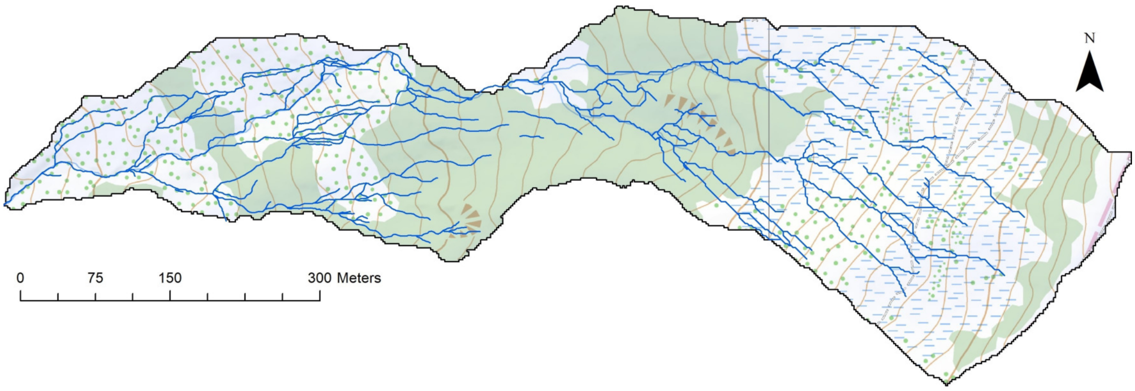


Figure 15: *The mapped stream network in the whole Studibach catchment, with the newly added streams in the lower part of the Studibach. Data Source for the background image: PK10; 1:10'000 (Federal Office of Topography Swisstopo, Bern).*

3.2 Temporal and Spatial Variation in Streamflow

For each field campaign a separate map was created to display the active network and the flow classification for each segment (according to table 3). See appendix A.3 for all 10 flow maps. Figure 16 shows the maps for three of the campaigns during varying discharge conditions: C1, C9 and C7.

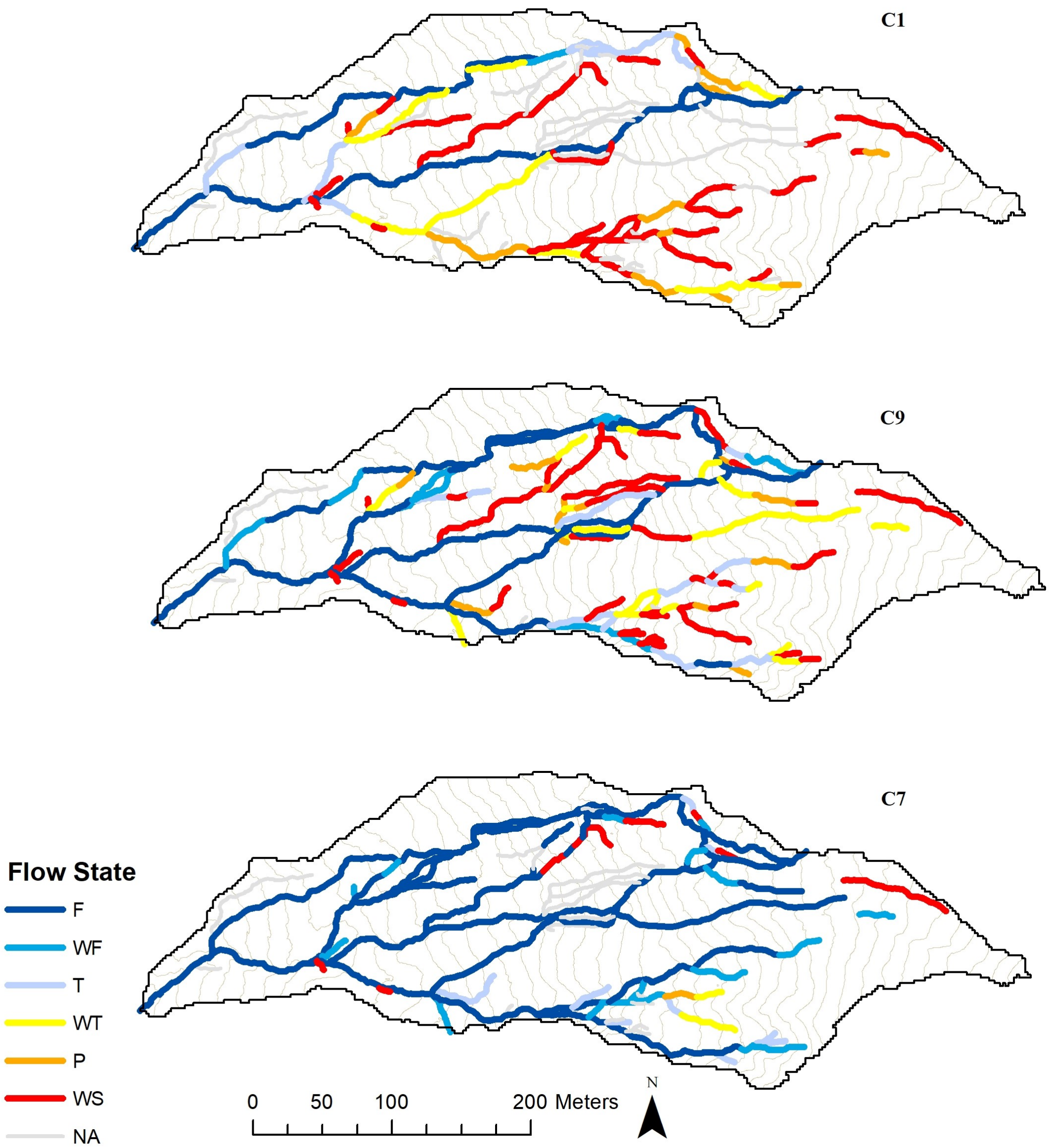


Figure 16: *Stream network in the lower Studibach catchment, with the flow class (Flowing, Weakly Flowing, Trickling, Weakly Trickling, Pools and Wet Streambed, see table 3) for each segment. NA denote that the stream segment was not mapped during the campaign. The active network was longest on the 7th of October, C7, which also had the highest mean daily discharge at the Studibach outlet, with 144 l/s. Mean daily discharge during C1 was 26 l/s and discharge during C9 was 57 l/s.*

During days with high precipitation the length of the active stream network was longer, as seen in Figure 17. The active stream network was shortest on C1, on the 18th of September with 1652 meters and the longest on C7, on the 7th of October with 3213 meters. Thus, the active network length increased by a factor of almost two between the driest and the wettest campaign day. The total network length is 4102 meters. Assuming that all streams that are a part of the full network would be flowing during large events, the network length increases from C1 by a factor of two and a half.

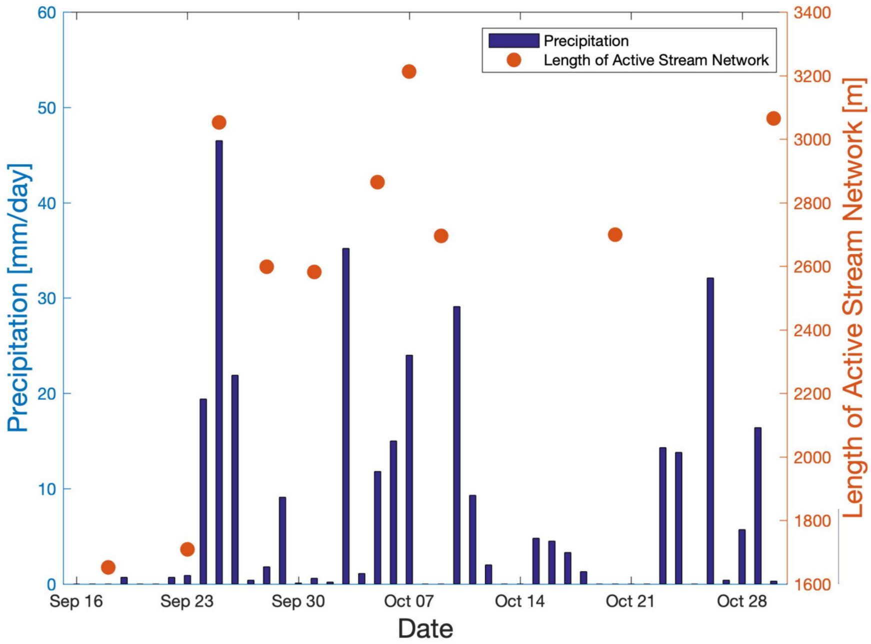


Figure 17: *Time series of daily precipitation and the length of the active network for the 10 campaigns.*

The relation between discharge and length of the active network is near linear on a log-log scale (Figure 18), with a slope or scaling factor of β = 0.37. This is in the range of 0.18-0.4 for the scaling factor given by Godsey & Kirchner (2014).

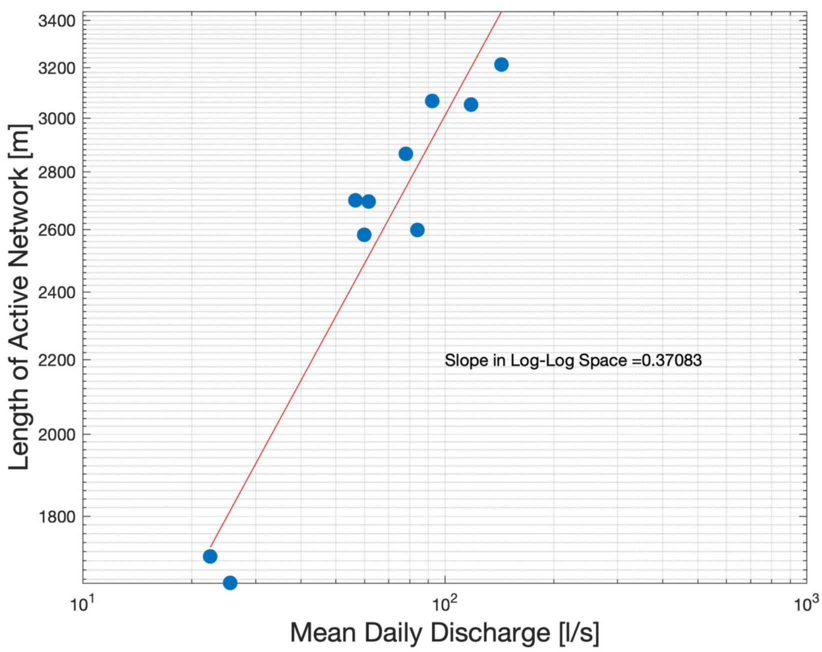


Figure 18: *Correlation between the mean daily discharge during a measurement campaign and the length of the active stream network. Spearman's ρ=0.86; p=0.035*

3.2.1 Camera Monitoring

The camera monitoring provided mixed results. Most of the photos did not provide much insight into the flow dynamics, either because of the placement of the cameras (too far away from the stream channel and flow could not be detected (Camera 4, 5, 6 and 7)) or because of cameras malfunctioning (Camera 1 did not work at all; Cameras 2, 8 and 11 stopped working and did not capture any rain events). However, there were a few cameras that provided provided insight into the dynamics and response of the network. Three cameras captured the flow on the 29th of October during a rain event. Comparing these time-lapse photos to photos from the 30th of October, one day later, the water is no longer visible, highlighting the quick changes from flowing to no visible water (Figure 19). A distinct increase in the water level during the precipitation event was observed by Camera 9, which was seldom seen *flowing* during campaigns but was rather *weakly trickling* or in *pools*.

(a) *Camera 3, 29.10.2020*

(b) *Camera 3, 30.10.2020*

(c) *Camera 9, 29.10.2020*

(d) *Camera 9, 30.10.2020*

(e) *Camera 12, 29.10.20*

(f) *Camera 12, 30.10.20*

Figure 19: *Comparison of flow during a precipitation event and the day after for three locations, showing a large difference in amount of water in the stream channel.*

3.3 Temporal and Spatial Variation in Stream Chemistry

The EC for the segments of the active stream network is shown for three different field campaigns (C2, C7 and C9) in Figure 20. The highest EC was measured during C1, the campaign with the lowest discharge. The lowest EC was measured during C7, the campaign with the highest discharge.

Figure 20 shows the spatial variations in EC within the catchment but this is even more clearly shown in Figure 21, which shows the relative difference (RD; equation 3) for the EC. The southeast part of the catchment had a higher stream EC than the rest of the catchment during all field campaigns. There was, furthermore, generally a lower EC in the upper streams. See Appendix A.4 Figure 44, 45 and 46 for maps from all the field campaigns.

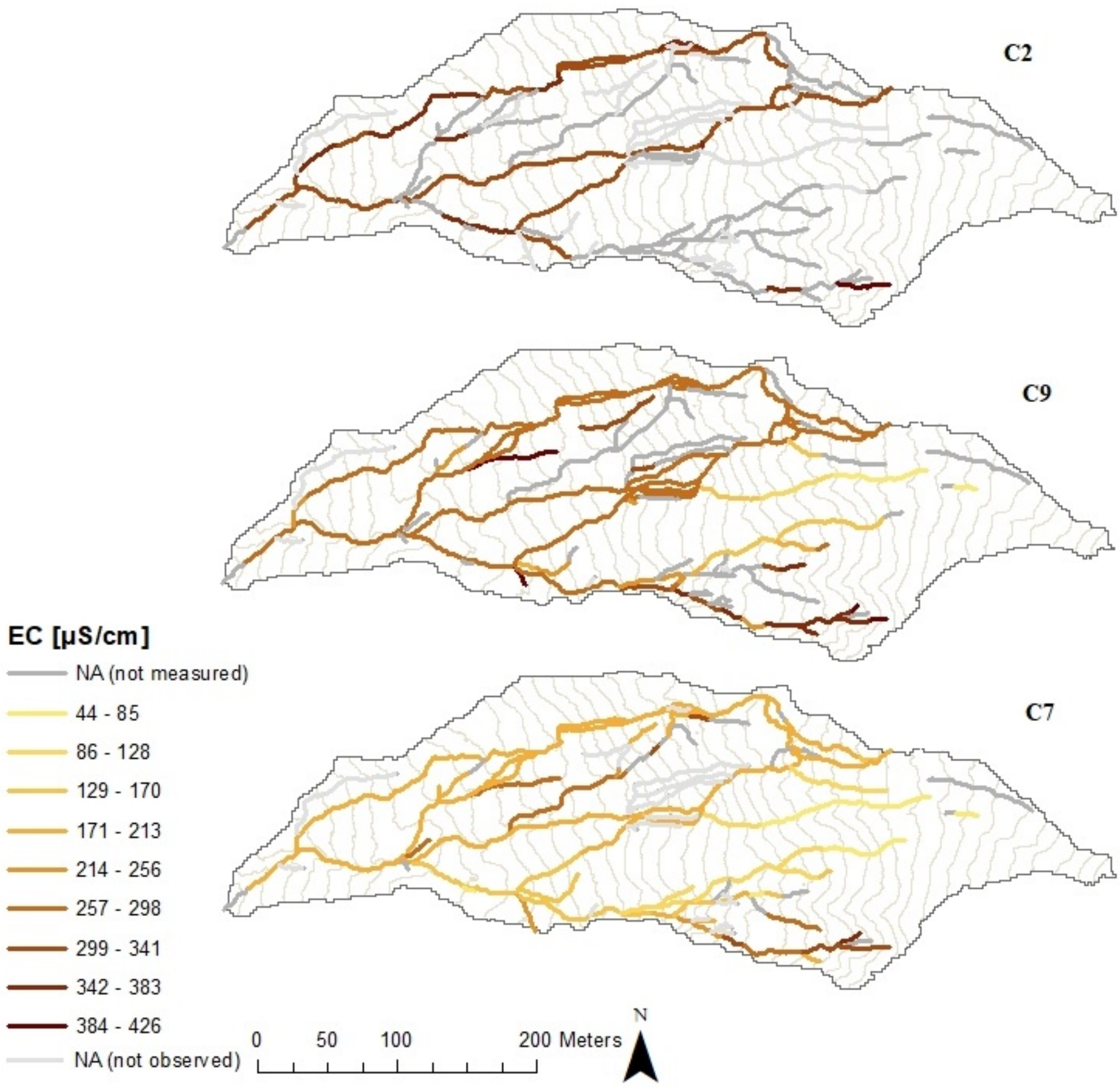


Figure 20: Maps of stream water EC in the lower Studibach catchment during three different field campaigns: C2, C7 and C9. In these campaigns the EC was highest during C2 and the lowest during C7, which had the highest discharge at the Studibach outlet, with 144 l/s. Discharge was 23 l/s during C2 and was 57 l/s during C9 .

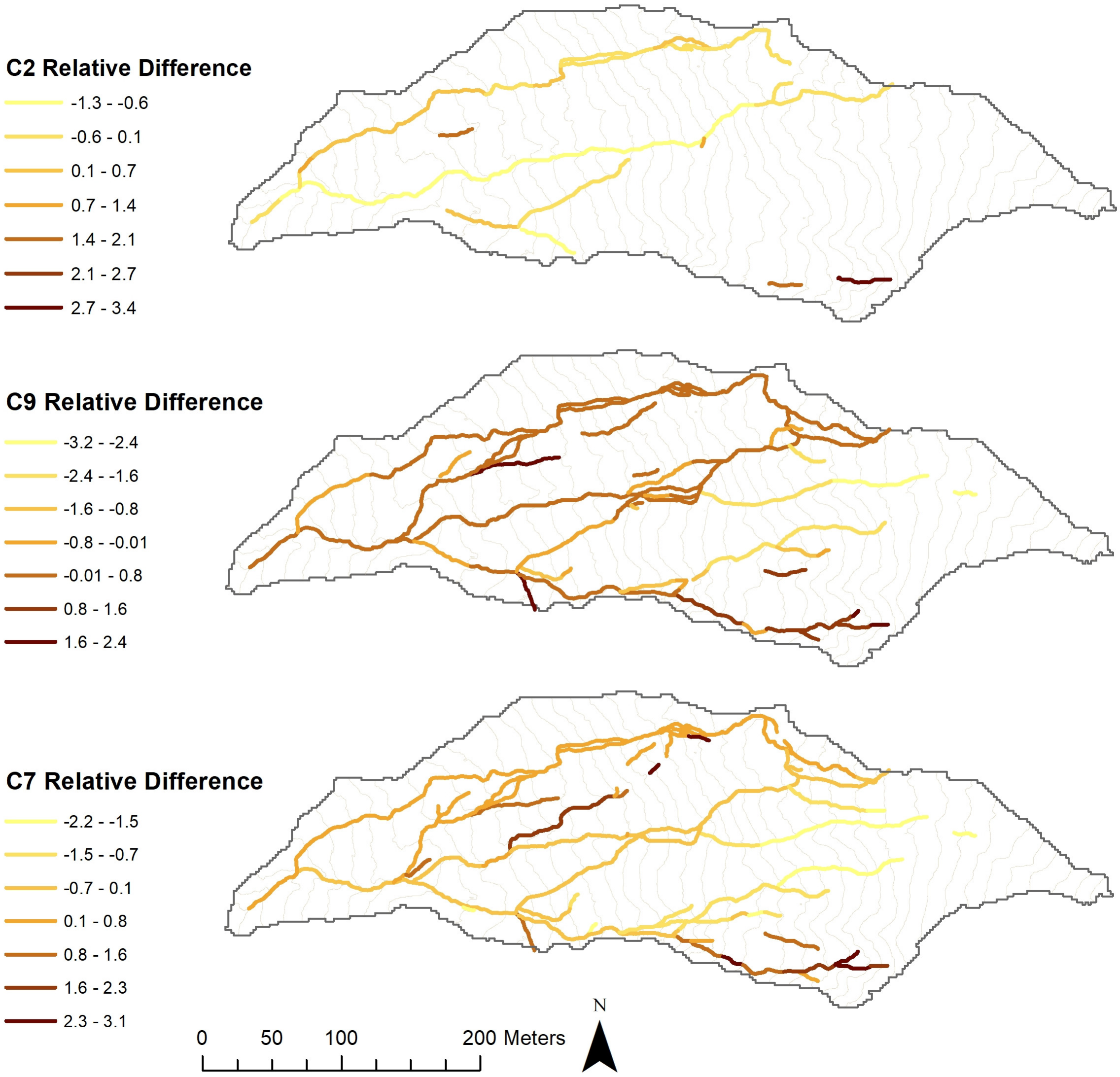


Figure 21: *Maps of the relative difference of EC during campaigns C2, C7 and C9 showing how the EC varied within the catchment during each campaign.*

The correlation between the discharge and the mean EC was strong (Figure 22). The mean EC for each field campaign in relation to the precipitation is shown in (Figure 23). The mean EC was highest during the first two campaigns, during relatively dry conditions. The mean EC value was highest during C1, on the 18th of September (344 μS/cm) and lowest for C7, on October 7th (183 μS/cm), during a large precipitation event.

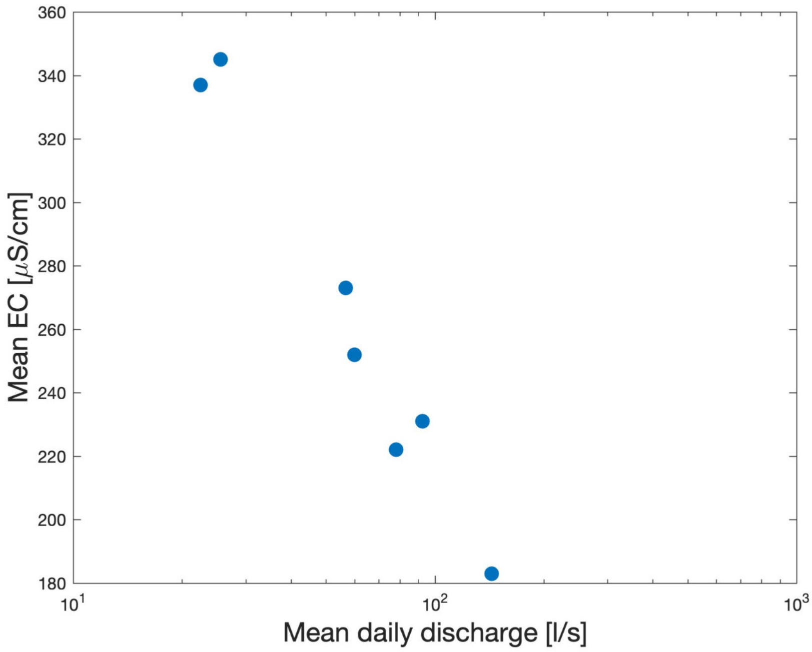


Figure 22: *Relation between the mean daily discharge and the mean EC for each measurement campaign. Spearman's ρ = -0.93 and a p-value of 0.0067.*

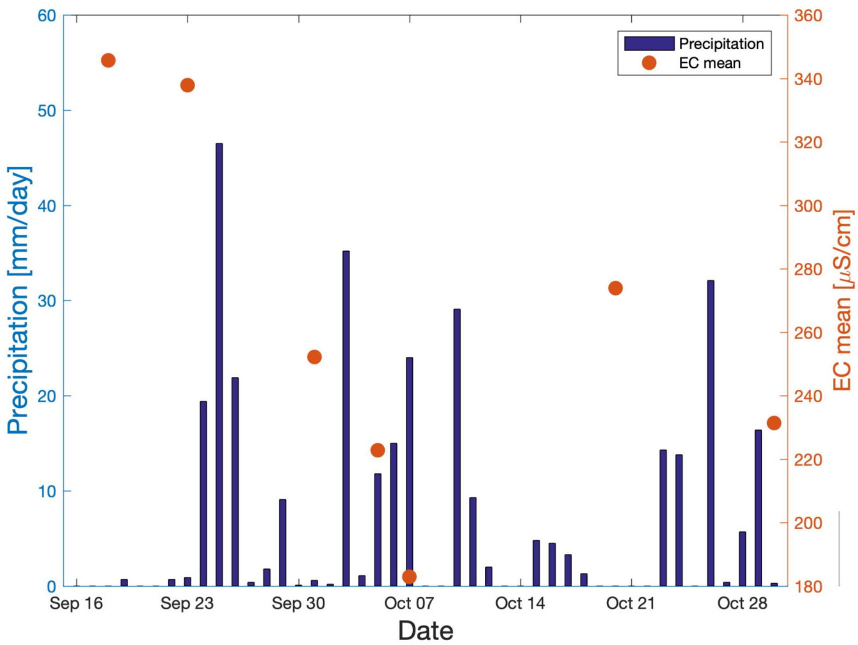


Figure 23: *Time series of daily precipitation and the mean EC of the stream water during the study period.*

The spatial and temporal variability in EC is shown in the boxplots in Figure 24. This Figure shows that the variation in EC increased during the campaigns with higher discharge and precipitation. There were also more outliers for the campaigns with higher precipitation and higher discharge compared to the drier campaigns.

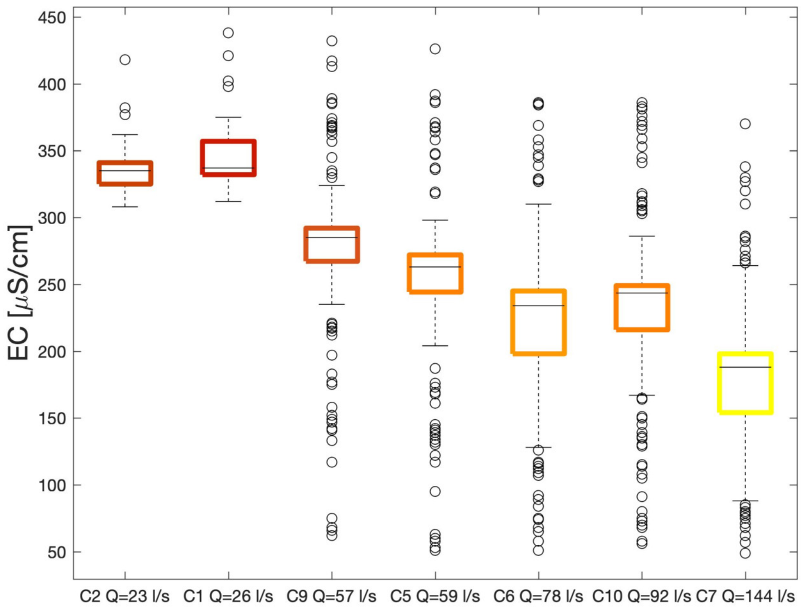


Figure 24: *Boxplots of the EC for each measurement campaign sorted by the mean daily discharge during the campaign. The box represents the 25th-75th percentile, the line the median and the whiskers extend to the most extreme value not considered as outliers. The circles represent all outliers. The colors indicates the EC with red as high and yellow as low. Spearman's* ρ*=-0.64 and p=2.22e-114, correlating EC and Q.*

The largest variation in measured EC within one segment was found for stream segments with a relative high Mean Relative Difference (MRD) or a relative low MRD (Figure 25). The segments with a medium ranking of the MRD and a high standard deviation generally had a high EC during the dry campaigns and a very low EC during the wetter campaigns. All the segments that had a high variance and a medium ranking were located in the southeast part of the catchment, which is shown in Figure 26.

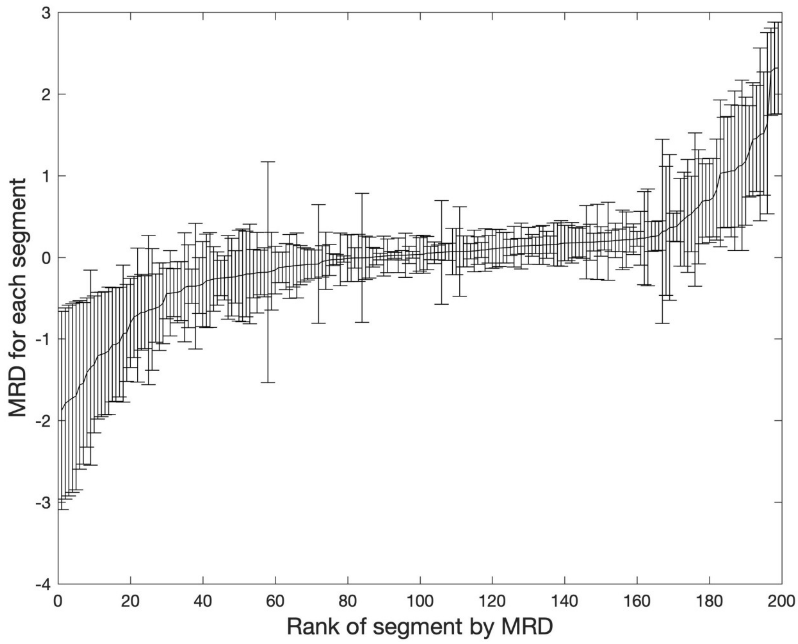


Figure 25: *The mean relative difference (MRD) of the EC and standard deviation of the relative difference (error bars) for each stream segment (ranked by MRD). The stream segments are ranked from low to high MRD.*

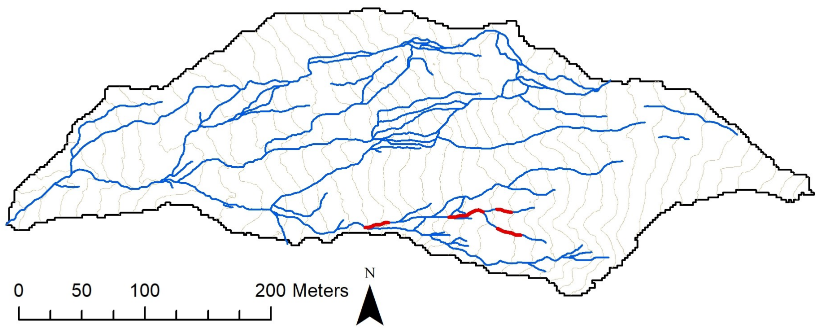


Figure 26: *Map showing the location of the stream segments with a medium ranking and a large standard deviation of the relative difference in red.*

3.3.1 EC during Events

The mean EC of the water collected in the EC-traps was generally lower than the mean EC of the stream segments measured during the campaigns (Figure 27).

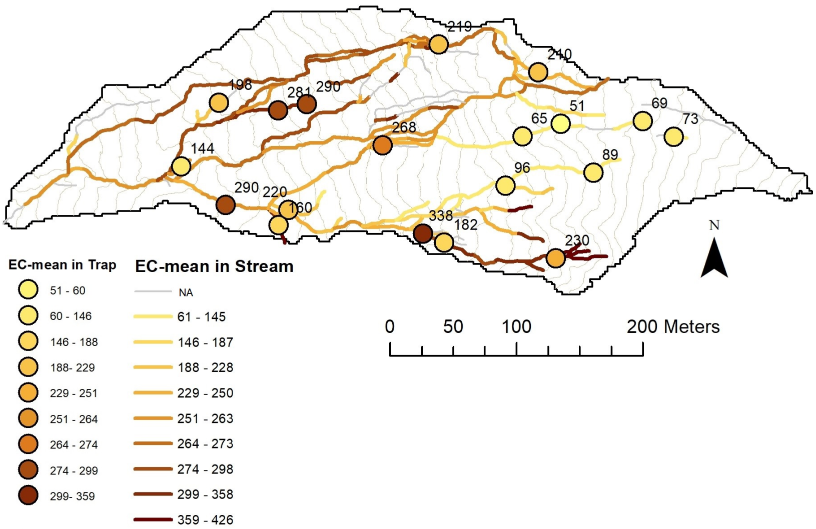
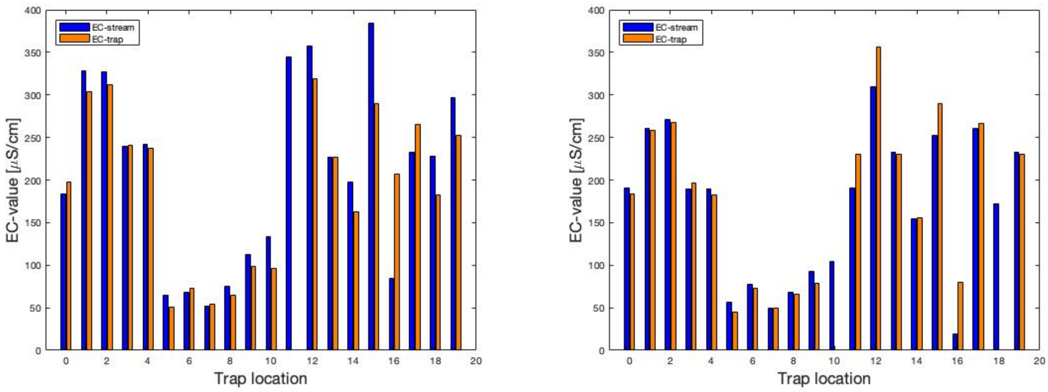


__Figure 27:__ Map displaying the mean EC of the water collected in the traps during campaigns C6, C7 and C9 (circles) and the mean EC of stream water during all seven EC-campaigns (lines).

The EC in the streams were much higher than the EC of the water in the traps during C6 on the 5th of October. This difference was much smaller during C7 on the 7th of October (Figure 28a and Figure 28b). During C7, seven traps had a higher EC than measured for the stream segments (Figure 28b). These traps were all located in the south part of the catchment, see Figure 12 for location for each trap. The EC was overall higher in both the traps and the stream during C6 than C7, and the difference between the EC in the traps and the stream was larger for C6 than C7. EC-values in the traps from C6, C7 and C9 can be seen in Figure 47 in Apendix A.5



***(a)** C6 Ocotber 5th*

***(b)** C7 October 7th*

__Figure 28:__ Bar plot showing the EC-in the stream and the EC-in the trap for each trap location during campaign C6 (left) and C7 (right).

3.4 Topographic Controls on the Stream Dynamics

To examine the topographic controls on the presence of flow and stream chemistry, the maximum Topographic Wetness Index (TWI) and the Upslope Accumulated Area (A) for each stream segment were determined. The TWI varied between around 4 and 16, and the Upslope Accumulated Area ranged from less than 100 to over 200 000 m^2. The maps of TWI and A (Figure 29) show that stream segments with the highest TWI and A are located in the lower part of the catchment, and at the north and south side of the catchment.

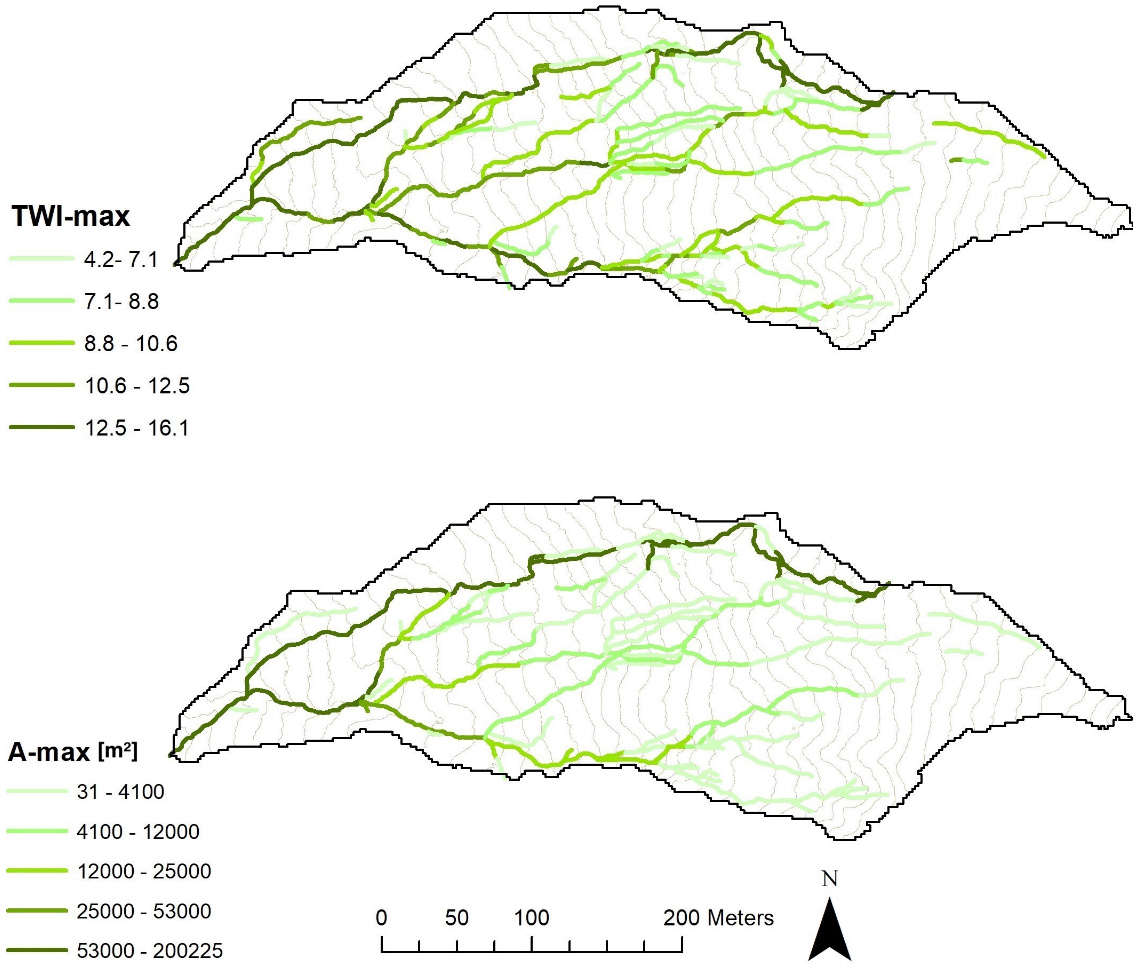
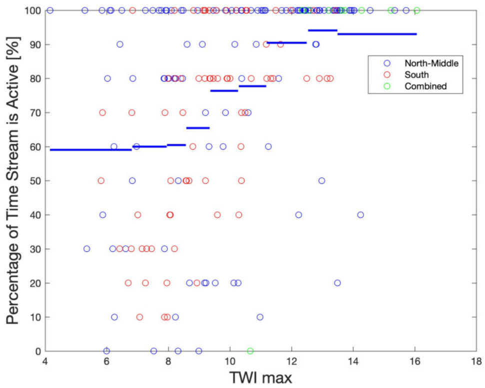


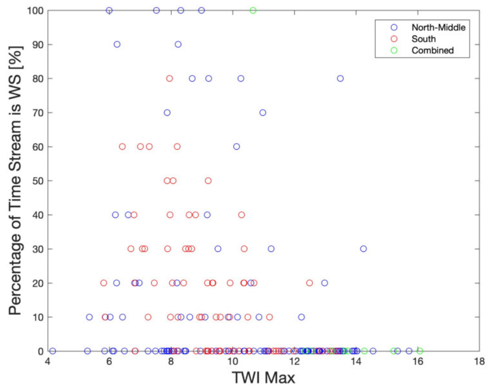
Figure 29: *Maps of maximum Topographic Wetness Index (TWI) and maximum Upslope Accumulated Area (A) for each stream segment.*

3.4.1 TWI and Streamflow

The stream segments with high TWI were active most often (Figure 30) but the Spearman's ρ indicates only a moderate correlation. Above a TWI-value of 8 there seem to be a continued increase in the fraction of campaigns during which flow occurred with increasing TWI. However some segments appear to have low a TWI but were still active in a high percentage of the campaigns. For the segments that were always active (i.e., 100 % of the time), there is a large spread of TWI values, covering the entire spectrum.



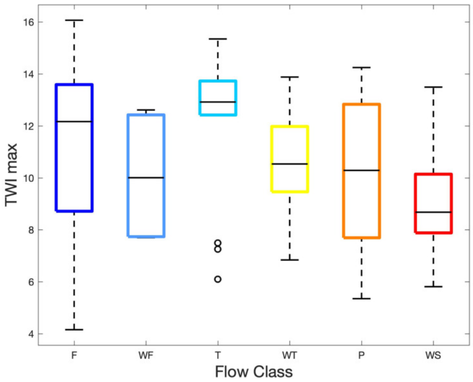
(a) *ρ=0.47 (p=6.8e-12)*



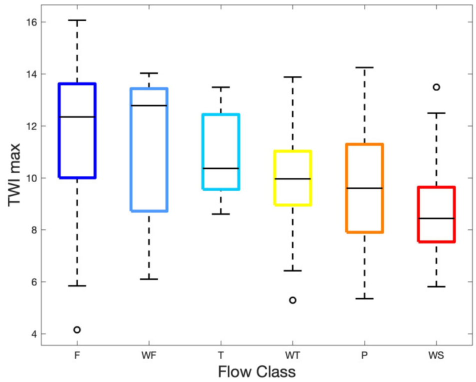
(b) *ρ=-0.44 (p=1.9e-10)*

Figure 30: *Relation between the maximum TWI for each segment and the percentage of campaigns that the segment was active (left) or had a Wet Streambed (right). Segments with missing data for more than half of the campaigns are not included. Lines in 30a are the running mean for 21 segments sorted by TWI. The different colors represent the different parts of the catchment, the north-middle part in blue, south in red and the lower streams receiving water from both south and north in green. For the boxplot, see Appendix A.6.*

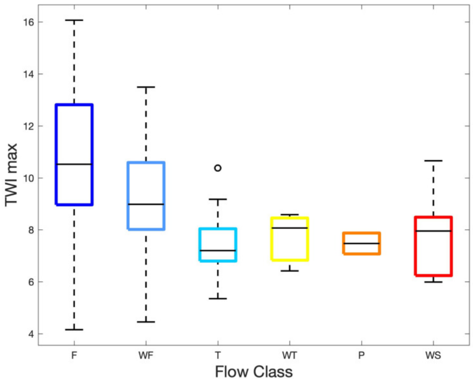
Segments with higher TWI-values generally also had a higher flow class (see Figure 31, and Appendix A.7). However, the relation is not linear for all campaings, instead there is a u-shaped patterns for some days, with the lowest TWI-values for segments with a weakly trickling flow class. The spread (i.e., large whiskers) in TWI-values for the stream segments that are mostly high flowing. The Spearman rank correlations between flow class and TWI are moderate but statistically significant for all campaign dates.



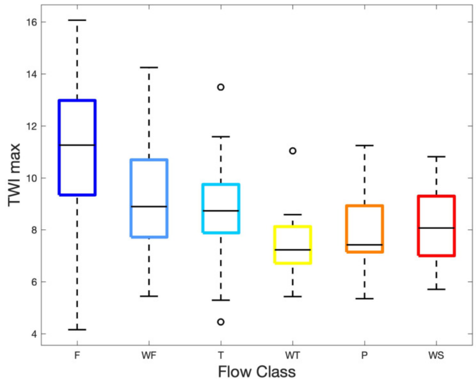
(a) *C1, Q=26 l/s*
ρ=-0,42 (p=1.5e-8)



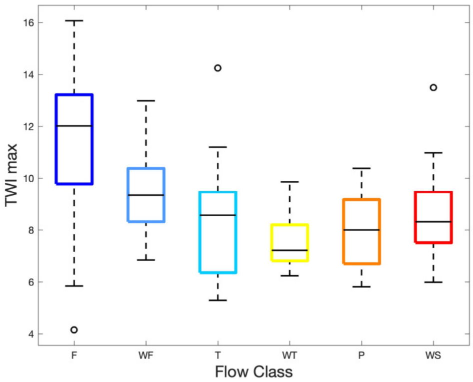
(b) *C2, Q=23 l/s*
ρ=-0.46 (p=1.5e-10)



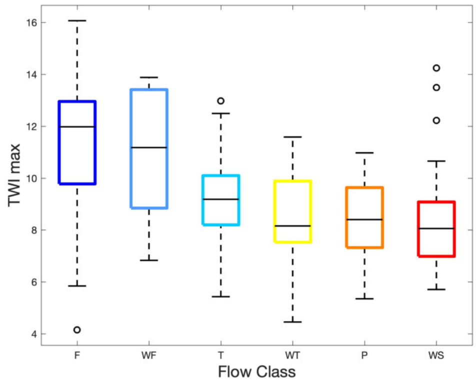
(c) *C7, Q=144 l/s*
ρ=-0.45 (p=4.6e-11)



(d) *C10, Q=92 l/s*
ρ=-0.52 (p=1.1e-16)



(e) *C6, Q=78 l/s*
ρ=-0.53 (p=2.8e-15)



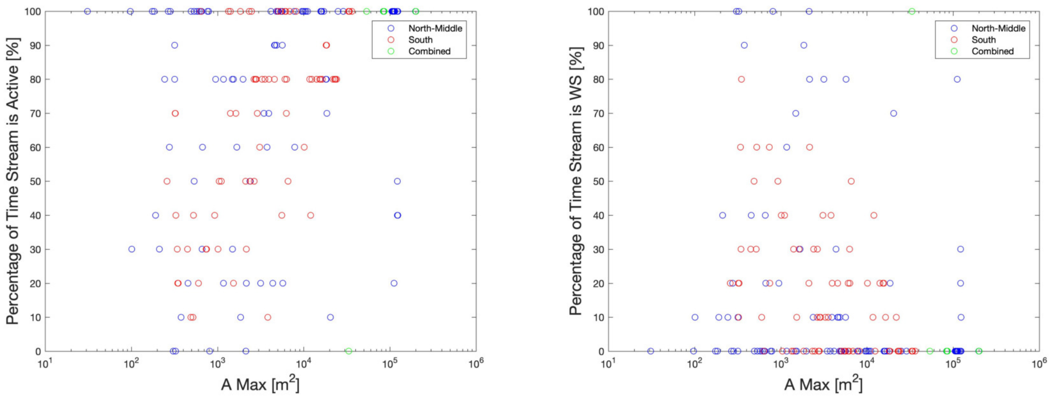
(f) *C9, Q=57 l/s*
ρ=-0.52 (p=2.9e-16)

Figure 31: *Boxplots of maximum TWI-values for each segment and the flow class for the segment during the different campaigns. C1 and C2 were dry days, C7 and C10 were very wet days and C6 and C9 took place during wetting up periods. Spearmans rank correlation calculated between flow class and TWI.*

The relation between discharge and the correlation between TWI and flow class suggest that the correlation is higher during wet conditions than during the more extreme conditions of very dry or very wet. See appendix A.8 for plot.

3.4.2 Upslope Accumulated Area and Streamflow

Similar to the TWI, Upslope Accumulated Area A can predict how frequently the stream is active. Stream segments with a larger A tend to be active more often (Figure 32). The Spearman rank coefficients between flow class and A indicate a moderate but statistically significant correlation.



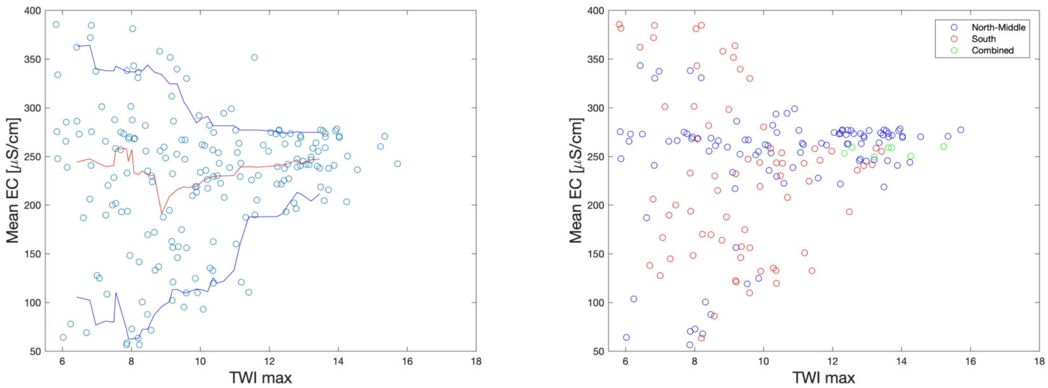
(a) *ρ=0.45 (p=2.4e-11)* ***(b)*** *ρ=-0.42 (p=1.5e-9)*

Figure 32: *Scatter plots of the maximum Upslope Accumulated Area for each section related and the percentage of campaigns the stream segment was active in 32a or had Wet Streambed in 32b. The y-axis is on a logarithmic scale. Every circle represent one segment. Segments with missing data (NA) for more than 50 % of the campaigns are not included. The different colors represent the different parts of the catchment, the north-middle part in blue, south in red and the lower streams that receive flow from both the south and north streams in green.*

The relation between Upslope Accumulated Area and flow classes also appear to be similar as those for TWI, with segments with larger A-values, having a higher flow class. However, results for the flowing class also includes segments with a low A (i.e., large lower whisker). See Appendix A.9 for the boxplots with ρ values.

3.4.3 TWI and Electric Conductivity

The relation between the mean EC (i.e., average for the different sampling dates) and maximum TWI for each segment is shown in the scatter plot in Figure 33a. There is a clear trend of decreasing variation in EC with higher TWI. Segments with a high TWI, above 13, tend to have more similar mean EC, ranging between 196 and 277 μS/cm than segments with a low TWI, below 8, for which the mean EC ranges from 56 to 381 μS/cm. This pattern is particularly clear for the south part of the catchment (Figure 33b). For the north-middle streams the mean EC values are more similar.



(a) ***(b)***

Figure 33: *Relation between the maximum TWI and mean EC for each stream segment, with the running mean (red) and 10 and 90 percentiles (blue) for five stream segments ranked by TWI (a) and color coded by reach (b), ρ= 0.05 and p=0.47.*

3.4.4 Upslope Accumulated Area and Electric Conductivity

The relation between the mean EC and the maximum A shows a similar trend of larger variation in mean EC for the stream segments with a smaller A (Figure 34). The mean EC values for the stream segments with a small A (<1000 m^2) ranges from 69 to 381 μS/cm. and with a large A (8000>m^2) ranges between 227 and 273 μS/cm.

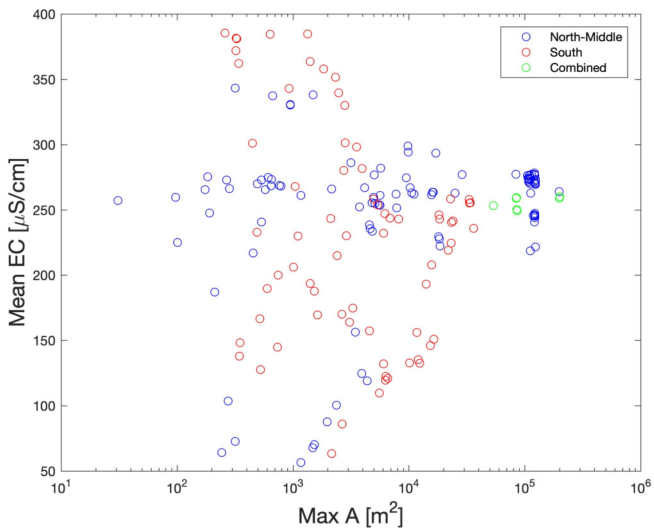
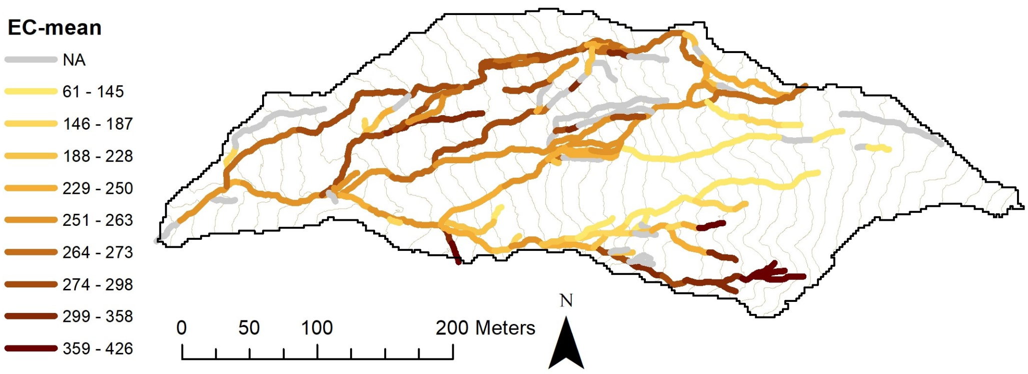


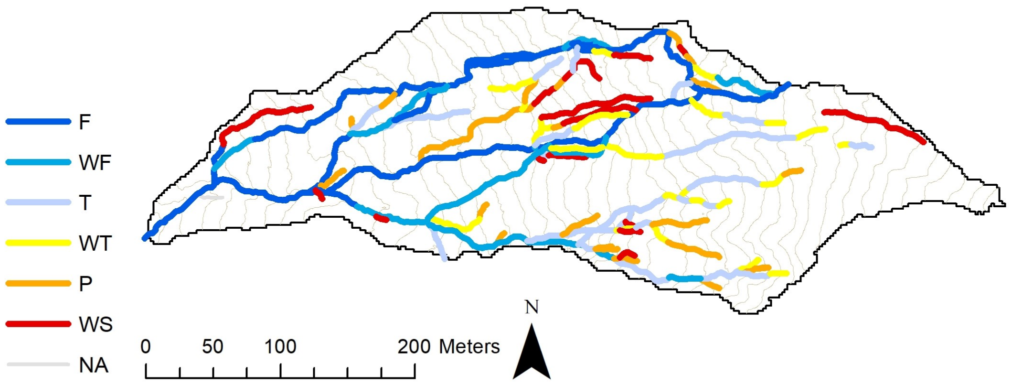
Figure 34: *Relation between the maximum accumulated area (A) and mean EC for each stream segment color coded by reach, ρ=0.032 and p= 0.66.*

3.5 Relationship Between the Frequency of Flow and EC

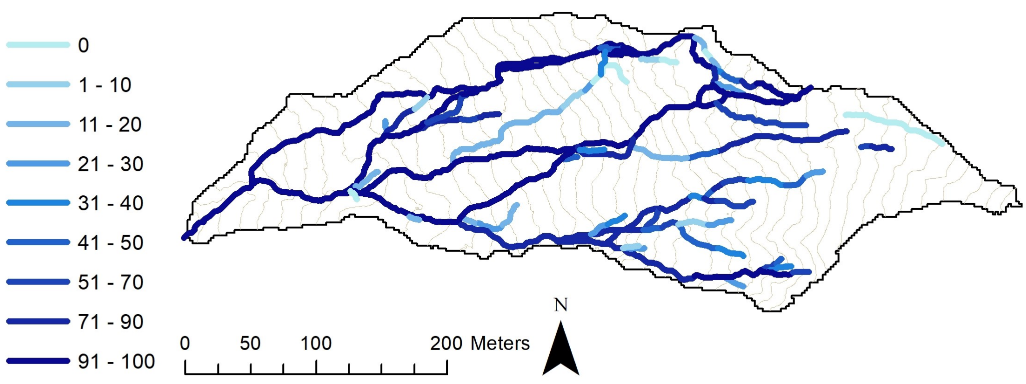
Figure 35 shows the maps of the mean EC, the dominant flow class and the percentage of the campaigns that the stream segments were active (35c). There is no visual agreement between the flow occurrence and mean EC, except that segments that were always active (100 % of the time) appear to have a similar EC. As shown before, segments that were always active, can be found over the full spectra of both TWI and A, but indeed had a similar mean EC. Contrary, for segments with a lower TWI and A that were rarely active, the mean EC varies a lot (Figure 36). The Spearman's ρ between the percentage of time the stream segments were active and the mean EC, however indicates a moderate, statistically significant, correlation (Figure 37). The length of the active stream network and the mean EC for that campaign day were highly correlated with a ρ value of -0.92. However this relation was not significant (p-value of 0.067) because there were only a few data points .



(a)

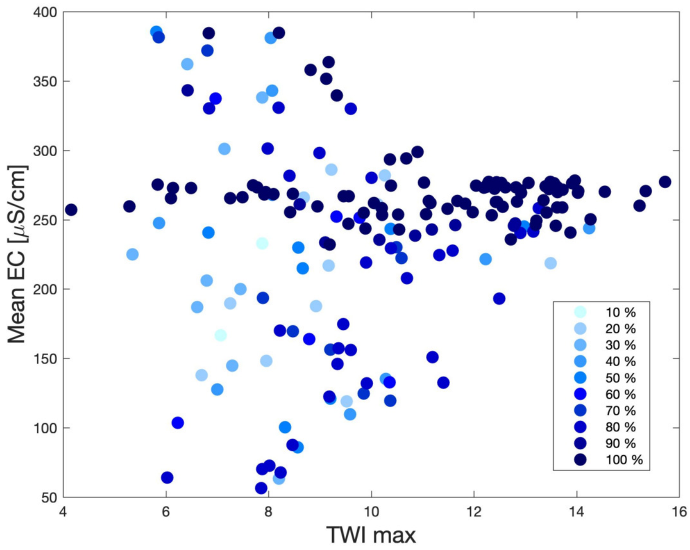


(b)

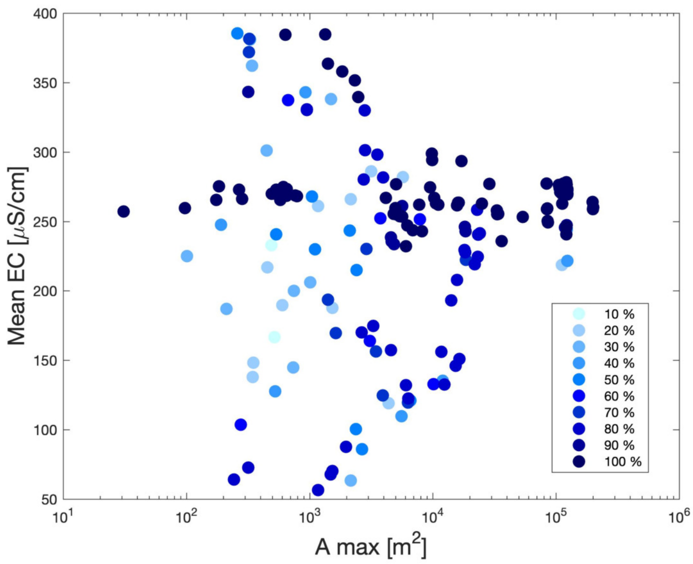


(c)

Figure 35: *Maps of the lower part of the Studibach with the mean EC for the seven EC campaigns (top), the dominant flow class for the ten campaigns (middle), and the percentage of campaigns that the stream segment was active (bottom).*



(a)



(b)

Figure 36: *The mean EC of stream water in a stream segment as a function of the maximum Topographic Wetness Index (TWI; a) and Accumulated Area (A; b), color coded by the percentage of campaigns that the stream segment was active.*

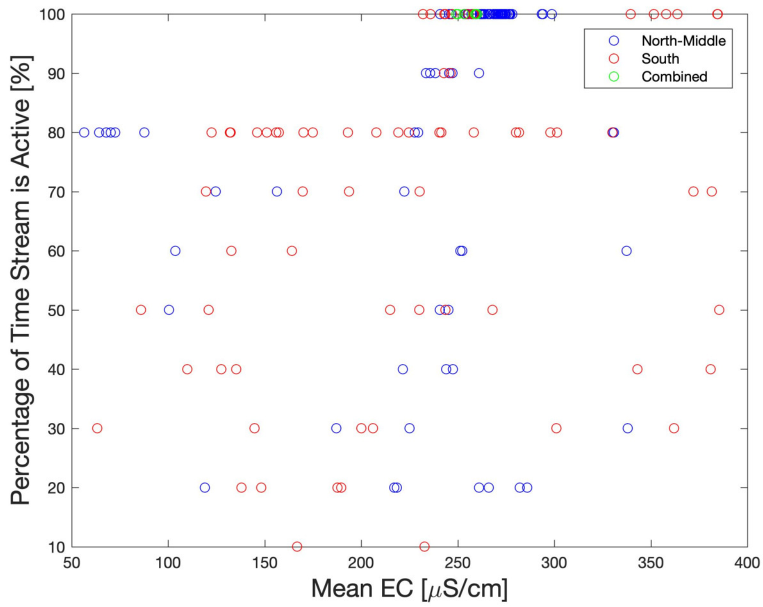


Figure 37: *Scatter plot of the percentage of campaigns that the stream segment was active and the mean EC of the stream water in that segment, color coded by reach.* ρ*=0.45 and p=1.2e-10.*

4 Discussion

4.1 Spatial and Temporal Variations in Streamflow

This study investigated how the presence of streamflow varies within the lower Studibach catchment and how this changes during precipitation events. The study highlights the significant expansion of the active stream network from a dry day to a wet day, with the network length increasing by a factor of almost two, from 1652 m to 3213 m. There is a power law relation between the length of the active stream network and the discharge at the outlet of the catchment (i.e., linear relation on a logarithmic scale). The scale factor of 0.37 is within the range (0.18 to 0.4) for different catchments given by Godsey & Kirchner (2014). However, it has to be noted that this study was only done in the lower part of the catchment, thus not the whole catchment, which might result in a different scaling factor. The scaling factor for the upper part of the Studibach catchment of Sjöberg (2015) was 0.19 and thus different to the one for the lower part of the catchment, however still within the range of Godsey & Kirchner (2014). Thus the results support the findings for other catchments that the temporary network is not static but contracts and expands (Ågren et al. 2015; Godsey & Kirchner 2014; van Meerveld et al. 2019).

The network was most expanded during a precipitation event, C7, when some streams were active that weren't active in most other campaigns. This was expected since forested catchments in general (Grip & Rodhe 2016) and the catchments within the Zwäckentobel (Fischer et al. 2017) tend to respond quickly to rainfall events. Being there during an event allows one to capture the high flow state. The response is confirmed by the camera surveillance, see Figure 19, where high flows are shown and recede within a day. This also shows the difficulty of stream mapping and being there at the exact time of the precipitation event to capture all the different flow conditions. It also suggests that even though some parts of the network were not observed to be active during the campaigns, they could still be a part of the active network during larger rain events.

The first large and overall largest precipitation event occurred on September 25th, C3 (see Figure 17). However, this was not when the active network length was the longest. A reason for this could be that this was the first large precipitation event after a drier period, and some areas might therefore have more storage available, so that more of the rainfall went to storage instead of creating runoff. This is supported by the discharge data, showing a larger peak discharge during C7 than during C3. However, potentially it could also be explained with the fact that it was early in the study period and that some streams had not yet been detected and were therefore marked as NA, when in fact they could have been active. Furthermore, it could also be a timing issue of when in the hydrograph the campaign was performed.

The expansion of the network appears to mostly follow a bottom up pattern. This can be seen in the flow maps in Figure 16 and in Appendix A.3, where the flow classes for the streams in the upper parts are often lower than further down. This is most clear in the southeast part of the catchment, where the top of the streams have less frequent flow than further downstream and can also be seen in the map of average dominated state (Figure 35b). It is also seen for the north part but less clearly. The pattern is reflected in the correlation between flow state or frequency of the site being active and the Upslope Accumulated Area (Figure 32). These results supports the previous findings for the upper part of the Studibach by Sjöberg (2015). However, for a few places a disjointed pattern can also be detected. For example the central eastern stream is active from the top during C8, C9 and C10 (see Figure 42 and 43 in Appendix A.3) but there is a section with a wet streambed before connecting to another active stream section below. This is where the water flows through a steeper area and seems to fill up small pools that do not spill over. There is one area where a top down pattern was observed. Where the lower part of the Studibach catchment connects to the upper part and the stream splits up, the northern stream seem to follow a top down pattern. This is most likely because the stream splits, and the water most often takes the other route. However, during high flow conditions during large precipitation events, the water fills up both paths. This can be seen for example in the map for C1, where the upper part of the stream is weakly trickling and further down water stands in pools, and in C9 where the upper part is weakly flowing and further down it is trickling.

In comparison to findings in other mountain catchments (Assendelft & van Meerveld 2020b; Godsey & Kirchner 2014; Jensen et al. 2017; Nadeau & Rains 2007; van Meerveld et al. 2015), there weren't any clear disconnections in the network. There is one area in the east side of the catchment (with higher elevation) there is a disconnection where the water seems to disappear under ground most of the time. This can also be seen in the southeastern part of the catchment, where some streams during the drier conditions were not connected to the main channels. However, in the large stream channels the flow was continuous.

Many stream segments were always active and may therefore not be temporary streams. The variations between the active flow states were large. The flow state in many segments that were always active varied from weakly trickling up to flowing during the study. Since the study took place during only two month period, it is possible that some of the streams do at some point during the year or during very dry years become inactive, and can therefore still be classified as temporary streams.

The temporal variations in the active stream network were large, as seen from the expansion of the network (Figure 16) but the spatial variation within the catchment was also notable. The north-middle side of the catchment, which is connected to the upper part of Studibach has more continued flow, even on the dry days, than the south side of the catchment, which responds more quickly during rain events but has less continued flow during dry periods. This is reflected in the discharge at the two v-notch weirs (see Appendix A.11): the discharge from the south stream receded much quicker than for the north stream which also had a higher baseflow. During the dry conditions of C1 and C2, see Figure 40 in appendix A.3, there was barely any flow in the streams on the south side, even in the large stream channels. After the first large precipitation event this changed and the main channels were mostly active. This reflects the wetting up pattern during the first large precipitation events and throughout the study period.

The findings in this study thus show both a temporal and spatial variation in streamflow. This goes well with other studies concerning temporary stream networks showing these large dynamic changes (Ågren et al. 2015; Sjöberg 2015). The expansion by a factor of two is also similar to what was found by Godsey & Kirchner (2014).

4.2 Spatial and Temporal Variations in Stream Chemistry

There was a high temporal and spatial variation in stream water EC and thus stream chemistry in the lower part of the Studibach catchment. The EC was higher during drier conditions and lower EC during wetter conditions (Figure 24). The mean EC during the driest conditions (C1) was 344 μS/cm while it was 183 μS/cm during the wettest campaign (C7), indicating a dilution by a factor of 2. This indicates an increased proportion of event water in the streams during events. This finding corresponds well with the previous findings in the area by Fischer et al. (2017) who found that increasing precipitation led to more event water in the stream. This finding is further supported by the EC-traps and the recorded EC during events. The EC values in the streams were generally higher than the EC in the traps (Figures 27, 28a and 28b). The EC-traps were generally emptied one or two days after the event, which could indicate that the streams fills up with event water and that the stream had already returned to baseflow conditions during the time of the sampling of the traps.

The EC-traps in the south part of the catchment had a higher EC than the stream during C7. This patterns did not occur in the north-middle part of the catchment, where the stream connects to the upper part of the catchment (Figure 28b). This finding indicates that the temporal variations within the catchment might vary and depend on different response times to precipitation events. It could also indicate varying compositions of streamwater depending on location in the catchment, since this finding may indicate that the first flush is more likely to contain pre-event water in the south part of the catchment. To draw any further conclusion regarding this finding a more detailed study is needed.

The spatial variation in the stream chemistry was high. The maps (Figures 20 and 21) show that for each campaign the EC was higher in the southeast part of the catchment, sometimes 100 μS/cm, or more, higher than the other streams. The location of the streams with the higher EC are spatially close to the groundwater wells with a higher EC than in the rest of the catchment, due to potentially a different bedrock or deeper groundwater discharge in this area (Kiewiet et al. 2019). The high spatial variation in the area corresponds with previous findings in the area by Grunder (2016) who found large spatial variations in the stream chemistry in the Studibach even on a small scale. The theory of groundwater influencing the large spatial variation in the stream chemistry is further supported by the findings by Zimmer et al. (2013) who also conducted a fine scale investigation of stream chemistry and concluded that the large spatial variation within the small catchment was influenced by the spatial variation of the groundwater in the area.

The spatial variation in EC was larger during the wetter campaigns, Figures (20 and 21). One reason could be that during the drier conditions only the bigger streams were flowing for which the EC was less variable. It could also be that during the dry conditions, the streamflow mainly consisted of groundwater, whereas during events different parts of the catchment respond differently, and contributions from low EC soil water and overland flow varied. However, also the groundwater EC is highly spatially variable (Kiewiet et al. 2019). In comparison with other studies in mountain catchments Singh et al. (2016) also found a smaller spatial variation in stream chemistry during direr conditions, but in that study the largest variation was found during the transition period between wet and dry conditions, which is contradictory with the findings in this study where the largest variation was found during the wettest campaign. To draw any further conclusion regarding this or to make a comparison of that finding with the variations within the Studibach, further studies are needed from a longer sampling period.

Looking at the variation in EC for the individual stream segments it appears that the temporal variability of the EC was highest for the segments with the most extreme EC (either highest or lowest mean EC) (Figure 25). One explanation could be that the most extreme values often were measured in pools. Another explanation could be that the streamflow in these streams mainly consisted of groundwater during baseflow conditions, but that they responded quickly to rainfall events leading to more event water in the streamflow during wetter conditions, resulting in the large variability in EC. The findings in the EC traps support this theory, with higher EC in the stream than in the EC-trap directly after an event, indicating that fraction of event water increases in the stream during events.

For a few segments (seen in Figure 26) with a near average EC (i.e., ranked in the middle in Figure 25) there was also a large temporal variation in EC. All these segments were located in the same area of the catchment (Figure 26). One explanation to why these segments have an average ranking but highly variable EC could be that they are located near the southeast area with the high EC, but that they were rarely fully flowing. This could lead to a high EC during drier conditions since the main contribution to water during these conditions is groundwater with high EC from the southeast area, but that during events the streamflow mainly contains event water with lower EC. The extreme variation in EC during the different conditions, then leads to an average mean EC that is comparable to that for the rest of the catchment.

The findings of this study thus indicate that the spatial variation of the stream chemistry in the lower Studibach catchment is high, which was expected considering the previous findings in the area by Grunder (2016) and Kiewiet et al. (2019). The temporal variation was also high, indicating that the streams contained more event water (or shallow soil water) after an event, which corresponds well with the previous findings by Fischer et al. (2017).

4.3 Role of Topography

Topography was investigated to see if it could predict the permanence of streamflow and the variation in stream chemistry. The Topographic Wetness Index and the Upslope Accumulated Area were used as topographic indices.

4.3.1 Relation Between Topographic Attributes and Streamflow at the Reach Scale

Based on previous findings by Sjöberg (2015), van Meerveld et al. (2019) and Assendelft & van Meerveld (2020a) topography was hypothesized to be a good predictor of the permanence of streamflow. Indeed, streamflow permanence was influenced by topography and therefore to some extent be a good predictor of streamflow. The results for the TWI and the A were similar: higher index values indicating a higher estimated flow class or higher flow permanence but there was also a large variation.

The assumption for TWI was that stream segment that are always or often active would have high TWI-values and sections with low TWI would seldom have flowing water, due to the smaller contributing area (Beven & Kirkby 1979). The scatter plots (Figure 30) show a clear increase in active stream percentage with higher TWI-values above a TWI of 8 and a moderate correlation. This trend corresponds to findings by Sjöberg (2015). The different sides of the catchment (north-middle and south) do not appear to show any prominent differentiating patterns according to Figure 30 in terms of topography. Since the two sides, however, seem to respond differently to precipitation events this is most likely not correlated to topography.

Similarly, we hypothesized that a larger Upslope Accumulated Area would correspond to more flow (e.g., (Goulsbra et al. 2014), (Gassman 2018)) because there is a larger area that can produce and therefore contribute to the discharge in the stream segment. The scatter plot (Figure 32a) and moderate correlations suggest this pattern is somewhat true but for the stream segments that were active all the time the spread in A is large. Areas with a smaller A appear to have continued flow, even during drier periods (e.g., in the central part). Similarly, the stream channel where camera 12 was positioned is clearly incised and an obvious channel but was in most campaigns dry. The water instead takes another route, and only flows in the stream channel during larger precipitation events, as recorded by the camera (in Figure 19e). This could partly be explained by outliers (see section 4.5.4) or because other factors that are more influential than topography. Instead flow might be related to geology, where the water either infiltrates through cracks in the bedrock or infiltrates in porous bed material or discharges in springs.

Thus, despite potential human errors in the flow classification due to the difficulty of correctly identifying a certain flow class, these results can be considered to correspond reasonably well to the statement that higher topographic indices also indicate more flow. Some outliers are expected to occur yet the graphs and the boxplots show that the flow classes and activation times are correlated to some extent to both TWI and the A. This answers the research question on topographic predictions on streamflow, suggesting that topography can to some extent predict streamflow but that other factors, such as geology or bed material, may be important as well.

4.3.2 Relation Between Topographic Attributes and Stream Chemistry at the Reach Scale

It was assumed that topography would influence stream chemistry because it affects the inflow of groundwater to the stream (Grip & Rodhe 2016). This study indeed shows that stream chemistry is related to topography. The scatter plots in Figure 33a and 34 show that segments with a higher TWI or A tend to have a smaller variation in mean EC. This finding of decreasing variation in EC with higher topographic indices can be explained with the Relative Elementary Area concept (REA), which means that the larger the contributing area, the smaller the variation in the stream chemistry gets. The small streams have very different EC, but as the streams join together their water is mixed, leading to a more homogeneous water chemistry further down in the catchment. This finding may corresponds to the fine scale of the sampling, similar results were found by Zimmer et al. (2013) who also found that a smaller samling scale lead to a larger REA-effect. The effect of REA on stream chemistry has previously been shown in modeling studies (Temnerud et al. 2007; Wood et al. 1988), but the findings in this study are interesting since they show based on data that this effect is significant even on a small scale.

It appears that the north-middle part of the catchment has more similar EC than the south part, where the spatial variability in EC is larger (Figures 33b. The north-middle side of the catchment is connected to the upper part of the Studibach-catchment, which means that some of these stream segments contain water from the upper catchment. The effect of a larger contributing area leading to a smaller variability might be already visible here. It is also possible that stream water at the south part is more variable because groundwater chemistry in some parts of this area are distinctly different from most hillslopes and riparian areas (Kiewiet et al. 2019). .

There was no significant correlation between TWI or A and EC. This could be due to the high spatial variation of EC within the catchment, indicating that spatial factors such as composition of groundwater, landslides and bedrock influence the stream chemistry more than the topography. This goes well with the findings by Kiewiet et al. (ibid.) who found that the spatial variation in groundwater has a large influence on the stream chemistry.

In summary, topography did not seem to have an influence on the EC in the streams, in terms of a high or low EC but has a large influence on the variation in EC. For segments with higher topographic index values, the variation of the EC in the stream was smaller, as would be expected based on the relative elementary area REA concept.

4.4 Relationship between EC and the Active Stream Network

The length of the network and mean EC for the different campaigns were strongly correlated (although statistically not significant due to the small sample size). This temporal correlation reflects that the stream network expands and the EC decreases during rainfall events.

It was expected that a lower EC in the segments that are only occasionally active due to the influence of rainfall and near surface flow pathways, and a high EC in segments that are always or very often active because of the higher groundwater contribution to these the streams. However, Figure 37 shows, this was not the case. There is no clear pattern or spatial correlation, except for streams that are 100 % active and have a similar EC. There is, however, a moderate correlation, most likely due to the 100 % active streams having a very similar EC. The differences can also be seen in the map of the mean EC (Figure 35a) and the average flow state map (Figure 35b), where the EC-values are not always low in the sections with low flows. This could be explained by the large spatial variation of the EC within the catchment.

What can be distinguished from the scatter plot in Figure 37 is that segments that always flow have a similar EC. The streams that are most often flowing are located further downstream, and collect all water from the upstream areas. All the variations in the upper streams are therefore integrated in the lower streams, leading to a similar EC in all 'permanently' flowing streams, whereas for the upper streams are characterized by spatial differences in mean EC and temporal changes in the flow state. This explanation does also apply for the scatter plots in Figure 36 which show a distinct pattern of segments always flowing having similar EC-values but also stretching across the whole TWI and A spectra. This is most likely the larger streams that are often flowing and that are flowing through many topographic changes.

Therefore it can be concluded that streams in the lower Studibach with a similar flow occurrence do not have a similar chemical composition of streamwater, apart from some main streams that are always flowing and have a similar EC.

4.5 Evaluation of the Methods and Future Improvements

4.5.1 Stream Mapping

The terrain in the lower part of Studibach is steep and has dense vegetation, making the mapping difficult. The mapping was time consuming and also included remapping and adjustments of the mapped streams. For some streams it was difficult to decide whether they would be classified as streams or just overland flow. This also suggests that the mapped network is dynamic and most likely the network will appear slightly different in the future. The groundwater wells that were marked out on the map provided a valuable resource for navigating. However some of the groundwater wells were during the field work discovered to be wrongly placed in the map, which could have provided some source of errors in the placement of the streams. For the smallest streams, sometimes only 20 centimeters in width, it was a difficult task to place them correctly on the map. However most of the mapping was checked against the contour lines and changes in the topography, and were not based on the groundwater wells alone.

4.5.2 Field Campaigns

As others have suggested, stream mapping is very time consuming (Jensen et al. 2017) and difficult to do during events for large areas or at a high temporal resolution (Godsey & Kirchner 2014). However it also allows for the type of fine scale investigations with high spatial resolution that otherwise would be difficult.

The field campaigns usually took around 5 hours to complete with two people. Being with two people allowed for faster recording of data and the possibility to obtain both EC data and flow classifications during the same campaign. During rain events, the changes in both EC and streamflow were fast. Therefore campaigns during events might be influenced by these changes and results depend on when during the event data was collected. For example, if the first samples were taken during peakflow, and the last samples 4 hours later, this puts the samples on different parts of the hydrograph, which might have influenced the results. This can be seen from the min and max discharge values during the campaign time in Table 3 2. Where the min and max values are very different on days with precipitation, for example during C3. To ensure that this issue did not affect the measurements too much, the EC was measured downstream at the beginning of the field campaign and at the end. The largest change of 20 μS/cm was considered to be a small change (particularly compared to the spatial variabillity) and would not affect the results much.

Snow appeared early in the season, which could have influenced some of the results for the campaigns affected by snow melt. For example the snowfall may have led to a lower estimated flow and a higher EC than expected due to the accumulation of snow instead of precipitation and direct runoff.

Classification of streams functioned well during the field work. However it was not always easy to distinguish between trickling and weakly trickling or trickling and weakly flowing, and there might be some sources of errors included. All the field campaigns were however performed by the same two people, which should ensure that potential errors are quite constant. Some areas appeared to sometimes experience overland flow rather than flow in specific channels. Where this happened over shorter distances and the water went back into one main channel, this was mapped as a stream. However during the classification these segments could have been given a lower flow class, even though in total the flow was larger, since the water had split into smaller rills.

The choice for using the EC to investigate the stream chemistry was chosen mainly based on the fact that it allowed to sample every stream in the whole catchment during one field campaign. Using stable isotopes and hydrograph separation would probably have been a better method to gain deeper knowledge of the chemical composition of the water, however this would not have allowed to sample all the streams at the fine scale that was used in this study. Since previous studies in the area by Fischer et al. (2015) also showed that the EC mainly corresponds to the Calcium ions, the EC was considered to be as a good indicator of which water flows in the stream.

4.5.3 Data Analysis

To make sure that all the data was added as attributes for the streams, different segments were created. The segments that were created represented one streamflow classification and one EC measurement, However in some areas the density of EC measurements was low and in some very high, depending on the availability of water in the stream. Segments were created according to the highest density of measurements but this also meant that in some campaigns with fewer measurement points, the same EC measurement was assigned to multiple segments. This could in some places be a source of error when relating the attributes of the segment to the topographic indices. However, these errors are most likely minor.

4.5.4 Artifacts from Pre-processing the Digital Elevation Model.

For both the Upslope Accumulated Area and the TWI, there are some values that are very low, even though water is constantly flowing. Some of these are most likely outliers caused by the stream burning, for example in the part of the catchment where it connects to the upper part of Studibach. Here the water most often take the left route and only during precipitation events or during large events also flows in the right path. However in the flow accumulation most of the water took the other way. This resulted in a low TWI and A for the part that usually has flow. This is also an explanation to why the segments with 100 % flow also had very varying values for the TWI and A, as seen in Figure 30a and 32a. This is hard to change in the burning since the algorithm cannot account for this. One way would be to split the streamflow 50/50 however this could also give wrong results, since we can not know for sure how the divide happens. Some areas could also have been affected by the burning if the incision of 50 cm was not deep enough, due to the surrounding area the stream might not receive water in the flow accumulation.

4.5.5 Suggestions for Future Studies

This study provides further proof of how dynamic temporary stream networks in a pre-Alpine catchment are. The newly mapped stream network can add another piece of the puzzle by providing a full stream network map of the Studibach catchment to continued research in the area. The maps of the state of the temporary streams can be used, together with those from the upper catchment (Sjöberg 2015), to determine where intermittent stream sensors (Assendelft & van Meerveld 2019) are most useful to understand the dynamics of stream network expansion and contraction. The fine scale EC measurements that were taken can provide a fine scale data set of the stream chemistry and inform future stream water sampling efforts.

The EC-traps that were used in this study showed interesting patterns of how the first flush during events varied in the catchment. To better understand these dynamics, further studies are needed. One interesting study would be to place the EC-traps along one stream in order to see how the EC of the first flush varies along the stream. In a future study it would also be interesting to use the time-lapse cameras to investigate when streams are activated during an event. If it varies in different parts of the catchment and how different stream segments respond. This could provide more insights into the runoff response from the catchment and provide high temporal resolution data.

5 Conclusions

This study found large temporal variations in the occurrence of flow in the streams. The active network length expanded by a factor two from dry conditions to wet conditions during precipitation events. The expansion generally displayed a bottom-up pattern. There was also spatial variation within the lower Studibach catchment where the southern part responded quicker to events and expanded and contracted quicker than the north side.

The stream chemistry was characterized by both temporal and spatial variation. Higher discharge and precipitation lead to lower EC in the streams, indicating the fraction of event water increasing in the streams during events. The variation in stream chemistry was higher during the campaigns with higher discharge, indicating different amounts of event water in different parts of the streams. The spatial variation in EC within the catchment was large and most likely depends on spatial variation in the groundwater chemistry.

Topography influences the presence of streamflow in the stream network and can predict to some extent the permanence of flow. Stream segments with a higher TWI and Upslope Accumulated Area generally have a higher flow class and a higher permanence of streamflow. However, there was significant scatter in the relation, indicating that other factors than topography also affect the presence of streamflow, which could be investigated in further research.

Topography did not show to have an influence on the EC in the streams. In general the same EC was found in streams with both high and low topographic indices. However, the topography has an influence on the variation in EC. The spatial variation in the EC was smaller for streams with higher topographic index values, a finding that can be explained by the mixing of water from different streams for the lower streams.

There was no distinct relation between the EC and flow permanence. Instead streams with similar streamflow permanence can have a very different EC, depending on where within the catchment they are located. This can be explained by the large spatial variations in EC within the catchment. However streams that were always active had a similar EC, most likely because they are located in the lower part of the catchment the water is a mixture from different sources.

This study found further evidence of the large temporal and spatial variation in both streamflow and stream chemistry, as well as indications of topographic influences on them.

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A Appendix

A.1 Pictures

Figure 38: *Snow cover in the catchment area 2020-09-28*

A.2 Lower Studibach Stream Network

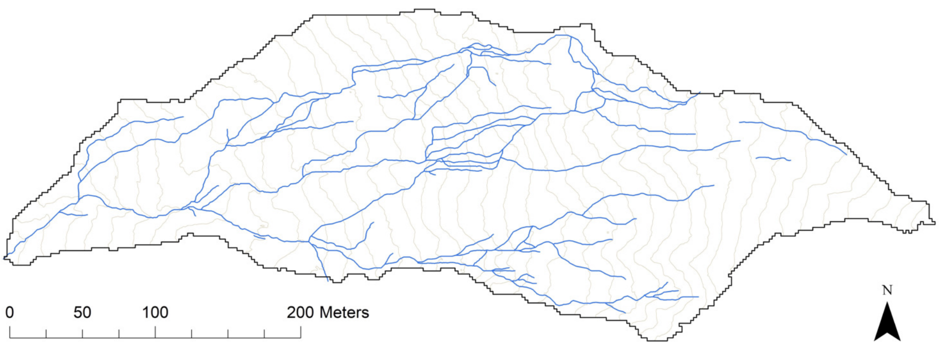


Figure 39: *The mapped stream network in the lower part of Studibach. With the outline of the lower part of the catchment, and contour lines of 5 meters derived from LiDAR elevation data (Data Source: DEM; swissALTI3D; (Federal Office of Topography Swisstopo, Bern)). Notice how some areas are more dense in streams than others, most of these areas are in locations subjected to landslide (or steep areas) where the water bifurcates and then reconnect*

A.3 Maps of the Stream Network With Flow Classifications during All 10 Field Campaigns

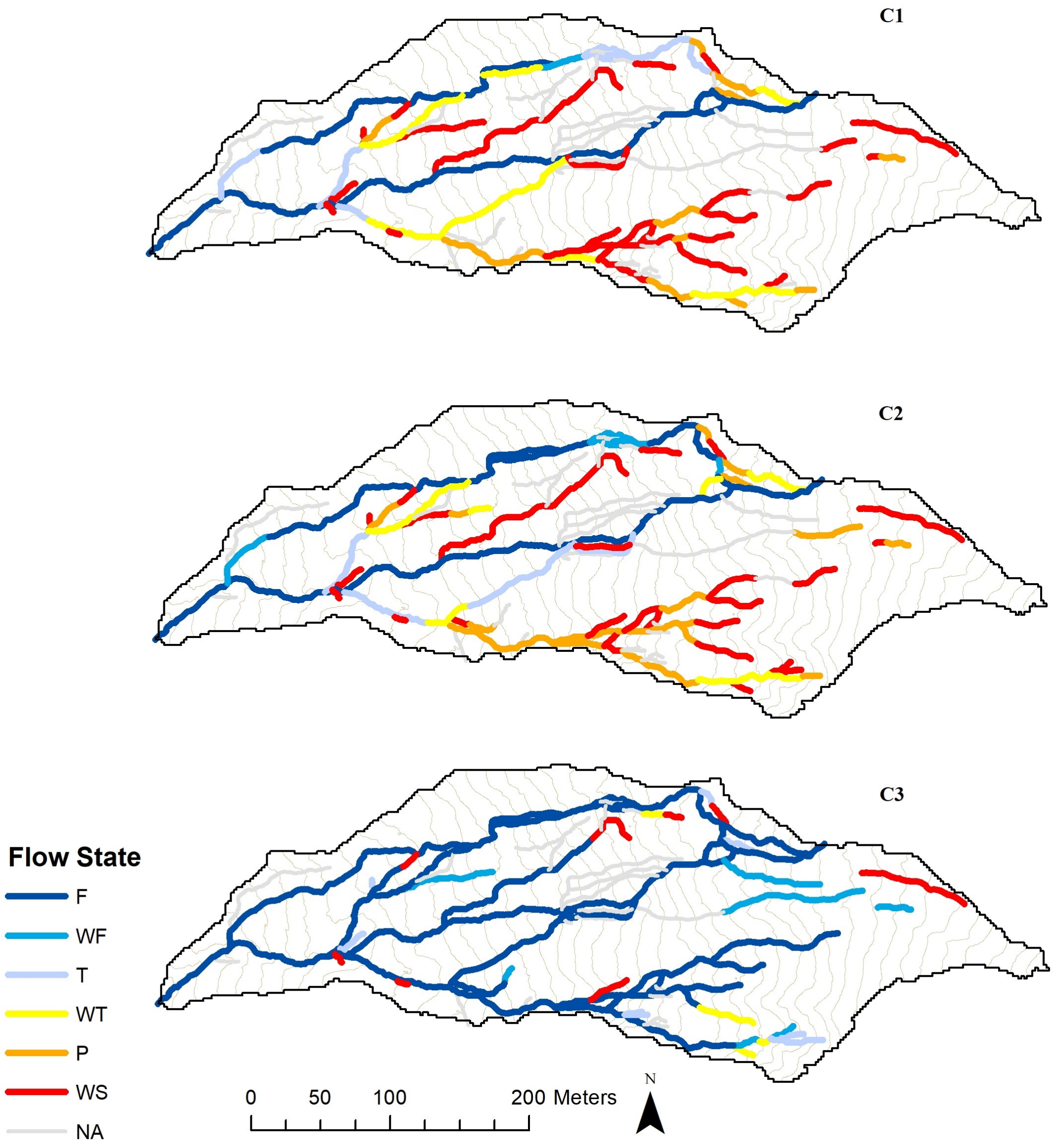


__Figure 40:__ Maps of the stream network from Campaign 1 to 3. With the mapped flow state according to the classification system. On campaign 3, the 25th of October there was a large precipitation event that increased the flow in the network.

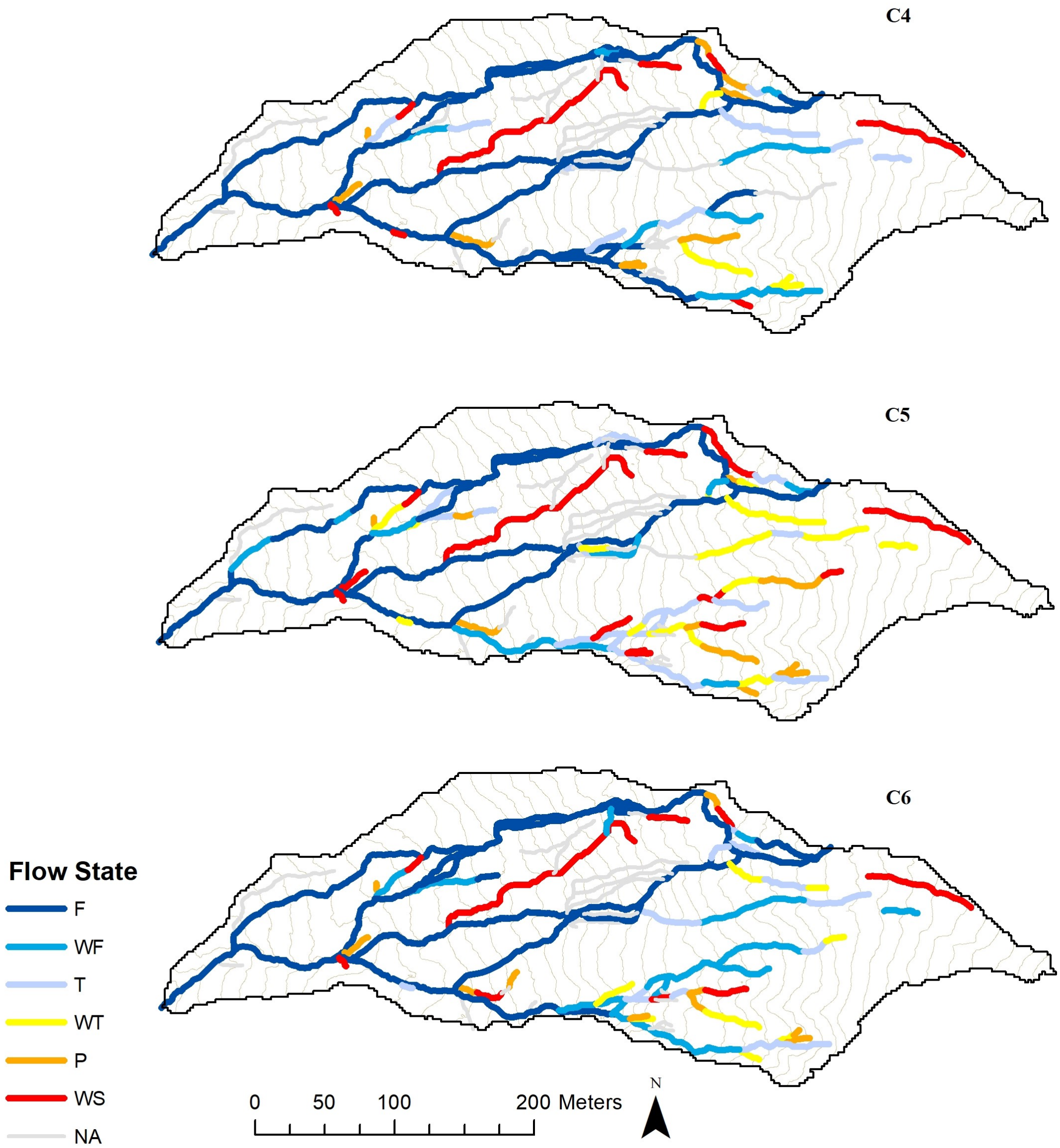


Figure 41: *Maps of the stream network from Campaign 4 to 6. With the mapped flow state according to the classification system.*

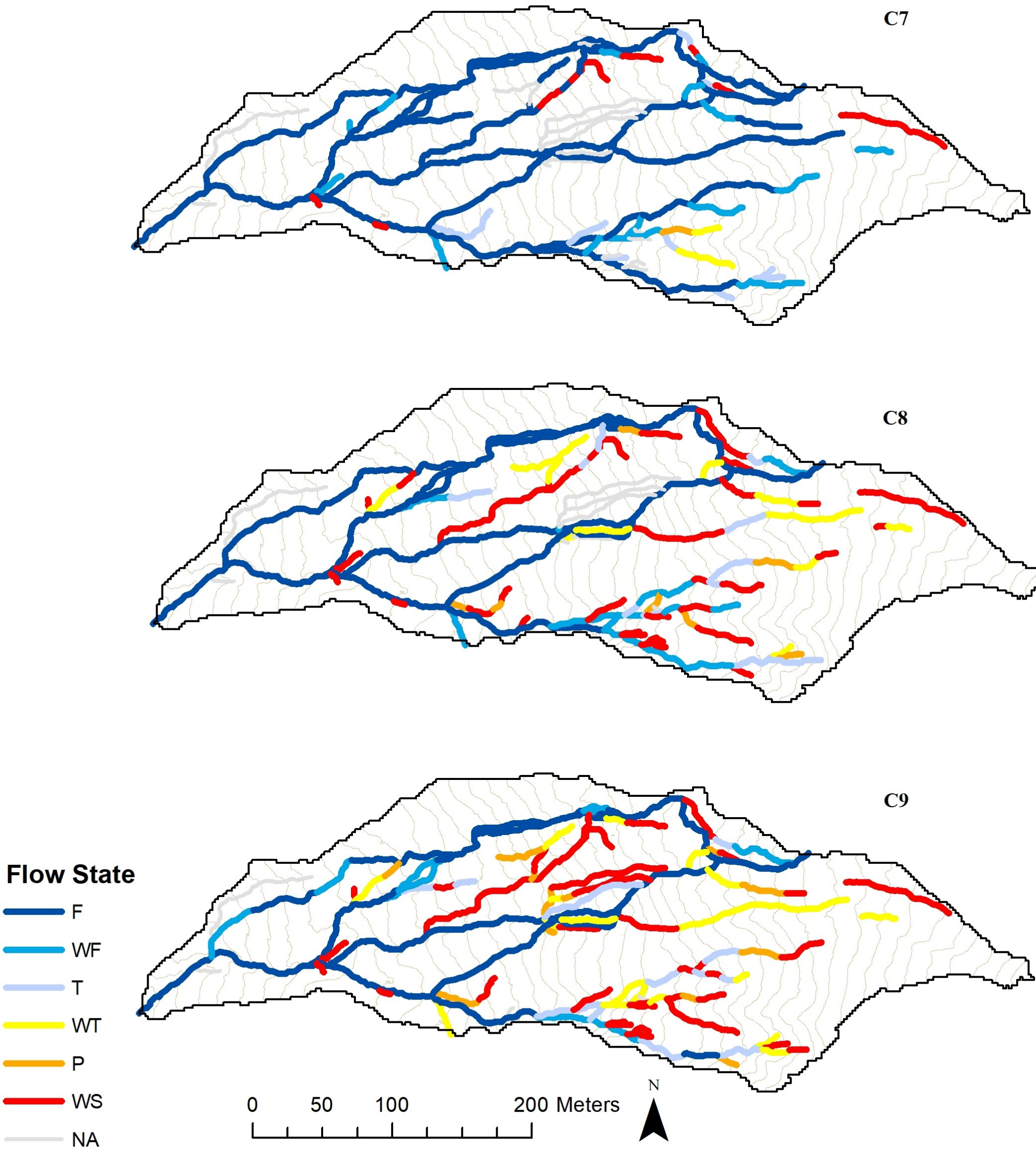


Figure 42: *Maps of the stream network from Campaign 7 to 9. With the mapped flow state according to the classification system. Campaign 7, the 7th of October, was performed during a precipitation event.*

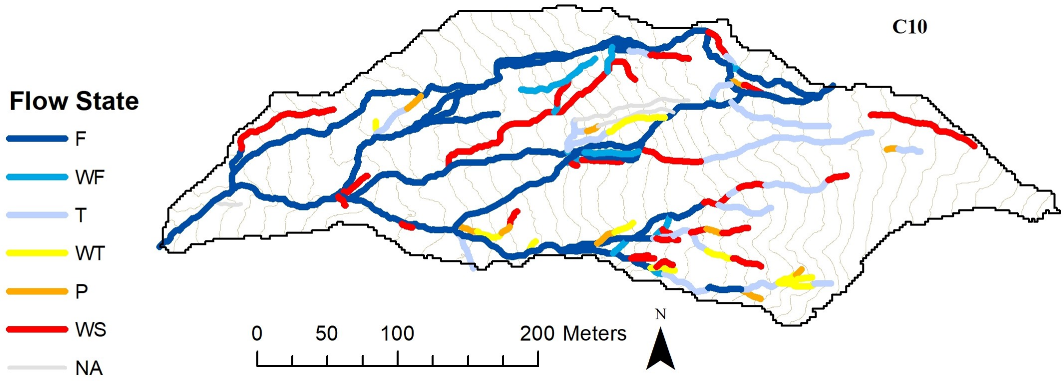


Figure 43: *Map of the stream network during the 10th and last campaign on the 30th of October.*

A.4 Maps of the EC during all 7 EC-Field Campaigns

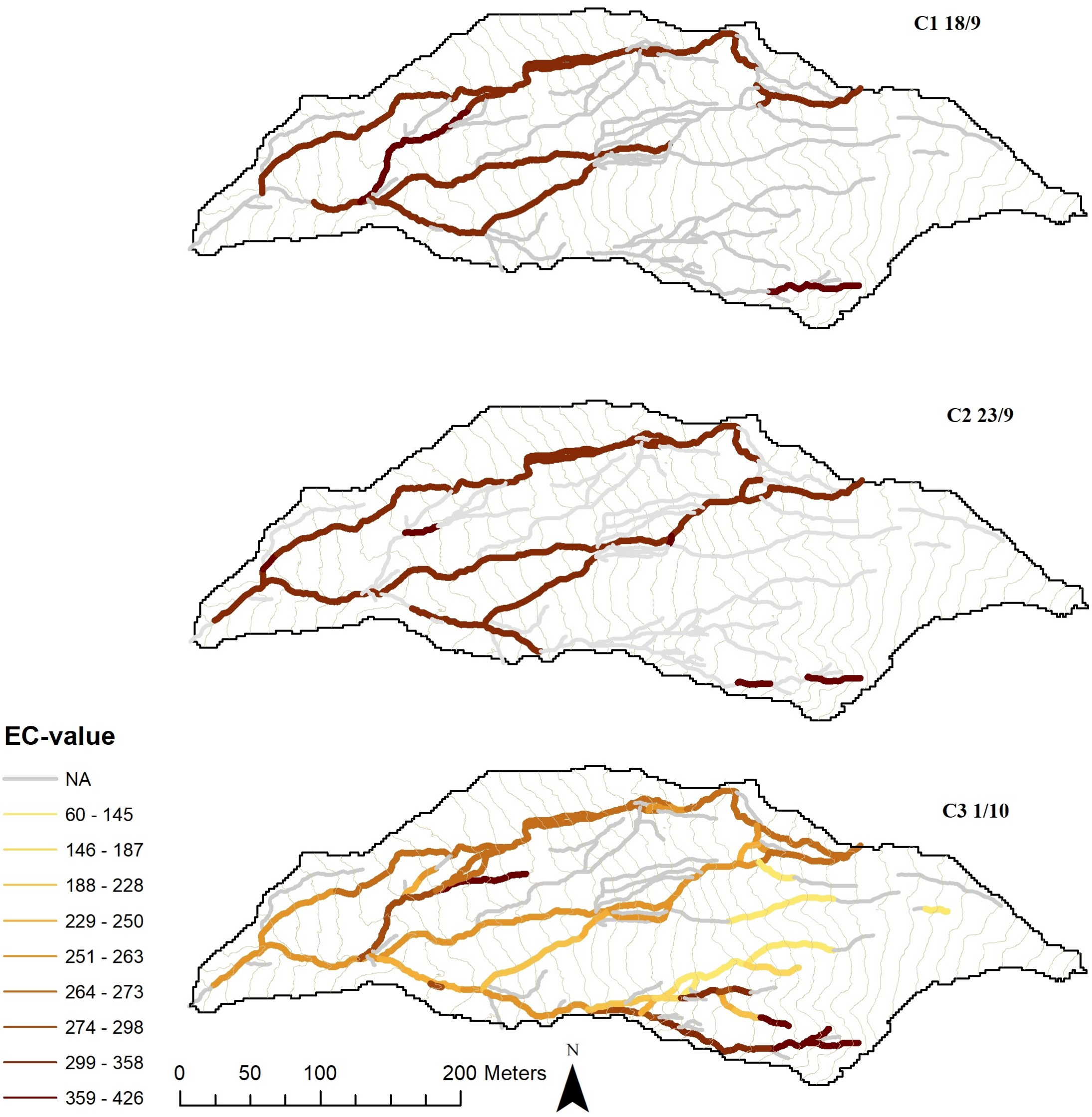


Figure 44: *Maps of EC-values in the lower Studibach catchment during 3 different campaigns, C1, C2 and C3.The highest EC-values of these campaigns were found in C1 and the lowest in C3. The South East part of the catchment had a higher EC compared to the rest of the catchment in all three campaigns.*

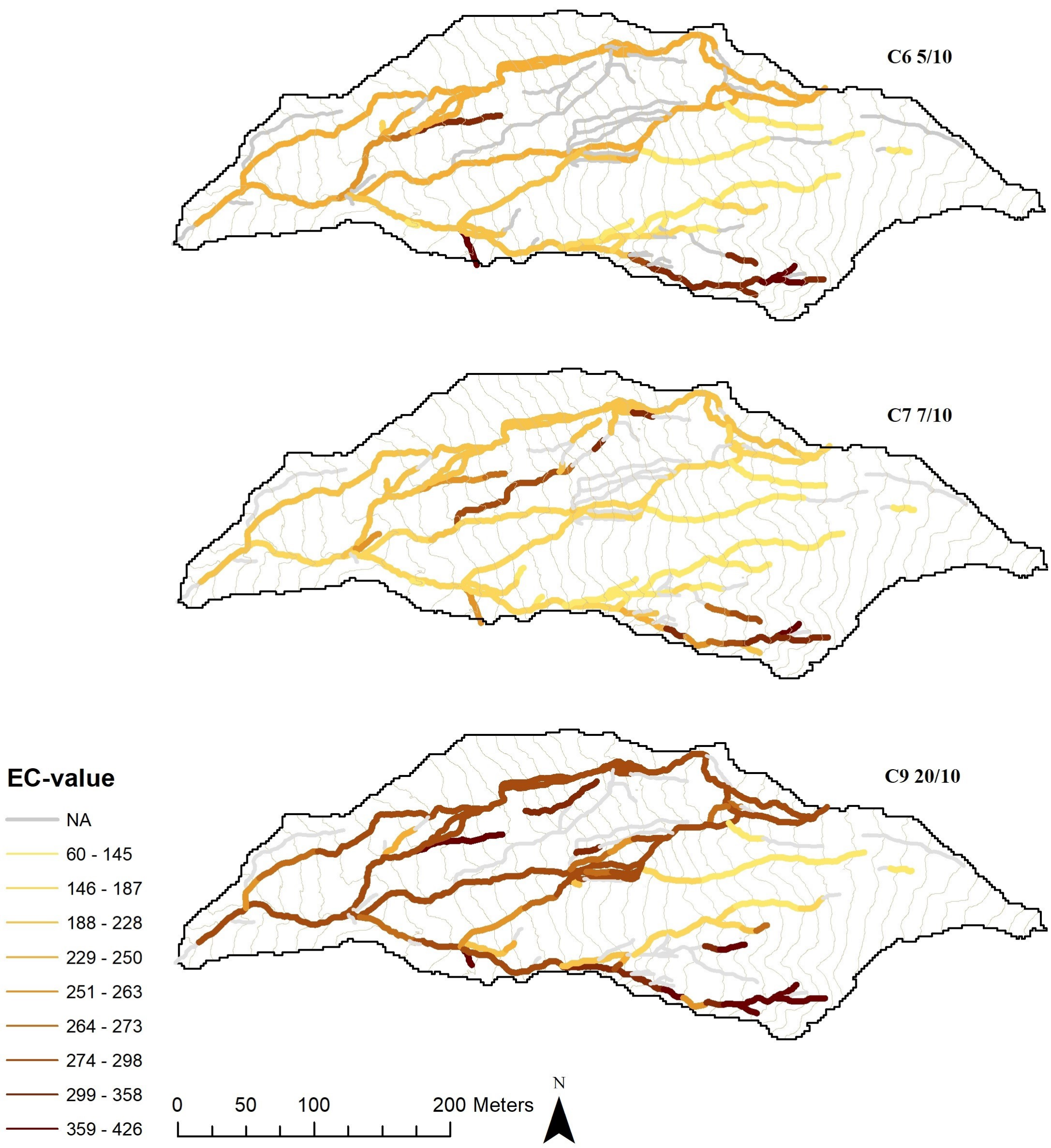


Figure 45: *Maps of EC-values in the lower Studibach catchment during 3 different campaigns, C4, C5 and C6. The South East part of the catchment had a higher EC compared to the rest of the catchment in all three campaigns.*

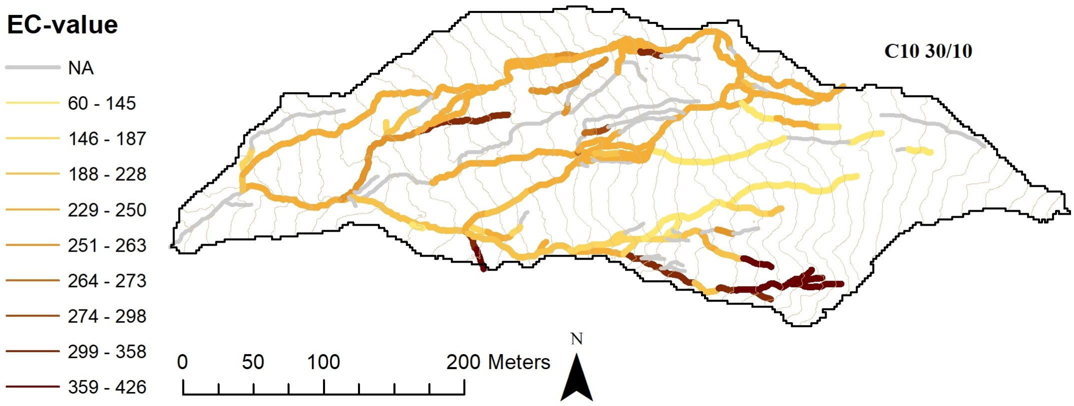


Figure 46: *Map of EC-values in the lower Studibach catchment during C7. The South East part of the catchment had a higher EC compared to the rest of the catchment.*

A.5 EC-traps

Figure 47 show how the EC-values varied in the traps between the different events. The bar plot show in the left part of the plot that the EC were generally higher in the traps during C6 the 5th of October, and this was especially significant for traps with lower numbers, located at the North part of the catchment.

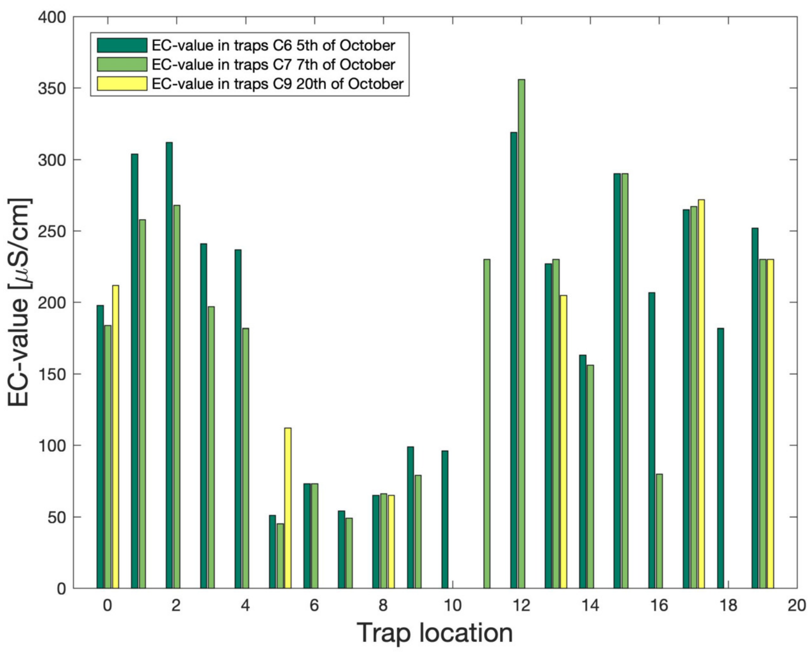


Figure 47: *Bar plot over the EC-values redorded in the EC-traps during C6, C7 and C9, 5th, 7th and 20th of October.*

A.6 Topographic Indices Streamflow

To present a different view of the scatter plot in Figure 30a, the values were inserted into a boxplot. Showing that for higher TWI-values, above 11, the median of the stream segment being active is 100 %.

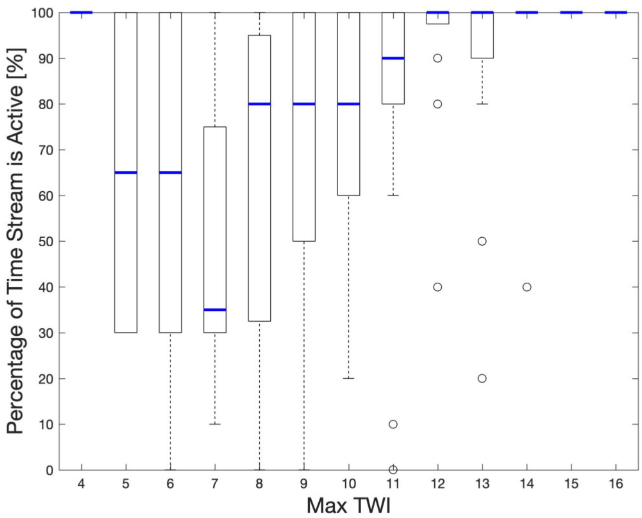
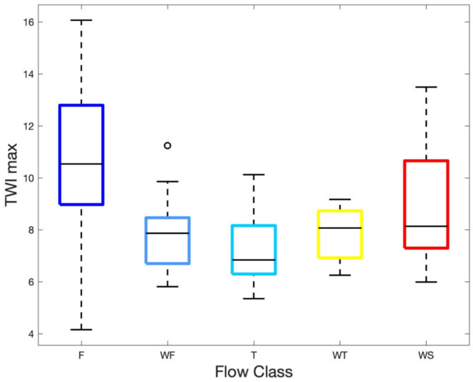
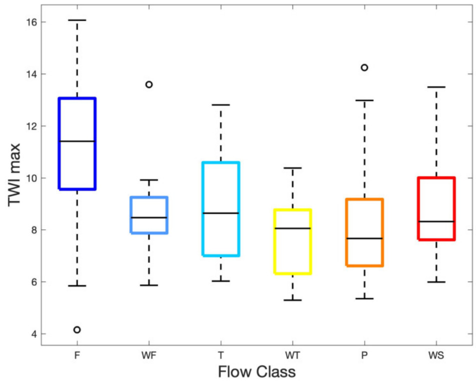


Figure 48: *Boxplot showing the percentage of campaigns the streams were active related to the maximum TWI-values for each segment. Stream sections that were never active have 0 on the x-axis and stream sections that were always active will have 100 on the x-axis. TWI-values are rounded to integers.*

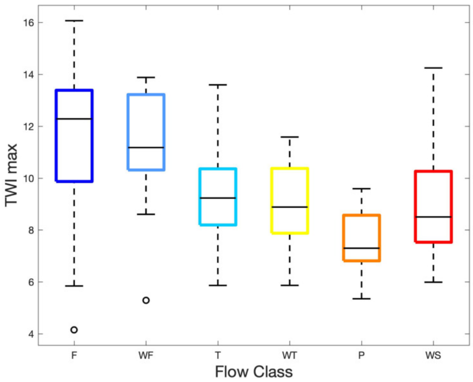
A.7 Boxplots of TWI and Flow Class



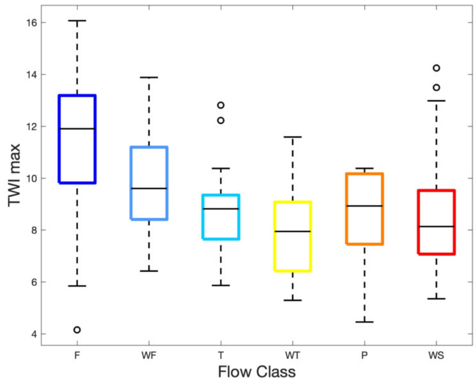
(a) *C3, Q=118 l/s*
ρ=-0.47 (p=7.8e-12)



(b) *C4, Q=84 l/s*
ρ=-0.49 (p=1.7e-12)



(c) *C5, Q=60 l/s*
ρ=-0.51 (p=1.2e-13)



(d) *C8, 62 l/s*
ρ=-0.51 (p=2.7e-15)

Figure 49: *Boxplots of maximum TWI-values related to the flow classes for each campaign date.*

A.8 Spearman's ρ from TWI boxes with Discharge

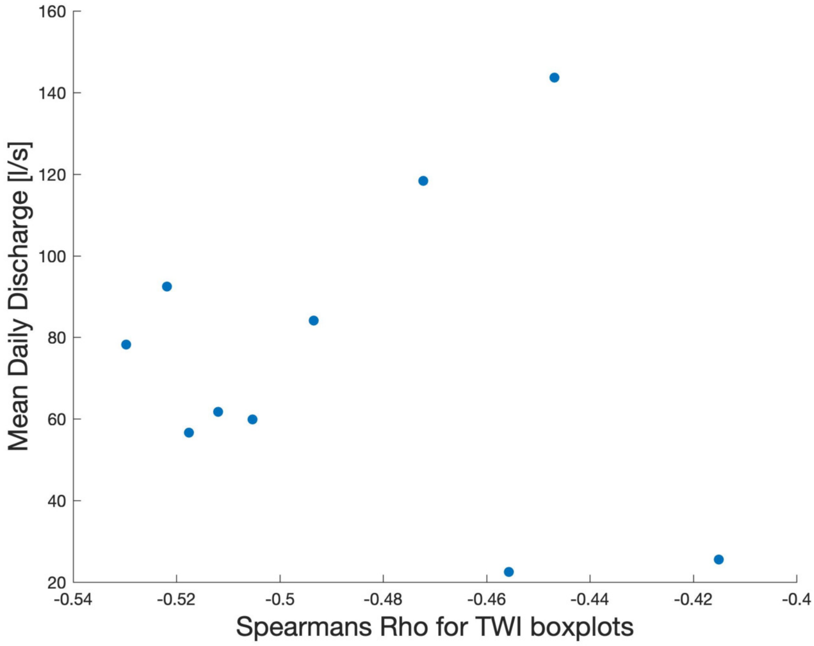
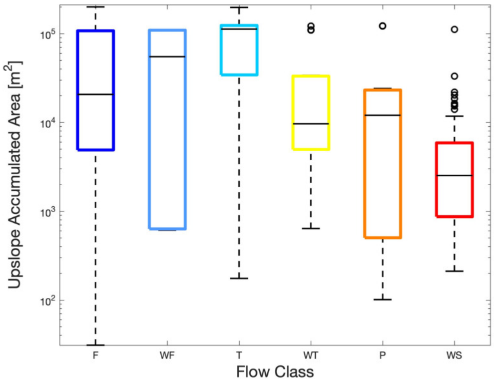
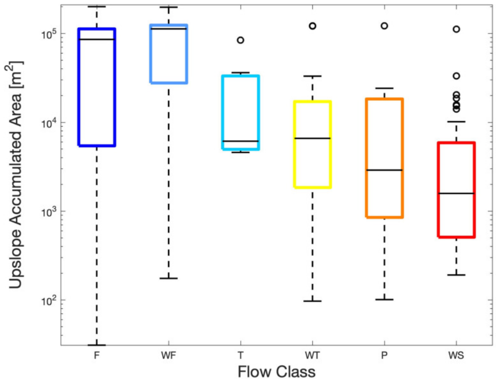


Figure 50: *Spearman's ρ for each of the TWI flow class boxplots, plotted against the mean discharge for each campaign date.*

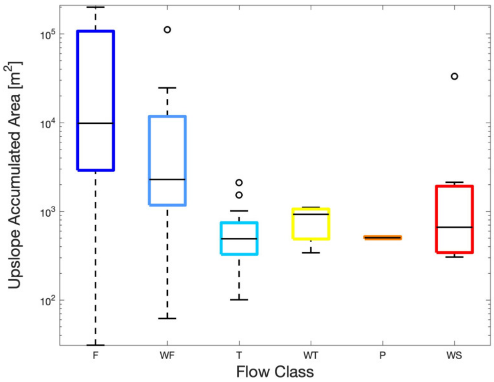
A.9 Boxplot of Upslope Accumulated Area and Flow Class



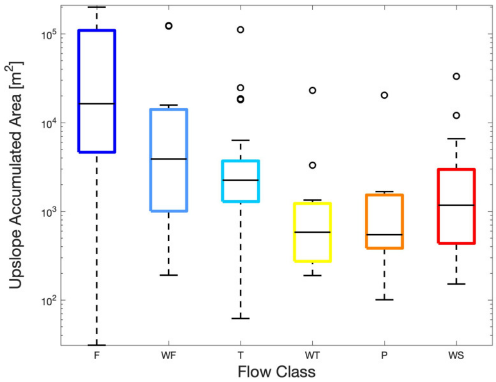
(a) *C1, Q=26 l/s*
ρ=-0.38 (p=1.9e-7)



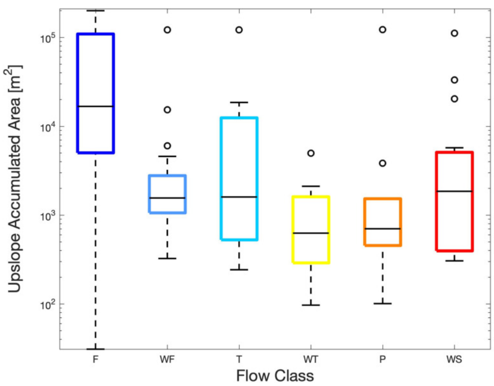
(b) *C2, Q=23 l/s*
ρ=-0.44 (p=6.0e-10)



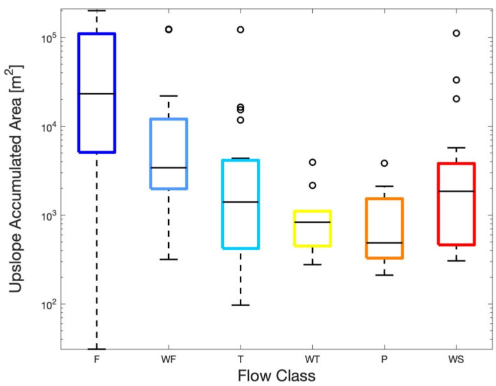
(c) *C7, Q=144 l/s*
ρ=-0.49 (p=4.0e-13)



(d) *C10, Q= 92 l/s*
ρ=-0.53 (p=1.5e-17)

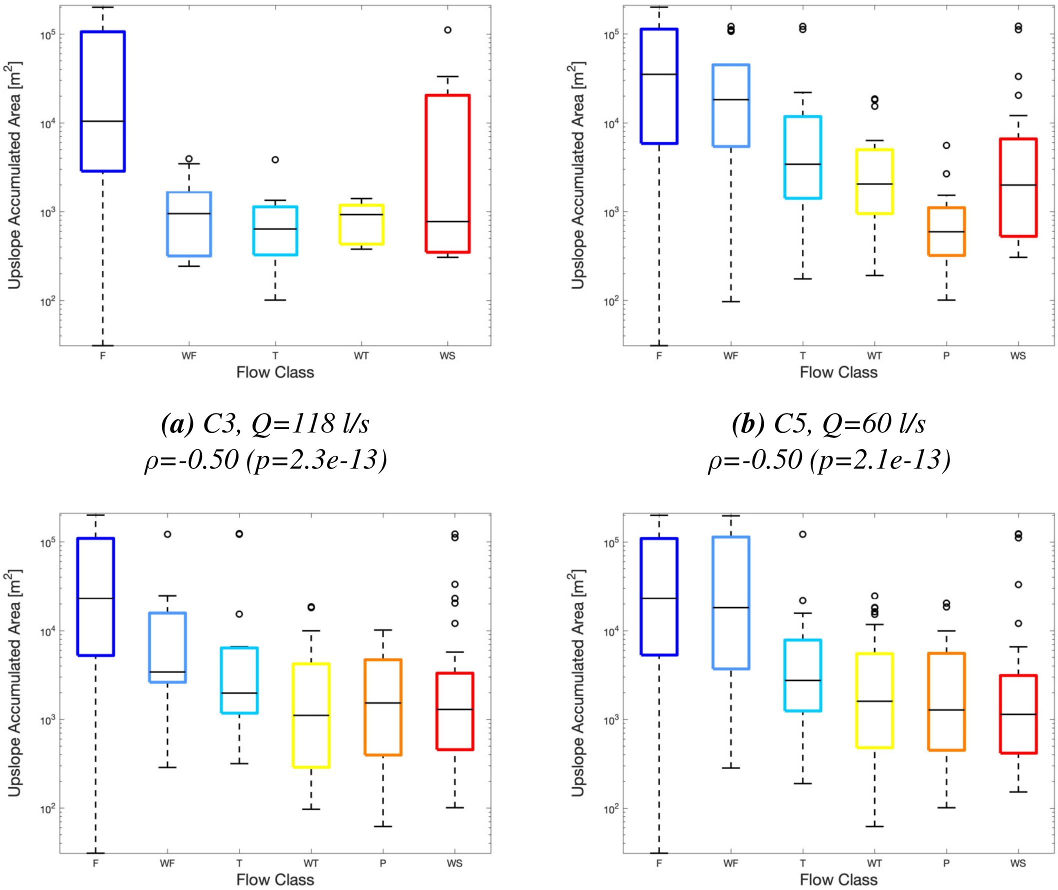


(e) *C4, Q= 84 l/s*
ρ=-0.50 (p=8.8e-13)



(f) *C6, Q=78 l/s*
ρ=-0.53 (p=2.4e-15)

Figure 51: *Boxplots of 6 campaigns performed in varied weather conditions, displaying the Flow Classes with the Upslope Accumulated Area*



***(a)** C3, Q=118 l/s*
ρ=-0.50 (p=2.3e-13)

***(b)** C5, Q=60 l/s*
ρ=-0.50 (p=2.1e-13)

***(c)** C8, Q=62 l/s*
ρ=-0.49 (p=3.3e-14)

***(d)** C9, Q=57 l/s*
ρ=-0.50 (p=7.3e-15)

***Figure 52:** Boxplots of flow class of each segment for each campaign date, related to the maximum Upslope Accumulated Area for the segment.*

A.10 Boxplot of EC and TWI

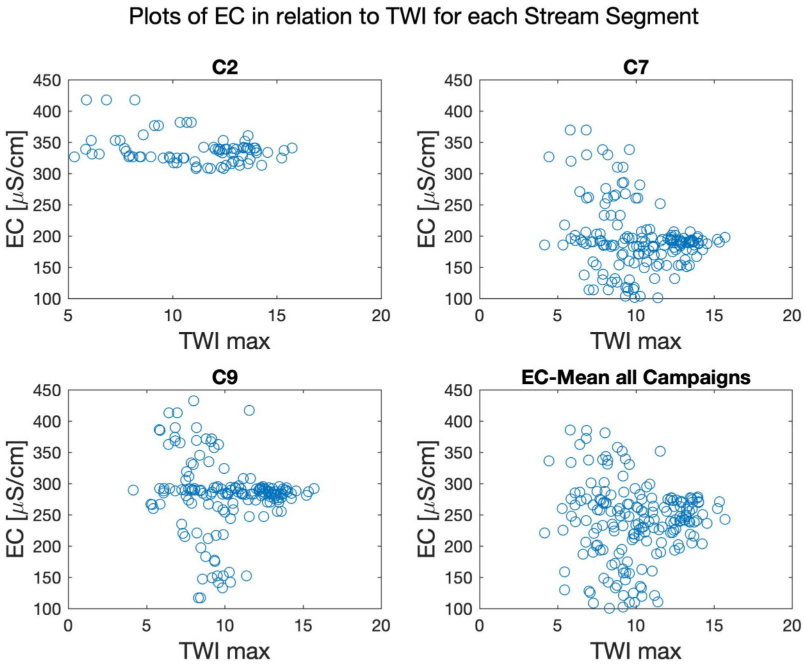


Figure 53: *Scatter plots over the relation between EC and TWI for the three campaigns C2, C7 and C9, and EC-mean for all campaigns in relation to TWI.*

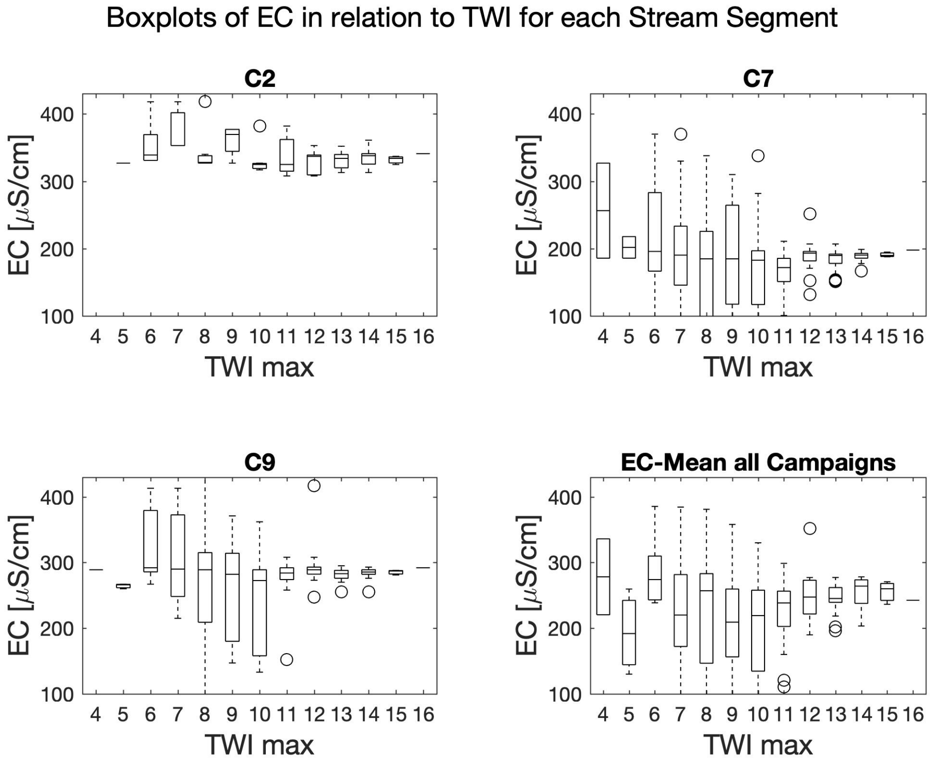


Figure 54: *Boxplots over the relation between EC and TWI for the three campaigns C2, C7 and C9, and EC-mean for all campaigns in relation to TWI.*

The scatter plots in Figure 55 show how the EC and A-max were related during the different campaigns of C2, C7 and C9. The scatter plots show that during the dry campaign C2 were the EC and A-max less correlated, compared to the wetter campaign C7 when there was a clear correlation of smaller variation in EC with increasing A-max.

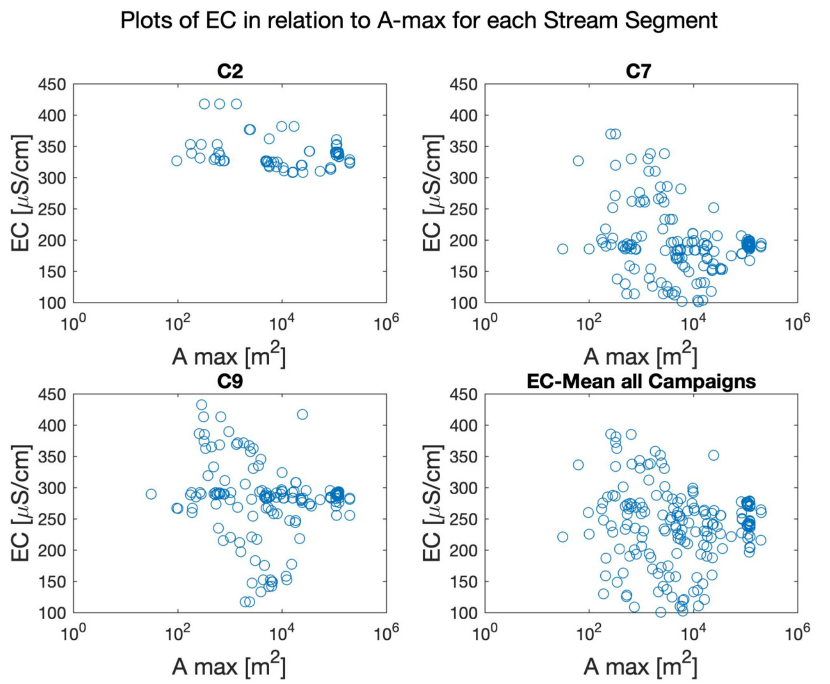


Figure 55: *Scatter plot showing the relation between EC-mean and A max for each segment, with EC-mean displayed on the y-axis and A max on a logged x-axis.For three different field campaings, C2, C7 and C9*

A.11 Discharge from v-notches

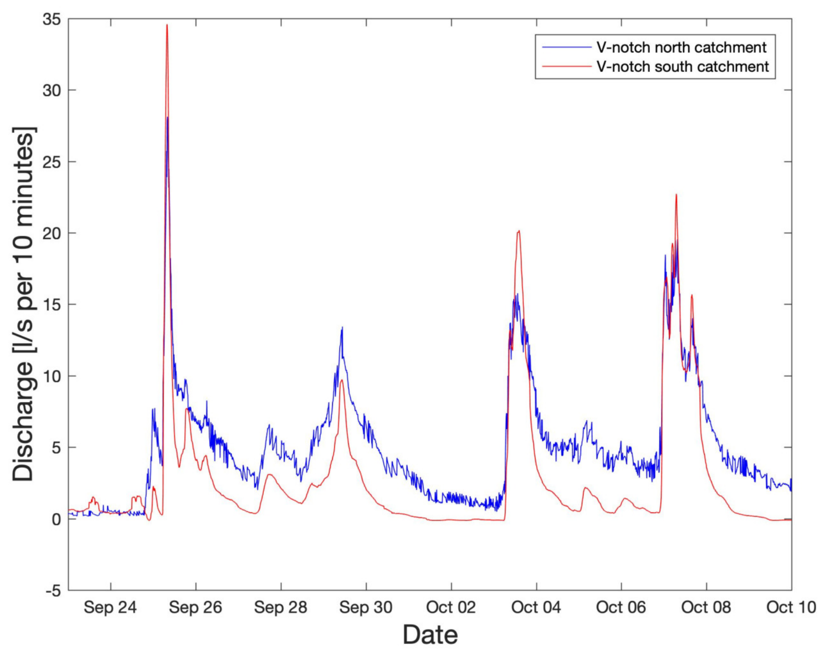


Figure 56: *Discharge from the two different v-notches located below the south and the north part of the catchment.*