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The Origin of Streams – Stream cartography in Swiss pre alpine headwater

Bäckarnas ursprung – Kartering över temporära bäckar i föralpina källområden i Schweiz

Oskar Sjöberg

ABSTRACT

The Origin of Streams – Stream cartography in Swiss pre-alpine headwater

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Temporary streams have received undeservedly little scientific attention and as a result their role in hydrological, biogeochemical and ecological processes is not yet fully understood. The ultimate goal of the research was to gain a better understanding of the temporary stream network and the processes that control it and determine how the active and connected stream length change with catchment wetness conditions to find simple methods to map seasonal and event-based changes in temporary flowing stream networks. Streams, springs and wetlands of four relatively small headwater catchments (11.7 – 25.3 km^2) and one wetland in the steep and remote Zwäckentobel catchment in Alptal, canton Schwyz (Switzerland), were mapped and stream segments were classified by flow type during different weather conditions using direct observations. The mapping was performed by an elite orienteer with mapping experience. The variation in streamflow was analysed and related to the catchment wetness and topography using the TWI-values and the upslope accumulated area of the stream segments.

As the catchments wetted up in response to fall rainfall events after a dry summer the flowing stream density increased up to five times and the connected stream density increased up to six times with a 150-fold increase in discharge. Also the number of flowing stream heads increased up to ten times. The best description of the pattern of stream expansion is a combination of the variable source area and the element threshold concepts, where surface topography, particularly TWI (Topographic Wetness Index) and upslope accumulated area (A), and local storage areas controls where streamflow is initiated and how flow in different stream segments connects. Streams in the Alptal show a seasonally bottom up or disjointed connection pattern.

Mapping the temporary streams in steep and remote watersheds as a function of hydrological conditions is not an easy task. It is however necessary in order to fully understand where water is flowing or not. A combination of field observations with monitoring equipment can facilitate this extensive work by providing a more detailed temporal resolution.

Keywords: *Temporary stream; Stream cartography; Drainage density; Hydrological connection; Topographic wetness index; Upslope accumulated area; Stream head; Headwater catchment*

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REFERAT

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Temporära bäckar har fått oförtjänt lite vetenskaplig uppmärksamhet och som en följd av detta är deras roll i hydrologiska, biogeokemiska och ekologiska processer ännu inte helt förstådd. Det huvudsakliga målet med denna studie var att öka förståelsen kring temporära bäcksystem och de processer som kontrollerar dem. För att uppnå detta var delmålet att avgöra hur den aktiva och anslutna bäckutbredningen förändras med varierande hydrologiska förhållanden för att kunna hitta enkla metoder att kartera säsongs- och händelsedrivna förändringar i det flödande bäcksystemet. I det övre loppet av det branta och svårtillgängliga avrinningsområdet Zwäckentobel i dalen Alptal, Kanton Schwyz (Schweiz) karterades och klassificerades bäcksegment, källor och våtmarker i fyra relativt små delavrinningsområden (11,7 – 25,3 km^2) samt ett våtmarksområde med direkta fältobservationer under olika väderförutsättningar. Karteringen utfördes av en elitorienterare med erfarenhet av kartritning. Variationen i bäckflödet analyserades och relaterades till våtheten och topografin i avrinningsområdet med hjälp av TWI och flödesackumulerande area för bäcksegmenten.

Resultaten visade att den flödande dräneringsdensiteten ökar med upp till fem gånger och den anslutna dräneringsdensiteten med upp till sex gånger med en 150-faldig ökning i avrinning. Även antalet bäckhuvuden ökar med upp till tio gånger. Expansionen av bäckflödet visade sig ske genom en kombination av att lokala vattenmagasin överskrids och av att utströmningsområdet ökar. Topografin, framförallt TWI och flödesackumulerande area, kontrollerar var bäckflödet börjar och hur flödet i olika bäcksegment ansluts. Det framgick att bäckarna i Alptal ansluts säsongsbaserat antingen från botten av avrinningsområdet och uppåt eller genom ett osammanhängande mönster.

Att kartera temporära bäckar i branta och svårtillgängliga avrinningsområden är ingen enkel uppgift. Det är däremot en nödvändig sådan för att helt kunna veta var vatten flödar eller inte. En kombination av observationer i fält med övervakningsutrustning kan förenkla detta omfattande arbete och tillgodose en mer detaljerad tidsupplösning.

Nyckelord: *Temporära bäckar; Bäckkartering; Dräneringsdensitet; Hydrologisk anslutenhet; Topografiskt blöthetsindex; Flödesackumulerande area; Bäckhuvud; Källvattenområde*

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PREFACE

This Master Thesis (30 ETCS) was part of the M. Sc. in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Science and was performed individually. It could, however, never have been successful without the people of the H2K group within the Department of Geography at the University of Zurich who welcomed me into their scientific family.

First of all Ilja Van Meerveld (Senior Scientist), my supervisor, who took the time to answer all my questions and emails, read through the report and guide me in the world of science. I especially want to thank you for that you supported my ideas and gave me the possibilities to explore the streams in Alptal in the way I wanted to. You never saw any restrictions in my work or in my plans and for that am I very grateful.

I also want to thank Benjamin Fischer (PhD Student) who guided me in Alptal and brought me to Riedholzbach to learn more about hydrological science in Switzerland, you were like a co-supervisor to me. You also taught me all about the beauty of the Zwäckentobel and the people living there. I am sorry that I spelled your name wrong throughout the study!

I want to thank Ander Osus Orbegozo for showing me how to map streams in Reppish and Rick Assendelft (PhD Student) for joining me in Alptal. We had a fun time together and I wish you both the best of luck in studying the streams in the future. I also want thank Manfred Stähli from the WSL for buying me coffee in Einsiedeln after the rainiest day of the autumn and providing me with data from Erlenbach.

I came in contact with this work through Jan Siebert (Professor), my subject reader, after a lecture in Uppsala. Thank you for giving me the change to come to Switzerland.

I want to thank my family. My parents for always supporting me, no matter what I do.

Finally, Bettina, for taking care of me and standing out with me, even when I come home late in evening with half of the Alptal stuck in my hair and clothes. You are really the best and this work is for you.

Bern, Switzerland, December 2015

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Bäckarnas ursprung – Kartering över temporära bäckar i föralpina källvattenmiljöer

Oskar Sjöberg

Vattenflödet i bäckar är inte, som kartor visar, ett statiskt fenomen. En signifikant mängd av våra vattendrag är sådana som någon gång på året inte har ett ytligt flöde av vatten. I dessa *temporära bäckar* kan det högst belägna vattenflödet vara långt ner i avrinningsområdet under den torra sommaren och sedan sträcka sig långt ovanför kartredovisningen efter ett långvarigt regn. Temporära bäckar har en troligtvis viktig men hittills oförstådd roll i både hydrologiska, biogeokemiska och ekologiska processer. Än mindre vet vi hur dessa processer påverkas av ett förändrat vattenflöde till följd av mänskliga och naturliga förändringar.

Tidigare studier har till exempel visat att temporära bäckar kan krylla av liv och inhysa både bostad och fortplantningsområde för permanenta och migrerande arter (så som fiskar, ryggradslösa djur, insekter, alger, mossor, svampar, amfibier, fåglar och växter) som har specialiserat sig på det unika habitatet det temporära vattenflödet skapar. De Europeiska vattenskyddsdirektiven ignorerar bäckar som inte uppfyller ett visst flöde och skyddar på så sätt inte dessa arter som är beroende av ett temporärt flöde. Med de rådande klimatförändringarna är det troligt att många av de idag konstant flödande bäckarna i framtiden kommer att få ett mer temporärt vattenflöde. Det är därför förvånande att så lite uppmärksamhet inom vetenskapen har riktats mot att rita ut våra temporära bäckar på den idag blanka kartan, så att vi kan öka förståelsen kring vad som påverkar vattenflödet.

Denna studie syftade till att kartera bäcksystemet på en brant och svåråtkomlig bergssluttning i den Schweiziska föralpina dalen Alptal under olika väderförhållanden, från sommar till vinter. Målet var att genom att göra detta, kunna se hur flödet i bäckarna förändrades, var i landskapet denna förändring skedde och huruvida topografin var relaterad till bäckflödet. Karteringen utfördes av en elitorienterare med erfarenhet i kartritning och förhoppningen var att kunna delge kunskaper och erfarenheter till framtida karteringsstudier av temporära bäcksystem.

Bäcknätverket, källor och våtmarker i fyra mindre avrinningsområden och ett våtmarksområde blev karterade i fält i slutet av den torra sommaren. I varje område genomfördes fem till sex fältkampanjer, under varierande hydrologiska förhållanden, där varje bäck blev uppdelad i segment baserat på hur mycket vatten som flödade i varje del.

I och med att årstiden skiftade, förändrades även utsträckningen av bäckflödet. Den totala längden av flödet visade sig öka upp till fem gånger som följd av höstens regn. Bäckflödets ökning sker först och främst i de mest låglänta delarna av bergskanten och växer sedan uppåt allt eftersom våtheten i området ökar. Alptal är ett område karakteriserat av hög och ofta förekommande nederbörd, låginfiltrerande jord och sedimentär geologi och därmed ligger grundvattenytan oftast mycket nära marken. Vid regn mättas därför marken snabbt och den ökande utsträckningen av bäckflödet sker fort. Topografin visade sig påverka vilka delar av bäcken som flödar och var bäckflödet börjar. När våtheten i området ökar så rör sig den yttersta delen av bäckflödet upp mot topografiskt torrare områden och det så kallade utströmningsområdet ökar.

Källor och våtmarker har också en påverkan på vattenflödet. Från källorna i Alptal sipprar ständigt ett litet kalkrikt vattenflöde som på sin väg nerför sluttningen troligen passerar ett av de många inströmmande våtmarksområdena. Flödet från dessa rännilar kan endast ansluta till ån i botten av dalen när dessa våtmarken inte kan förvara mer vatten och börjar sippra. Bäckflödet är på så sätt beroende både av topografin och av lokala vattenmagasin, så som våtmarker och sjöar i landskapet.

Att kartera temporära bäckar i branta och svårtillgängliga avrinningsområden är ingen enkel uppgift. Det är däremot en nödvändig sådan för att helt kunna veta var vatten flödar eller inte. En kombination av observationer i fält med övervakningsutrustning, för att kunna bevaka flödet i en bäck, kan förenkla detta omfattande arbete och tillgodose en mer detaljerad tidsupplösning i framtida arbeten. Genom att kartera utsträckningen av bäckflödet i avrinningsområden av varierande klimat och landskap, kan det vara möjligt att skapa ett klassifikationssystem där lika områden har liknande variationer i det temporära bäcksystemet. Ett sådant arbete skulle kunna ligga till grund för skapa mer realistiska hydrologiska modeller och i arbetet att skydda våra vattenresurser på ett mer effektivt sätt.

Berget Grosse Mythen som vakar över dalen Alptal i innersta Schweiz.

LIST OF ABBREVIATIONS

A – Upslope accumulated area (m^2)

B – Scaling factor or exponent

D_d – Drainage Density (m/m^2)

DEM – Digital Elevation Model

n – Number

P – Precipitation (mm)

TWI – Topographic Wetness Index

Q – Discharge (l/s or mm/d)

GLOSSARY

Active stream – A stream with flowing water

Catchment basin – The area where surface water drains to a single outlet

Connected stream – A stream with a continuously streamflow to the outlet of the basin

Drainage Density – The length of the stream network per catchment area

Headwaters – The uppermost parts of a stream or river

Flow routing – A procedure to model flow at a point of interest

Interflow – Subsurface flow that returns to the surface before it becomes groundwater

Spring – A location where water naturally emerges from an aquifer to the surface

Stream head – The location where streamflow initiates in a stream

Stream segment – A part of a stream

Temporary stream – A stream that stops to flow for a variable time period

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1. INTRODUCTION

1.1 TEMPORARY STREAM NETWORKS AND DYNAMICS – STATE OF THE ART

In contrast to perennial streams that maintain continuous flow throughout the year, temporary streams stop to flow for variable time periods. Even though this definitional difference might seem small, recent studies have pointed out that a significant gap in scientific knowledge exists between the two, with basically all hydrological research focusing on the perennial stream network (Godsey and Kirchner 2014; Buttle et al. 2012; Boon et al. 2012).

Even though streamflow constitutes only a very small fraction of the total water on our planet, it is important for society. Both positive, e.g. drinking water, aggregation, biota, and negative, e.g. floods, land-slides (Bishop et al. 2008). Considering that most temporary stream networks in headwater regions are blank spaces on maps, Bishop et al. (2008) ask how well we really know our flowing water. Figure 1 shows a sketch of a valley in headwater regions (inspired by Alptal, Switzerland), field observation in the area of the inset map shows a lack of streams while, in reality, this area is full of streams.

The portion of the total stream network that consists of temporary streams, is unknown. Datry et al. (2014) approximated, based on previous studies, that intermittent streams constitute around half of the worlds stream network but acknowledge is that this does not include headwater regions, since these are too difficult to map from air- and satellite photos. It is estimated, that of the streams in these regions more than 70% could be temporary (Datry el al. 2014). Also historical changes and future predictions in intermittency, due to water abstraction and climatic changes, have not been well considered. In regions where such processes take place, streams are likely to become more and more temporary in the future (Larned et al. 2010).

As the balance between precipitation and evapotranspiration changes, so does the streamflow in a temporary stream network. Whenever there is flow in a temporary stream, it is said to be active (Gurnell 1978). As the catchment becomes drier or wetter, the active part of the stream network contracts or expands in a seemingly complicated manner. These fluctuations can according to Dunne (1969) be related to factors that vary spatially and temporally, such as topography, soil properties, antecedent moisture conditions and climate. As the start of a flowing stream moves up and down the valley, it reveals the transition point between surface and subsurface flow (Godsey and Kirchner 2014). This expansion and contraction of a temporary stream network has an important, but not well understood effects on ecological, biogeochemical and hydrological processes (Bishop et al. 2008; Meyer et al. 2007; Larned et al. 2010; Wigington et al. 2005).

Studies of temporary stream networks in the 1960-70s (e.g. Gregory and Walling 1968) focused mainly on the hypothesis that drainage density was a first-order control on the hydrological response to precipitation. When this turned out to be wrong, there was an abandonment of the subject which, according to Godsey and Kirchner (2014), may have been premature. They ask, like Blyth and Rodda (1973) and Goulsbra et al. (2014), why it has been ignored that the drainage network is not static but dynamic.

The lack of understanding has led to a variation in policy and protection of temporary streams. Acuña et al. (2014) argue that temporary waterways should be defined within the river network if they sometimes have a connected flow or are habitat for organisms in the dry bed. Improved mapping of temporary streams is therefore needed. Even though there has been an inquiry for more understanding and protection of headwater streams in the U.S. (Bishop et al. 2008), Guidelines from the US Environmental Protection Agency (EPA) in the Clean Water Act and the European water legislation ignore, and therefore fail to protect, dry streambeds that do not fulfil certain criteria (Steward et al. 2012; Acuña et al. 2014).

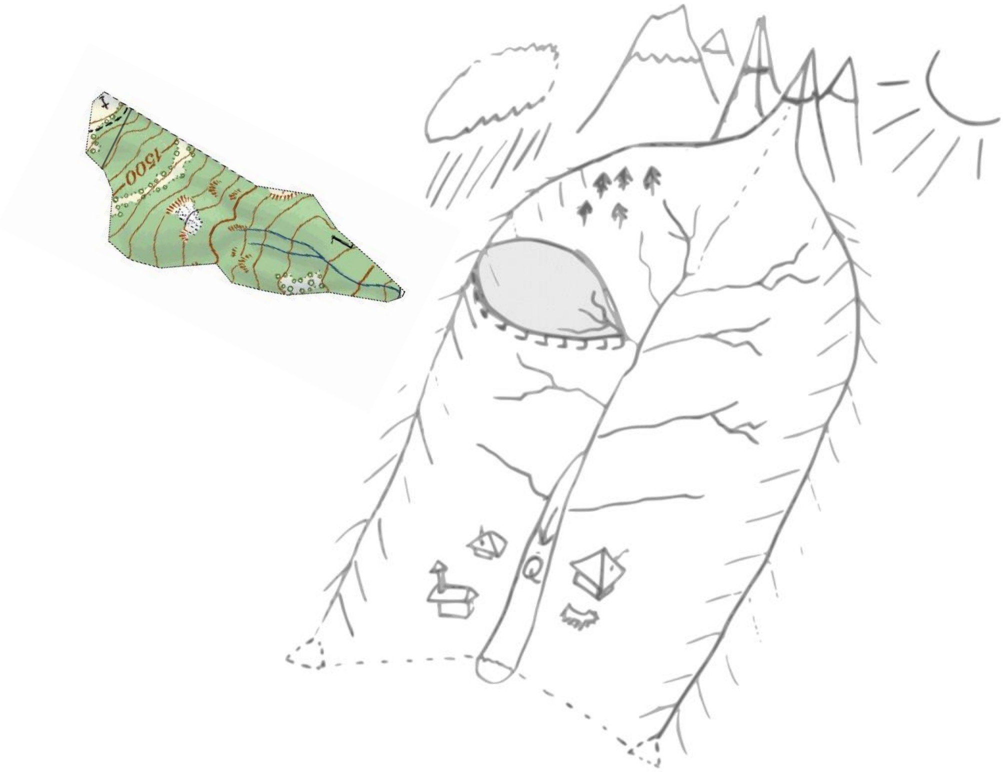


Figure 1. *Sketch over a valley, inspired by observations in the Alptal, Switzerland. The region is gaining water from rainfall and snow melt and loses water from evapotranspiration and runoff. The village at the bottom of the valley experiences floods during large events or droughts during drier periods. With both anthropogenic and natural changes these risks can be harder to predict. Better understanding of headwater catchments (example in grey) can support these predictions and help the village to manage its water resources. The inset map is an example of how a small headwater catchment in Alptal is presented on a topographic map. Notice that the stream network is only drawn halfway up the catchment. In reality, this stream extends almost all the way up to the ridge during events and dries out during dry periods. Even though just two small streams are mapped, this headwater catchment is filled with a complex branched stream network.*

1.1.1 Intermittent, Ephermal and Episodic stream definitions

According to Uys and O'Keeffe (1997) an intermittent stream can be distinguished from a perennial stream if surface flow in the stream disappears during periods of time due to of seasonal or aseasonal changes in moisture conditions. When not only surface flows, but also surface water disappears, the stream is ephermal or episodic. In these cases, the water level is below the position of the bottom of the stream bed at all times (see fig. 2). While perennial and intermittent streamflow are dependent on groundwater flow, ephermal streams consist of surface runoff and interflow (Peirce and Lindsay 2014), mainly during rainfall or snowmelt events (Buttle et al. 2012). Episodic streams occur mainly during extreme weather events (Uys and O´Keeffe 1997). In this paper the term "temporary" includes all intermittent, ephermal and episodic streams.

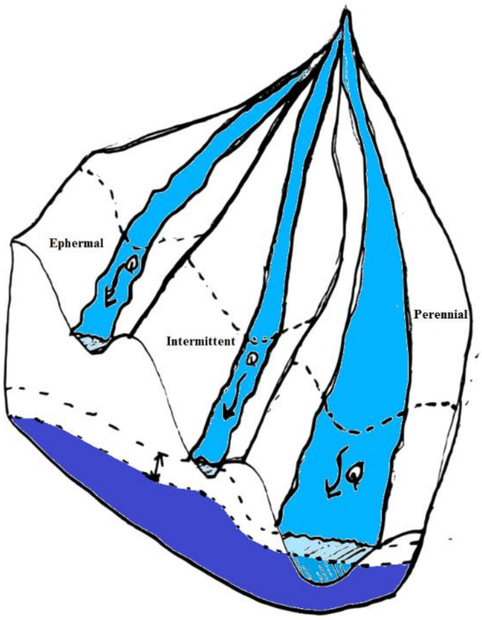


Figure 2. *Sketch showing the difference between ephermal/episodic, intermittent and perennial streams. Ephermal and episodic streams are always located above the groundwater level and are only fed during events. Intermittent streams temporary gain groundwater, while the perennial streams always receive groundwater. The dotted lines indicate the variability in the groundwater level during various periods.*

Channels are defined as the geomorphic stream bed, created from landslides and erosion from channelized seepage, with definable banks (Montgomery and Dietrich 1978). Overland flow can accumulate in small rills in wetlands and can also be classified as a temporary stream without the existence of any obvious stream bed or channel. Moreover, the stream can extend beyond the channel, especially during wet conditions (see fig. 3).

The stream head is defined as the upper-most position in every stream where flow occurs, i.e. the initiation of streamflow. In this definition, spots where the stream is disconnected from the mainstream are not included. This definition of a stream is thus different from the one used by Henkle et al. (2006) who defines the stream head as the upper-most part of the perennial flow, which of course would not applicable for a "temporary stream".

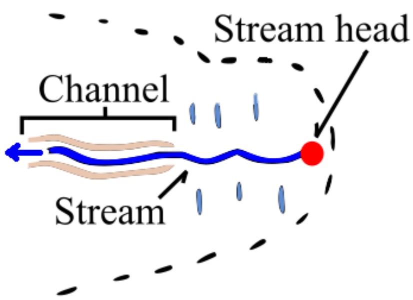


Figure 3. *Sketch showing the extension of a channel with defined banks, a stream and the initiation of the streamflow at the stream head. Notice that in this definition, the stream extends beyond the channel in small rills in wetlands or by overland flow.*

1.1.2 Expansion, contraction and connection patterns

In previous studies, three different patterns of stream network expansion have been observed: "Bottom-up" (e.g. Morgan 1972; Hewlett and Hibbert 1967; Dunne 1978), "Disjointed" (e.g. Day 1978 and 1980) and "Top-down" (e.g. Day 1978; Hewlett and Hibbert 1967; Bhamjee and Lindsay 2011). See also Goulsbra et al. (2014) and Peirce and Lindsay (2014) for more information.

The Bottom-up expansion reflects the Variable Source Area (VSA) concept (Hewlett and Hibbert 1967; Dunne 1978). As a result of the potentiometric gradient, groundwater is more likely to reach the soil surface and exfiltrate at lower points in the landscape (Buttle et al. 2012). As water infiltrates the ground during rainfall or snowmelt events, there will be an increase in soil moisture and a rising water table, which also causes groundwater to reach the soil surface at points higher up in the landscape, (see fig.Figure **4**). As the rising soil moisture and groundwater reaches more permeable layers, with a higher hydraulic conductivity streamflow increases. The stream head will also expand upwards (see fig. 5). The stream length thus increases and the discharge at the outlet increases as saturated overland flow occurs. Figure 4 shows the location of the groundwater table and water runoff generation, according to the VSA-concept, in a hillside profile before and during a rainfall or snowmelt event.

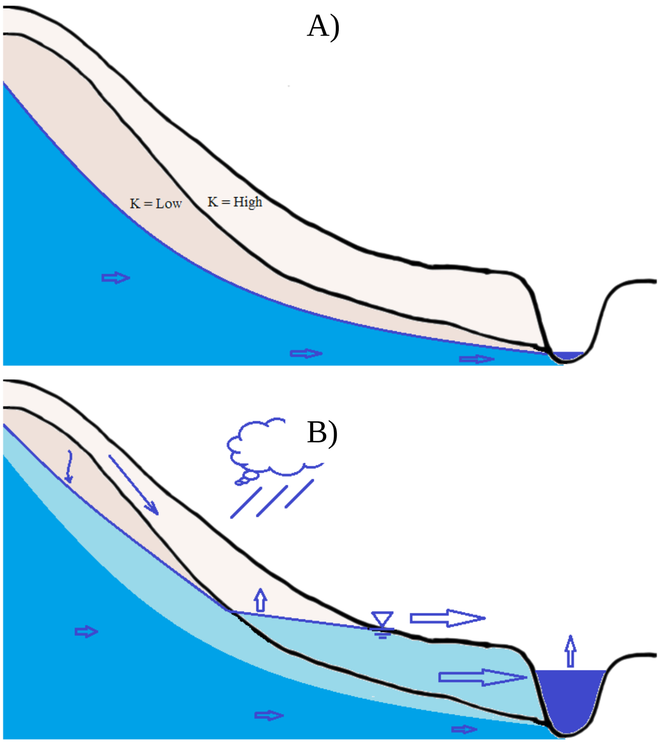


Figure 4. *A hillside profile with a lower low-permeability and an upper high-permeability soil layer. A) During dry periods, the perennial river in the bottom of the hill is only fed by groundwater from the lower layer. As this layer has a low permeability, the discharge to the river, here indicated with blue arrows, is. B) During rainfall or snowmelt events water percolates through the unsaturated upper layer down to the ground water and the groundwater level rises. The discharge to the river increases as more permeable layers become saturated and the slope of the ground water increases (lower slope on the water table in the upper than in the lower soil layer). Saturated overland flow occurs when the soil is fully saturated.*

Figure 5 shows the expansion of a temporary stream network according to the VSA-concept, i.e. bottom-up, from dry to wet.

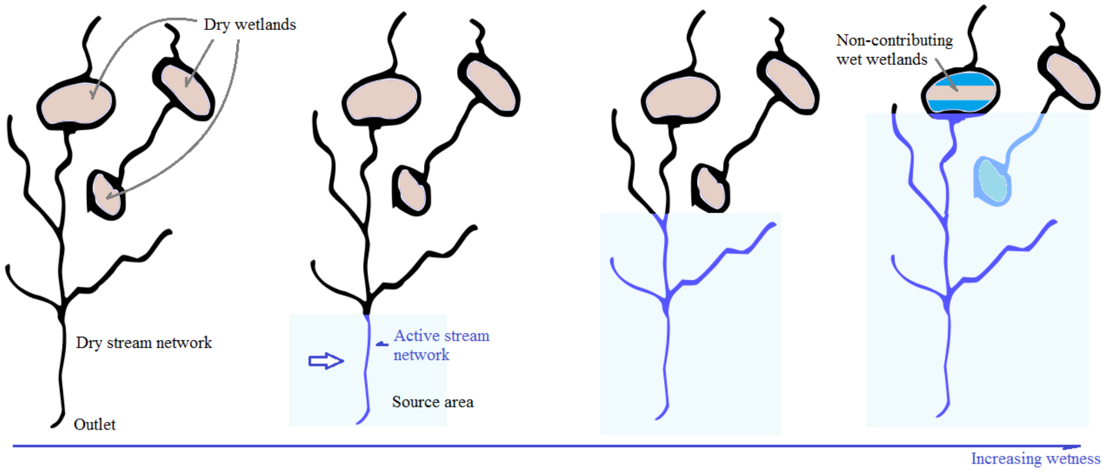


Figure 5. *Sketch over a bottom-up stream expansion of the stream network according to the Variable Source Area (VSA) concept, seen from above. The expanding source area (indicated with light blue) causes the flowing stream network to reach further up the hillside. The regions in brown or blue-brown are local storage areas (e.g. wetlands).*

Top-down expansion means that the stream is activated from upper reaches and connects downwards (see fig. 6). At places where the precipitation exceeds the local soil infiltration capacity or shallow soils became saturated, Horton or saturation overland flow will occur. As the water reaches temporary channels these will be filled from the upper part of the hillside and expand downwards. This pattern of expansion is therefore expected in areas with a low infiltration capacity or during heavy rainfall or snowmelt events (Day 1978, Goulsbra 2010, Bhamjee and Lindsay 2011). This pattern may also occur in catchments with large gradients in rainfall and evapotranspiration where soils higher up in the catchment are wetter than lower in the catchment.

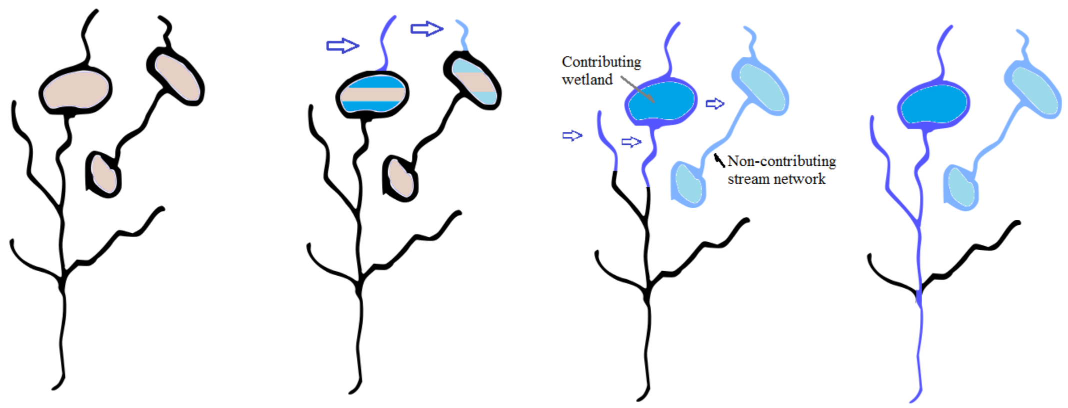


Figure 6. *Top-down expansion of a stream network from dry to wet conditions (see* fig. 5 *for more information). The uppermost streams are placed in areas with low infiltration capacity or high soil moisture. These streams will fill the wetlands or other storage areas below until maximum storage capacity is reached. Addition of more water causes the stream network to expand from these wetlands downwards. Notice that the stream network on the left bank in each figure is not connected to the main channel and therefore does not contribute to the flow at the outlet of catchment.*

Disjointed expansion, also called the coalescence model (Bhamjee and Lindsay 2011), can be seen as a mixture of the bottom-up and top-down pattern (fig. 7). It is caused by a heterogeneous landscape where local storage areas, like small pools in a stream, are filled with water until the storage capacity is reached. Addition of more water causes the pools to overflow, transmit, and connect the stream to reaches with continuous flow. This phenomenon is also referred to as complete coalescence. Equally, disjointed expansion can cause an incomplete coalescence. This is the case if a section of the channel becomes connected without causing full stream expansion.

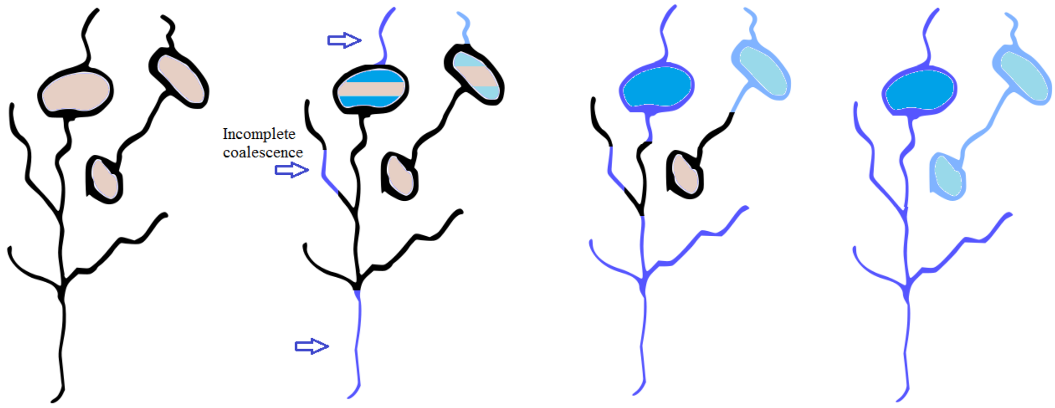


Figure 7. *Disjointed expansion with both complete and incomplete coalescence of small pools in the stream and exceedance of storage areas in the upper parts. The expansion pattern can be seen as a mixture of the bottom-up and top-down patterns. See figure 5 for more information.*

Top-down and disjointed expansion constitute the Element Threshold (ET) concept of stream expansion (Spence and Woo 2006). In a heterogeneous landscape, with variation in local storage capacity, runoff is only generated when a local threshold value is exceeded. Streamflow in a temporary stream is therefore dependent on the local storage properties, such as the placement of wetlands (Buttle et al. 2012). Spence and Woo (2006) suggest that headwaters can be divided into landscape units (or elements), according to the local physiography (topography, vegetation and soil properties) which affect the hydrological response to rainfall and snowmelt. As the behaviour of each hydrological element is dependent on the precipitation and antecedent moisture conditions, they will react differently in time and space. Topography can give an indication of areas with a low or high saturation threshold.

The discharge response during a rainfall event depends on how the local stream network expands. According to Buttle et al. (2012), the VSA concept means that the quick flow-precipitation ratio increases with the size of the rainfall event. Even during summer periods, a minimum saturated area of the hillside can exist. During precipitation events, this area quickly expands upwards. The varied nature of the Element Threshold concept on the other hand, causes a modest rainstorm that exceeds the local threshold value to have the same quick flow-precipitation ratio as during a larger event. Rainfall events that do not contribute enough water to exceed the local storage capacity might not contribute any quick flow. Consequently, differences in runoff between a small and modest rainstorm during equal antecedent moisture conditions can be significant, causing a temporary stream to be either active or inactive. This can result in a threshold relation between precipitation and streamflow (see fig. 8B).

Contraction of a stream network occurs either in a top-down pattern or disintegration pattern. As the catchment gets drier, soil moisture decreases and the water level drops. The stream head will move downwards on the hillside, causing a top-down contraction according to the VSA concept (Hewlett and Hibbert 1967). In the heterogeneous landscape, the capacity of the local storage areas is no longer exceeded and the stream stops flowing in a disintegrated manner as the pools disconnect. The flow duration depends on the capacity of the storage areas to store, contribute and transmit water (Spence and Woo 2007; Buttle 2006; Bhamjee and Lindsay 2011).

It is important to distinguish between seasonal and event-based changes in stream network expansion, contraction and connection (Ambroise 2004). Some streams in a watershed can for example expand in a disjointed pattern during an event, while the whole catchment might expand from the bottom-up seen during the fall wetting up period. Mapping only some streams in a catchment can therefore provide a misleading result of changes in the stream network over the whole watershed. Investigating and comparing temporal stream connections and water storage across catchments during various seasons in different climates and landscapes could provide information for a catchment classification system (Spence et al. 2010; McDonnell and Woods 2004; Boon et al. 2012). This could help our understanding of the anthropogenic and natural changes in temporary stream responses and runoff (Buttle 2006) and may even be used for water management (Wigington et al. 2005; Bracken et al. 2013).

1.1.3 Active and connected streams

Active streams are those that contain observable flowing water. The connected stream network of a catchment is, in this study, defined as all the active streams which have a direct surface flow to the outlet of the basin (Ambroise 2004). A stream that drains a wetland or hillslope in the upper part of the catchment can for example end up in a wetland below. If this wetland still has an unfilled storage capacity the channel draining this area is dry and the stream above it does not transmit and therefore does not contribute to the outlet of the catchment. However, during wetter periods, the lower wetland might become fully saturated and upper parts of the catchment connected with the outlet at the bottom, at this time is the stream defined as connected (see fig. 6 for an example).

Spence et al. (2010) found a hysteretic relationship between storage and streamflow by examining the distribution and influence of storage areas in a heterogeneous catchment. They state that runoff production in the catchment is controlled by the location of the storage and how the water can access and leave the outlet. Connectivity between active areas is thus an important, but difficult to measure, factor for catchment response. Spence et al. (2010) therefore call out techniques to measure and quantify the processes and patterns of the connectivity at catchment scale.

Subsurface connectivity, similarly, affects hillside flow production. Tromp-van Meerveld and McDonnell (2006) presented the “fill and spill” hypothesis of subsurface stormflow production. By analysing stormflow production from 147 storms, they showed that the response followed a threshold-dependent pattern as a result of bedrock micro-topography. Local bedrock depressions can be seen as storage elements, which are filled until spilling (see fig. 8A). When this flux is connected to the outlet, a large increase in stormflow can be observed. Shallow soils which have a lower threshold, since saturation is reached faster, respond to smaller storms than deeper soils with a higher threshold. Soil and bedrock variations along the hillslope thus cause various patterns in subsurface connection expansion, similar to what has been observed for temporary streams (see fig. 8).

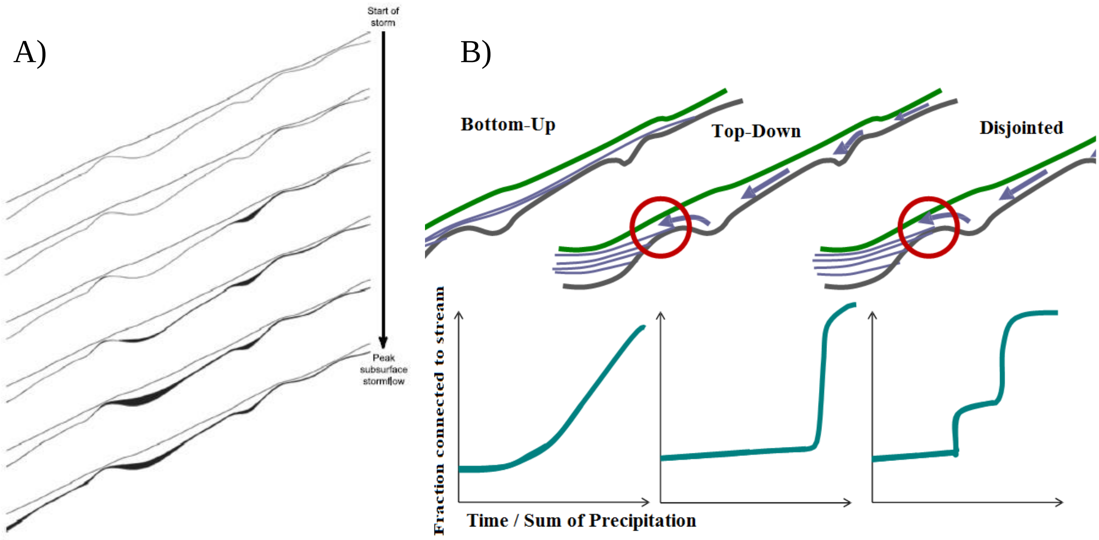


Figure 8. *The fill and spill hypothesis for subsurface stormflow production (from Tromp-van Meerveld and Mcdonnell 2006). A) Schematic representation of the fill and spill process. The shaded areas represent the locations of subsurface saturation. The upper parts of the figure are at the start of the storm and the lowest during the peak. B) Various patterns of subsurface stream connection. Bottom-up reflects the situation of the VSA concept when subsurface stormflow is connected from the lower parts upwards. Top-down patterns occur when bedrock depressions and soils are shallower in the upper hillslope than the lower hillslope create a threshold-like stormflow response, according to the fill and spill hypothesis. The disjointed pattern can be seen as a combination of the two. The graphs show the fraction connected streams with increasing precipitation input.*

Obviously, the connected length varies depending on which processes and functions are included in the definition of "connected". According to Bracken et al. (2013), there has been a confusion regarding the term hydrological connectivity between scientists, leading to different ways of measuring and interpreting connectivity. Water that flows through pipes or macro pores would for example not be an available path for certain organisms, however it still connects energy and matter (Pringle 2003). Ali and Roy (2009) summarize from previous studies that comparing and extrapolating connectivity between catchments seems to be misleading since the processes are different. Bracken et al. (2013) classified previous studies on hydrological connectivity in five themes (soil moisture, flow processes, terrain, models and indices) and call out for a better understanding of the controlling processes.

1.1.4 Ecological and biogeochemical status

The expansion, contraction and connection of a stream network affects the ecology and biogeochemistry of the headwater stream (Godsey and Kirchner 2014). According to Meyer et al. (2007), headwater streams provide habitat for a range of permanent and migrant unique species, such as fishes, invertebrates, insects, algae, bryophytes, fungi, amphibians, birds and plants (more information in Meyer et al. 2007), of which many only can be found in the temporary stream network. These species have solely adapted to the unique habitats in each specific headwater. There dry stream beds are threatened by anthropogenic (e.g. urbanization, logging, mining, agriculture and hydrological alterations) and natural (e.g. climate changes) changes (Larned et al. 2010; Acuña et al. 2014; Buttle et al. 2012). The movement of migrants causes the effects of changes in headwaters to propagate further down the system and can therefore affect downstream riparian ecosystems and whole river systems (Meyer et al. (2007).

Wigington et al. (2005) showed that nonpoint-source pollution, such as nitrate-nitrogen in an agricultural landscape, was larger during winter than summer. They suggest that this could be caused by the higher portions of LCLU (Land Cover – Land Use) in the temporal stream network than in the perennial network. When the stream network expands during a hydrological event, water can bypass riparian buffers downstream, which limits their function and allows pollutants to enter the perennial network. Stream network expansion is therefore a controlling factor for nutrients transport from agricultural fields to perennial streams, and it is thought that this effect expands in catchments with low relief and poorly drained soil. Wigington et al. (2007) conclude that prediction of the extent and influence of stream network expansion is needed, particularly further research on the influence of soil drainage classes and topography is needed.

1.1.5 Mapping and monitoring temporary streams

When it comes to mapping and monitoring the stream network of a headwater catchment, there is a trade-off between the densities of sensors within the study watershed (spatially) and how often the stream can be monitored (temporally). Most studies on ephermal stream mapping and monitoring have used a flow or no flow classification, but with different spatiotemporal resolutions (Bhajmee and Lindsay 2011).

Godsey and Kirchner (2014) mapped four mountainous Californian headwater streams of different topography, geology and climate during four field campaigns in different seasons by walking the total stream length each time. The disadvantages of mapping by hand (also known as direct observation) are mainly the logistical difficulties, especially in steep terrain (Godsey and Kirchner 2014), and that it does not provide high spatiotemporal resolution data. Patterns of expansion and contraction during and following a rainfall event are difficult to observe because of the limitations in gathering data (Bhajmee and Lindsay 2011). Examples of earlier studies on stream network dynamic with direct observation are Day (1980) and Blyth and Rodda (1973). For example, Day (1980) investigated stream network expansion in six catchments during rainfall events by observing the active stream length with pegs placed every tenth of a metre along the stream bed. However, it remained difficult to determine the active length during storm events.

Bhajmee and Lindsay (2011) summarize different available monitoring techniques for ephermal streams. Except from direct observations and ER-sensors, which are described in more detail below, current meters, pressure transducers, optical and acoustic sensors, floats and temperature sensors are examined. The first three give the possibility to obtain information on the discharge, however current meters and pressure transducers are associated with high costs as well as being sensitive to erosion and debris. Obtaining with high tempo-spatial resolution with these techniques is therefore difficult. Attaching floats to ephermal streams can help to determine the maximum distance flow during a time period but as it is not possible to tell when this flow occurred, the temporal resolution is poor. Temperature sensors below the stream bed can provide data of when water occurred and not. This data is, however, associated with a high degree of errors since the sensors are sensitive to sudden changes in air-temperatures (for more information see Bhajmee and Lindsay 2011).

Goulsbra et al. (2014) successfully used electrical resistance (ER) sensor to monitor the absence or presence of water in an ephermal channel network in a UK peatland catchment.

With around 40 sensors, they monitored different streams during two different periods (in total around four months). The expansion and contraction occurred in similar disjointed patterns between different events, with the water table as a key factor. They suggest that localized spatial controls related to the local water table, such as "drainage area, local dissection, channel slope and gully morphology", are important for flow generation where saturation overland flow is the main mechanism for runoff.

Peirce and Lindsay (2014) monitored three ephermal streams in a headwater catchment in Canada with single and stacked ER sensors. They consider ER sensors as a potential effective and inexpensive way to monitor flow in ephermal channels. The limitations in the method are first of all the inability to distinguish between flowing and standing water and secondly the limited sensitivity during freezing temperatures. Peirce and Lindsay (2014) showed that despite the streams being in the same subwatershed, different factors controls led the expansions and contraction of the flowing network. This indicates that the prediction of ephermal streamflow might be more complex than assumed in previous studies. Water table depth, which was found important in other studies (Goulsbra et al. 2014), was not a primary control on the occurrence of water in the stream in this study. The expansion and contraction of the stream was best described as incomplete coalescence.

1.2 TERRAIN FEATURES, ATTRIBUTES AND INDICES

In hydrological models indices are used to characterize the terrain of the study catchment. In this study, drainage density, upslope accumulated area and the topographic wetness index were used to investigate the topographic controls on streamflow in temporary streams.

1.2.1 Digital Elevation Models (DEM) derived from Lidar-data

A Digital Elevation Model (DEM) is a *model* of the continuous surface elevation. This model not is an exact representation of the real landscape. In a gridded DEM, the elevation (z) is represented in equally distributed two-dimensional cells (x and y), which size determines the resolution (O'Callaghan and Mark 1984; Tarboton 1997; Zhou and Liu 2002). Errors are found in both the sampling method and in the method used to derive attributes (Zhou and Liu 2002). These errors can be propagated in hydrological studies if not taking in account for.

Ground surveys, air-photos and laser altimetry can be used to obtain data for a DEM. The use of Lidar (also known as light detection and ranging) in the early-90s and the technique significantly improved in accuracy over the years. The method is based on airborne laser scanning of the landscape. Laser signals are transmitted toward the surface and the reflections are collected in order to predict the vertical position of both the vegetation and the ground-surface, from the elapsed time (Ritchie 1996; Ackermann 1999; Wehr and Lohr 1999; see fig. 9). The spatial position is corrected with a stationary GPS station somewhere on the ground. The first returning signals represent the vegetation, and the last the ground. By interpolation of the obtained data, a digital model of the continuous terrain elevation can be created. Data collection and interpolation both contain errors and uncertainties. Estimating these errors and uncertainties is outside the scope of this thesis.

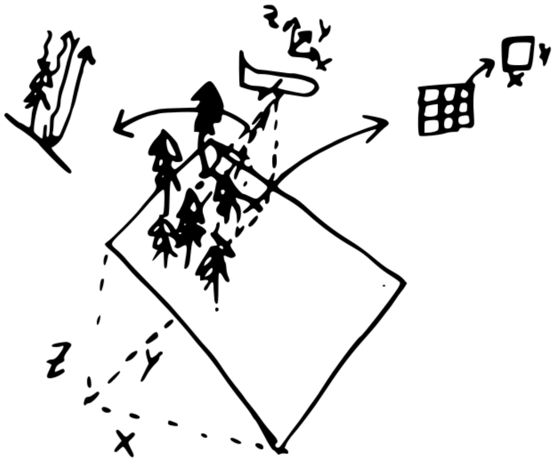


Figure 9. *Sketch showing the airborne Lidar procedure. From the airplane, laser signals are send toward the ground. The first returning signals represent the vegetation and the last the ground surface. The spatial position is corrected with a GPS station somewhere on the ground. The obtained data can then be interpolated and gridded to a DEM.*

The resolution of a gridded DEM has a major impact on the features that can extracted from it. While high resolution DEMs, such as one to five metres, are computational exhausting, a resampling to coarser DEMs can cause less accurate results (Vaze et al. 2010). Several previous studies have shown how the resolution impacts the hydrological features and indices. Vaze et al. (2010) argue that it is important to be careful when using terrain indices derived from DEMs and that higher resolutions are preferred over coarser ones. High-resolution DEMs are however not always the best choice. In studies which are less dependent on small-scale topography, such as ground water studies, a coarser resolution can be more useful (Seibert and Sörensen 2007).

1.2.2 Flow routing

There are several methods to derive attributes and indices from DEMs, with various results. The methods are commonly based on a flow routing algorithm, in which the flow direction within and between each cell of the DEM is computed (Tarboton 1997). The distribution of flow can either be modelled as a gathered flow to a single cell, e.g. the D8-algorithm (O'Callaghan and Mark 1984) or by partitioning it between multiple cells, e.g. the FMFD-algorithm (Freeman 1991; see fig. 10). Since the calculated upslope area depends on how this distribution of flow occurs, it is important to investigate how the method is working and if the results are reliable.

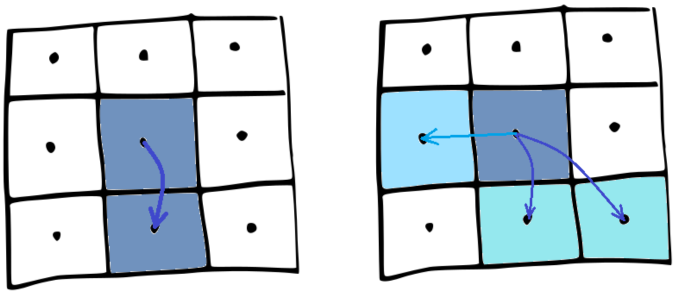


Figure 10. *Sketch of single and a multiple flow routing algorithms. In single routing, flow from the mid-cell is transmitted towards one neighbouring cell. In the multiple flow routing, the flow is divided between different neighbouring cells.*

Eskrine et al. (2006) compared modelled upslope areas from DEMs with various resolutions and flow routing methods. They found that the choice of method was most important when using a high resolution DEM and found that the multiple flow routing algorithm was less sensitive than the single flow routing algorithm. Zhou and Liu (2002) found similar results and show that the multiple flow algorithms had a good accuracy and the single routing algorithms produced unacceptably large errors. Sinks in the landscape are a main cause for errors in flow routing algorithms. A method to deal with this problem is to raise the elevation of the sink until it is filled (O'Callaghan and Mark 1984).

1.2.3 Drainage density (D_d)

The Drainage density of a catchment, first described by Horton (1932), is the total stream length per unit area:

$$D_d = \frac{\Sigma L}{A} \quad (1)$$

Where D_d is the drainage density (m/m^2), L the stream length (m) and A the catchment area (m^2). In this study, the active drainage density is defined as the active stream length per unit area and thus describes the flowing proportion of the streams. The drainage density is a simple way of describing how well a basin is drained. Horton (1945) describes the importance of accounting for both perennial, intermittent and ephermal streams when calculating D_d. From a topographic map, only using the perennial stream network would cause an underestimation in areas with a lot of intermittent streams. Gregory and Walling (1968) investigated how well topographic maps covered the intermittent stream network. They showed that because drainage density varies within one catchment due to wetness conditions, it could only be compared between basins when derived using the same methods and for similar specific hydrological conditions. The stream network shown on British topographic maps usually represents low flow conditions.

Several previous studies have shown the increase and decrease in drainage density within catchments (e.g. Gregory and Walling 1968; Blyth and Rodda 1973; Robert and Archibold 1978; Day 1978; Day 1980; Wigington et al. 2005; Godsey and Kirchner 2014; Goulsbra et al. 2014). For example, Godsey and Kirchner (2014) found that the active stream length in four streams decreased by a factor of two to three during flow recession. A decrease of up to two Strahler orders was detected as well, indicating that the Strahler order of a stream network is not a fixed element. Stream network characteristics such as the total active length and the number of flowing stream heads could be described by a

Power-law function of discharge. Variations in the active drainage density from some selected previous studies are shown in table 1.

Table 1. *Variation in active drainage density described in selected previous studies. The β-values are the scaling factors for active drainage density as a function of discharge (mm/d) (log-log scale) from Godsey and Kirchner (2014)*

Authors, source and location	Duration of study	Active Drainage Density (km/km^2)	Scaling factor (β)
Gregory and Walling (1978) England	One year	0.8 – 3.5 0.9 – 6.5	0.29 – 0.43
Blyth and Rodda (1973) England	Apr – Dec	0.55 – 2.7	0.10 – 0.27
Robert and Archibold (1978) British Columbia	Feb – Apr Nov – Mar	6.5 – 16	0.02 – 0.20
Day (1978) Australia	One year	0 – 3.45 0.05 – 5.16 0.11 – 1.85 0.10 – 7.50 1.95 – 7.66 9.11 – 16.66	0.04 – 0.37
Wigington et al. (2005) Oregon	Jul – Sep Feb	0.24 – 8.00 0.63 – 4.67 0.42 – 3.29 0.54 – 2.90 0.66 – 3.23	-
Godsey and Kirchner (2014) California	2006 - 2008	0.56 – 1.29 0.61 – 1.95 1.88 – 3.91 0.50 – 0.99	0.27 – 0.56
Goulsbra et al. (2014) UK	Autumn and Summer	1.40 – 30.0	-

1.2.4 Upslope accumulated area (A)

The upslope accumulated area A, also known as contributing area, upslope area, source area or flow accumulation, for a specific point in the landscape is the area that has a potential to generate discharge to the position (see fig. 11).

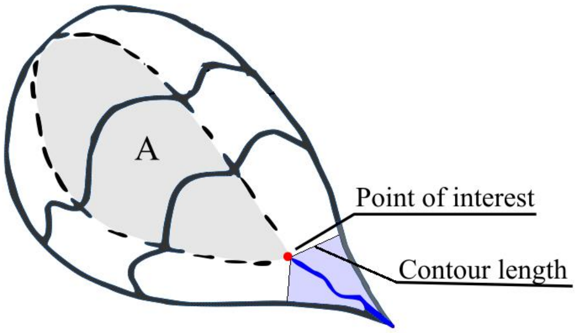


Figure 11. *Sketch of the upslope accumulating area A to the point of interest. L is the contour length below the point of interest.*

The upslope accumulated area is estimated from digital elevation models and has according to Erskine et al. (2006) been used to derive terrain attributes to model stream networks, soil moisture distributions and saturation, landslides and soil erosion. If the point of interest is the stream head, the upslope area will change as the stream expands or contracts (see fig. 12). Montgomery and Dietrich (1988) showed that the upslope accumulated area of flowing channel heads in a humid-temperate climate decreased with an increase in local slope, which would mean that the initiation of flow is controlled by erosion.

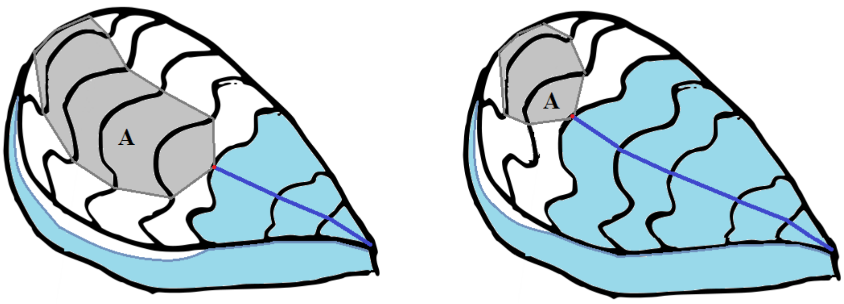


Figure 12. *Sketch of the upslope accumulating area A related to the initiation of the stream before (left) and after a rainfall or snowmelt event (right). Notice how A decreases as the stream expands.*

1.2.5 Topographic Wetness Index (TWI)

Anderson and Burt (1978) showed that interflow from a hillslope is correlated with maximum saturation. This suggests that topography, particularly in areas with shallow soils, is an important control of groundwater level and soil saturation and consequently the stream discharge. Topography is therefore often included in runoff response models. As a part of the runoff model TOPMODEL Beven and Kirkby (1979) introduced a simple hydrological model, in which the upslope accumulated area (A) per unit contour length (L), here referred to as *a* (m), is divided with the local slope angle, tan*b* (°), called the Topographic Wetness Index (TWI):

$$TWI = \frac{a}{tanb} \quad (2)$$

The assumptions when using the TWI in models are that the whole accumulating area provides groundwater to the site and that the local slope angle represents the local hydraulic gradient. These assumptions, also known as the TWI-assumptions, are more or less valid depending on local variations in catchment characteristics (e.g. soil properties and surface topology) and temporal differences in flow (Rinderer et al. 2014). Previous studies have shown that the TWI-assumptions hold in generally wet areas with shallow soils (Anderson and Burt 1978; Troch et al. 1993; Rinderer et al. 2014) when the changes in groundwater level are slow (Rinderer et al. 2014). The TWI reflects the topographic influence on hydrological behaviour, as groundwater level.

1.3 AIM OF STUDY

There is a call out for better understanding off the processes that control the dynamics of flowing stream networks (e.g. Godsey and Kirchner 2014). Instead of trying to predict the hydrological response as a function of the expanding stream network (which was the focus during the 1960s-1970s), this study aims to develop practical methods to predict the active stream length as a result of hydrological conditions.

The ultimate goal of the research is to gain a better understanding of the temporary stream network and the processes that control it and determine how the active and connected stream length change with catchment wetness conditions to find simple methods to map seasonal and event-based changes in temporary flowing stream networks in steep and remote catchments.

1.3.1 Hypotheses

1. Increasing wetness conditions (represented by increasing discharge) leads to an increase in active drainage density and connected drainage density
2. Streams in the Alptal show a bottom up connection pattern
3. Topography, particularly TWI and A, determines which sections of the stream are flowing
4. The location of the stream heads can be predicted by topography, particularly TWI and A

1.3.2 Objectives

1. Create maps of flowing stream sections of the temporary stream network in the Alptal catchment during different weather and wetness conditions and to relate these changes to the surface topography and wetness
2. Develop practical methods to map active stream length in steep terrain to provide recommendations for future studies
3. Determine how the active and connected stream length change with catchment wetness conditions
4. Analyze the variation in the starting points of streamflow in temporary streams

2. METHODS AND STUDY AREA

In order to test the hypotheses and to learn more about temporary streams, extensive field work was conducted. Streams, springs and wetlands of four relatively small headwater catchments and one wetland in the Zwäckentobel catchment in Alptal, canton Schwyz (Switzerland), were mapped and classified during different weather conditions.

2.1. ZWÄCKENTOBEL – STUDY AREA

The Zwäckentobel in the pre alpine mountainous headwater valley of Alptal (SZ), 40 km south of Zürich (Switzerland) (see fig. 13). Between 1967 and 1978, the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) installed several hydrological and meteorological measuring stations, including a robust runoff station at the bottom of the Erlenbach. This station is still operational and provides long-term data of runoff and water quality. Also the University of Zurich has done research in the area. For example, Rinderer et al. (2014) analysed topographic controls on shallow groundwater levels using data from 51 groundwater wells, placed in areas with various topographic characteristics. They also installed several V-notches and HS-flumes to measure streamflow. They found that on a steep hillside with low permeable soils catchment, groundwater is related to topographic indices as TWI and A.

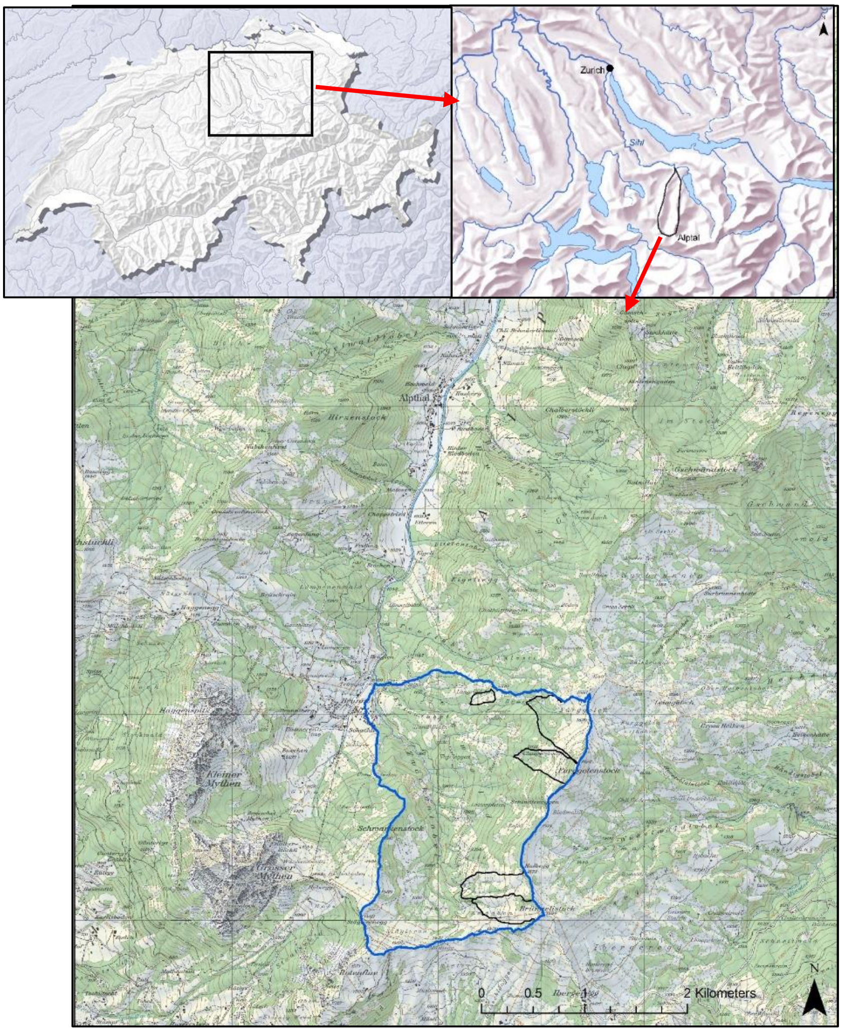


Figure 13. *Map of the Zwäckentobel catchment (blue lines), and the specific headwater catchments mapped during this study (in black), in Switzerland.*

The hillsides of the Zwäckentobel, which range from 1000 to 1600 metres in altitude, are concealed with a mix of spruce forest (mainly Norway spruce (Schleppi et al. 1998), meadows and wetlands (Fischer et al. 2015). The vegetation is related to topography, with forest on convex and steep areas, grass on flatter parts and wetlands in the concave areas. The topography, first created by landslides, forms a terrace-like profile with altering accumulating and draining stages. The upper and also more open part of the headwater is used as pasture or a ski-slope, depending on the season. The lower parts are generally covered with forest or old harvested areas. The region is part of the wilderness protection reserve of Ibergeregg (SZ).

The bedrock in the Zwäckentobel consists of poorly permeable tertiary flysch (sedimentary rock) formations with different calcareous sedimentary layers of schist, marl and sandstone (Fischer et al. 2015). The soil is a shallow umbric gleysol 0.5m deep at ridges and 2.5m deep in wetlands (Rinderer et al. 2014; see fig. 14). This gleysol consists of a silt- and clay-rich bottom layer and a rich upper layer. In the wetlands, this topsoil is fully consistent of muck humus, while in the forested areas also a drier mor humus exists (Schleppi et al. 1998; Feyen et al. 1996; Fischer et al. 2015).

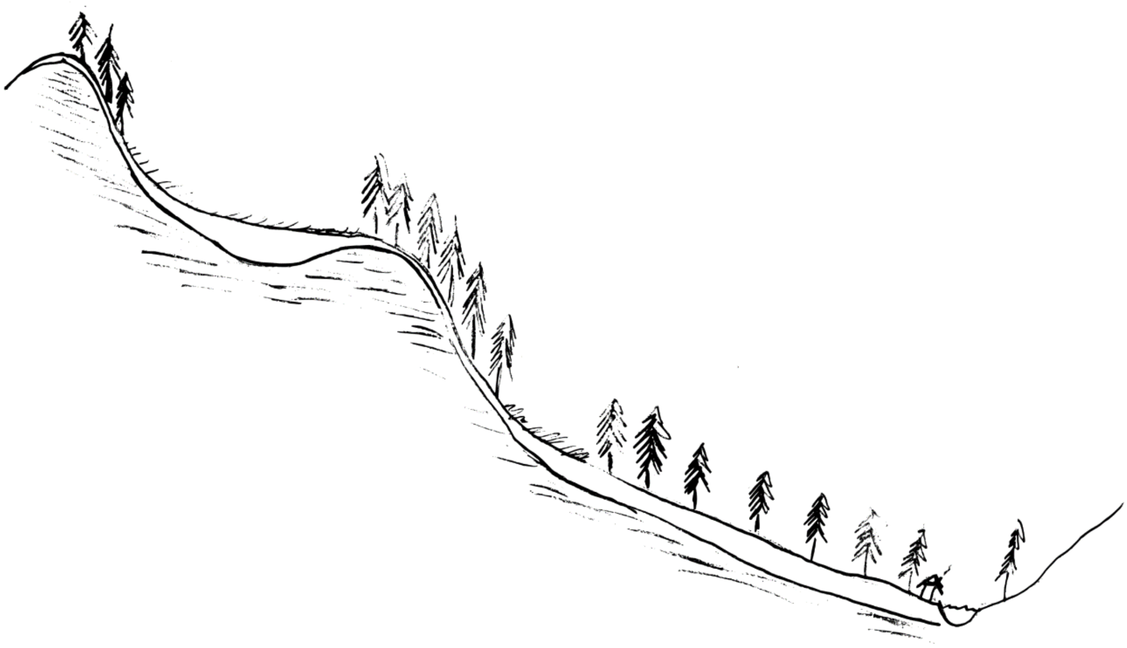


Figure 14. *Sketch of the hillside profile of the Zwäckentobel, from the top at Furgelenstock down to the perennial river. The ground consists of a less-permeable Flysch geology with a gleysol soil. Notice how this soil is shallow at the steep forested slopes and thicker in the more flat wetlands. The thickness of the soil has an important effect on the temporary stream network.*

The climate is humid-temperate with generally low mean temperatures (annual mean 6 ºC), that vary between -2ºC in February to 18ºC in August (humid-temperate climate). The mean annual precipitation is high (2300 mm/year) and much higher than the average of Switzerland (1500 mm/year). The mean monthly distribution of rainfall ranges from 135 mm in October to 270 mm in June. Almost one third of the precipitation annually drops as snow (Stähli and Gustafsson 2001). Rainfall occurs approximately every second day. The combination of the high annual precipitation, the low mean temperatures and the poorly permeable flysch bedrock and soil result in shallow groundwater levels. Stream responses are rapid with a high peak discharge (Fischer et al. 2015). Shallow subsurface flow in highly conductive layers and/or surface flow are expected to be important flow components during rain or snowmelt events (Rinderer et al. 2014). Erosional processes, such as landslides and soil creeping is very common and studied by WSL (Burch 1994).

After advice from Benjamin Fischer (PhD student H2K, University of Zurich), who has extensive field experience in the Zwäckentobel catchment, and field surveys four minor headwater catchments and a wetland area were selected for the field study (see fig. 15). The four headwater catchments are all located upslope from the perennial stream network near the ridge and are a mixture of forest, wetlands and meadows.

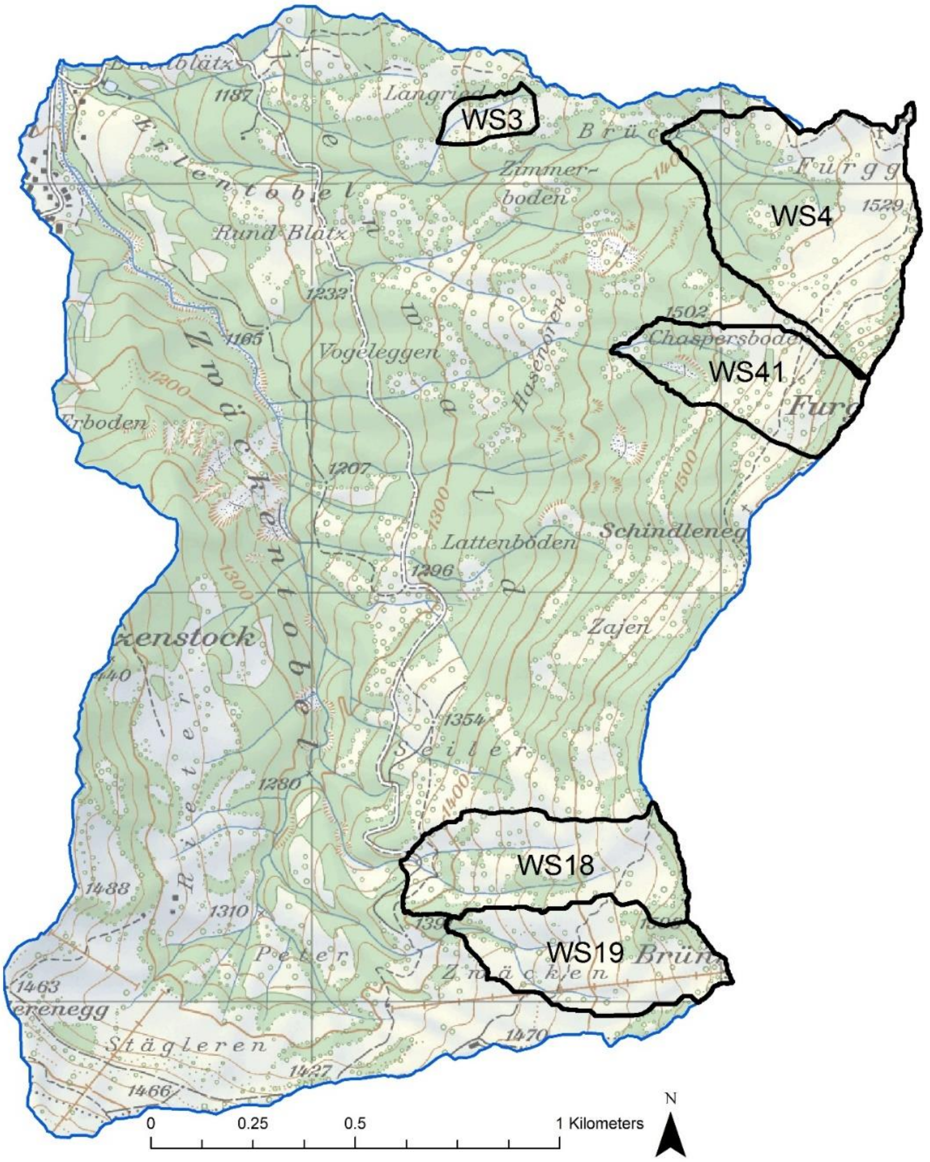


Figure 15. *Map over the Zwäckentobel catchment and the five subcatchments of this study. For the location in Switzerland see* fig. 13*.*

Table 2 and fig. 16 show the characteristics of the subcatchments in terms of area, land-use and topographic properties. The land-use layers are based on the work by Fischer et al. (2015) who derived the proportions of forest, meadow and half-open meadow using air-photos and field surveys. The term wetlands is based on a federal survey of flachmoor (peatland) which is a type of wetland of national importance (Swiss federal office environment, Bern). Shallow-soils (<1 m) were delineated at places where the slope exceeded 20º and checked with a hand auger in the field by Fischer et al. (2015). The topographic properties (altitude and slope) were derived from a Lidar-based DEM using the open-source software SagaGIS. The area of each subcatchment was initially based on a catchment calculation in ArcGIS. These catchment boundaries did however not represent the reality in all situations because some streams flowed from one catchment into the next and therefore the boundaries were updated in the field.

The two most southern catchments, here referred to as WS18 and WS19, are located in an area used for ski-slopes during the winter and are therefore generally more open than the two northern catchments, here referred to as WS4 and WS41. All four catchments contain steeper and flatter parts, but the gradient is generally more uniform in the southern catchments than in the northern catchments, in which steep landslide-affected hillsides exist. All of the catchments contain both natural and artificial streams and channels.

The wetland area, here referred to as WS3, is located downslope of WS4 and is an artificially drained old harvested area. Since most of the draining age system is not natural, WS3 was expected to respond to rainfall differently than the other catchments. WS3 is not really a full catchment because that the main stream continues above the catchment boundaries. The purpose of this subcatchment was therefore to compare the pattern with the other catchments. It also differs from the rest of the areas because it doesn’t have a perennial stream. Instead a main channel, with straight connected tributaries, drains the area after rain or snow-melt inputs. WS3 is almost fully open with only a small forested part north and south of its boundaries. The slope is almost the same throughout the catchment.

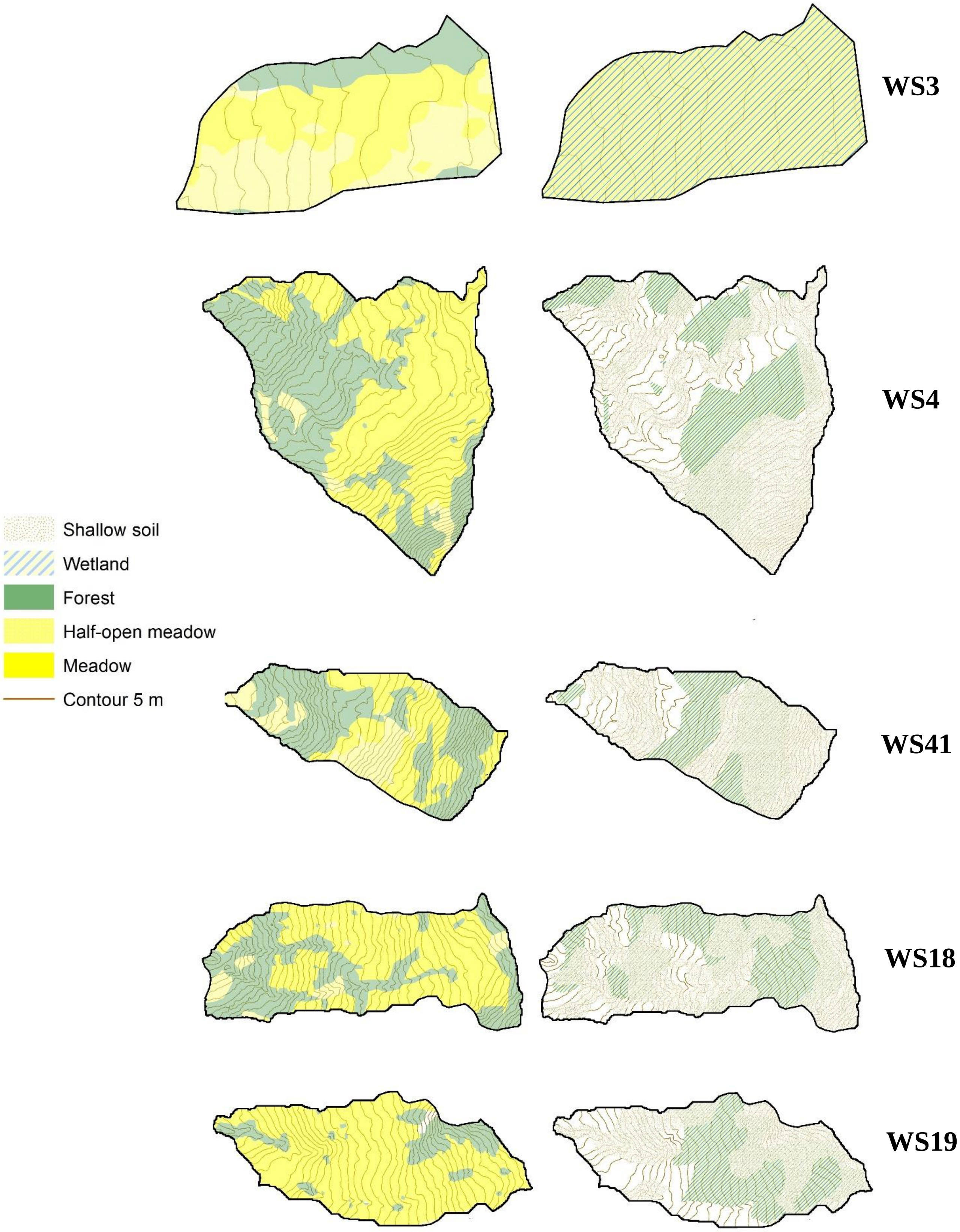


Figure 16. *Maps of land-use (left) and wetlands and shallow soils (right), for each subcatchment used in the study. Notice that the scale between WS3 differs from the other catchments. White on the land-use maps means no-data. See figure 15 for Scale and orientation.*

Table 2. *Characteristics of the five different subcatchments for the field study and the number of field campaigns in each catchment. The topographic data is derived from a 2x2m DEM created from Lidar-data and the land-use from recent field work in the area (Ficher et al. 2015). The area of each catchment was based on the DEM and updated throughout the field work*

		Catchment				
		WS3	WS4	WS18	WS19	WS41
Area	km^2	0.02	0.25	0.15	0.13	0.12
	ha	2.3	25.3	15.0	13.4	11.7
	Forest	17	42	37	16	51
Land use	Half-open meadow	40	4	8	0	17
(%)	Meadow	43	54	55	84	32
	Wetland	100	36	55	53	46
Shallow soil (<1m, %)		0	53	57	47	63
	Min	1277	1382	1357	1406	1421
Altitude	Mean	1309	1501	1475	1504	1533
(m)	Max	1331	1656	1599	1599	1656
	Range	53	274	241	193	235
Slope	Max	37.6	61.9	60.4	61.4	65.7
(°)	Mean	12.4	18.4	20.1	18.6	22.2
Field campaigns	n	5	5	5	5	6

2.2. FIELD WORK

The fieldwork to map the streams was initiated at the end of august 2015. The mapping was based on a stream network map created in the commercial software ArcGIS. The modelled stream network was derived from a D8-flow routing algorithm, based on a 2x2m DEM-raster created from Lidar-data. The choice of flow routing algorithm was based on the best fit with the results from a field survey where a small stream network was mapped. In order to detect first and second order streams that were not represented correctly by the flow-routing model, the map was combined with an air-photo from the area. The mapping was performed by an elite orienteer with experience in cartography.

2.2.1. Flow-type classification system

During a field survey, before the actual mapping started, a classification system for different stream flow types was created (see table 3). In Zwäckentobel there is no clear black and white difference between dry and fully flowing streams but there is rather a grey-scale between the two extremes. Some areas have standing water or water is dripping. The purpose of the different classes was to be able to represent these types of flow and their properties in a simple manner and to see if they responded differently to various inputs. The flow was not measured, but estimated.

Table 3. *Classification of stream flow types used during the field work*

Type	Estimated flow (≈l/min)
Dry (D)	0
Standing Water (S)	0
Weakly Trickling (WT)	<1
Trickling (T)	1-2
Weakly Flowing (WF)	2-5
Flowing (F)	>5

2.2.2. Field mapping

During the field survey the mapping with a field-GPS device, with a measurement error of ±8m, was compared with the "manual" observational mapping with compass and pen. Because the large number of stream segments in each catchment, the latter method was used for the remainders of the field work. Some stream segments were as small as two metres, so a measurement error of up to 8 m was not accurate enough. Mapping by observations was preferred both for its simplicity and for its more accurate result when used right, mapping or classifying incorrectly risks a propagation of errors throughout the hydrological study.

The first mapping was done during very dry conditions the 30th and 31th August (year 2015). The streamflow during these two days was very limited. Where flow was occurring it occasionally infiltrated in the bottom of the channel or flowed through the channel bed and reappeared further down, sometimes five to ten times within only a couple of meters stream length. Because of the difficulties in mapping this repeated behaviour, only areas where flow obviously disappeared in the subsurface, with no surface flow present, for at least 2 m were marked on the map. If the flow reappeared in less than 2 m, it was drawn as continuous flow. Each time the flow type changed it was marked on the map and the distance between each marking was mapped as a stream segment. In order to map these segments in their correct spatial location it was important to compare the direction of the stream, its altitude position (relative to the elevational contours on the map) and the length to other features on the map, such as the location of distinct trees or wetlands.

Since WS18, WS19 and WS3 are mainly open an air-photo, the modelled stream network, 1 m elevation contours and a compass were enough for navigation (see fig. 17). For the large forested parts in WS4 and WS41 the air-photo was of no use. Navigation in these areas was instead based on the use of land-use polygons and elevation contours (see fig.18).

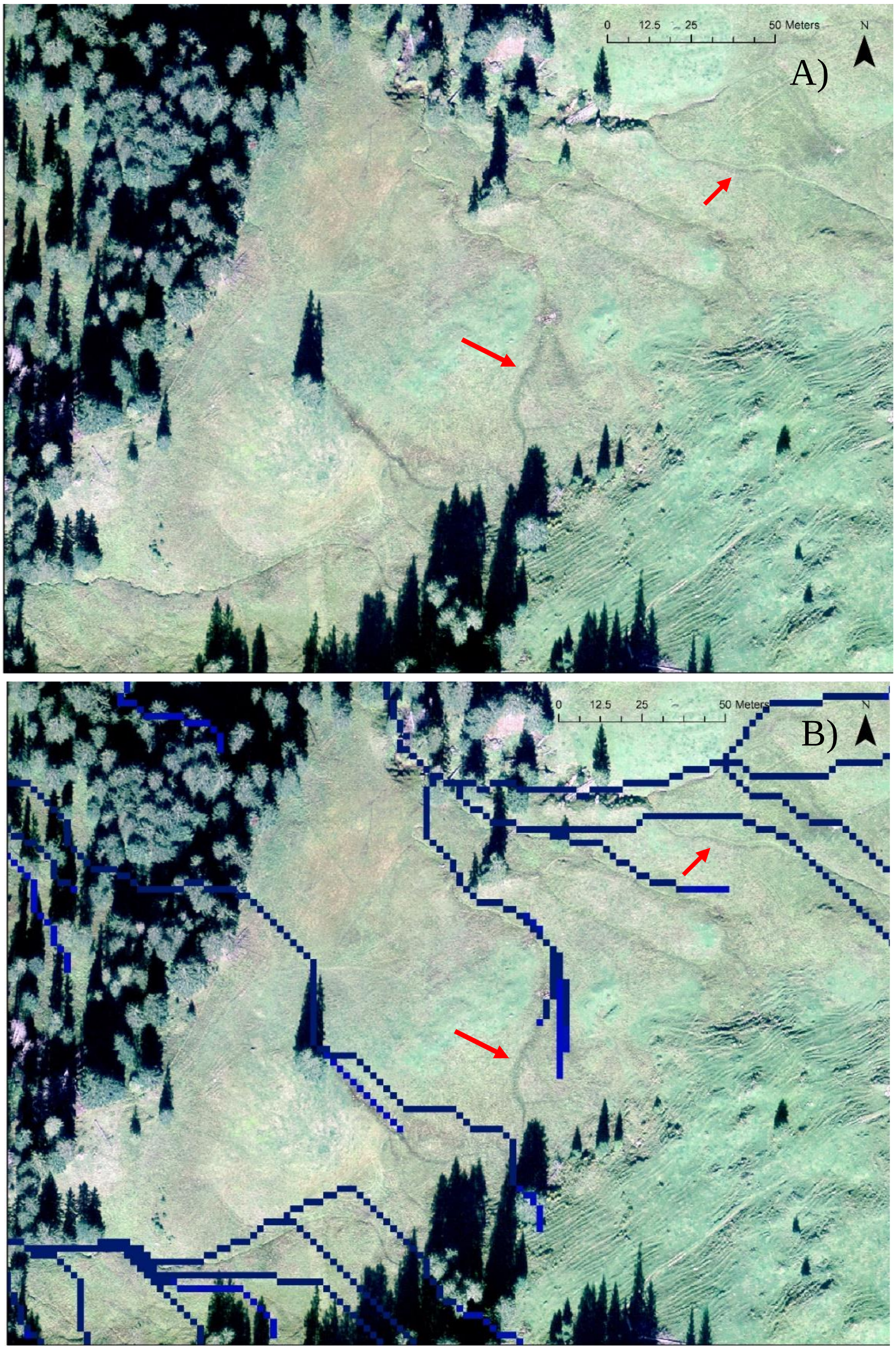


Figure 17. *Example of a map used for the mapping of the temporary stream network in the upper parts of WS4. The 1 m elevation contours is not shown in this example. A) Air-photo without flow routing model. Many streams are visible by either a darker colour or by a distinct channel bed. B) Air-photo with the flow-routing (in blue) which was used for the mapping. The modelled stream network covers many of the streams that were visible*

from the air-photo, but far from all. Also many modelled streams either did not exist or were located wrong (red arrows).

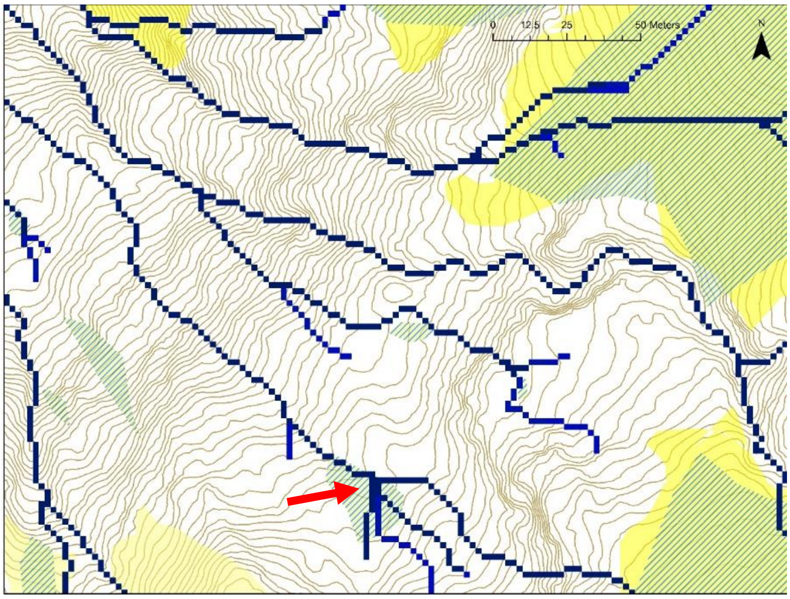


Figure 18. *Map used for the mapping of a forested part (in white) in WS4, with 1 m contour lines. The blue lines are derived from the flow routing model and not the actual mapped stream network. The model generally did well in the steep parts where most of the flow occurred in deep channels, but the accuracy in flat areas was not satisfying (see the red arrow for an example). The blue-yellow raster are the wetland polygons from the land-use layer.*

The resulting stream segments were drawn in ArcGIS as polylines, based on the field-map and assigned the flow category. During the second and third field campaigns, the original map was checked and updated at obvious false positions in order to minimize error propagations. As the conditions were very dry during the first field visits, some streams were not noticed. These were later added to the original map as dry streams. Also the shape and the position of the streams were updated but not the assigned the flow class. Errors in the stream mapping mainly occurred in flat wet areas or steep slopes where overland flow could occur. When Horton overland flow occurred, it was drawn on the map as a single stream, even though in reality it appeared more as a sheet. At some areas also high vegetation made the mapping difficult because it covered the streams.

To cover as large of an area as possible during the field work days, it was found that a mapping route for each catchment did not only facilitate the task but also minimized the risk that some streams not were mapped (see fig. 19A). The mapping route could not be strictly followed in reality (as in fig. 19B). The idea was to follow a zigzag pattern from the top to the bottom of the catchment, crossing all streams almost perpendicular to the flow direction. If the stream was dry or had standing water, the route was followed according to the plan, however if it was flowing, the stream was followed upwards until the flow ceased (or until reaching an earlier mapped area). Following this mapping pattern had the advantage of not having to climb up and down each stream, which was sometimes hundreds of meters in altitude. It was also found that mapping a stream is much simpler coming from above, since it provides a good overview of where the stream is flowing. Surveying a stream bottom-up is not only more physically challenging but also increases the chances of errors in mapping. It should be mentioned that the mapping route only was followed after the whole area already been mapped and investigated. In this way, the risk that some streams were excluded during the entire field work period was minimized.

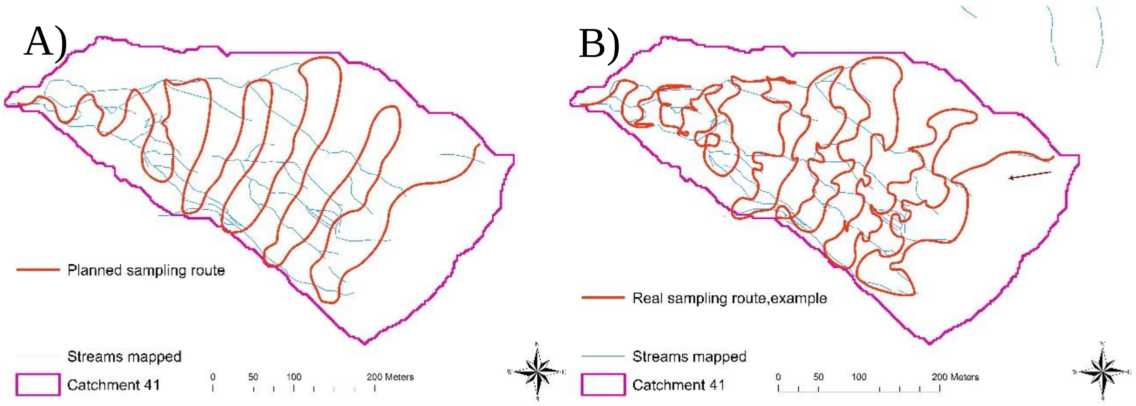


Figure 19. *An example of a fictitious walking route during a field campaign. The stream network was surveyed from the top of the catchment downwards. A) The planned route. B) How the route could have been followed in reality.*

The total number of field campaigns in each study catchment was either five or six (see table 2). During one field day, several catchments could be mapped. The aim was to capture the flowing stream network during a wide spectrum of hydrological conditions. Figure 20 shows the discharge and precipitation at the Erlenbach runoff station during the field study period. The red arrows represent the field campaigns. The two first campaigns captured very dry conditions. The streams were also mapped during the three most intense rainfall events, with a maximum precipitation up to 3.5 mm/10 min. In total, 26 field campaigns during 12 field days were conducted. In each catchment, the stream network was captured during both dry conditions and rainfall events.

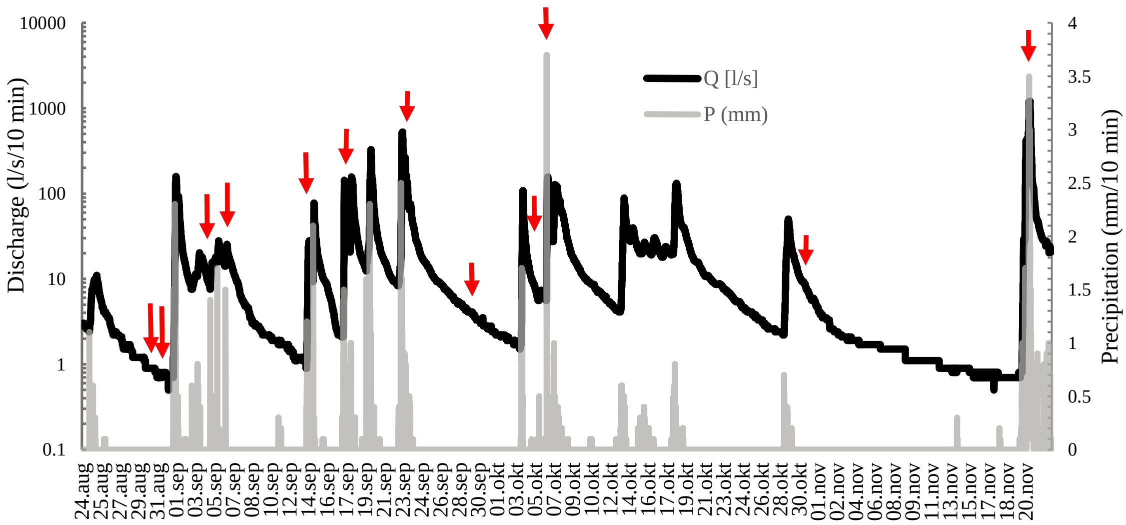


Figure 20. *The discharge (in black) and the precipitation (in grey) at the Erlenbach station during the field study. Red arrows show the field campaigns. Notice how the field work successfully captured a wide scale of hydrological conditions. The precipitation on 15th October fell as snow, otherwise all precipitation was rainfall.*

2.2.3. Other mapped features

Springs, wetlands, obvious pipes or macropores, pumping stations and wells that all affected the stream behaviour were also mapped. Trickling flow originating from springs, usually at the foot of a steep slope or below an impermeable landslide area, occurred at many locations in all of the headwater catchments (WS3 excluded), even during dry weather conditions. The spring flow is high in Ca, suggesting that the emerging flow originates from deeper ground water, which has calcareous layers in the ground (Fischer et al. 2015). When this Ca-rich water enters the surface it reacts with the surrounding air and causes a deposit of calcium carbonate, also called tufa. These deposits, white-yellow in colour, gave a good indication of where the springs were located.

Since the spring flow has a different isotopic and hydrochemical composition than the surroundings it is possible to trace it throughout the landscape (Fischer et al. 2015). As the Ca-rich spring water flows downstream it is mixed and diluted but keeps part of its spring-signature. Fischer et al. (2015) found that deep groundwater constitutes most of the upper spring flow and total base-flow in the Zwäckentobel. For future work of the H2K department of Zurich University, water samples and electrical conductivity data were collected and measured in the upper spring zone and in the intermediate and perennial stream network, during both dry and wetter conditions. The water samples will be analysed in a lab environment. However, the results from this analysis were not available for this thesis.

Fischer et al. (2015) found that flow originating from wetlands has a higher amount of DOC and lower Ca-concentration than spring-water and does not significantly contributes to base-flow in Zwäckentobel. Wetland areas acted as a passive unit to base-flow. In order to determine the influence of wetlands, the wetlands that had a direct effect on the flowing properties of the streams were also mapped. Generally these places existed in local low-points and flatter areas in the stream network. Notice that these features differ from the wetlands on the land use map.

At many locations, especially in WS18 and WS19, there was pipe and macro pore flow. This could usually be heard below wetlands in both convex and concave areas. Usually there was no real stream bed at the surface, indicating that surface flow probably rarely occurred at most of these places. There were however also locations where pipe or macro pore flow occurred below a dry or wet channel bottom. Covering all pipes would be a massive work, but places where they obvious existed were marked on the map. Goulsbra et al. (2014) found that pipeflow could affect the flow production in a peatland catchment. They argue that investigating the nature and location of piping could help to explain some of the unaccounted flow. Holden and Burt (2002) showed that pipeflow contributes with around 10% (at occasions even up to 30%) of streamflow in a deep peatland catchment and maintains baseflow during drier periods. According to Holden (2006) pipes increase linearly with age after drainage in blanket peat. This would suggests that “older” channels, that tends to be deeper, could be more affected of piping (Goulsbra et al. 2014). Uchida et al. (2005) found that pipe activation was controlled by thresholds and that the total pipe flow increased with total hillslope runoff, in wet and steep catchments. A further study of pipeflow was beyond the scope for this study.

Two pumping stations in WS4 and two wells in WS4 and WS19, which could affect the streamflow were also mapped. Especially the two pumping stations, which actively drained a grassland for pasture, significantly influenced the amount streamflow. These stream segments were therefore excluded in the analysis.

Mapped streams, wetlands, springs and pumping stations in all catchments are shown in appendix A.

2.2.4. Test of ephermal and intermittent streamflow monitoring

During the field survey, ephermal streams were found in all study catchments. These streams were mostly located in forested parts, on steep slopes with soils with a locally high infiltration capacity. Incoming streamflow in these channels infiltrated in the bottom of the dry bed and reappeared further down the hillside during dry conditions. Typically, these areas were characterized by of landslides, fallen trees and large stones. It was obvious that surface flow in these area could occur, but probably only during larger rainfall events when the surface flow could exceed the infiltration capacity of the soil. The slope of these streams was not only steep, but also rather homogenous, with no signs of local low points where water could accumulate in pools. It was therefore expected that these streams expanded top down, controlled by the increased streamflow from above. To investigate the timing of activation of these ephermal channels, three digital cameras (here referred to as C1, C2 and C3) were installed in different streams in WS41. Each camera took one photo every half an hour between the 29th September and 26th October, Two rainfall events on the 4th and the 6th October and one snowmelt event on the 18th October, were captured (see fig. 20 for precipitation and discharge during this time). Because the aim was to see if and when flow occurred, only one camera was installed in each stream. C1 and C2 were placed close the bottom of the slope and C3 just above the steepest edge (see fig. 21).

Most of the intermittent channels were located in less steep areas. Flow in these streams seemed to depend on upslope conditions, such as upslope wetlands or streams, which storage needed to be exceeded to cause streamflow. The slope of these streams was not necessary steep and the groundwater table was shallow, so that local pools existed in the channels. It was expected that with an increasing wetness these pools might connect and transmit a streamflow. The intermittent streams can in that way expand in a disjointed pattern by coalescence. It was also expected that when the storage capacity of the upslope element was exceeded, the streamflow in the channel would increase significantly. Even though it was expected to be difficult to capture this stream expansion with a digital camera, one camera (C4) was placed just outside WS41 in such an intermittent stream (see fig. 21). In order to better catch the disjointed stream expansion, direct observation during a rainfall event was used. Every ten metre in a channel in WS18 was marked with a stick before a heavy rainfall event on the 6th October. The expansion of the stream could then be followed live from dry to fully active.

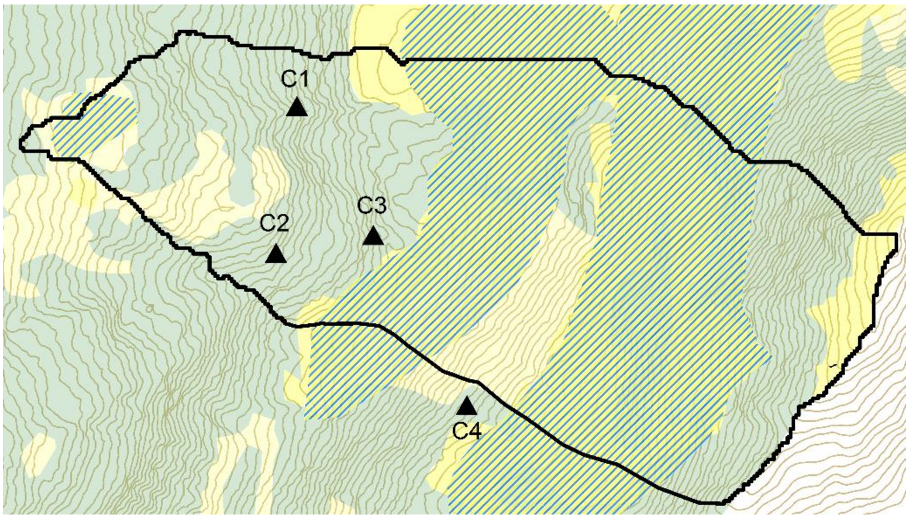


Figure 21. *Location of the digital cameras. C1-C3 were installed at ephermal streams on a steep slope in WS41. Notice how C1 and C2 were placed in the bottom of the slope and C3 further up. C4 was installed at an intermittent stream just outside WS41. Contour elevation is 2.5 m. See fig. 16 for land-use description.*

2.3. STATISTICAL ANALYSIS

The field data were statistically analysed in order to see changes in the active drainage density, connected drainage density, number of flowing stream heads and to relate them to surface properties (TWI and A) for each flow type as a function of hydrological conditions. Runoff and precipitation data was obtained by WSL (Swiss Federal Institute for Forest, Snow and Landscape Research) from the hydrological and meteorological measuring station at the Erlenbach. The mean runoff during each field campaign, which usually took around 2 hours, was used to describe the hydrological conditions of the hillside. The precipitation data were used to visually compare the timing of the discharge. Because the catchments respond very quickly to rain or snowmelt inputs, no larger storage features, such as lakes exists, it was assumed that the runoff at the bottom of Erlenbach could also represent the hydrological conditions in the headwaters.

2.3.1 Analysis of Drainage Density

In the study all stream segments with flowing water (the weakly trickling, trickling, weakly flowing and flowing classes) were defined as active. The streams that was continuous active, without any disconnections, down to the outlet of the basin was defined as connected to the outlet of each basin. Both the active and connected stream segments for each catchment and field campaign were extracted, analysed and compared to the discharge in the Erlenbach using a linear regression.

2.3.2 Analysis of stream initiation

In order to analyse where and how the streamflow was initiated, the closest segment to each stream head was extracted and for each field campaign the TWI, A and initiation type (i.e. spring, pipe, shallow soil, wetland, Horton overland flow and from a storage area) was determined. The data for each catchment was summarized to see if there where trends in where and how the streams initiated during various hydrological conditions.

2.3.3 Surface wetness analysis with TWI and A

In order to test the hypothesis that the location of the active stream network is related to the surface topography, the field data were statistically analysed using TWI and A.

According to Rinderer et al. (2014) TWI can represent soil wetness in WS41 and the TWI assumptions hold best during slow groundwater changes between rainfall events. TWI and A were determined with the use of a multiple flow routing algorithm (FMFD) based on the same high resolution DEM (2x2m) as the one used for the field work in SagaGIS. The multiple flow routing algorithm was chosen because it gives a less sensitive result than a single flow routing algorithm (see section 1.2.2). The TWI and A for all mapped stream segments were extracted in ArcGIS and analysed in Excel for each field campaign. Because the stream layer was not always located in the area with the highest TWI and A (see fig. 22) the maximum values of TWI and A around the stream segments span were selected to represent the stream and further analysed. In order to get a realistic value each segment was maximum 100 meter long.

Figure 22. *Maps showing problems related to the TWI and A data. To the left is an air-photo of the area and to the right the TWI layer. The mapped stream (light blue) fits the air-photo, however not with the TWI layer. In order to fix these small errors the maximum value of TWI around each stream segment was used to represent the TWI of the stream segment. For some small segments (indicated with a red arrow) a manual correction was needed.*

2.3.4 Outliers in the TWI and A Data

After plotting the TWI and A data, outliers were recognised and further investigated. Three types of outliers existed. The first type was found in small stream segments, up to ten metres in length, which were assigned a falsely low TWI or A value. These outliers were changed manually (see section 2.3.3 and fig. 22). The second type was found in segments which intersected with one of the main channels and caused unrealistic high values. In reality there was a height difference in the intersection because the smaller stream connected to the deeper channel at the top of its bank. To fix this problem, the TWI and A values from the grid cell above the intersection was manually chosen to represent the TWI and A of the stream segment. The third type of outlier was found for segments where pipe-flow occurred. As pipe-flow not was marked as a surface flow, these places would either be classified as dry or standing water, even though flow actual occurred just below the surface. In some places this pipe-flow occurred in sections with a deep channel bed, resulting in a high value of TWI or A. These situations mainly occurred during the dry periods, which resulted in higher values of TWI and A for dry or standing water sections than flowing ones. Since this study investigates the surface flow, these outliers were not changed.

2.3.5 Analytical methods with Kruskal-Wallis and Dunn´s test

Analysis of the differences in the TWI- and A-values for each stream class and field campaign was performed with the Kruskal-Wallis analysis of variance (ANOVA) with Dunn´s post-hoc test, because the data were not normally distributed.

The Kruskal-Wallis H-test is an example of a test using ranks that assumes that all of the data come from independent observations:

$$\mathrm{H} = \frac{12}{n(n+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(n+1) \qquad (2)$$

Where k is the number of samples, n_i is the number of samples in the i observation, N is the total number of observations in all samples and Ri is the sum of the ranks in the i observation. The null hypothesis in this test is rejected for high H values (Kruskal and Wallis 1952).

The post-hoc Dunn´s test was used to compare if there was a significant difference in the TWI or A for every single flow type. In other words, the Dunn post-hoc test was used to investigate which flow type classes significantly differed from each other in terms of TWI and A after the Kruskal-Wallis test had shown that there were differences between the samples. Dunn´s test can be seen as a multiple comparison non-parametric analogue to the t-test for normal ANOVA, but for ranked sums. For more information regarding the Dunn´s test, see Dunn (1964).

Since the probability of rejecting the null-hypothesis even though it is true (i.e. Type I error) increases when using multiple comparisons, the Dunn-Sidak correction was used throughout the analyse. This means that for each null hypothesis, for each pair that is compared, the significant level α (0.05) is not used, but a corrected significant level α_c:

$$\alpha_c = 1 - (1 - \alpha)^{\frac{1}{m}} \qquad (3)$$

3. RESULTS AND OBSERVATIONS

The maps from the field work showed that the active stream network, in all catchments, expanded, contracted and connected during the study period. The increased wetness, as a result of the precipitation in the Zwäckentobel, caused the flowing streams to expand in a more branched network and the number of stream heads to increase. The active network expansion caused stream segments to move up in flow type class and stream segment with a lower TWI and upslope accumulating area (A) to flow. The results also showed that the distribution of temporary streams and wetlands in the landscape affects the connectivity in the study catchments.

3.1 EXPANSION OF THE FLOWING STREAM NETWORK

The stream network maps from the field work showed that in each study catchment the flowing stream network expanded, contracted and connected/disconnected in response to precipitation and drainage. The total length of streams with a trickling flow was largest on October 30th when the area was wet, but the meteorological conditions dry. During rainfall events, such as on the 17th September, these streams received more water and were therefore instead classified as weakly flowing or flowing. As a result the total trickling stream length decreased, even though the discharge of the whole catchment increased. Figure 23A also shows that the contributing stream network is almost the same as the active network. This means that almost all streams in WS3 were connected with the outlet and that local elements had a minor impact on the connectivity.

For example, figure 23 shows the expansion of the flowing stream network in WS3 during three out of the total five field campaigns. These campaigns captured the very dry conditions in late August and the wet conditions during the rainfall event on the 17th of September. The stream network changed during this time from 0% active to 80% active. The expansion seemed to follow a disjointed pattern, where some streams expanded bottom-up and others top-down. Notice in figure 23A how one stream, located in the forested northern part of the catchment, did not have any flow during the field study. The upper most location of this stream was at the intersection with the main channel bank. This stream will therefore probably only be activated when the water level in the main channel reaches high enough to cause seepage and a top down expansion of the network. The other streams in WS3 were intermittent. As the area became wetter, most of these streams started to flow and during the event of the 17th of September none of them were dry.

The active drainage density (m/m^2) of WS3 increased almost linearly with the logarithm of the discharge (l/s), with a scaling factor of 0.0065 (see fig. 23A). Also the number of heads increased in a similar way, with a scaling factor of 1.57 (see fig. 23B).

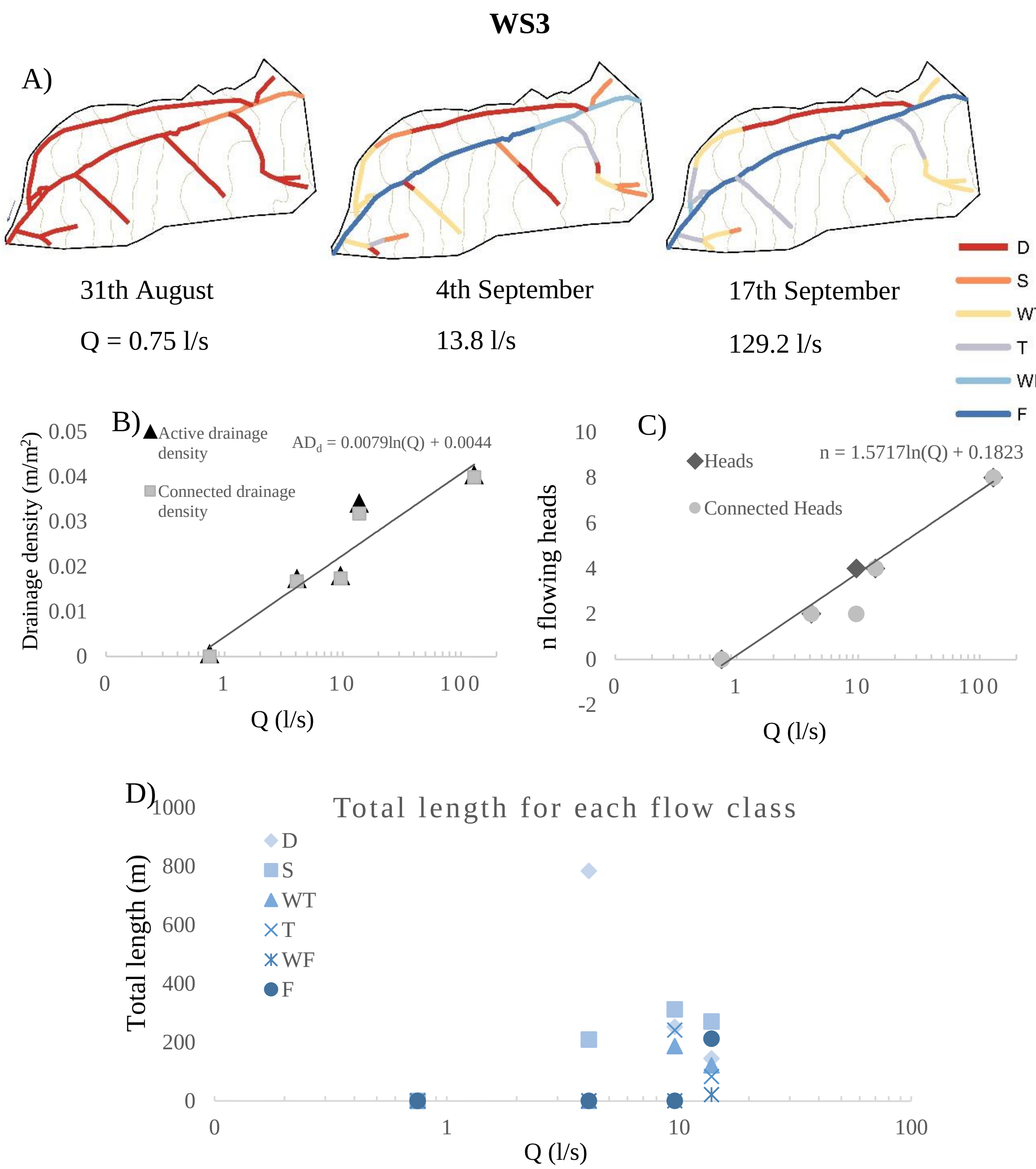


Figure 23. *The expansion and connection of the active stream network in WS3 as function of the discharge at the Erlenbach station. A) Maps showing the change in flow type within the stream network during three of the five field campaigns. The runoff-values (Q) are the mean runoff during each campaign. B) The active and connected drainage density as function of the discharge (log-scale). C) The number of flowing stream heads and connected stream heads as a function of the discharge (log-scale). D) The length of each flow-type as a function of the discharge (log-scale). See* table 3 *for the flow classes.*

Despite that WS3 is smaller than the other catchments, has an unnatural stream network and a relatively uniform surface, all of the study catchments responded similar to changes in hydrological conditions (see fig. 24-26). The active drainage density of all catchments increased almost linear with the logarithm of discharge and had scaling factors between 0.0018 (WS4) and 0.0043 (WS18) (see fig. 24-26B). The flowing stream network of WS41 was weakly connected to the outlet of the stream (see fig. 25B). The connected network was less than 50% of the total active network and number of flowing heads less than 20% were connected with the outlet (see also table 4). This was significantly less compared to the other catchments (see fig. 27B) and caused by a steep slope with a high infiltration capacity in the middle of catchment. As the wetness in the catchment increased, the flowing network expanded in the areas above and below this slope, which is seen in the increase of the active drainage density. This increased wetness was however not enough to fully connect the two parts (see fig. 25A). Only during the largest rainfall event did one of the streams connect a part of the upper zone with the lower zone (see the main channel in the northern part in fig. 25A). The result was an almost two-fold expansion of the connected stream network.

The stream network in WS18 and WS19 had overall a very similar response to changes in hydrological conditions (see fig.26). This is not very surprising since they are neighbouring catchments and are very similar in size and shape. However WS18 has a significantly more branched stream network than WS19. This can also be seen in the scaling exponent of the number of flowing heads (9.25 for WS18 and 5.65 for WS19, see fig. 27C). WS18 had despite its small size the largest number of flowing heads of all catchments during wet conditions (fig. 27C).

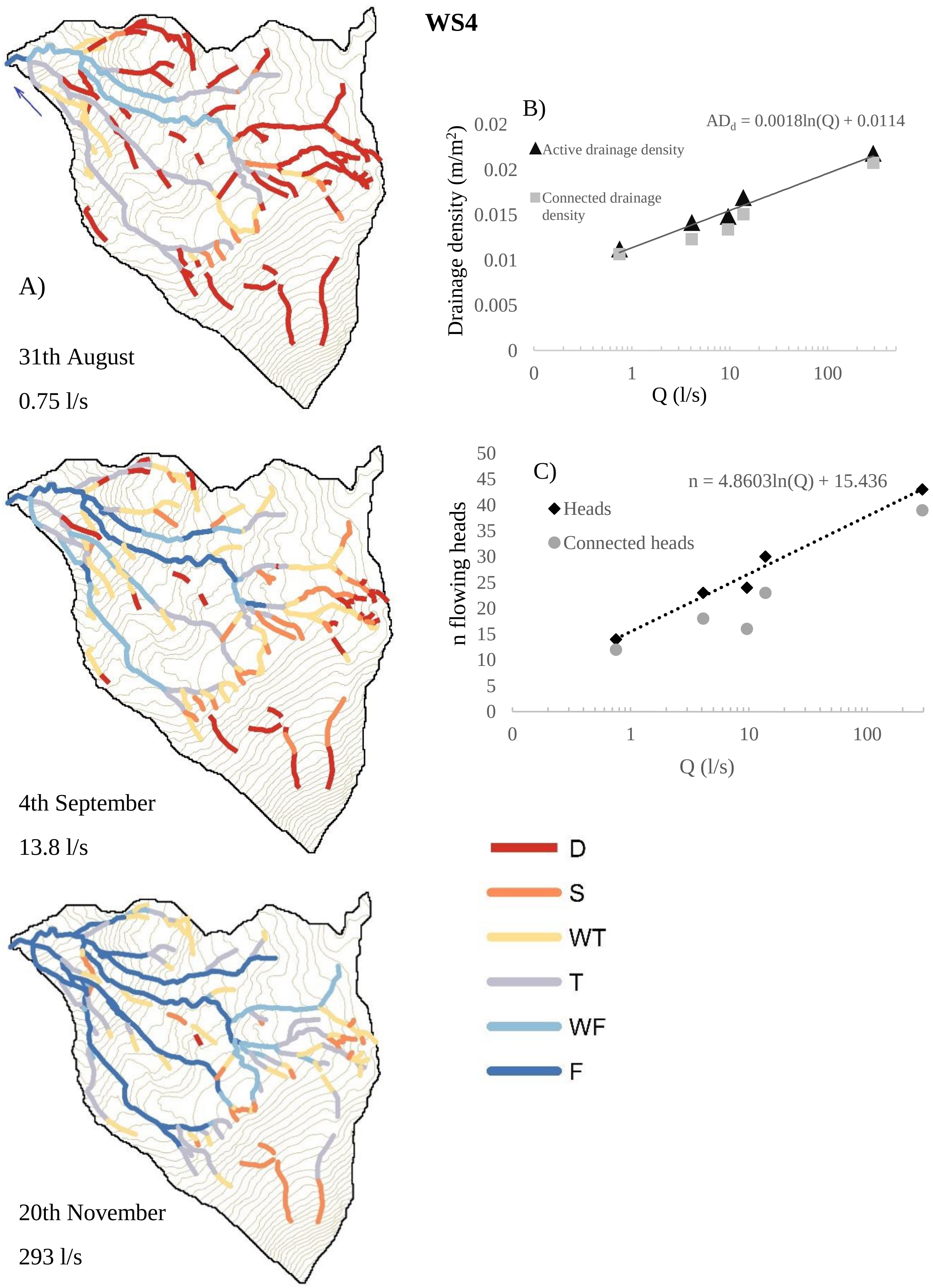


Figure 24. *The expansion and connection of the active stream network in WS4 as a function of the discharge at the Erlenbach station. A) Dynamic maps showing the change in flow type within the stream network during three of the five field campaigns. The runoff-values (Q) are the mean runoff during each campaign. B) The active and connected drainage density as a function of the discharge (log-scale). C) The number of flowing stream heads and connected stream heads as a function of the discharge (log-scale). See table 3 for the flow classes.*

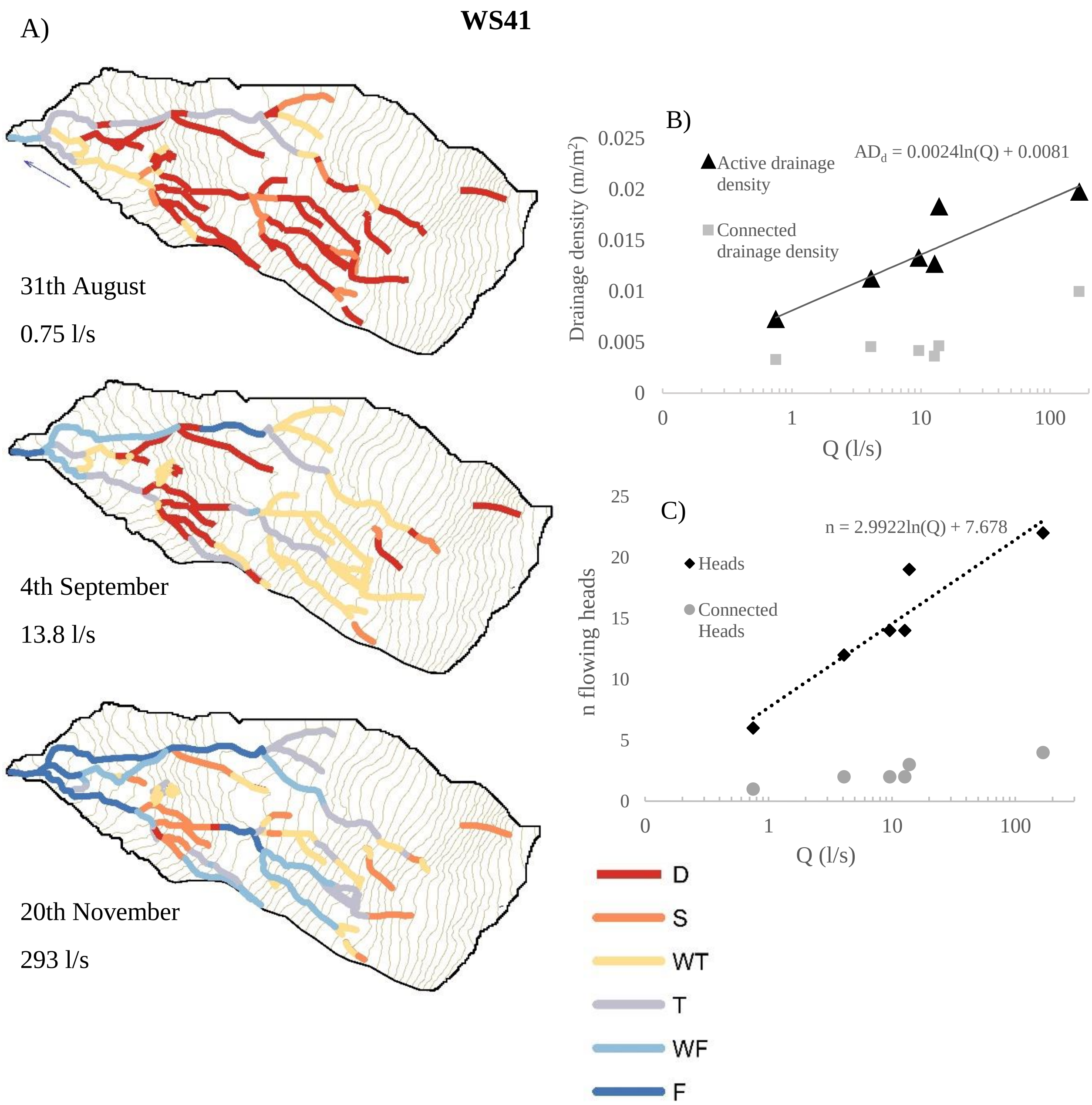


Figure 25. *The expansion and connection of the active stream network in WS41 as a function of the discharge at the Erlenbach station. A) Dynamic maps showing the change in flow type within the stream network during three of the six field campaigns. The runoff-values (Q) are the mean runoff during each campaign. B) The active and connected drainage density as a function of the discharge (log-scale). C) The number of flowing stream heads and connected stream heads as a function of the discharge (log-scale). See table 3 for the flow classes.*

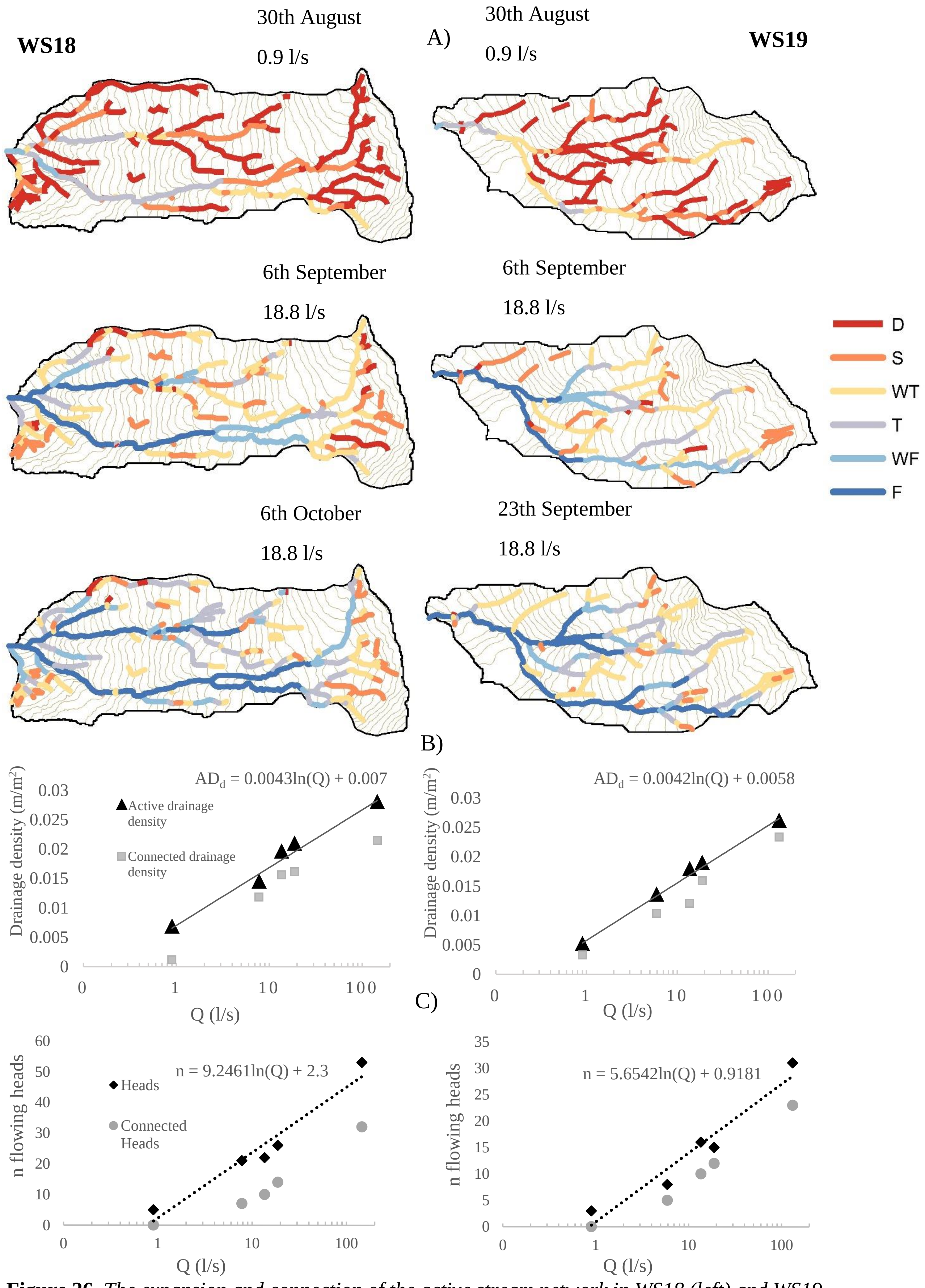


Figure 26. *The expansion and connection of the active stream network in WS18 (left) and WS19 (right) as a function of the discharge at the Erlenbach station. A) Dynamic maps showing the change in flow type within the stream network during three of the five field campaigns. The runoff-values (Q) are the mean runoff during each campaign. B) The active and connected drainage density as a function of the discharge (log-scale). C) The number of flowing stream heads and connected stream heads as a function of the discharge (log-scale). See table 3 for the flow classes.*

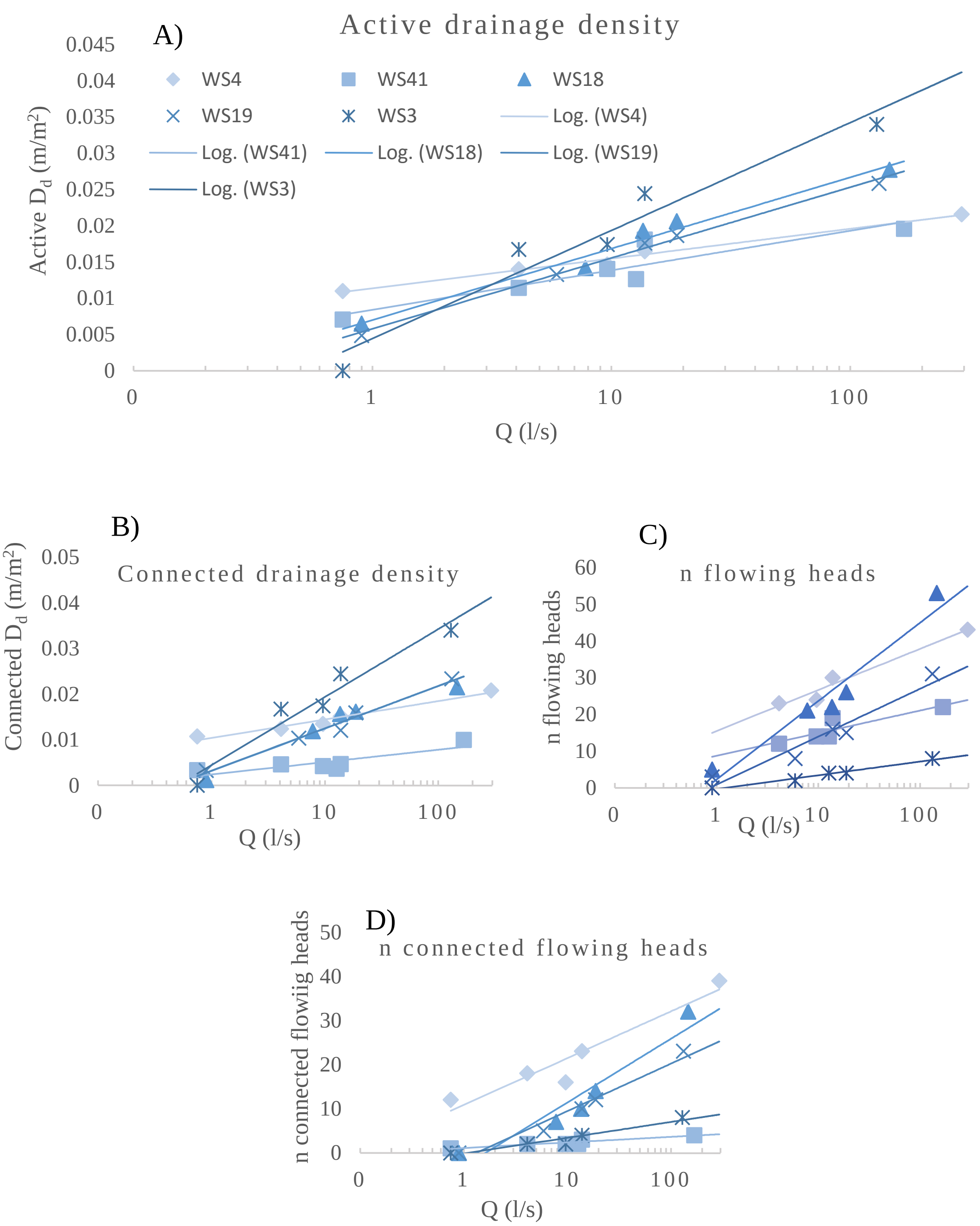


Figure 27. *Comparison of the flowing stream network between all five study catchments as a function of the discharge (log-scale). A) The active drainage density: the smaller catchments WS3, WS18 and WS19 have a more temporally varying network than other catchments. The stream network in these catchments have both the lowest and highest drainage density. B) The connected drainage density. WS41 clearly differs from the other catchments with less than 50% connected streams. C) The total number of flowing heads. WS18 has despite its relatively small size the largest number of stream heads during wet conditions, indicating a more branched stream network. D) The total number connected stream heads. Less than 20% of the total number of stream heads was connected in WS41.*

In order to compare the scaling factors (β-values) with previous studies (see table 1), the active drainage density and number of flowing heads were also plotted on a log-log scale as a function of Q (in mm/d) (see table 4). The scaling factors are the slope and varied between 0.11 and 0.34 for the active drainage density and 0.18 to 0.58 for the connected drainage density. The scaling factors varied between 0.18 and 0.48 for the number of flowing heads and 0.20 and 0.50 for the number of connected heads. Since WS3 is not a full catchment, it was not used in the comparison with the previous studies.

Table 4. *Summary of the scaling factors for the active drainage density and number of flowing heads, connected drainage density and number of connected heads, in WS4, WS41, WS18 and WS19, compared with the best-fit slopes from Godsey and Kirchner (2014). See* table 1 *for the scaling factors for the active drainage density from some other previous studies*

		WS			
		4	41	18	19
Active	D_d (m/m^2)	0.011 - 0.022	0.007 - 0.0020	0.0065 - 0.028	0.0049 - 0.026
	β (D_d)	0.11	0.19	0.29	0.34
	n flowing heads	14 - 43	6 - 22	5 - 53	3 - 31
	β (n)	0.18	0.24	0.46	0.48
Connected	D_d (m/m^2)	0.011 - 0.021	0.0033 - 0.010	0.0011 - 0.021	0.0038 - 0.023
	β (D_d)	0.11	0.19	0.58	0.39
	n heads	12 - 39	1 - 4	0 - 32	0 - 23
	β (n)	0.20	0.25	0.50	0.46

Godsey and Kirchner (2014) (Best-fit slope)		
	Active D_d:	0.27±0.04
	Connected D_d:	0.41±0.08
	n flowing heads:	0.36±0.06
	n connected heads:	0.48±0.06

3.2 TOPOGRAPHIC CONTROLS ON STREAMFLOW

The study of TWI and A for each stream segment in all catchments during the field campaigns showed several trends, both in individual catchments and in the whole study area. These patterns were very similar for TWI and A.

3.2.1 TWI

During each individual field campaign, the segments with a higher flow type classes, i.e. larger flow amount, were located in areas with a higher TWI than those with a lower flow type. Furthermore, as the wetness of the catchments increased, most of the stream segments had more flow. This caused flow activation in areas with a smaller TWI than during dry conditions. In general, the most significant changes were observed for the S, WT, T and WF classes. The fully flowing streams (F) were most commonly restricted to the main channels, which all had high TWI-values. These streams already flowed at medium wetness conditions. Only during larger rainfall events did the flowing network move up into smaller streams, however not in the same proportion as the other flow classes. During dry conditions the T and WF segments were restricted to the main channels. With the increased wetness, segments upwards in the catchment that used to have much less flow or no flow also became T or WF. This indicates that the active stream network expanded to topographically drier areas (with lower TWI and A values) in the landscape. The mean and minimum TWI values of the dry class increased during rainfall events. This may seem surprising. When investigating which streams were dry during events, it turned out to be channels in steep areas with a high infiltration capacity, in areas with a high TWI.

Figure 28 shows the range of TWI values of the stream segments that belong to the different stream classes in WS4. During the driest field campaign, with a discharge of 0.75 l/s, only one stream segment was classified as flowing (F) (see fig. 28B). This segment was located in a area with a maximum TWI value of 15.37. During the following field campaigns, the discharge increased to a maximum of 293 l/s. At this time the lowest TWI-value of the flowing stream segments was 7.80. This segment was classified during the driest field campaign as trickling and flowed only during the largest rainfall event. The boxplots of the TWI-values for each flow type segment for the other catchments are shown in appendix B.

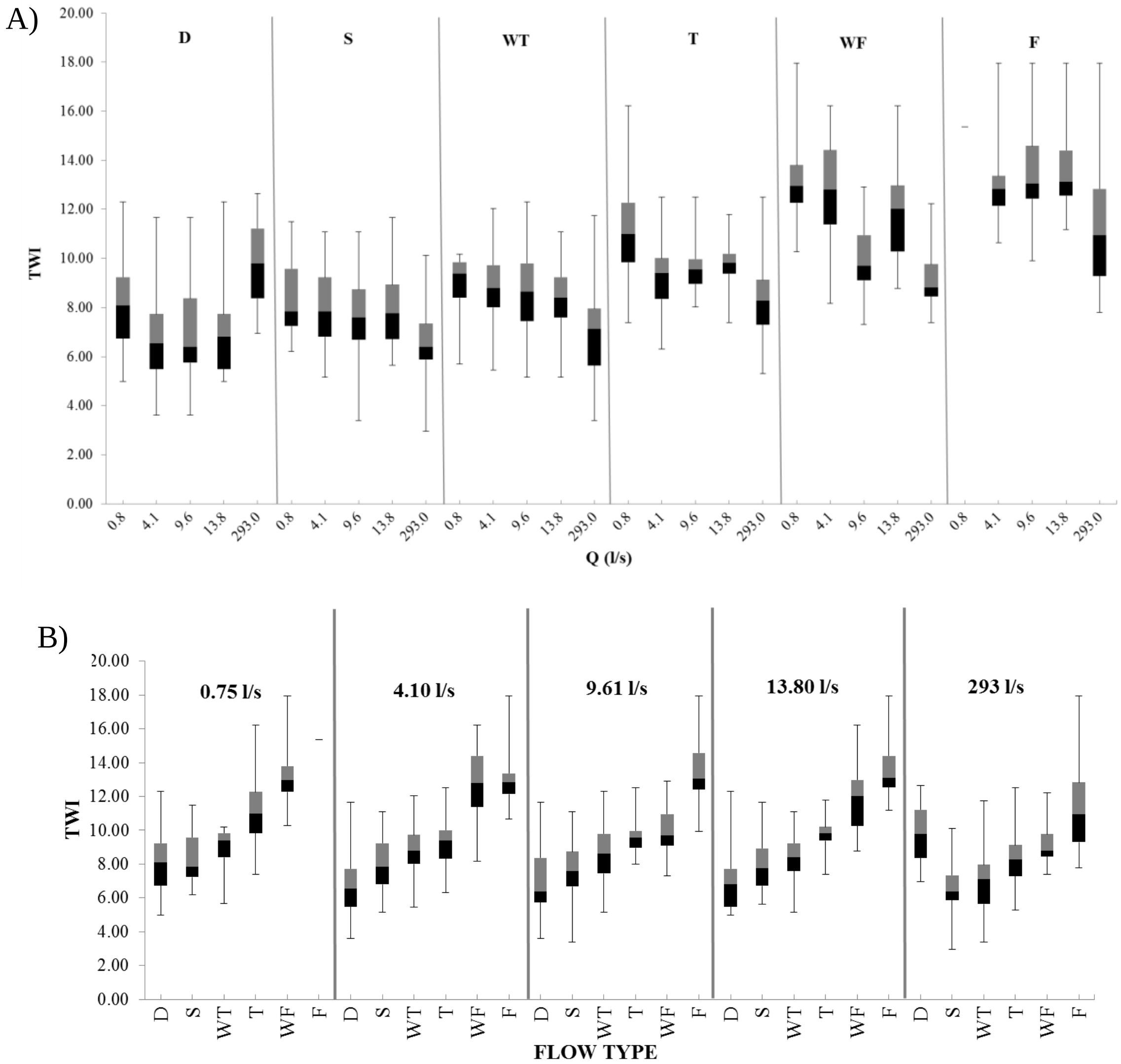


Figure 28. *Boxplots of the TWI-values for each stream segment that belongs to a certain flow class in WS4 during the five field campaigns. The whiskers of each boxplot show the minimum and maximum values and the top and bottom of the box the 75th and 25th percentile. The line separating the black and grey inside the box shows the mean value.*

A) The data for the flow type classes ordered by the discharge. Notice how the TWI values of the standing water to flowing segments decreases with increasing discharge. This indicates that the flowing network expanded to more topographically dry areas in the landscape. The dry class does not follow this trend. B) TWI values of the stream segments of the different flow classes during each field campaign. During most of the field visits, the stream segments located in topographically dry areas of the landscape, i.e. low TWI, had a low flow-type class (D-S).

In most cases the TWI values of the WT, T and WF segments were not significant different in the analysis of variance between flow classes. The TWI values of the D and S segments were similar during dry conditions, but as conditions changed, the TWI values of the S segments were lower than for the D segments. The TWI values of the F segments during dry and mid-wet conditions were significantly different from the other classes. The TWI values of the D and F segments were similar during wet conditions due to the remaining dry streams being located in areas with high TWI-values. Figure 29 shows a simplified example between dry and wet conditions. To simplify, the TWI values of the S to WF segments (in the red box) responded similar to increasing wetness and the TWI values of the D and F segments not.

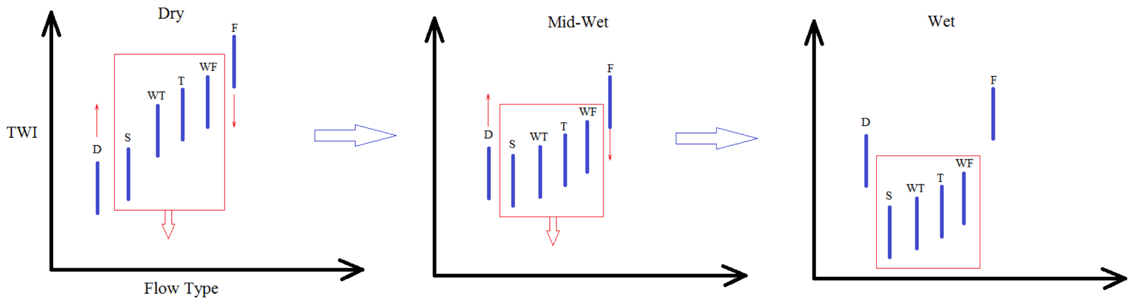


Figure 29. *Example of the change in TWI values of stream segments of a certain flow class as the catchment changes from dry to wet conditions. In the red box are those stream classes whose TWI values were not statistically different. The TWI values of these classes became more similar with increasing wetness. The TWI values of the segments in the D class shifted slightly towards higher values, while the TWI values of the segments in the F class became smaller. These two classes which were significantly different during dry conditions became in this way more similar during events.*

Table 5 shows the TWI values of the segments with flow type classes that were not statistically significant different in the analysis of variance for WS4 as a function of discharge. The letters A-D indicates these groups in which the flow type classes were not significantly different. For example, during the driest campaign the TWI values of segments in the D, S and WT flow classes were not significant different (group A). Also the TWI values of the segments in the T and WF flow classes were not significant different (group B). However are the TWI values of the segments in group A significant different from the TWI values of the segments in group B. The TWI values of the segments in the D and F flow class are only in the same group during the largest rainfall event. The tables from the analysis of variance of the TWI of the different flow classes in WS18, WS19 and WS41 are shown in appendix C.

Table 5. *Analysis of variance of the TWI of the different flow classes in WS4 as a function of discharge. The analysis was performed with a Kruskal-Wallis test with Dunn´s post hoc test. The letters, A-D, indicates groups in which the flow type classes were not significantly different during each field campaign.*

WS4	Flow type					
Q (l/s)	D	S	WT	T	WF	F
0.75	A	A	A	B	B	-
4.10	A	AC	C	C	B	B
9.61	A	AC	CD	D	BD	B
13.80	A	AC	C	B	B	B
293.0	ABC	A	A	C	C	B

The analysis of variance also showed that for each catchment, three statistically different types of hydrological conditions were captured. The first campaign in each catchment represented very dry conditions, with a discharge between 0.75 and 0.90 l/s. For these conditions, the TWI values of the segments in the F class were significantly different from the TWI values of the segments of the other flow and the TWI values of the segments in the D class were similar to the TWI values of the S and WT segments. The second condition were the three or four mid-wetness conditions campaigns, with a runoff between 4.1 and 18.8 l/s. During these mid-wetness conditions the TWI values of the segments in all flow type classes, except F, were similar. The third condition type occurred during events, with discharge in the range 129 – 293 l/s. As described before the TWI values of the segments in the D and F classes, and in the S to WF classes, were not significantly different.

3.2.2 Upslope accumulating area

The relation between the upslope accumulating area of a stream segment and the flow class showed very similar results as for the TWI. For example, figure 30 shows the distribution of the upslope accumulating area of the stream segments of different flow classes in WS4 during different hydrological conditions. Notice the similarities with the TWI-graphs in figure 28. The only stream segment in the F class during the driest field campaign had an upslope accumulating area of 233161 m^2, this segment flowed throughout the field study, which can be seen in the constant upper whisker of F in figure 30A. During the rainfall event, other locations with an upslope area larger than 1400 m^2 were also flowing. The boxplots of the upslope accumulated area for each flow type segment for the other catchments are shown in appendix D.

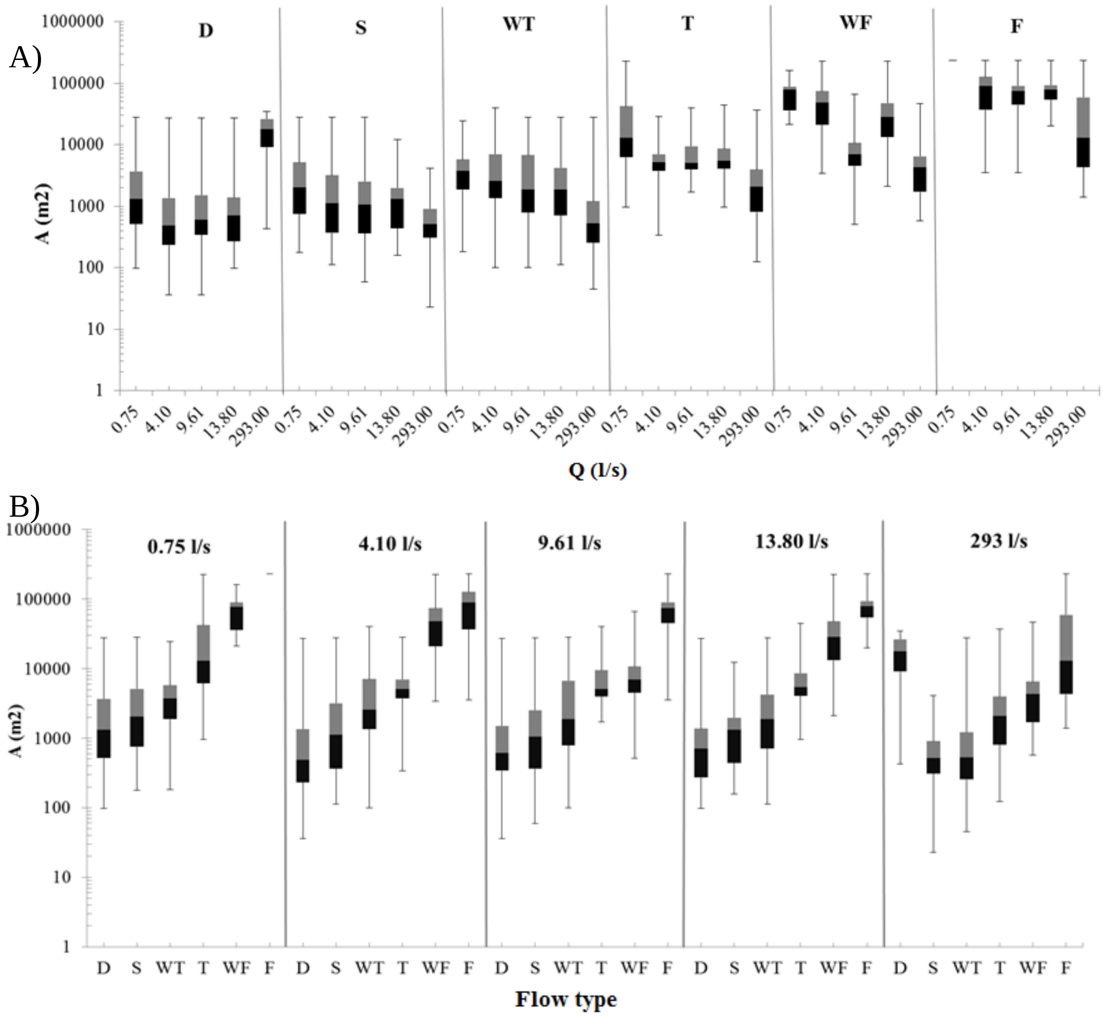


Figure 30. *Boxplots of the upslope accumulated area of stream segment in different flow classes in WS4 during the five field campaigns. The whiskers of each boxplot show the minimum and maximum values and the top and bottom of the box the 75th and 25th percentile of the samples. The line separating the black and grey parts of the box shows the mean value. A) The flow type classes as a function of the discharge. Notice how the upslope accumulating area of the segments with the standing water to flowing classes decreases with increasing discharge. This indicates that the flowing network expanded to sites with smaller contributing area. B) The distribution of accumulated area for the flow type class during each individual field campaign. Notice how the trends is similar to the TWI-graphs in figure 28.*

3.3 STREAMFLOW INITIATION

The changes in the TWI and the upslope accumulated area of the uppermost flowing stream segment and in the characteristics of the locations of flow initiation, i.e. the flowing heads, with increasing discharge were different between the catchments. This indicates that different patterns of streamflow expansion were dominant in various catchments. In the majority of the catchments the bottom-up and/or the disjointed patterns were most common.

3.3.1 Location of flow initiation

Where streamflow was initiated in the landscape was highly variable between the study catchments. Figure 31 shows the number of flowing streams that started in shallow soils, wetlands, springs, pumps, man-made ditches, pools or by Horton overland flow due to low infiltration capacity, for WS4, WS41, WS18 and WS19, as a function of discharge. Data for WS3 is not shown because almost all flowing streams were located in man-made ditches (appendix E).

In appendix E is the location of the streamflow sources are summarized and presented as a percent of the total number of heads for each study catchment and field campaign. In all of the catchments, except WS3, around 50% of the streams were initiated in areas with shallow soil. This is not very surprising since that areas with shallow soils constitute almost 50 % of these catchments. It is also important to clarify that the stream source can be located both in an area of shallow soil and at for example a spring. By excluding the shallow soils it is possible to see that in WS4, wetlands are the most common source of flow initiation, especially during wet conditions. Even though the number of streams that initiated in wetlands increased with wetness conditions in WS4, WS41 and WS18 (fig. 31) the percentage of the total number of streams that initiated in wetlands stayed rather constant (appendix E).

In WS41, most flowing heads are located in wetlands and springs and during wet conditions also in areas with low infiltration capacity. Since both WS18 and WS19 are located in more open areas, which are used for ski slopes during winter, man-made ditches are more common than in WS4 and WS41. The number of heads originating from springs remained rather constant throughout the study period (fig. 31). In for example WS41, springs were the most common stream source during low to mid-wet conditions. Flow heads that started with Horton overland flow occurred in areas with a compact soil. Most of these stream sources were on trails in the upper most area of each catchment. Some heads were also found in former landslide areas and on a field used for agriculture. Some streams in WS18 and WS19 initiated from pipe-flow. These sites acted similar to the springs, with a relatively constant flow from the subsurface. The relative importance of these was therefore also the largest during dry conditions. The mapping of the pipe-flow was however not detailed enough to draw any other conclusion of its importance to streamflow. The pumping station in WS4 and two small man-made pools in WS18 and WS19 had a minor influence of the streamflow.

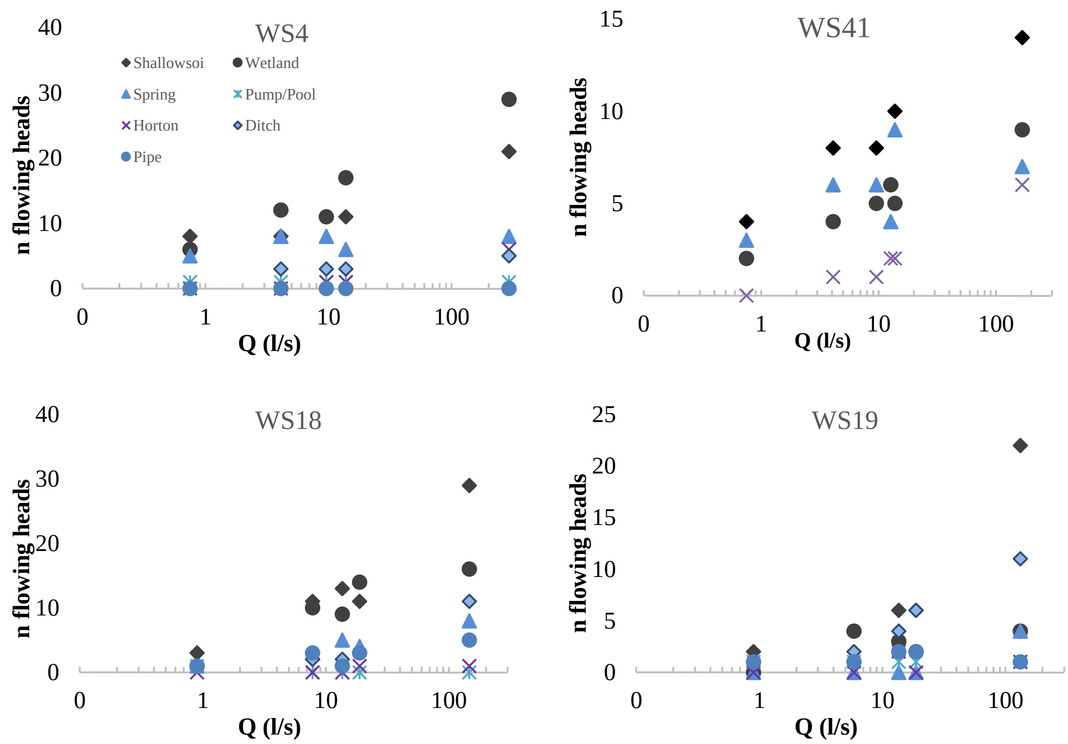


Figure 31. *Number and characteristics of locations of flow initiation in WS4, 41, 18 and 19 as a function of the discharge (log-scale).*

3.3.2 TWI, upslope accumulated area and slope at the position of flow initiation

As the hydrological conditions of the subcatchments of Zwäckentobel changed from dry to wet, the position of the initiation of streamflow changed. The investigation of the TWI, upslope accumulated area and slope at the uppermost active segment of all streams showed a general pattern with local variations in all sub-catchments (see fig. 32). The results from the TWI and A analyses showed that stream heads tended to move to topographically drier locations with smaller a smaller TWI and upslope area as the wetness increased. But the strength of this trend was different in each of the catchments. Only for WS18 was there a statistically significant decreasing trend in the change of TWI for the uppermost active segment of all streams with increasing discharge. For WS4, WS18 and WS19 there was a significant decreasing trend in A for the uppermost active segment of all streams with increasing discharge (see fig. 32A and B). In table 6 the minimum, maximum and mean values of TWI, A and slope of the uppermost active segment of all streams during the driest and wettest field campaign are shown for each study catchment. The minimum and mean values of TWI and A of the flowing stream heads decreased for all catchments from dry to wet conditions. The minimum TWI needed for flow initiation changed from 5.31–8.05 to 2.46–4.31 and the minimum accumulated area from 182–534 m^2 to 30–84 m^2. For WS4, WS41, WS18 and WS19 the stream heads also appeared on shallower slopes as discharge increased (see fig. 32C). This could be due to the saturation and flow activation of wetlands in flatter recharge areas. The minimum slope needed for a stream initiation in these catchments changed from 12.5–22.53° to 6.53–12.14°. In WS3 the trend was however the other way around, because streamflow was also initiated in the more branched and steep ditch network.

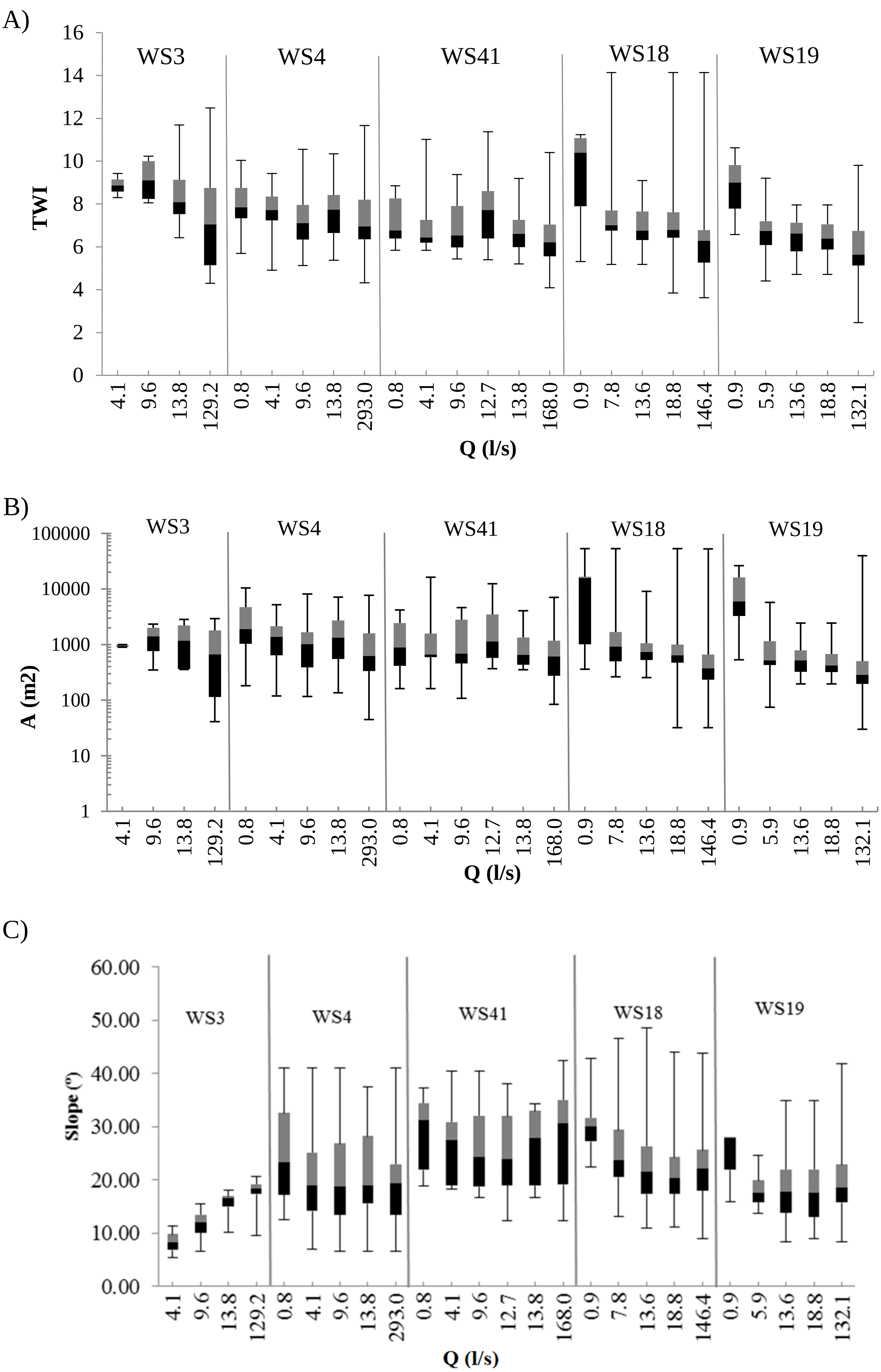


Figure 32. *Surface properties of the upper most segment to each flowing stream head in all study catchments as a function of the discharge. The whiskers of each boxplot show the minimum and maximum values and the box the 75th and 25th percentile. The line*

separating the black and grey area inside the box shows the mean value. A) TWI, notice how stream initiation tends to also occur in locations with lower TWI as the wetness increases. Only the results for WS18 show a statistically significant trend. B) Upslope accumulated area (m^2) in log-scale. The graph looks almost similar to the TWI-chart with a slight decrease in the upslope area where the stream initiation occur with increased wetness. The trends for WS4, WS18 and WS19 are statistical significant. C) Slope (º), notice how the trend is different from catchment to catchment. In WS3 the stream heads occur in steeper slopes as the wetness increases, in the other catchments the stream sources also occur in flatter areas as wetness increases. None of the trends are a statistically significant.

Table 6. *The minimum, maximum and mean (with the standard deviation) TWI, upslope accumulated area (A) and slope of the uppermost flowing stream segment in all streams during the driest and wettest field campaign*

		TWI			A (m^2)			Slope (º)		
WS	Dry/Wet	Min	Max	Mean (STD)	Min	Max	Mean (STD)	Min	Max	Mean (STD)
3	D	8.1	10.2	9.1±1.1	350	2324	1368±903	6.6	15.5	11.6±3.7
	W	4.3	12.5	7.4±2.7	41	2918	1102±1198	9.5	20.7	17.4±3.6
4	D	5.7	10.0	7.9±1.3	182	10406	3005±2769	12.5	41.1	25.0±9.4
	W	4.3	11.7	7.2±1.6	45	7668	1210±1549	6.5	41.1	19.8±8.5
41	D	5.8	8.9	7.2±1.2	162	4189	1554±1615	18.8	37.3	28.9±8.0
	W	4.1	10.4	6.5±1.5	84	7052	1237±1641	12.1	42.4	28.8±9.3
18	D	5.3	11.2	9.2±2.5	360	52917	17332±21351	22.5	43.0	30.9±7.6
	W	3.6	14.1	6.3±1.7	32	52577	2486±8875	8.9	43.9	23.3±8.1
19	D	6.6	10.6	8.7±2.0	534	26315	10945±13587	15.9	27.9	23.9±6.9
	W	2.5	9.8	6.7±1.4	30	39554	2394±7779	8.5	41.9	21.3±9.0

3.4 MONITORING TEST OF STREAMFLOW DURING EVENTS

The test to monitor temporary streamflow with cameras was. From the photos it was possible to determine the timing of stream activation, but not the pattern of expansion. The Field observations could capture both the timing and pattern.

3.4.1 Results from the digital cameras

Of the four digital cameras, C1, C3 and C4 captured the timing of stream activation during the three events during the monitoring study (see table 7). The stream segment monitored by C2 was however never activated, even though the rainfall event on the 6th of October was the second largest event during the whole field study. This indicates that the stream segment of C2 is activated less frequently than the other segments and is likely episodic in nature. The flow in the stream segment of C1 appeared one to two hours later than C3 and lasted also one to two hours shorter, probably because C1 was installed further down the slope than C3. Even though one hour can seem little, the discharge at the Erlenbach station significantly changed during this time. The stream segment of C1 was activated when the runoff at this station was between 110 and 150 l/s, which was close to the peak runoff. Visual inspection during field visit showed that when the stream segment at C1 was active, the whole stream network was connected to the perennial stream network. This indicates that for the season of the field study, around 19 mm of rainfall or 10 mm of snowmelt was needed to connect the stream with the outlet. The stream segment of C3, however, never fully connected. Field observations showed that the stream expanded downwards to the position of the camera but the water infiltrated in the steep slope just below it. This indicates that if the camera was placed just some meters down the slope, it would never had captured any flow.

The stream segment of C4 responded differently than C1 and C3. The photos showed stream network expansion due to a large flood wave (see fig. 33). The time of activation was similar to C1 and C3, however, the flow duration was significantly longer. It was also more difficult to determine if flow occurred or not as water accumulated in local pools in the channel.

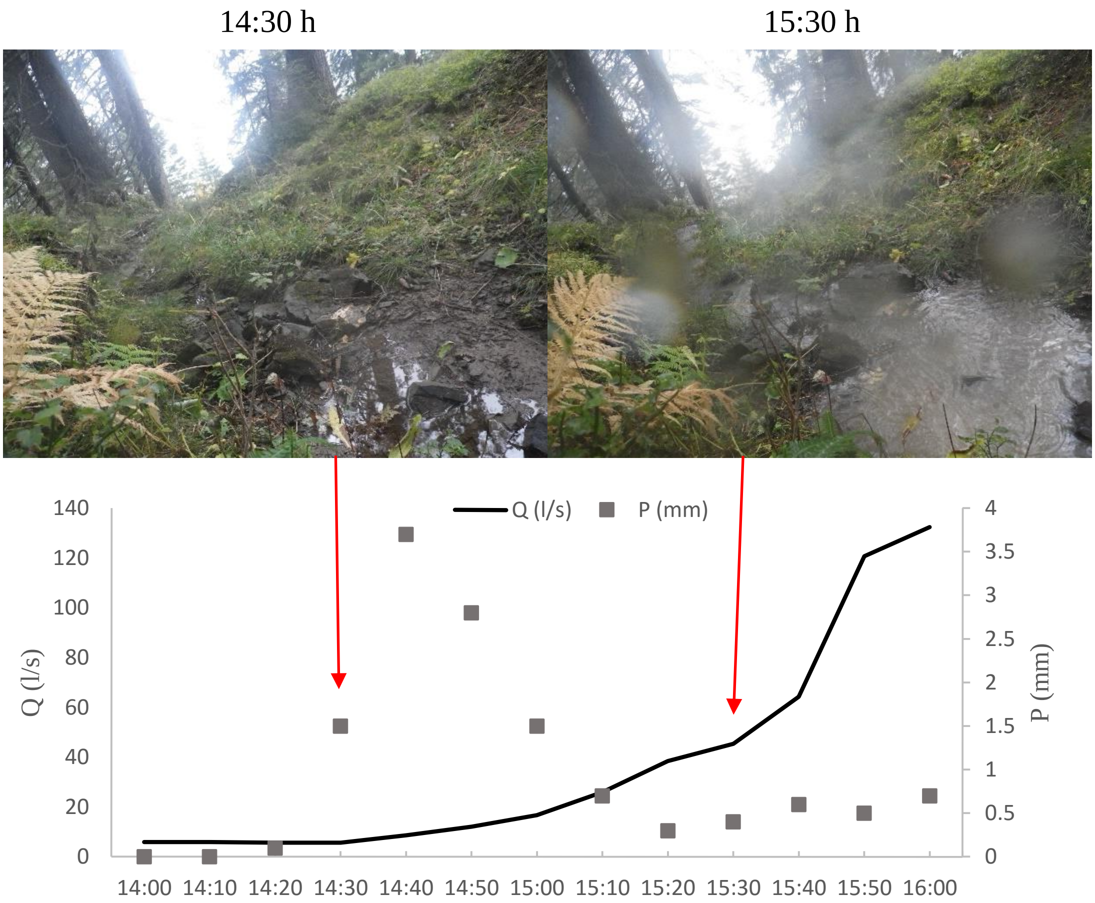


Figure 33. *Photos of the intermittent stream at C4 before (left) and during (right) the rainfall event the 6th of October. The photos are taken within one hour of each other. The hydrograph shows the discharge and the precipitation at the Erlenbach station during the start of the rainfall event.*

Table 7. *Stream characteristics derived from camera C1, C3 and C4 during two rainfall and one snowmelt event. The time of activation is the time of the photo that first showed activation (flow). The total precipitation is the amount of precipitation until the time of activation. The discharge values (l/s) are the runoff at the Erlenbach station at the time of activation and deactivation (on/off) and the flow duration is the duration that the stream was active. C2 was never activated during the study. The time interval between each consecutive photo was 30 minutes*

Camera		Event		
		04-oct Rain	06-oct Rain	18-oct Snowmelt
C1	Time of activation	09:30	16:30	14:50
	Total P (mm)	19	19	10
	Q (l/s) at activation	110	150	48
	Q (l/s) at deactivation	50	30	~ 23
	Flow duration (h)	1.5	46	~ 35
C3	Time of activation	08:00	15:30	13:00
	Total P (mm)	16.5	11	10
	Q (l/s) at activation	35	45	23
	Q (l/s) at deactivation	75	25	~ 23
	Flow duration (h)	2.5	48	~ 40
C4	Time of activation	07:30	15:30	-
	Total P (mm)	13.5	11	-
	Q (l/s) at activation	2	45	-
	Q (l/s) at deactivation	20	≈ 20	-
	Flow duration (h)	12	≈ 60	-

3.4.2 Field observation

During the field observation in WS18 during the rainfall event on the 6th of October, the pattern and timing of stream expansion could be seen much in more detail than with the camera photos. The time between the start of the rainfall until the time of first expansion was almost one hour. Total precipitation during this time was 11mm. The water level in small pools in the channel was raised during this time but not enough to cause a coalescence. Instead the flow from the upslope wetland increased until it quickly filled the channel top-down. The flood wave moved from pool to pool in the stream, filling them until the storage capacity was reached. From the start of activation the stream expanded almost ten metres every five minutes (the front of the flood wave moved at a speed of 0.33 m/s). This flow connected the upper wetland to a lower wetland but did not fully connected to the main channel, probably because the water infiltrated in a pipe or in a macropore and moved subterranean downwards.

4. DISCUSSION

The objectives of the study were all well fulfilled. The hypothesis of the study held mostly well with the results of the research:

1. *Increasing wetness conditions (represented by increasing discharge) leads to an increase in active drainage density and connected drainage density*

The active drainage density and the connected drainage density in the subcatchments of the Zwäckentobel increased as the discharge increased when the summer dry period ended during autumn. The expansion was different in size depending on where the stream was located in the landscape. Most variation in the networks was found in the small and open catchments, where a maximum five-fold increase in flowing streams was related to a 150-fold increase in discharge.

2. *Streams in the Alptal show a bottom up connection pattern*

The active stream network in most of the catchments were well connected with the outlet and expanded seasonally in a bottom up or disjointed pattern. On reach scale, however, some streams expanded top down during rainfall events when above laying local storage areas were quickly exceeded.

3. *Topography, particularly TWI and A, determines which sections of the stream are flowing*

The flowing stream network was controlled by the surface topography and the location in the landscape of the different flow classes changed. With an increased discharge streams in topographically drier location, with lower TWI and A values, became activated.

4. *The location of the stream heads can be predicted by topography, particularly TWI and A*

The surface topography has an effect on the flow initiation, however, in order to understand the controlling factor of where the stream begins, local properties of the stream head need to be studied as well. The upslope accumulated area of the location the flowing heads showed a more significant decreasing trend than the TWI with increasing discharge.

4.1 EXPANSION IN STREAM NETWORK LENGTH, DENSITY AND NUMBER OF FLOWING HEADS

The active drainage density (D_d, m/m^2) of each study catchment could be best approximated on the form:

$$Active\ D_d = \beta * lnQ + m \qquad (4)$$

Where β is a scaling factor and Q the discharge in l/s. The R^2-values differed between 0.83 (WS41) and 0.99 (WS19). When representing the active stream length (km) as a function of discharge in mm/d, the β-values of the slope on a log-log scale can be compared with the results from previous studies. The scaling exponent of this power function ranges between 0.11 and 0.34 for the active drainage density and 0.11 and 0.58 for the connected drainage density. These values are within a normal range (see summary in Godsey and Kirchner 2014).

Also the number of flowing heads, N, in each catchment could be best approximated on the form:

$$N = \beta * lnQ + m \qquad (5)$$

Where Q is the discharge in l/s. The scaling factor β ranges between 1.27 and 9.25 and was highest in WS18. The β-values of the slope of the power function (with Q in mm/d) on a log-log scale varied between 0.18 and 0.48 which also are within a normal range compared with Godsey and Kirchner (2014).

WS18 and WS19 have both the largest scaling factors of the active drainage density and the number of flowing heads. This indicates that the stream networks in these catchment have many temporary streams and expand a lot during events. This is because these catchments have the highest percentage of wetlands and streams that begin in ditched stream networks. During dry conditions the wetlands acted as a flow accumulating element in the landscape, especially in local low-points. As the conditions turned wet, many of these low located wetlands became saturated and started to contribute to streamflow. The man-made ditches were created to drain water from the hillslopes to the main channels. Since these are mostly not as deep as the natural stream network and did not create local low points, the flow was only activated during wet conditions. Since these ditches are often branched, the number of flowing stream heads increased significantly when they were activated. WS18 and WS19 had also a lower number of heads that started in springs than WS41 and WS4. Many of these springs seemed to constantly receive ground water flow from the above laying hillside. The combination of many streams that started in wetlands and ditched networks with few streams initiating from springs lead to low active drainage densities and number of flowing heads when the conditions were dry but increased significantly as the wetness increased.

WS4 had more active stream segments than the other catchments during dry conditions, which resulted in a smaller scaling exponent than the other catchments. It is important to remember that the choice of the position of the outlet of a catchment has a direct effect on the drainage density. The most branched network is found in the headwaters, similar to the crown of a tree or our blood-veins. Choosing the outlet at a high position on results in a smaller area and a more branched network, i.e. high drainage density. WS4 is located further down in the perennial stream network and has therefore a smaller increase in the active drainage network than for than the catchments. In order to have more consistent scaling factors it would be necessary to choose the outlet at the same altitude, or the starting point of the perennial flow, for all catchments.

4.2 PATTERN OF STREAM NETWORK EXPANSION AND CONNECTION

The increase in the number of stream heads during rainfall events is due to the filling of storage in wetlands and soils, and the activation of flow man-made ditches. Areas with a high water table, or very low infiltration capacity, are also quickly activated. The increase the number of stream heads can therefore be used to describe if the stream expands top-down or bottom up. If the flowing length of a stream increases, but the number of heads stays constant, the stream expands top-down or a disjointed pattern. This is the case for streams which emerge from springs. Changes in the location of the stream head indicate that the stream expands in a bottom-up or a disjointed pattern. The results of the analysis of the TWI and upslope accumulated area of the location of the stream initiation show that the flowing heads are located in topographically drier locations in the landscape as the catchment wets up. However, this trend is most significant in catchments with a small numbers of spring-flow, i.e. WS18 and WS19. Most of the streams in these catchments expand in either a bottom-up or disjointed pattern. WS41 is the catchment with the largest proportion of springs and steep slopes and has also the weakest trend in the variation of the location of the flowing heads with upslope accumulated area. The streams in this catchment expand in either a top-down or disjointed pattern.

The flow activation in a temporary stream can cause the contributing flowing stream length to increase in a threshold like way. However in WS3, WS4, WS18 and WS19 the connected length was very similar to the total active length. This means that the temporary streams in these catchment do not have similarly important role for the connection of the network as in WS41. The expansion of these temporary streams are either caused by the swift rise of the water table during a rainfall event or the exceedance of an above laying storage element. The lower streams in the landscape are more likely to gain groundwater flow than upper ones and the network will therefore generally expand in a bottom-up pattern. Because the connection to the outlet however depends on local properties of storage areas, such as wetlands, one can expand the dynamic pattern on reach scale to catchment scale.

The patterns of expansion on catchment scale are not the same in all the study catchments. Visual examination of the maps show that most of the catchments expand in a bottom-up or with a disjointed pattern. The exception is WS41, which is separated in an upper and lower parts by a steep slope where water can infiltrate quickly. The flowing stream network in these two areas expands in a bottom-up or disjointed, similar to the other catchments but a connection only occurs at a certain threshold when the infiltration capacity of the soil on the steep slope is exceeded. One of the stream segment in the monitoring study was only connected after around 19 mm of precipitation and the segment expanded in a top-down pattern. The overall connected stream network however expands in a disjointed pattern seen over the whole season.

The large number of wetlands in the Zwäckentobel catchment, area a local storage element that has a major impact on the stream network. During dry conditions water accumulates from upslope areas in the wetlands. Streamflow that emerges from a spring or by Horton overland flow is most likely going to cross one of the many wetlands on its way down. This flow only contributes to the perennial flow when the storage capacity of these wetlands is exceeded. In a discharging wetland, the slope is large enough to drain it and the flow therefore continues on its route downwards. A recharge wetland instead accumulates water in a local low point. Thus, neither the variable source area concept nor the element threshold concept can fully explain the expanding streaming network but a combined view might well could. Only explaining the stream expansion with the variable source area concept would for example not tell why the stream expansion and connection was larger in WS18 than in WS41, even though they are similar in size and altitude. The stream expansion in the flatter parts of these catchments seem to well be explained by the bottom up pattern of the variable source area concept. However the temporary stream expansion in the steeper parts are better explained by the exceedance of a local storage element according to the element threshold concept. Since WS41 have many steep parts the element threshold concept better explain the connection of this catchment than in WS18 which flowing stream network is more affected by the numerous wetlands.

4.3 EVALUATION OF METHODS TO STUDY THE STREAM NETWORK AND FUTURE RESEARCH DIRECTIONS

In order to better capture the expansion of the flowing stream network on reach scale, during single events and seasonally, a combination of field mapping and streamflow monitoring is recommended. The field mapping gave a good overview of how the streams in the catchment interacted. The temporal resolution is however a problem because it is impossible to observe all streams at the same time. The mapping of one catchment in this study took approximate two hours, when performed by trained master student. During a rainfall event, a stream can significantly change its flowing properties during the two hours period. Using the mean runoff during this campaign does not fully represent the hydrological conditions at the time a single stream was mapped. It was also a problem if the meteorological condition changed during the time of mapping. This happened on the 17th September in WS4 when a rainfall event occurred after half of the area was already mapped. This data was in the end not used in the study.

To see patterns in the expansion and contraction of the stream network at the reach scale, a major monitoring investigation would be needed. Monitoring these streams is though not an easy task, because the slopes are very steep, the rocky terrain and the high sediment loaf of the rivers, the equipment risks to be flushed away when flow occurs. From the literature study, the best available equipment would be electrical resistance sensors. However, it is impossible to separate flowing from standing water using this technique and they have only been tested in flat areas with low sediment loads. The use of cameras gave a good indication of when water was flowing. The use of digital cameras are, however, limited by the cost and especially the time-consuming evaluation method. Direct observations of stream expansion during rainfall events provide the pattern about how a stream connects to the main channel. After this, monitoring equipment can be installed at strategic locations in order to determine the timing of connection. In this way the hard work of mapping the flowing stream network properties on a steep hillside during heavy rainfalls can be facilitated.

The surface analysis of topographic controls on the stream network showed very similar results for A and TWI, which of course is not surprising as A is used in the calculation of TWI. To simplify future work, either one of them could be used to represent the topographic wetness of the surface. The results from the analysis of the upslope accumulating area showed slightly more statistically significant results than the results from the analysis of the TWI. It is therefore suggested to use the upslope accumulated area in the future. In future work, a buffer zone, around each mapped stream would minimize the consequence of falsely located stream segments. Another solution would also be to map the stream network directly on the surface representation but this cause errors in the DEM to propagate more into the hydrological study. The analysis also shows that the flowing stream network of the subcatchments expanded in three steps as a function of the hydrological conditions: Dry, mid-wet and during rainfall or snowmelt events. Three field campaigns would therefore have been enough to explain the topographic control on the stream network.

Some of the flow type classes were very similar and hard to separate in the field. This work supports the use of the simple classification system based on observations.

Measuring the flow in each tributary would be too time consuming. It is, however, important to remember that this subjective method can cause large errors when multiple field workers map different areas, or when the results are compared with other studies. It would, therefore, be recommended to do a “calibration” survey. For example everyone in the group can map the same area during equal conditions and the results can be compared to determine the uncertainty of the method. The flow-type classes, WT, T and WF appear in similar surface locations throughout the study and the removal of at least one of them can be justified. A recommended flow type classification could be dry, standing water, dripping, weakly flowing, flowing and gushing. It is also recommended to map the streams using the top-down technique. It is not only less physically demanding, but also easier to get an overview of the flowing streams. The use of an accurate flow-routing model and air-photos, in which the streams in open lands are well visible facilitate the mapping of the streams at the right position. Even the use of drones could be an interesting future direction in very remote areas, but is challenging in forested terrain or for small overgrown streams.

Future questions are:

Can we use similar classification for surface and subsurface connectivity and can that be used to classify hillslopes?

Does studying surface connectivity help us understand subsurface connectivity (and vice versa)?

Can a greater understanding of the controlling processes lead to better ways in predicting the temporary streamflow and how it is altered by anthropogenic and natural changes?

5. CONCLUSION

Temporary streams have received undeservedly little scientifically attention and as a result their role in hydrological, biogeochemical and ecological processes are not yet fully understood. The flowing properties of a stream network are not, as many might think, static. As the Alptal wetted up in response to fall rainfall events after a dry summer the flowing stream density increased up to five times. The best description of the pattern of stream expansion is a combination of the variable source area and the element threshold concepts, where surface topography and local storage areas controls where streamflow is initiated and how flow in different stream segments connects.

Mapping the temporary streams in steep and remote watersheds as a function of hydrological conditions is not an easy task. It is however necessary in order to fully understand where water is flowing and not.

The conclusions are:

1. Increasing wetness conditions (represented by increasing discharge) leads to an increase in active drainage density and connected drainage density

2. Streams in the Alptal show a seasonally bottom up or disjointed connection pattern

3. Topography, particularly TWI and A, controls which sections of the stream are flowing

4. The surface topography has an effect on the flow initiation, however, in order to understand the controlling factor of where the stream begins, local properties of the stream head need to be studied as well.

5. A combination of field observations with monitoring equipment can facilitate this extensive work by providing a more detailed temporal resolution.

6. REFERENCES

Ackermann, F., (1999). “Airborne laser scanning – present status and future expactations.” *ISPRS Journal of Photogrammetry & Remote Sensing* **54**: 64–67.

Acuña, V., Datry, T., Marshall, J., Barceló, D., Dahm, C. N., Ginebreda, A., McGregor, G., Sabater, S., Tockner, K., Palmer, M. A., (2014).”Why Should We Care About Temporary Waterways?” *Science* **343**: 1080-1081.

Ali, G.A., Roy, A.G., (2009). “Revisiting hydrologic sampling strategies for an accurate assessment of hydrologic connectivity in humid temperate systems.” *Geography Compass* **3**: 350–374.

Ambroise, B., (2004). “Variable, ‘active’ versus ‘contributing’ areas or periods: a necessary distinction.” *Hydrological Processes* **18**(6): 1149–1155.

Anderson, M.G., Burt, T.P., (1978). “The role of topography in controlling throughflow generation.” *Earth Surface Processes and Landforms* **3**: 331-344.

Beven, K. J., and Kirkby, M. J., (1979). “A physically based variable contributive area model of basin hydrology.” *Hydrological Sciences Bulletin* **24:** 43–69.

Bhamjee, R., Lindsay, JB., (2011). “Ephemeral stream sensor design using state loggers.” *Hydrology and Earth System Sciences* **15**(3): 1009–1021.

Bishop, K., Buffam, I., Erlandsson, M., Fölster, J., Laudon, H., Seibert, J., and Temnerud, J., (2008). “Aqua Incognita: The unknown headwaters.” *Hydrological Processes* **22**: 1239-1242.

Blyth, K., Rodda J., (1973). “A Stream Length Study.” *Water Resources Research* **9**(5): 1454-1461.

Boon, S., van Meerveld, H.J., Huxter, E. H., Peters, D. L., Spence, C., Whitfield, P. H., (2012). “Introduction to Special Issue: Prediction in Ungauged Basins (PUB) Workshop on Temporary Streams.” *Canadian Water Resources Journal* **37**(4): 275-278.

Burch, H., (1994).“ Ein Rückblick auf die hydrologische Forschung der WSL im Alptal.“ *Beiträge zur Hydrologie der Schweiz: Mitteilungen der Versuchsanstalt für Wasserbau der ETH Zürich* **175**: 18-33.

Buttle, JM., Boon, S., Peters, DL., Spence, C., van Meerveld, HJ. (Ilja), Whitfield PH., (2012). “An Overview of Temporary Stream Hydrology in Canada.” *Canadian Water Resources Journal* **37**(4): 279-310.

Buttle, J.M., (2006). “Mapping first order controls on streamflow from drainage basins: the T^3 template.” *Hydrological Processes* **20**: 3415–3422.

Datry, T., Larned, ST., Tockner, K., (2014). “Intermittent Rivers: A Challenge for Freshwater Ecology.” *BioScience* **64**: 229-235.

Day, D.G., (1978). “Drainage density changes during rainfall.” *Earth Surface Processes* **3**: 319–326.

Day D.G., (1980). “Lithologic controls of drainage density: A study of six small rural catchments in New England.” *N.S.W. Catena* **7**: 339– 351.

Dunn, O. J., (1964). “Multiple comparison using ranked sums.” *Technometrics* **6**(3): 241-252.

Dunne, T., (1978). “Field studies of hillslope flow processes.” *Hillslope hydrology* **1**: 227-293.

Erskine, R. H., Green, T. R., Ramirez, J.A., MacDonald, L.H., (2006). “Comparison of grid-based algorithms for computing upslope contributing area.” *Water resources research* **42**(9): W09416.

Feyen, H., Leuenberger, J., Papritz, A., Gysi, M., Flühler, H., Schleppi, P., (1996). “Runoff processes in catchments with a small scale topography.” *Physics and Chemistry of the Earth* **21**: 177–181.

Fischer, B. M. C., Rinderer, M., Schneider, P., Ewen, T., Seibert, J., (2015). “Contributing sources to baseflow in pre-alpine headwaters using spatial snapshot sampling.” *Hydrological Processes:* DOI: 10.1002/hyp.10529.

Freeman, T., (1991). “Calculating catchment area with divergent flow based on a regular grid.” *Computers and Geosciences* **17**(3): 413–422.

Godsey, S.E., Kirchner, J.W., (2014). “Dynamic, discontinuous stream networks: hydrologically driven variations in active drainage density, flowing channels and stream order.” *Hydrological Processes* **28**: 5791-5803.

Goulsbra, C. S., Evans, M., Lindsay, J., (2014). “Temporary streams in a peatland catchment: pattern, timing and controls of a stream network expansion and contraction.” *Earth Surface Processes and Landforms* **39**(6): 790-803.

Gregory, K. J., Walling, D. E., (1968). “The variation of drainage density within a catchment.” *International Association of Scientific Hydrology* **13**:2, 61-68.

Gurnell, AM., (1978). “The dynamics of a drainage network.” *Nordic Hydrology* **9**: 293–306.

Henkle, J. E., Wohl, E., Beckman, N., (2011). “Locations of channel heads in the semiarid Colorado Front Range, USA” *Geomorphology* **129**: 309- 319.

Holden, J., Burt, T. P., (2002). “Piping and pipeflow in a deep peat catchment.” *Cantena* **48**: 163-199.

Holden, J., (2006). “Sediment and particulate carbon removal by pipe erosion increase over time in blanket peatlands as a consequence of land drainage.” *Journal of Geophysical Research* **111**: F02010.

Horton, R. E., (1932). “Drainage basin characteristics.” *American Geophysical Union* **13**(1): 350-361.

Horton, R. E., (1945). “Erosional Development of Streams and their Drainage Basins; Hydrophysical Approach to Quantitative Morphology.” *Bulletin of the geological society of America* **56**: 275-370.

Hewlett, J. D., and Hibbert, A. R., (1967). “Factors affecting the response of small watersheds to precipitation in humid areas.” *Forest hydrology* **1**: 275–290.

Kruskal, W. H., Wallis, A. W., (1952). “Use of Ranks in One-Criterion Variance Analysis.” *Journal of the American Statistical Association* **47**(260): 583-621.

Larned, ST., Datry, T., Arscott, DB., Tockner, K., (2010). “Emerging concepts in temporary-river ecology.” *Freshwater Biology* **55**: 717–738.

McDonnell, J. J., Woods, R., (2004). “On the need for catchment classification.” *Journal of Hydrology* **299**: 2–3.

Meyer, JL., Strayer, DL., Wallace, JB., Eggert, SL., Helfman, GS., Leonard, NE., (2007). “The contribution of headwater streams to biodiversity in river networks.” *Journal of the American Water Resources Association* **43**(1): 86–103.

Montgomery, D. R., Dietrich, W. E., (1994). “A physically based model for the topographic control on shallow landsliding.” *Water Resources Research* **30**: 1153–1171.

Morgan, R., (1972). “Observations on factors affecting the behaviour of a first order stream.” *Transactions of the Institute of British Geographers* **56**: 171–185.

O’Callaghan, J. F., and Mark, D. M., (1984). “The extraction of drainage networks from digital elevation data.” *Computer Vision, Graphics, and Image Processing* **28**: 323–344.

Peirce, S. E., Lindsay, J.B., (2014). “Characterizing ephermal streams in a southern Ontario watershed using electrical resistance sensors.” *Hydrological Processes* **29**: 103-111.

Pringle, C., (2003). “What is hydrologic connectivity and why is it ecologically important?” *Hydrological Processes* **17**: 2685-2689.

Rinderer, M., van Meerveld, HJ. (Ilja), Seibert, J., (2014). “Topographic controls on shallow groundwater levels in a steep, prealpine catchment: when are the TWI assumptions valid?” *Water Resources Research* **50**: 6067–6080.

Ritchie, J. C., (1996). “Remote sensing applications to hydrology: airborne laser altimeters,” *Hydrological Sciences Journal* **41**(4): 625-636.

Robert, MC., Archibold, OW., (1978). “Variation of drainage density in a small British Columbia watershed.” *Journal of the American Water Resources Association Water* **14**(2): 470–476.

Schleppi, P., Muller, N., Feyen, H. (1998). „Nitrogen budgets of two small experimental forested catchments at Alptal, Switzerland.” *Forest Ecology and Management* **127**: 177-185.

Sidak, Z., (1967). “Rectangular Confidence Regions for the Means of Multivariate Normal Distributions.” *Journal of the American Statistical Association* **62**(318): 626-633

Spence, C., and Woo, M. K., (2006). “Hydrology of subarctic Canadian Shield: Heterogeneous headwater basins.” *Journal of Hydrology* **317**: 138-154.

Spence, C., Guan, XJ., Phillips, R., Hedström, N., Granger, R., Reid, B., (2010). “Storage dynamics and streamflow in a catchment with a variable contributing area.” *Hydrological Processes* **24**: 2209-2221.

Steward, A. L., von Schiller, D., Tockner, K., Marshall, J. C., Bunn, S. E., (2012). “When the river runs dry: Human and ecological values of dry riverbeds.” *Frontiers in Ecology and the Environment* **10**(4): 202-209.

Sörensen, R., Seibert, J., (2007). “Effects of DEM resolution on the calculations of topographical indices: TWI and its components.” *Journal of Hydrology* **347**: 79– 89.

Tarboton, D. G., (1997). “A New Method for the Determination of Flow Directions and Upslope Areas in Grid Digital Elevation Models.” *Water Resources Research* **33**: 309–319.

Troch, P. A., Mancini, M., Paniconi, C., and Wood, E. F., (1993). “Evaluation of a distributed catchment scale water balance model.” *Water Resources Research* **29**(6): 1805–1817.

Tromp van Meerveld, H.J. (Ilja), McDonnell, J.J., (2006). “Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis.” *Water Resources Research* **42**: W02411.

Uchida, T., Tromp van Meerveld, H.J. (Ilja), McDonnell, J. J., (2005). ”The role of lateral pipe flow in hillslope runoff response: an intercomparison of non-linear hillslope response.” *Journal of Hydrology* **311**: 117-133.

Uys, M. C., and O’Keeffe, J. H., (1997). “Simple words and fuzzy zones: Early directions for temporary river research in South Africa.” *Environmental Management* **21**: 517-531.

Vaze, J., Teng, J., and Spencer, G., (2010). “Impact of DEM accuracy and resolution on topographic indices.” *Environmental Modelling & Software* **25**(10): 1086–1098.

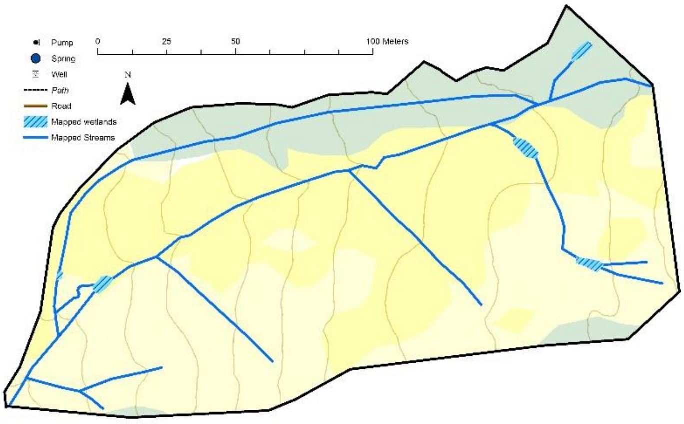
Wehr, A., Lohr, U., (1999). “Airborne Laser Scanning – An introduction and overview.” *ISPRS Journal of Photogrammetry and Remote Sensing* **54**: 68-82.

Wiginton, Jr P. J., Moser T. J., Lindeman D. R., (2005). “Stream network expansion: a riparian water quality factor.” *Hydrological Processes* **19:** 1715-1721.

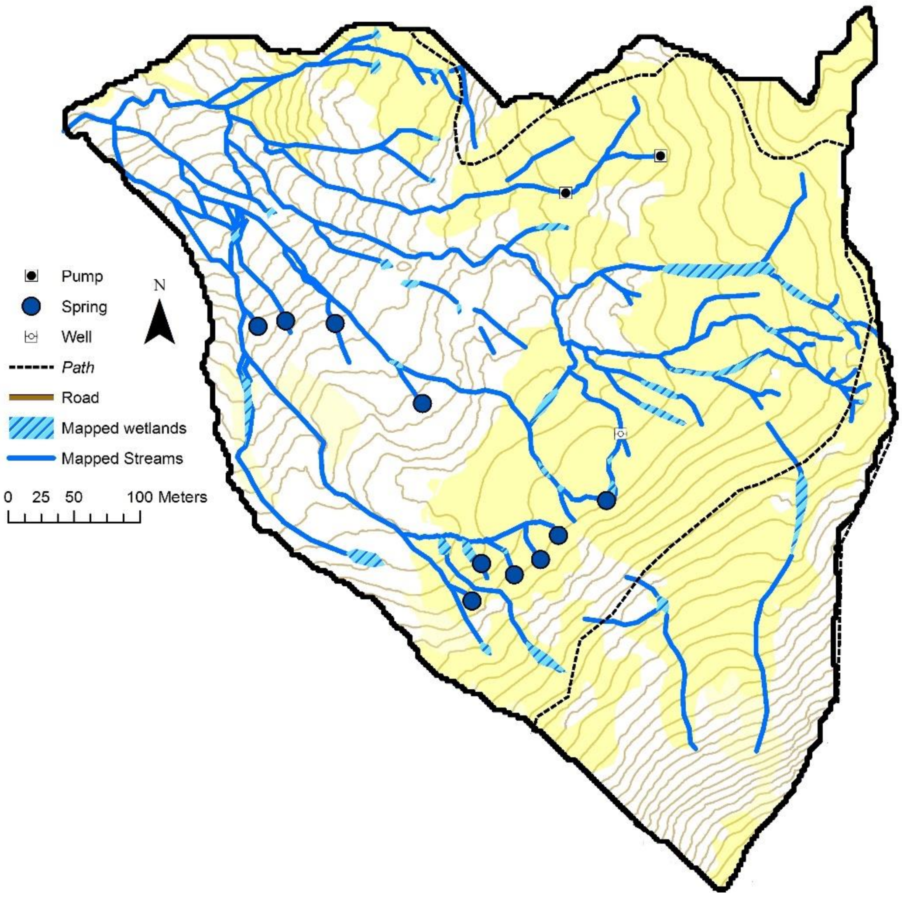
Zhou, Q. and Liu, X., (2002). “Error assessment of grid-based flow routing algorithms used in hydrological models.” *International Journal of Geographical Information Science* **16**(8): 819–842.

APPENDIX A – MAPS OF MAPPED STREAMS, WETLANDS, SPRINGS AND PUMPING STATIONS IN ALL CATCHMENTS

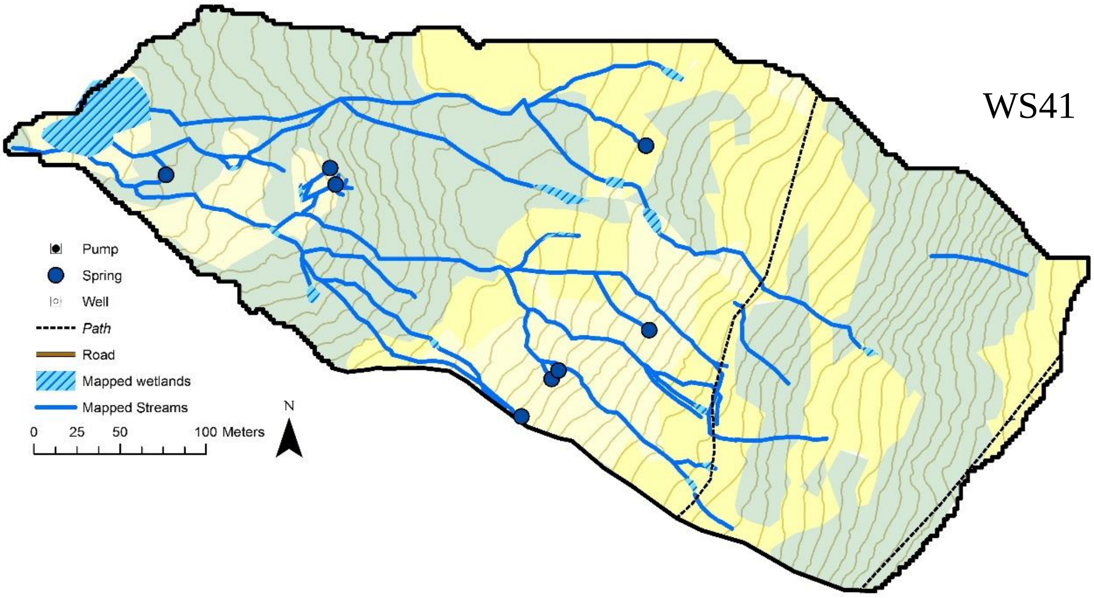
Notice that the scale differs between the catchments. The mapped wetlands are such that affect the streamflow directly, they differ from the federal wetland survey shown in the land use maps (fig. 16).

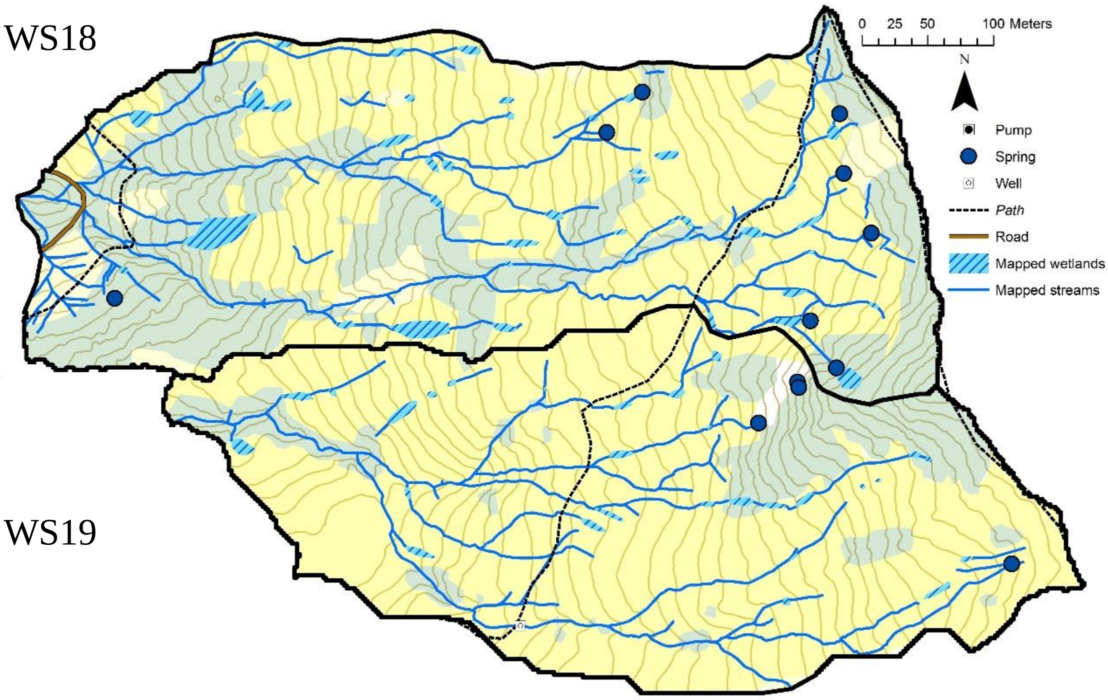


WS3



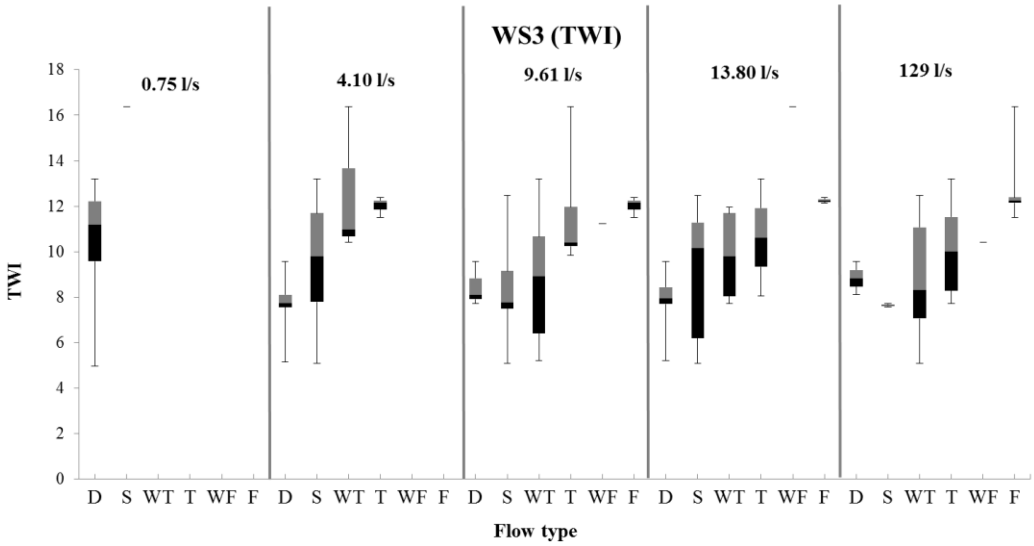
WS4

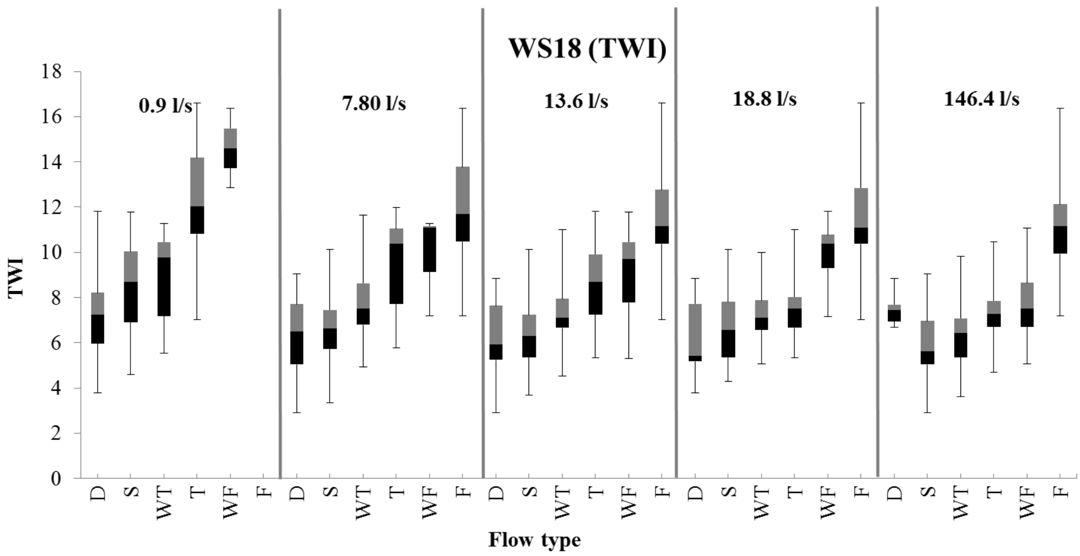

WS41
Pump
Spring
Well
Path
Road
Mapped wetlands
Mapped Streams
N
0 25 50 100 Meters

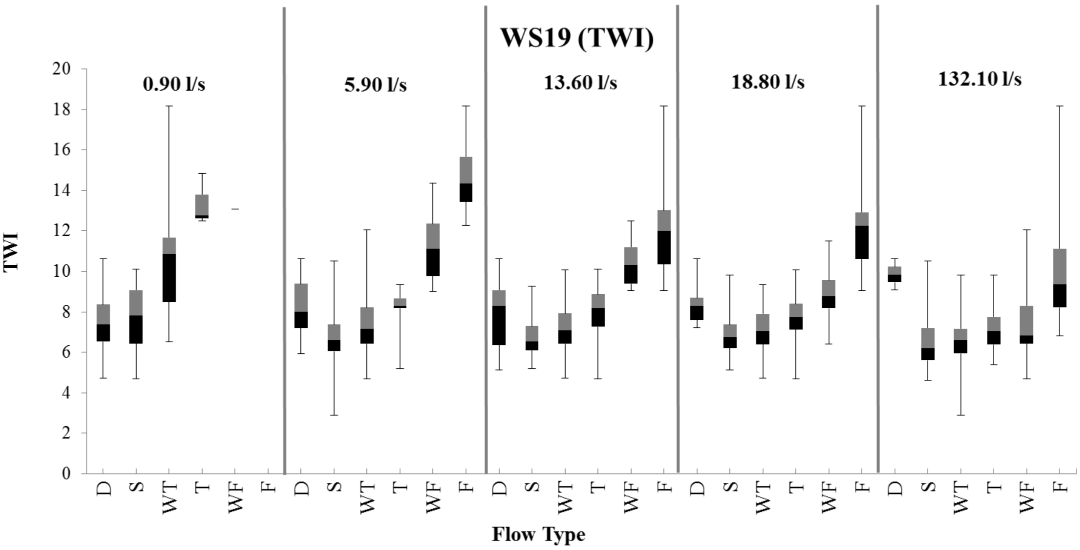

WS18
WS19
0 25 50 100 Meters
N
Pump
Spring
Well
Path
Road
Mapped wetlands
Mapped streams

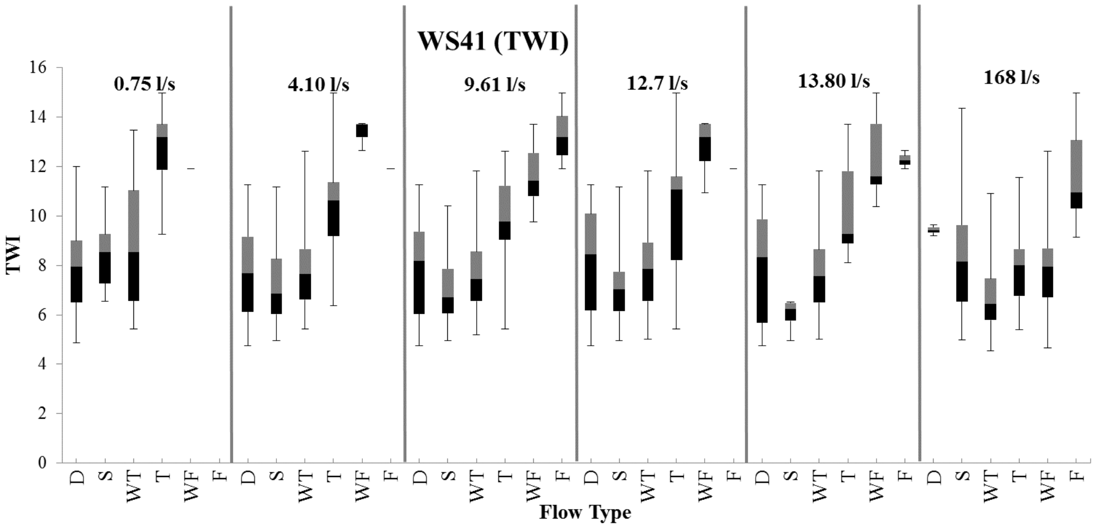
APPENDIX B – BOXPLOTS OF THE TWI OF THE STREAM SEGMENTS IN WS3, WS18, WS19 AND WS41

Boxplots of the TWI-values for each stream segment that belongs to a certain flow class in WS3, WS18, WS19 and WS41 during the five or six field campaigns. The whiskers of each boxplot show the minimum and maximum values and the top and bottom of the box the 75th and 25th percentile. The line separating the black and grey inside the box shows the mean value.






WS19 (TWI)
0.90 l/s
5.90 l/s
13.60 l/s
18.80 l/s
132.10 l/s
TWI
Flow Type
D
S
WT
T
WF
F


WS41 (TWI)
0.75 l/s
4.10 l/s
9.61 l/s
12.7 l/s
13.80 l/s
168 l/s
TWI
Flow Type
D
S
WT
T
WF
F

APPENDIX C - ANALYSIS OF VARIANCE OF THE TWI OF THE FLOW TYPE SEGMENTS IN WS18, WS19 AND WS41

Analysis of variance of the TWI of the different flow class in WS18, WS19 and WS41 as a function of discharge. The analysis was performed with a Kruskal-Wallis test with Dunn´s post hoc test. The letters, A-D, indicates groups in which the flow type classes were not significantly different

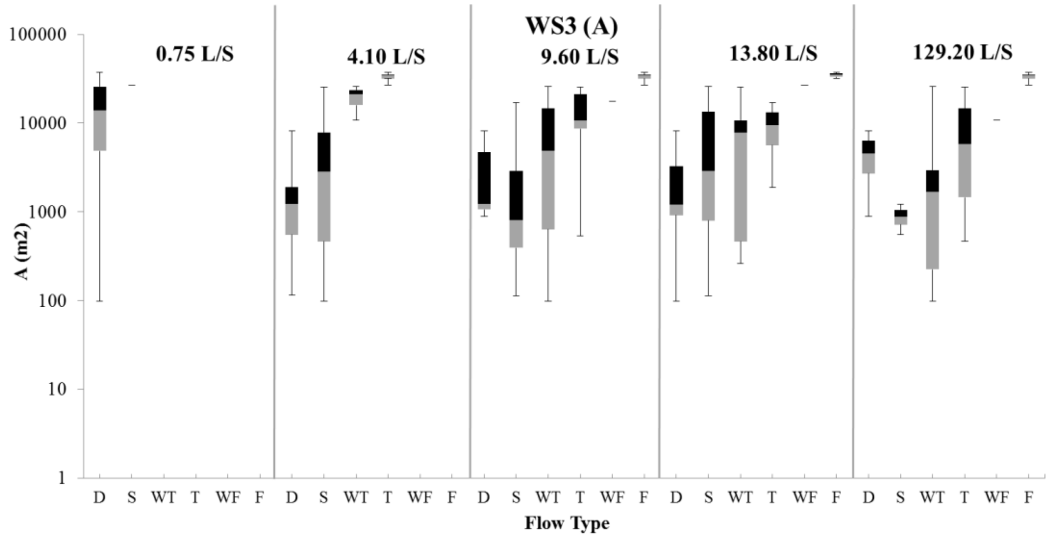
WS18	Flow type					
Q (l/s)	D	S	WT	T	WF	F
0.90	A	A	AB	B	AB	-
5.90	ABC	C	C	A	A	B
13.6	AC	C	AD	AB	BD	B
18.80	AC	AC	CD	BD	ABCD	B
132.08	A	A	A	AC	BC	B

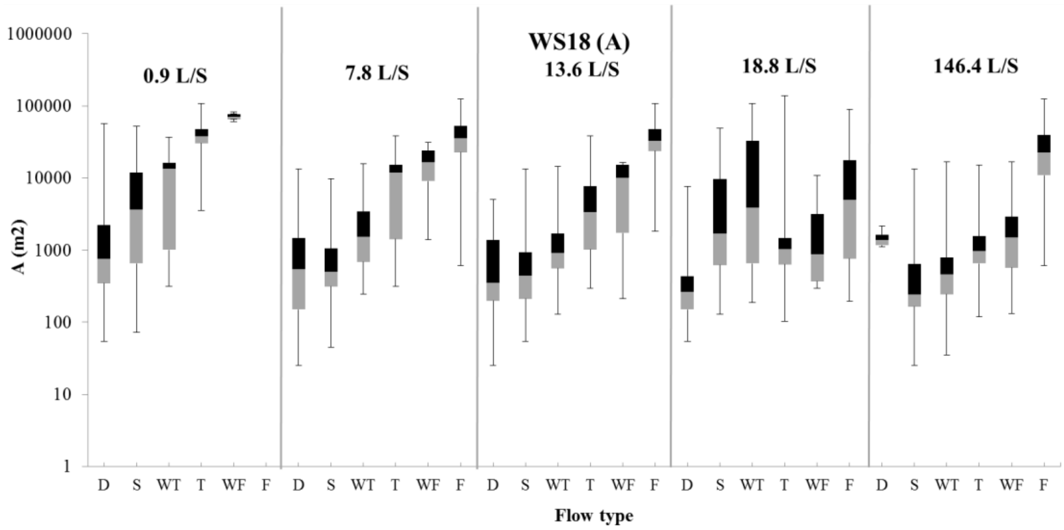
WS19	Flow type					
Q (l/s)	D	S	WT	T	WF	F
0.90	A	AC	BC	B		
5.90	AB	A	A	A	A	B
13.6	ACD	C	D	AD	AB	B
18.80	AB	A	A	AB	B	B
132.08	ABC	A	A	AC	BC	B

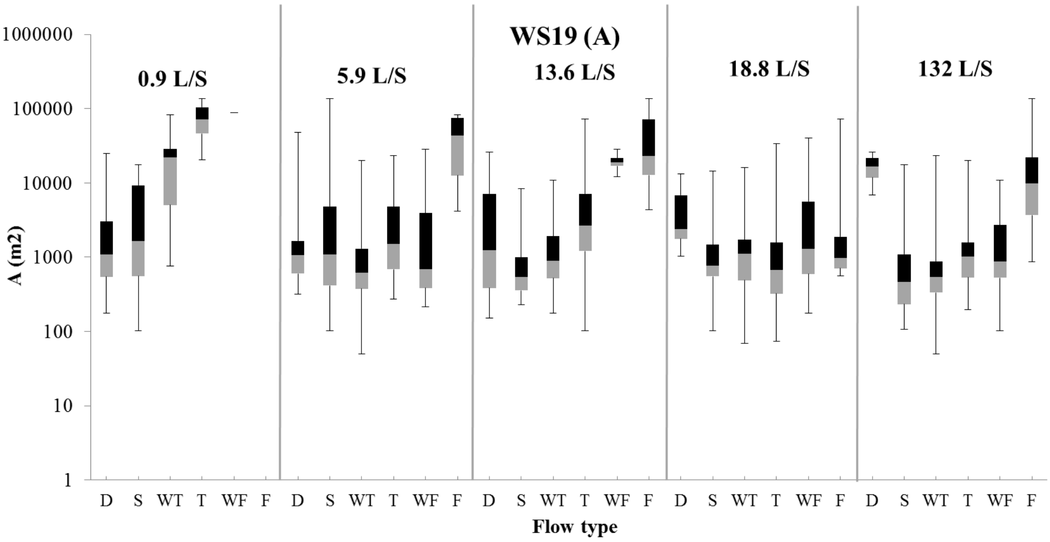
WS41	Flow type					
Q (l/s)	D	S	WT	T	WF	F
0.75	A	AB	AB	B		
4.10	AC	A	AC	BC	B	
9.61	ABC	A	A	CD	D	BCD
12.7	AC	C	AC	AB	B	B
13.80	A	A	AB	C	BC	
168	AB	A	A	A	A	B

APPENDIX D - BOXPLOTS OF THE UPSLOPE ACCUMULATED AREA OF THE STREAM SEGMENTS IN WS3, WS18, WS19 AND WS41

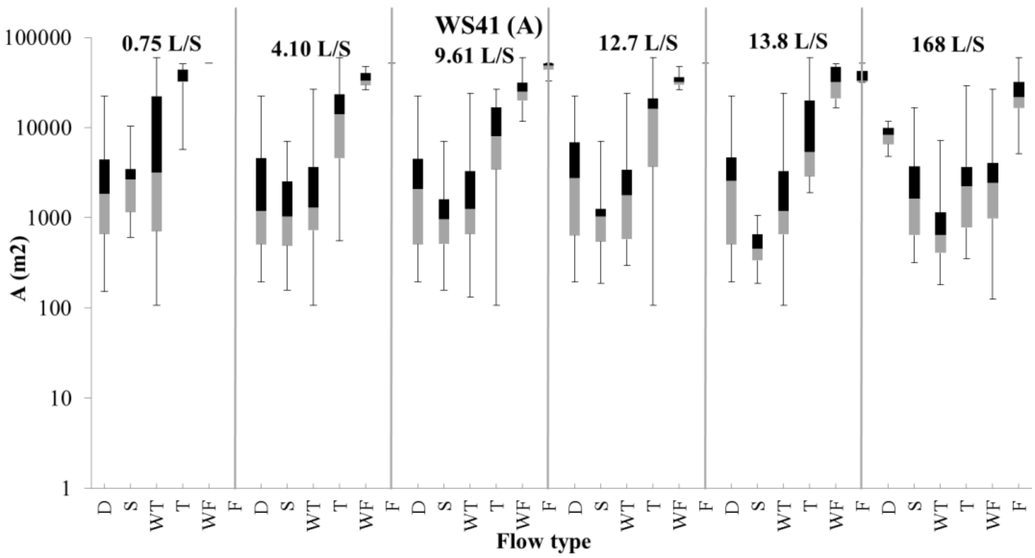
Boxplots of the upslope accumulated area of stream segment in different flow classes in WS3, WS18, WS19 and WS41 during the five or six field campaigns. The whiskers of each boxplot show the minimum and maximum values and the top and bottom of the box the 75th and 25th percentile of the samples. The line separating the black and grey parts of the box shows the mean value.







WS19 (A)
0.9 L/S
5.9 L/S
13.6 L/S
18.8 L/S
132 L/S
A (m2)
Flow type
D S WT T WF F



WS41 (A)
0.75 L/S
4.10 L/S
9.61 L/S
12.7 L/S
13.8 L/S
168 L/S
A (m2)
Flow type
D S WT T WF F

APPENDIX E – STREAM HEADS IN THE STUDY CATCHMENTS

The number of stream heads (n), the percent connected heads and the location of the source (in percent), in each study catchment as a function of discharge. Notice that a stream source can be located in multiple categorizes, such as shallow soil and spring and that the percentage can thus add up to >100%

WS	Q (l/s)	N	Connected (%)	Shallow soil	Wetland	Spring	Pipe	Pump/Pool	Horton	Ditch
3	0.8	0	0	0	0	0	0	0	0	0
	4.1	2	100	0	50	0	0	0	0	50
	9.6	4	100	0	25	0	0	0	0	75
	13.8	4	50	0	25	0	0	0	0	75
	129.2	8	100	0	12.5	0	0	0	0	75
4	0.8	14	86	57	43	36	0	7	0	0
	4.1	23	78	35	52	35	0	4	0	13
	9.6	24	67	46	46	33	0	4	4	13
	13.8	30	77	37	57	20	0	3	3	10
	293.0	43	91	49	67	19	0	2	14	12
41	0.8	6	17	67	33	50	0	0	0	0
	4.1	12	17	67	33	50	0	0	8	0
	9.6	14	14	57	36	43	0	0	7	0
	12.7	14	14	43	43	29	0	0	14	0
	13.8	19	16	53	26	47	0	0	11	0
	168	22	18	64	41	32	0	0	27	0
18	0.9	5	0	60	20	20	20	20	0	20
	7.8	21	33	52	48	14	14	0	0	10
	13.6	22	45	59	41	23	5	0	0	9
	18.8	26	54	42	54	15	12	0	4	12
	146.4	53	60	55	30	15	9	0	2	21
19	0.9	3	0	67	0	0	33	33	0	33
	5.9	8	63	13	50	0	13	13	0	25
	13.6	16	63	38	19	0	13	6	13	25
	18.8	15	80	40	13	0	13	7	0	40
	132.1	31	74	71	13	13	3	3	3	35