Department of Geography

Occurrence and Chemical Composition of Overland Flow in a Pre-alpine catchment, Alptal (CH)

GEO 511 Master's Thesis
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Cover picture: overland flow collector installed at a wetland site (T. Sauter, September 2016)

Abstract

Heavy precipitation can lead to high peak flows in streams and to floods downstream. Overland flow, as a fast runoff process, contributes to these peak flows. Overland flow occurs frequently on low permeable and shallow soils because of low infiltration rates and limited storage capacity, respectively. In pre-alpine regions, little is known about frequencies of overland flow occurrence and its chemical composition under natural rainfall conditions. This initial study focuses on the overland flow occurrence on four different land cover types (bare land, forest, meadow, and wetland) in a pre-alpine headwater catchment with shallow Gleysols. To capture the spatial and temporal variability, 50 overland flow collectors were installed in the field and served as ON-OFF-detectors and as overland flow samplers. For 14 events between August and October 2016, the rainfall characteristics were compared to the frequency of overland flow occurrence for the different land cover types. Three events were sampled and analyzed on stable water isotopes and element concentrations. Fractions of pre-event water in overland flow were calculated based on δ^2H, $\delta^{18}O$, Ca concentrations and electrical conductivity. Onset times of overland flow were measured with built-in electrical resistance measurement devices at 9 locations to get additional information on overland flow generation.

Overland flow occurrence and its chemical composition vary largely within few meters. It was found that overland flow occurs the most frequent on bare land (78 %) and on wetland (66 %). Overland flow occurs less frequent on meadow (42 %), even less in forest (5 %). However, the variability of the frequency of occurrence was relatively high for locations of the same land cover type. The frequency of occurrence was significantly controlled by rainfall characteristics, in particular, by rainfall amount and by maximum 1 hour rainfall intensities. Antecedent soil moisture condition showed no clear influence on the frequency of overland flow occurrence. Event water fractions were generally high for bare land, and low for wetland, while meadow was in the medium range of 50 % event water. Overall, the results point to saturation-excess overland flow as dominant overland flow generation process for the land cover meadow, wetland and forest. On bare land, infiltration-excess overland flow cannot be excluded due to the very small hydrologically active horizon over almost impermeable Flysch. However, different overland flow processes may even occur with changing rain characteristics and antecedent soil moisture conditions on the same land cover.

Overland flow is a frequent and spatiotemporally variable runoff component in the Studibach catchment with shallow and low permeable soils. This study shows the necessity to take overland flow processes into account for the understanding of runoff generation in the catchment. A follow-up study could quantify this contribution of overland flow with a focus on heavy precipitation. The understanding of overland flow processes is important to assess their fast contribution to peak flows. Since the Sihl has a large risk potential due to the high vulnerability of Zurich to floods, an accurate assessment of peak flows is important

Key words: overland flow generation, frequency of overland flow occurrence, land cover comparison, chemical composition, isotope hydrology, fractions of pre-event and event water

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List of used abbreviations

Al	aluminum [concentration in µg l^{-1}]
B; BA, BB, BC	bare land; bare land sites
BF	base flow
C	element concentration or degree Celsius [°]
Ca	calcium [concentration in mg l^{-1}]
DEM	digital elevation model
DRI	double ring infiltrometers
EC	electric conductivity [μS cm^{-1}]
F; FA, FB	forest; forest sites
f_e; f_p	event water fraction; pre-event water fraction
GMWL	global meteoric water line
GW	groundwater
HOF	infiltration-excess overland flow or Hortonian overland flow
K	potassium [concentration in mg l^{-1}]
K_{sat}	saturated hydraulic conductivity [mm h^{-1} or m day^{-1}]
LMWL	local meteoric water line
M; MA, MB, MC	meadow; meadow sites
NP	not possible
OFC	overland flow collector
P	precipitation
Q	discharge
sd	standard deviation
SL	suction lysimeter
SM	soil moisture, soil water
SOF	saturation-excess overland flow
TF	throughflow
TWI	topographic wetness index
W; WA, WB, WC	wetland; wetland sites
WT	water table
Zn	zinc [concentration in µg l^{-1}]

1. Introduction

Climate change affects the hydrological cycle. Heavy precipitation increased in frequency and intensity for more than 90 % of the Swiss observation stations during the 1901-2014 period (Scherrer et al., 2016). Heavy precipitation is defined locally based long-term precipitation measurements as the range of daily precipitation that is surpassed by 1 % of events. This definition results varying thresholds for heavy precipitation between 25 mm d^{-1} and more than 100 mm d^{-1} for different meteo stations in Switzerland (Scherrer et al., 2016). Heavy precipitation can occur in intense thunderstorms that last for less than a few hours or in less intense precipitation over a longer time period. Precipitation intensity and the precipitation amount both affect the hydrological processes on the ground surface and in the soil. Before reaching the ground, rainwater is partly intercepted by vegetation. On the natural ground, rainwater will either infiltrate into the soil, be stored in micro-depressions, or flow downslope on the surface as overland flow or surface runoff. Infiltrated water will either replenish soil moisture, flow as subsurface flow towards a stream or recharge groundwater. All these processes have different travel times and lead to a different runoff response. Since overland flow has a shorter travel time than subsurface flow, overland flow reaches the stream faster (Moody and Martin, 2015; Sidle et al., 2007; Pilgrim, 1976). Additionally, overland flow can have a high connectivity to the stream and can connect large areas (Srinivasan et al., 2002; Gomi et al., 2008). Hence, overland flow can lead to high peak stream flows during heavy precipitation and floods in downstream areas (Elsenbeer and Lack, 1996; Dunne and Black, 1970a).

Overland flow is also an important process for erosion, and sediment and solute transport. Overland flow transports particles that were detached from the soil by raindrop splash erosion, and when concentrated in microtopographic rills, overland flow also leads to rill erosion (Wainwright et al., 2000; Horton, 1945). Dense vegetation on grassland reduces the erosion, but nutrient transport by overland flow can be increased by the vegetation (Wainwright et al., 2000). In agricultural catchments, fertilizer and pesticides are mainly transported by overland flow to the streams (Kurz et al., 2005).

1.1. Objectives

Most studies on overland flow have been conducted in agricultural areas, semi-arid areas, where vegetation is limited, and in tropical areas, where rainfall intensities are high. Relatively little is known about overland flow in pre-alpine catchments. In this Master thesis, overland flow is studied on bare land, forest, meadow and wetland in a pre-alpine catchment. The chemical composition of overland flow is analyzed to document its chemical variability and to determine the source and composition of overland flow, i.e., rainwater, soil water and groundwater.

The objectives of this master thesis are to

- document the occurrence and determine the importance of overland flow in a Swiss pre-alpine headwater catchment,
- determine the effect of land cover, rainfall amount, and intensity on the occurrence of overland flow for a Swiss pre-alpine headwater catchment,
- determine the chemical composition of overland flow, its spatiotemporal variability in chemistry, and the fraction of event and pre-event water in overland flow
- infer the main process of overland flow generation.

1.2. Research Questions

The specific research questions are:

1. During which conditions (rainfall amount, rainfall intensity, and antecedent soil moisture condition) does overland flow occur and how does the land cover (bare land, forest, meadow, and wetland) affect the frequency of occurrence of overland flow?
2. What is the spatiotemporal variability in the chemistry and the isotopic composition of overland flow?
3. How does the fraction of event (rainfall) and pre-event (soil) water in overland flow vary for different rainfall conditions and how is it affected by land cover?

2. Literature Review

2.1. Overland flow processes

Overland flow is the downslope movement of water on the land surface. Overland flow is the initial phase of surface runoff and flows as broad sheet flow or as concentrated flow in microtopographic rills, before overland flow reaches a defined channel (Emmett, 1970).

There are two main processes of overland flow generation: Horton Overland Flow (HOF; Figure 1) and Saturation-excess Overland Flow (SOF; Figure 2). If the rain intensity is higher than the infiltration rate into the soil, the resulting flow on the surface is called infiltration-excess overland flow (Figure 1). It is also called Horton Overland Flow (HOF) after Robert E. Horton (Horton, 1933). The infiltration rate (in mm h^{-1} or m day^{-1}) is the volume that infiltrates into the soil in a given time and is highly affected by pore size and pore connectivity (Hendriks, 2010: 60). During a rainfall event, the infiltration rate decreases because of the decrease in sorptivity (i.e. hydraulic gradient) as the wetting front deepens. The steady state infiltration rate is then equal to the saturated hydraulic conductivity (K_{sat}). The hydraulic conductivity describes the rate of water transmission through the soil pore system and can be determined for saturated or unsaturated conditions. The K_{sat} is usually used in the literature because the unsaturated hydraulic conductivity is more difficult to measure and depends on the moisture content of the soil. Low saturated hydraulic conductivities will lead to low lateral and vertical flow and to a fast saturation of the soil during rainfall events (Hendriks, 2010: 64f).

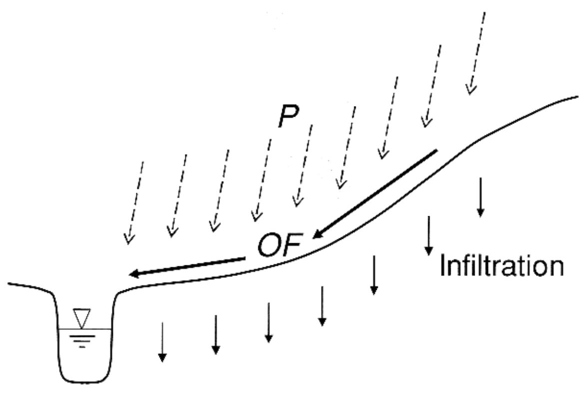


Figure 1: Scheme of the infiltration-excess overland flow (HOF) mechanism: The precipitation rate (P) exceeds the infiltration capacity of the soil, and the precipitation surplus will flow downslope on the ground surface (from Brutsaert 2005:443).

When the water table rises to the soil surface and no more water can infiltrate into the soil because there is no available storage in the soil, the resulting overland flow is called Saturation-excess Overland Flow (SOF; Figure 2; Dunne and Black, 1970a). SOF starts only after the rainfall saturated the soil or the soil horizons over a low permeable horizon. The interplay between overland flow and saturated areas was studied with a dense measurement system for overland flow and soil moisture on a seldom mowed grassland plot by Srinivasan et al. (2002). The response of overland flow on the hillslope was dependent on the rainfall amount. Saturated areas and areas with overland flow varied during and between events and did partly overlap, so that not all saturated areas produced SOF, and HOF was also occurring on not saturated areas (Srinivasan et al., 2002).

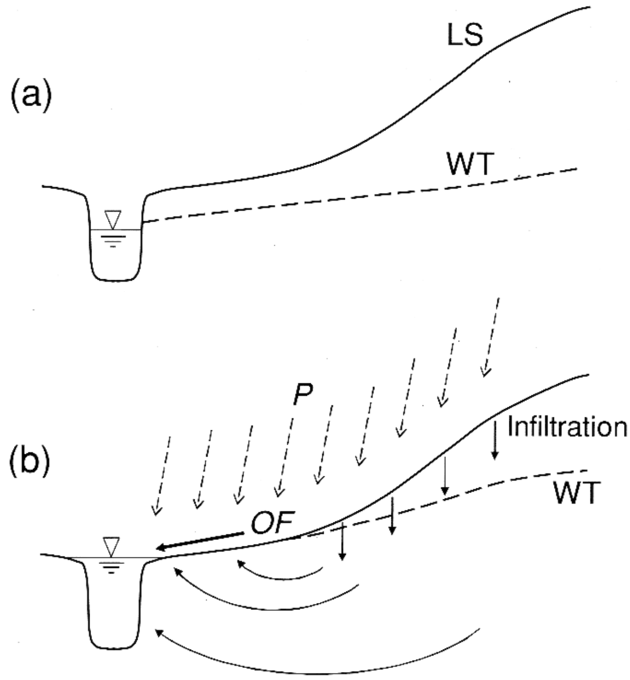


Figure 2: Scheme of the saturation-excess overland flow (SOF) mechanism: (a) the water table (WT) is below the ground surface prior to the rainfall event and groundwater contributes to the stream. (b) the water table (WT) rises during a rainfall event due to infiltration in unsaturated areas (where infiltration rate > precipitation rate). SOF occurs where the soil is completely saturated and the WT reaches the ground surface. Then overland flow, throughflow and groundwater flow are sources of streamflow (from Brutsaert, 2005: 444).

Subsurface water that exfiltrates and then flows over the surface as overland flow is called return flow. Exfiltration can occur when lateral inflows are higher than the drainage capacity, when the (perched) ground water level rises above the soil surface or when macropore pipes get activated and intersect the soil surface (Wainwright et al., 2000; Elsenbeer and Lack, 1996; Feyen et al., 1996). Subsurface flows that are intercepted by roads or by landslides can also lead to exfiltration and overland flow (Ziegler et al., 2001; Megahan, 1983). SOF is often a mixture of rain water, soil water, and return flow.

Scherrer and Naef (2003) and Lima (1989) subdivided these two main overland flow processes further based on the overland flow responses during artificial irrigation experiments: immediate HOF and delayed HOF, and immediate SOF, delayed SOF, and topsoil SOF. Immediately HOF occurs on relative impermeable surfaces, for example, natural surfaces with very low infiltration rates (soils with high clay content, compacted soils, bedrock) and impermeable surfaces in urban areas. Temporary and delayed HOF can occur caused by special soil properties (hydrophobicity, crusted soils) or by changes in the soil due to wetting. The infiltration rates on swelling clay soils can decrease quickly when the wetness increases. Immediate SOF occurs on soils with a high initial water level and little lateral flow. Delayed SOF occurs on thick macroporous soils and occurs only after extensive rainfalls. Topsoil SOF occurs on shallow soils with little lateral flow over less permeable soils or bedrock (Scherrer and Naef, 2003; Lima, 1989). For temperate grassland, Scherrer and Naef (2003) developed a decision scheme to indicate dominant hydrological surface and subsurface flow processes. The decision scheme is valid for grassland soils that are not significantly influenced by groundwater. Other decision schemes are needed for arable land and forest due to the more complex surface-topsoil interface (Scherrer and Naef, 2003).

2.2. Factors affecting overland flow

Overland flow has been studied in different contexts and in various areas over the world. Factors that affect overland flow can be of meteo-hydrological (Moody and Martin, 2015; Zimmermann et al., 2014), topographical (Sinun et al., 1992), pedological (Scherrer, 1996) and geological (Godsey et al., 2004) type. Overland flow characteristics can further be altered by land cover and vegetation (de Moraes et al., 2006; Abrahams et al., 1994), or by anthropogenic influences (Kurz et al., 2005). As overland flow is affected by many factors, there is a high spatial and temporal variability of overland flow (Srinivasan et al., 2002; Elsenbeer and Lack, 1996). Elsenbeer and Lack (1996) measured frequencies of overland flow occurrence for different locations in a rainforest catchment. Locations with high frequencies of overland flow (> 80 %) were in close proximity to locations with low frequencies of overland flow occurrence (< 20 %). For three locations, continuous overland flow volume measurements led to insight into different inter-event and intra-event responses of overland flow. The differences in overland flow varied for the different locations with antecedent soil moisture conditions (Elsenbeer and Lack, 1996). Srinivasan et al. (2002) studied the spatiotemporal variability of overland flow on a hillslope with a dense measurement system for overland flow and saturation of the soil. Changing rainfall intensities and increasing rainfall amounts led to SOF and HOF areas of varying spatial extents (Srinivasan et al., 2002). Dynamic factors, for example, rainfall characteristics, can therefore lead to different overland flow processes on the same surface. In this subchapter, the factors affecting occurrence of overland flow are reviewed from a world perspective to a regional perspective for Switzerland and the pre-alpine region.

2.2.1. Factors affecting spatial variability in overland flow occurrence

2.2.1.1. Soil characteristics

Soil types are characterized by soil properties, soil material and diagnostic horizons (IUSS Working Group WRB, 2014). Soil properties and especially topsoil properties can influence the overland flow generation. Hydraulic conductivity, that is affected by soil density and soil porosity, determines the infiltration capacity of rainfall and the drainage rate and therefore affects overland flow generation (Dehotin et al., 2015; Ziegler et al., 2004). Soil depth determines the storage capacity of water, for example, shallow soils need less precipitation until saturation (Ferreira et al., 2016). High initial soil moisture content can accelerate the saturation process. The soil material influences the soil properties and the chemistry of overland flow due to specific solutes in the soil water. Therefore, the overland flow generation can be generally deduced from soil types and its properties (Scherrer, 1996). Overland flow is also influenced by the microtopography of the soil surface, for example, by soil roughness and depression storage (Peñuela et al., 2015), but overland flow also forms the microtopography of the soil (Darboux et al., 2001).

Since soil type depends also on the lithology, neighboring catchments of different lithology in Panama rainforest showed different responses to rainfall (Godsey et al., 2004). The flashy response of the Cambisol catchment over siltstone and basalt was caused by frequent SOF due to a soil layer with a low hydraulic conductivity at 30 cm depth. The Oxisol catchment developed on andesite has a delayed rainfall response and only locally generated overland flow with a low frequency probably caused by deeper soils; the soil layers with low hydraulic conductivity are only expected below 50 cm depth (Godsey et al., 2004).

An irrigation study compared overland flow processes for different soil types in Switzerland (Scherrer, 1996). Gleysols and Podsols in a pre-alpine and alpine region had the highest overland flow runoff coefficients (> 80 %). Both soils had limited subsurface runoff. Cambisols and Regosols had distinct lower overland flow runoff coefficients (< 20 %), with one exception for a loamy Cambisol. In some locations, subsurface runoff was up to 20 %. Deep percolation was therefore the dominant process in Cambisols and Regosols (Scherrer, 1996).

Badoux et al. (2006) showed that Gleysol and Cambisol had different overland flow magnitudes and processes. The plots with Gleysol and Cambisol had different rooting depths less than 350 mm to more than 650 mm, respectively. The irrigation experiments resulted in overland flow runoff coefficients (i.e. the percentage of total precipitation that results in runoff) between 39 and 94 % for Gleysols, and between 0 and 16 % for Cambisols. On Gleysols, subsurface flow was the second dominant runoff process after overland flow, while deep percolation was dominant for Cambisols. For natural rainfall, runoff coefficients for 23 events varied between 4 and 70 % for Gleysols, and between 0 and 6 % for Cambisols. The overland flow processes were identified as SOF for Gleysol and temporary HOF for Cambisols caused by hydrophobic reaction of the litter layer (Badoux et al., 2006).

The topsoil K_{sat}, or infiltration rate, allows an estimation, if HOF occurrence is likely to occur (Dehotin et al., 2015). Occurring rainfall intensities that are exceeding the local topsoil K_{sat} will lead to overland flow because the rainwater cannot infiltrate the soil. However, hydraulic conductivity may vary from soil sample to hillslope scale and in lateral and vertical direction depending on the soil properties (Brooks et al., 2004). Swelling of the soil (e.g. with high clay content) and in-washing of fine materials into the pores of topsoil horizons can decrease the K_{sat} (Hendriks, 2010: 174). K_{sat} values can change also with land cover change (Dehotin et al., 2015; Ziegler et al., 2004). Sharp decreases in permeability with depth can lead to perched groundwater tables. Deeper soil horizons usually have a lower K_{sat} than upper ones due to the higher clay contents from illuviation, fewer roots and less bioturbation (Zimmermann et al., 2013; de Moraes et al., 2006). In catchments with low K_{sat} at shallow depths, ponding may occur above this horizons causing saturation, so that SOF is generated. This can lead to a flashy hydrologic response (Zimmermann et al., 2014).

In mountainous northern Vietnam, the highest mean K_{sat} values were found for upland fields (103 mm h^{-1}), grasslands (93 mm h^{-1}) and for the forest (63 mm h^{-1}), while abandoned fields (28 mm h^{-1}) had low K_{sat} values (Ziegler et al., 2004). The secondary vegetation on an abandoned field led to medium K_{sat} values. Human-created consolidated soils on roads and paths for the timber removal had K_{sat} values below 10 mm h^{-1}. The low K_{sat} will allow frequent HOF generation on consolidated surfaces. Because these surfaces are often linked to the stream, the hydrological impact of these surfaces is disproportionally high (Ziegler et al., 2004). In an overland flow-dominated forested catchment, K_{sat} values for the topsoil layer increased with increasing distances from gullies. Mean K_{sat} values were 4 mm h^{-1} in flowlines, 22 mm h^{-1} 5 m off flowlines, and 80 mm h^{-1}10 m off flowlines. Therefore, the potential for overland flow is high in and around flowlines (Zimmermann et al., 2013).

Soil roughness, defined as variation in the surface elevation, affects overland flow depression storage, infiltration and runoff velocity (Govers et al., 2000). Depressions in the microtopography have to be filled, before the depressions connect hydrologically, and overland flow occurs. Steeper slopes generally have less depression storage (Peñuela et al., 2015). The initiation of overland flow runoff is therefore also determined by soil roughness. Darboux et al. (2001) found that overland flow onset is not only influenced by the microtopographic roughness, overland flow also modifies the microtopographic structure and connects depressions. The Darcy-Weissbach friction factor is a way to quantify the roughness and resistance to overland flow and is mainly affected by plant stem and litter cover for grassland and by gravel cover and gravel size for bare inter-shrub land (Abrahams et al., 1994).

2.2.1.2. Land cover

Overland flow studies often investigate one specific land cover type with different management forms or recent changes. The land cover, mostly defined by the vegetation, affects the topsoil by organic litter of the respective plants and the deeper soil horizons by roots. Different topsoil humus horizon form under different moisture conditions, which can also indicate saturated areas for overland flow, for example, muck humus (Feyen, 1998). Roots influence the porosity of the soil by developing pores of different size. The type of the vegetation determines the root density and the root depth. Higher porosity of the soil leads to a higher subsurface flow response and therefore less overland flow (Weiler et al., 1998).

Abrahams et al. (1994) used rainfall simulations in semi-arid regions in Arizona to compare overland flow on grassland and sparsely vegetated shrubland. They found that infiltration and resistance to flow were higher for grassland than shrubland because of the denser vegetation and root system. The intershrub area was more exposed to raindrop impact, rill development and stripping of the topsoil (Abrahams et al., 1994). This resulted in a higher erosion rate on the intershrub area than on the grassland. Higher amounts of nutrient were transported by overland flow on the grassland. Even with lower overland flow volumes on grassland, the higher nutrient concentration led to a higher transport overall (Wainwright et al., 2000).

Kurz et al. (2005) investigated the chemical composition of overland flow on managed grasslands in Ireland under natural rainfall conditions. Higher overland flow quantities were found in plots with lower depth to gleying and higher average water tables. Saturation overland flow (SOF) is therefore identified as the predominant process. They also found that grazing animals have led to elevated phosphorus and nitrogen concentrations in overland flow of these grasslands. High nitrogen concentrations were also measured after nitrogen fertilizer application (Kurz et al., 2005). Surface soil properties can be altered by trampling by cattle (Kurz et al., 2006; Pietola et al., 2005). The effects on overland flow were studied for a soil with a high clay content and for four grass sites with different magnitudes of soil damage, from no visible signs of trampling up to drinking sites with homogenized surface soils and destroyed vegetation. Infiltration rate at drinking sites was only 10-15 % of infiltration rates under natural pastures, probably caused by the reduced porosity and a decrease in macropores. Even low intensity grazing can lead to lower infiltration rates (Pietola et al., 2005). The effect of cattle on the soil hydrological characteristics was longer lasting than the elevated nutrient concentrations in overland flow (Kurz et al., 2006). Cattle trampling will further increase the soil roughness and the depression storage.

Overland flow is an important hydrological process in wetlands (Holden et al., 2008). Different velocities of overland flow were found for different peat surface covers. Spaghnum has a higher hydraulic roughness than peatland grass, therefore overland flow is slower on Spaghnum (Holden et al., 2008). In Finland, the resistance of vegetation is used for nutrient retention in overland flow treatment of peat mining water (Huttunen et al., 1996).

Overland flow has been little studied on natural bare lands. For unpaved roads in Thailand, Ziegler et al. (2001) found that HOF is the dominant source during typical rain event in this area. Irrigation experiments for different surface types showed generally lower times to peak in overland flow runoff for bare clay than for pasture (Li and Chibber, 2008). Lower antecedent moisture conditions for bare clay led to significantly longer times for overland flow to travel to the outlet in impulse runoff experiments (Li and Chibber, 2008).

Overland flow has been studied intensively in rainforest areas in South America. De Moraes et al. (2008) compared a forest and a pasture site in a small Brazilian Amazon catchment. They found that replacement of the forest by a pasture, 30 years ago, led to larger overland flow volumes (19 % of annual rainfall) due to a decrease in K_{sat}, higher water storage, and a reduction in macropores. On pastures, both processes (SOF and HOF) occurred. In the forest, 4 % of the annual rainfall run off as SOF (de Moraes et al., 2006). Similar results of overland flow dominance were also found for a pasture on former rainforest by Chaves (2008).

In Japan, Gomi et al. (2007) observed HOF on hillslopes of a cypress forest, a hinoki forest, and a deciduous forest. The occurrence of HOF was explained by hydrophobicity, flow on litter (leaves, branches) and flow on the horizontal root network (Gomi et al., 2008). Overland flow caused by hydrophobicity in eucalyptus forest in Portugal never exceeded 2.2 % of the rainfall (Ferreira et al., 2016).

In Swiss forests, Badoux et al. (2006) studied runoff generation at the profile and plot scale during irrigation experiments (60 mm h^{-1}) and natural rainfall events in two sub-catchments: an intact forest and a heavy damaged and cleared forest area. The degree of forest damage had no influence on the overland flow runoff coefficients from plots, but forest types with a thicker organic litter layer showed a higher magnitude of hydrophobic reaction and HOF (Badoux et al., 2006).

2.2.1.3. Topography

The slope and the shape of the surface affect overland flow because they influence the moisture conditions of the soil. For example, soil on ridges tend to be dry and fast draining, and soils in flatter areas and small depressions tend to be moist. Overland flow has been studied on various slopes and occurs on flat terrain (Li and Chibber, 2008) and on steep hillslopes (Gomi et al. 2008; Sinun et al. 1992).

Small slopes of under 1° showed no significant influence on overland flow occurrence (Li and Chibber, 2008). Plots of different slopes were studied in Malaysia, but only slightly higher overland flow runoff ratios were found for steeper slopes, and surprisingly, higher erosion rates were found for less steep slopes (Sinun et al., 1992). Erosion by overland flow should generally be higher for higher slopes (Julien and Simons, 1985). It is conceivable, that a non-linear relationship between slope and overland flow exists, which depends also on the soil and the land cover type. Zimmermann et al. (2014) measured overland flow in flow lines, where the highest frequencies of overland flow occurrence were reached for slopes between 12 and 15° (10 m resolution digital elevation model). Elsenbeer and Lack (1996) found that microtopographic flow lines and return flow from soil pipes override influences on overland flow from topography on a larger scale in overland flow-dominated catchments in an Amazon rainforest (Elsenbeer and Lack, 1996). In a natural rainfall experiment on bare soil plots in Turkey, uniform plots along the hillslope are found to produce more overland flow and eroded material than convex or concave plots and have higher overland flow runoff coefficients (Şensoy and Kara, 2014). The results are explained by the influence of the slope shape on the flow paths of overland flow, but are not further investigated (Şensoy and Kara, 2014).

An approach to quantify the local wetness based on the topography is the Topographic Wetness Index ($\text{TWI} = \ln(\alpha/\tan\beta)$, where α is the upslope contributing area per unit contour length [m], and β is the local slope gradient [°]; Rinderer et al., 2014). The TWI can be used to estimate where SOF is likely to occur (Guentner et al., 1999). In the field, the wet areas were mapped based on a hydromorphic soil profile and a predominance of wetness indicating plants according to Ellenberg (1992). The comparison of the calculated areas with the mapped saturated areas revealed that other factors than topography are more important for saturated area generation, such as geological factors, for example, compact till deposits had a tendency to be waterlogged, and springs from fractures in the crystalline bedrock led to occurrence of saturated areas on steep slopes (Guentner et al., 1999).

2.2.2. Temporal factors

2.2.2.1. Rainfall characteristics

High rainfall intensities are necessary for HOF generation. SOF can be produced at the same site by an event with lower intensities but a higher total rainfall, which leads to saturation of the soil (e.g. Srinivasan et al., 2002). Therefore, the rain events need to surpass certain thresholds regarding rainfall intensity or total rainfall to produce overland flow. The same rainfall events can lead to different responses in neighboring catchments of two different soil types due to different thresholds of rainfall amounts, that are needed to produce overland flow (Godsey et al., 2004).

Moody and Martin (2015) studied time-to-ponding, overland flow travel times and time to fill surface depressions on a burnt forest in Colorado. The ponding process varied most and was regarded as a controlling process of overland flow initiation. Onset times for overland flow were dependent on the rainfall amount, the rainfall acceleration and the soil-water-deficit. 96 % of the variance in the onset times of overland flow was explained by the rainfall characteristics; soil-water-deficit explained 80 % of the variance (Moody and Martin, 2015). In a Panama rainforest, Zimmermann et al. (2013) found a good correspondence between frequency of rainfall intensities, increasing K_{sat} values closer to the flowlines and actually measured frequency of overland flow occurrence in transects across flowlines. Due to a fast decrease in K_{sat} in shallow soil layers, SOF cannot be excluded (Zimmermann et al., 2013).

A study by Schneider et al. (2014) investigated the runoff formation processes (overland flow, shallow subsurface flow, and subsurface flow) on a meadow hillslope with deep Gleysols in a pre-alpine catchment in Switzerland. Two sprinkling experiments with different rainfall intensities led to different runoff generation patterns. For the first experiment, overland flow occurred only after an increase of the sprinkling rate to 25 mm h^{-1} after sprinkling for two hours with 20 mm h^{-1}, while subsurface runoff started after half an hour. For the second experiment, the rainfall intensity was first 25 mm h^{-1} for one hour and then decreased to 20 mm h^{-1}. About 50 minutes after the start of sprinkling, overland flow responded shortly before the onset of subsurface flow. While subsurface flow rates (1.5 mm h^{-1}) stayed the same for the two experiment, overland flow showed significantly higher flow rates of 11 mm h^{-1} for the second experiment (first experiment 1.5 mm h^{-1}). However, the variability of the overland flow rate was higher, and overland flow runoff stopped shortly after the sprinkling; subsurface flow decreased over few hours. SOF was identified as the process; HOF was excluded because the soil moisture increased significantly before the onset of overland flow. Rainfall intensities over 20 mm h^{-1} for longer periods are therefore the threshold for overland flow in the catchment. For intensities of over 20 mm h^{-1}, air entrapment may prevail, and full saturation of the soil profile is not needed to generate overland flow (Schneider et al., 2014).

2.2.2.2. Antecedent soil moisture conditions

Antecedent soil moisture conditions describe the relative wetness or dryness of soils in a catchment, and can be quantified by the volumetric moisture content (volume fraction of water-filled pores in a soil) of soils before rain events (Hendriks, 2010: 151). Antecedent soil moisture conditions can have two opposite effects on overland flow. For wet antecedent soil moisture conditions, a large amount of water is already stored in the soil, such that less rainfall is needed to saturate the soil and to start SOF (Dehotin et al., 2015). Dry antecedent soil moisture conditions can lead to a reduced infiltration rate caused by the establishment of hydrophobicity in the topsoil during longer dry periods (Ferreira et al., 2015). Many studies have examined the effect of the antecedent wetness conditions on overland flow (Ferreira et al., 2016; Dehotin et al., 2015; Zimmermann et al., 2014; Elsenbeer and Lack, 1996).

Different metrics can be used to quantify the antecedent wetness conditions, for example, soil water content, antecedent dry period or cumulative precipitation prior to the event. In flashy rainforest catchments, antecedent soil moisture influences the volume of overland flow to the stream, but overland flow pathways are mostly activated regardless of the antecedent conditions (Elsenbeer and Lack, 1996). In an oak forest in Portugal, wet pre-event conditions are needed to produce SOF (Ferreira et al., 2016). While for dense eucalyptus plantations, severe hydrophobicity, that led to HOF, could only develop after long-term dry weather (Ferreira et al., 2016).

Antecedent conditions can lead to temporal and spatial variation of overland flow occurrence. For similar sized events (40 mm), overland flow connectivity in flow lines varied between 40 and 100 % in Panama rainforest (Zimmermann et al., 2014). The long-term antecedent wetness (the antecedent precipitation index for 128 days prior the event) was the most important predictor variable for overland flow of all descriptors of pre-event conditions. Therefore, the seasonality of antecedent soil moisture conditions affects the overland flow occurrence more than short-term (less than two week) variation in antecedent soil moisture conditions during the different seasons in the Panama rainforest. However, overland flow is primarily controlled by the rainfall amount and the maximum rainfall intensities in this rainforest catchment. Increased rainfall amount and rainfall intensities results in wider expansion of overland flow lines, and varying antecedent soil moisture conditions only increase the variability of overland flow occurrence thereupon (Zimmermann et al., 2014).

2.3. Flow paths and connectivity

Overland flow pathways are difficult to follow under natural conditions. Some overland flow will reinfiltrate or fill depressions on the surface. Therefore, overland flow paths vary in lengths, and not all overland flow reaches the stream. In catchments with dense drainage networks, overland flow occurs for only for short distances before contributing to concentrated streams (Pilgrim, 1976). Overland flow on the surface can flow faster than soil water and groundwater in the soil and has therefore a shorter travel time than throughflow and base flow (Figure 3a, Moody and Martin, 2015). Overland flow can be slowed down by dense vegetation and litter horizons (Sidle et al., 2007). Because of generally faster travel times of overland flow and high connectivity to the stream, overland flow is controlling the rising limb of a storm hydrograph of an overland flow-dominated catchment (Figure 3b).

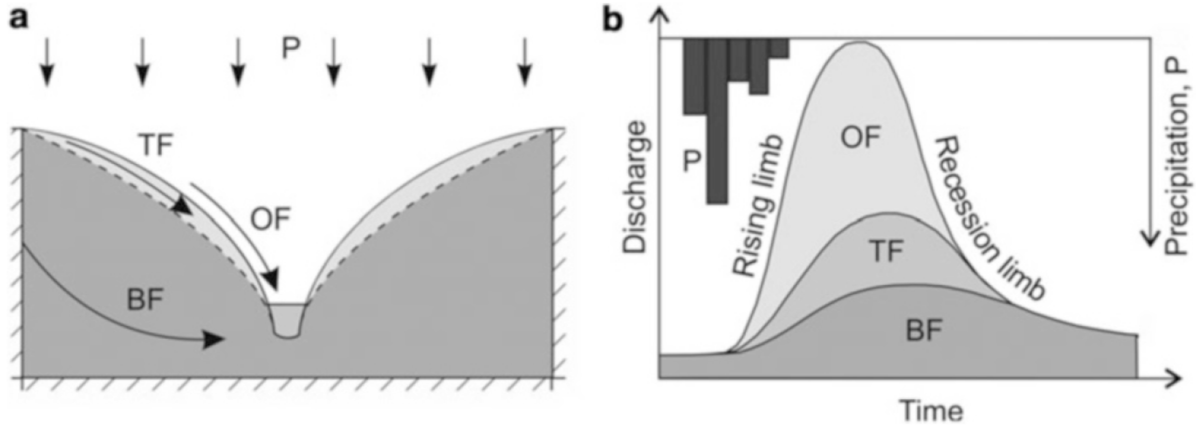


Figure 3: (a) The response of the three different flow paths (overland flow OF, throughflow TF and base flow BF), that contribute to the streamflow, produced by precipitation P. (b) Schematic illustration of a storm hydrograph with the respective contributions of OF, TF, and BF to discharge per time (from Rumynin, 2015).

The varying overland flow path length generally leads to lower overland volumes on larger plots than smaller plots. For example, in Joel et al. (2002), overland flow runoff coefficients on larger plots (50 m^2) were on average only 40 % of those observed on than smaller plots (0.25 m^2). Exchange between overland flow and shallow subsurface flow is conceivable for overland flow paths through reinfiltration and return flow (Kienzler and Naef, 2008). Flow path length influences the concentration of nutrient in overland flow. At a field scale, nutrient concentrations of dissolved phosphate increased in overland flow with increasing flow paths on Gleysol grassland soil (Doody et al., 2006). Flow paths analysis with brilliant blue dye tracer on a Gleysol showed lateral preferential flow paths mainly in the organic topsoil (0-10 cm), but few lateral features were found in the subsoils (Go and Gr horizons; Schneider et al., 2014). The patterns of the dye in the stained topsoil indicated interaction between organic layer flow and SOF. Alternation between the two flows seems possible, depending on the flow path and the surface microtopography (Schneider et al., 2014). Similar results were found in Japanese forests, where short-lived HOF was measured, but flows in the upper organic rich horizon (biomat) were 3 to 8 times higher for all studied forest (Sidle et al., 2007). This slope parallel biomat flow, over the mineral horizon, was a slower than HOF and less erosive (Sidle et al., 2007).

Seasonal changes in precipitation can also affect the connectivity of wetland groundwater and therefore the response of overland flow in these wetlands. During dry periods, a disconnection of the uplands groundwater occurred for the wetlands on a deep till layer (1-3 m) in Ontario, Canada, while for the wet seasons, the upland connection led to high water tables and rapid response to rainfall with SOF (Devito et al., 1996).

2.4. Chemical composition of overland flow

Overland flow is generally a mixture of event water (rain water) and pre-event water (soil water and groundwater; Buttle, 1994). The contribution of soil water to overland flow can even be higher than the contribution of rain water, especially for overland flow and return flow (Figure 4). Overland flow therefore has a different chemical composition than rainwater or soil water. Additionally, element concentrations in overland flow can be increased by an uptake of soluble elements along the flow path or decrease by an uptake of plants from nutrient in overland flow (Doody et al., 2006). However, very few studies have analyzed the chemical composition of overland flow directly.

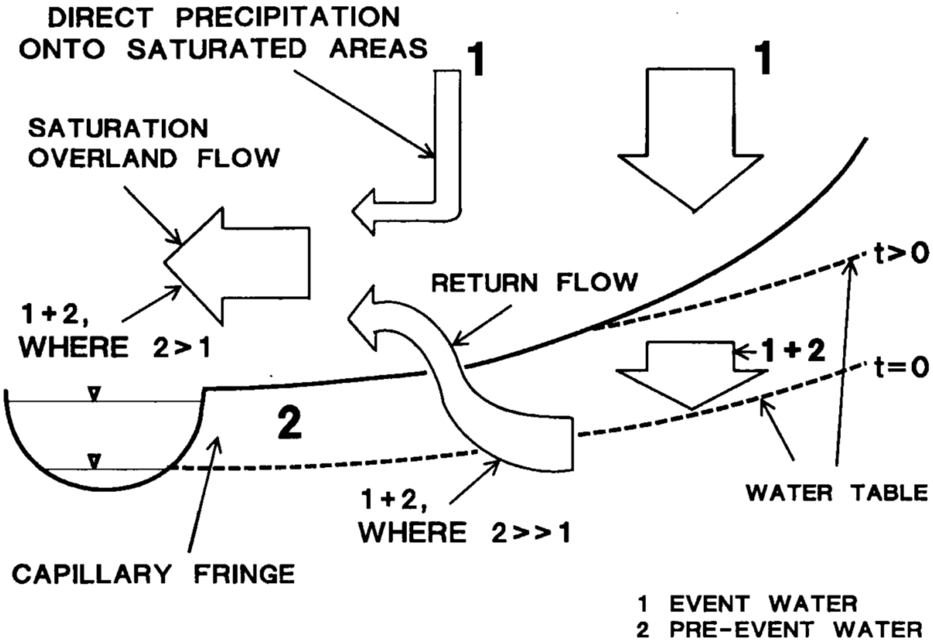


Figure 4: Schematic mixing behavior of event (1) and pre-event (2) water resulting in SOF (with 2>1). Pre-event water in the soil, that was fed by event water (2>>1), emerges as return flow and undergoes further mixing with precipitation (event water) at the surface. Rain characteristics and antecedent soil moisture conditions have an influence on the respective contribution of event water and pre-event water to overland flow (from Buttle, 1994).

Elsenbeer and Lack (1996) used the ratio of potassium to silica (K SiO_2^{-1}) to distinguish throughfall and overland flow (high ratio) from baseflow and soil water (very low ratio). This ratio is useful in the rainforest catchment because potassium dissolves quickly from the vegetation on the surface, and concentrations are thus high in throughfall and overland flow, while silicia is more slowly dissolved by water at the deeper soil horizons and bedrock and almost absent in rainwater (Elsenbeer and Lack, 1996). A distinct signal in overland flow was found for a range of other chemical elements (namely, calcium, dissolved organic carbon, magnesium, and sodium) by Barthold et al. (2016). Overland flow generally had higher concentrations in potassium than baseflow and a high variability in the mean concentration of dissolved organic carbon (sub-event samples of 2 to 6 events), depending on the different overland flow locations. Baseflow had higher concentrations in calcium, magnesium, silicia, and sodium than overland flow (Barthold et al., 2017). The chemical variability in overland flow has not yet been studied in pre-alpine regions.

2.5. Fraction of pre-event water and event water

The fractions of pre-event and event water can be calculated based on chemical element concentrations and concentrations of isotopes, as it can be done for stream flow based on the mass balance for water and solutes or isotopes (Pearce et al., 1986):

$$Q_{of} = Q_p + Q_e$$
$$C_{of}Q_{of} = C_pQ_p + C_eQ_e$$

where Q is the runoff, and C is the element concentration. The subscripts denote the event water (e; rain water), pre-event water (p; soil water or groundwater), and overland flow (of) runoff or concentrations (Pearce et al., 1986). The fraction of the event water f_e in overland flow can be calculated based only on the element concentrations, i.e., no runoff volumes are needed:

$$f_e = \frac{Q_e}{Q_{of}} = \frac{(C_{of} - C_p)}{(C_e - C_p)}$$

The fraction of pre-event water f_p can then be calculated based on f_e by $f_p = (1 - f_e)$.

These fractions of pre-event and event water can only be determined accurately based on naturally occurring conservative tracers. Conservative tracers do not decay, are not influenced by chemical reactions, and are not sorbed to the soil particles. Stable water isotopes are the ideal conservative tracer (Genereux and Hooper, 1998) because water in the subsurface is not influenced by evaporation (McGuire and McDonnell, 2008). Other chemical tracers have to be first tested on their conservative behavior under the prevailing conditions of the catchment (Hooper and Shoemaker, 1986). However, electrical conductivity (EC; Penna et al. 2015) or single element concentrations (Barthold et al., 2017) have also been used to calculate fraction of event water in stormflow.

High event water fractions based on $\delta^{18}O$ were used to indicate HOF on unpaved roads, where almost no mixing on the surface with pre-event water can occur and intercepted subsurface flow was therefore excluded (Ziegler et al., 2001). Lower event water fractions than for HOF are expected for SOF because more mixing of event and pre-event water can happen in the saturated soil. SOF and HOF generally have higher fractions of event water than return flow, that consists of a higher fraction of pre-event water (Barthold et al., 2017). However, overland flow and return flow were found similarly important in contributing to the stormflow (26-48 % and 17-53 %, respectively; Barthold et al., 2016).

Uranine and naphthionate as artificial tracers for event water were positively tested on their conservative behavior on Cambisols in Switzerland, and no sorption of tracers was observed (Kienzler and Naef, 2008). Fractions of pre-event water decreased in overland flow from 30 % to 14 % during a sprinkling experiment (40-50 mm h^{-1}) with traced water on meadow. The fraction of pre-event water in the soil increased from 40 % to 60 % during the same time, while the macropore flow behaved similarly to overland flow. The pre-event water fractions in overland flow ranged from 7 % to 26 % on other meadow test sites (Kienzler and Naef, 2008).

3. Study Site

3.1. Study site description

This research is conducted in a headwater of the Studibach catchment (WS41). The Studibach is a sub-catchment of the Zwackentobel catchment, which is situated on the eastern flank of the Alptal, a valley in the pre-alpine region of canton Schwyz, 40 km southeast of Zurich (Figure 5). Sub-catchment WS41 has an area of 12.5 ha and ranges in altitude from 1470 to 1656 m a.s.l. The sub-catchment WS41 is located at 698 100 m E/210 550 m N in the Swiss coordinates system or 47°02′20″N and 8°43′45″ E in WGS 84. The area is prone to soil creep and landslides, which results in a step shaped landscape with alternating steep slopes and flat areas. The maximum slope is 47°, while the mean slope is 21° (Fischer et al., 2017).

Figure 5: Location of the Alptal valley in Switzerland (from Feyen, 1998).

The Zwackentobel catchment is characterized by a cold and wet climate. The average annual air temperature is 6° C; the mean temperatures in January and July are -1° C and 14° C, respectively (Schleppi et al., 1998). The mean annual precipitation is 2300 mm year^{-1} and 30 % of the precipitation falls as snow (Feyen et al., 1999). The total precipitation in the Zwaeckentobel is double the amount that falls in Zurich. This high precipitation is caused by wet air being pushed in to the valley by prevailing west-winds. Runoff measurements in the Erlenbach, a sub-catchment of the Zwackentobel catchment showed that on average around 75 % of the precipitation contributes to runoff (Turowski et al., 2009). The mean number of rain days per year is 161 (Turowski et al., 2009), therefore it rains almost every second day in the Erlenbach catchment. Most of the rain falls in June (270 mm) and least in October (135 mm; Feyen 1998).

The geology in the Zwackentobel consist of low permeable tertiary Flysch, consisting of alternating layers of argillite and bentonite shists and calcareous sandstones (Schleppi et al., 1998). The Studibach catchment comprises the Schlieren- (42 %), Wild- (42 %) and Wägitaler-Flysch (16 %; Fischer et al., 2017). Throughout the Zwackentobel catchment Flysch bedrock is overlain with shallow, low permeable umbric Gleysols (IUSS Working Group WRB, 2014; Feyen et al., 1996). Gleysols are soils that are or were influenced by groundwater. Saturation of the soil because of rising groundwater can lead to anoxic conditions in the soil, which causes the typical color patterns with grey horizons (IUSS Working Group WRB, 2014). The Gleysols in the catchment have a soil depth of 0.5 to 2 m. Shallow soils, less than 1 m deep, cover 55 % of the area (Fischer et al., 2015; Figure 10). In areas of the catchment with low mean groundwater tables, Gleysols consist of a humic Ah horizon, a fully oxidized Go horizon, and a partly reduced Gor horizon (Feyen, 1998). The Ah horizon has 47 % clay, 47 % silt, and 6 % sand and the grain size distribution stays about the same for the deeper horizons (Schleppi et al., 1998). At locations with high groundwater levels, Gleysols have a muck humus horizon Aa, a partly reduced Gro horizon and a fully reduced Gr horizon (Feyen, 1998). Here, the grain size distribution varies for the horizons. The Aa horizon has 51 % clay, 45 % silt, and 4 % sand, while the Gr horizon has 43 % clay, 42 % silt, and 15 % sand (Schleppi et al., 1998).

The two dominant types of A-horizons in the catchment are mor and muck humus (Feyen, 1998). In the forested areas on dry ridges, mor humus is the dominant topsoil, while the wetter muck humus occurs in flatter areas and small depressions. In the wetland areas, only muck humus is found. Feyen (1998) found better structured soils under mor humus, where vertical micro-structures were formed by stones and tree roots. Soils with a muck humus A-horizon are almost completely reduced. These soils are not well structured and contain only some old root residuals, calcareous stones and few pores (Feyen, 1998). In better drained grassland areas, a range from a thin mull humus to a mollic epipedon can be found on top of the mineral topsoil (Hagedorn et al., 2000)

Land cover in the Zwackentobel catchment includes forest, partly forested areas with shrubs, meadow, and wetland (Figure 7). In the upper part of catchment WS41, meadow, shrubs and partly forested areas are the dominant land cover (57 % of catchment WS41). During the summer, the meadows are used as pasture for cattle. The lower part of the catchment is covered by coniferous forest (43 %) of Norway spruce (Picea Abies) and Silver fir (Abies Alba; Feyen, 1998). The understory is sparsely vegetated by Vaccinium myrtillus on dry ridges and Equisetum and ferns on wet depressions. Wet areas cover 40 % of the catchment (Fischer et al., 2017)

Large parts of the Alptal valley are under protection as a natural conservation area including sub-catchment WS41. The forest provides habitat for many endangered species like the western capercaillie (Tetrao urogallus), that does not like disturbances. In summer, cows of dairy farmers are grazing the meadow near the ridges. The Mythen region is popular for hiking in summer and in the winter the hills around Brunni are also used for skiing.

3.2. Previous Hydrological Research in the Zwackentobel

The hydrology in the Alptal has been intensively studied by the University of Zurich, the Swiss Federal Institute for Forest, Snow and Landscape (WSL) and others for many years. In this subchapter, the findings related to overland flow are reviewed.

In the Erlenbach catchment, the European NITREX (Nitrogen saturation experiments) investigated influences of runoff processes on nitrogen export from forested catchments (Feyen et al., 1996). The measurements showed fast surface and subsurface runoff responses. Low hydraulic conductivity of the soil indicated fast flow paths that by-pass the soil matrix. Overall only 5 % of the runoff was contributed by overland flow and return flow caused by a rising groundwater table (Feyen et al., 1996). Cumulative measurements of two months showed that less than 1 % of the total runoff was overland flow for the two plots with trenches; overland flow for grassland topsoil (muck humus) was double of that for forest topsoil (mor humus; Feyen 1998).

The response of the groundwater in the Studibach catchment has been studied by Rinderer et al. (2016). They found that topography (Topographic Wetness Index, TWI) controls groundwater, and rainfall characteristics are only a secondary control. Antecedent soil moisture conditions have a minor effect on groundwater response (Rinderer et al., 2016).

Runoff generation processes of the different catchments in the Alptal were studied by Benjamin Fischer in his PhD. Rainfall and streamwater was sampled for 13 different rainstorms to perform a two-component isotope hydrograph separation (Fischer et al., 2017). Under stormflow conditions, the contribution of pre-event water to the headwater was controlled largely by the rainfall amount and intensity, while land cover had a small influence. With increasing rainfall amount, the contribution of pre-event water increased. This controlling effect of rainfall amount on the pre-event water proportion was explained by the small active storage of available pre-event water in the shallow soils (Fischer et al., 2017). In the Erlenbach, water from the subsoil also dominated streamflow during baseflow conditions, while the highest contribution of throughfall was measured in the initial phase of the event according to an end member mixing analysis with dissolved organic carbon and dissolved organic nitrogen (Hagedorn et al., 2000).

The hydrochemistry of baseflow in the different catchments in the Alptal was analyzed for three snapshot sampling campaigns (Fischer et al., 2015). No significant differences in hydrochemistry was found for the different catchments. Wetlands were found to have a distinctly different chemical composition, with generally low calcium concentrations and low concentration in dissolved organic carbon. The hydrochemical concentrations were not correlated with the fraction of wetland area. This suggests that during baseflow conditions wetlands are less connected to the stream and do not contribute significantly to the streamflow.

However, it was not possible to make a hydrochemical distinction of the stream samples between the land covers forest, meadow and wetland (Fischer et al., 2015).

In a Master's thesis, the saturated hydraulic conductivity was measured by slug tests for different locations in the Studibach catchment (Zehnder et al., 2013). No significant relations to site-characteristics were found, but there was a tendency of a higher hydraulic conductivity at sites with tree cover and a low hydraulic conductivity for lower soil horizons. The mean K_{sat} of all tested sites was 2.33 10^{-7} m s^{-1} (0.84 mm/h). The K_{sat} ranged from 3.62 10^{-9} m s^{-1} to 1.71 10^{-6} m s^{-1}, this corresponds to infiltration rates of 0.01 to 6.16 mm h^{-1} (Zehnder et al., 2013). However, these K_{sat} values are measured in different depths (0.5 to 2 m) and cannot be directly assigned to infiltration rates on the surface.

3.3. Current research in the Zwackentobel

Other studies were ongoing in the Studibach catchment during this Master's thesis. This led to collaboration in the field and in the laboratory. PhD student Rick Assendelft investigates the patterns, controls and importance of stream network expansion and contraction. PhD student Leonie Kiewiet studies spatio-temporal variability of shallow groundwater chemistry and its effect on stream water quantity and quality. Nadja Grunder writes her Master's thesis on spatial variability in groundwater and streamflow composition for baseflow conditions.

4. Methods

4.1. Experimental setup

4.1.1. Review of overland flow collection and measurement devices

Hydrologists and scientists from related disciplines have used a broad variety of devices and techniques to measure overland flow, for example, automatic overland flow height loggers, the use of tracers, overland flow traps, or surface runoff experiments at profile and plots scale. The devices were evaluated and a design that fitted our objectives was chosen based on the characteristics of the devices.

Tracer studies to detect overland flow were conducted by Lange et al. (2015). They laid tea bags with tracer and tea balls with charcoal to capture overland flow with tracer on a hillslope. This method makes it possible to analyze the flow paths and the flow length of overland flow. Moody and Martin (2015) detected overland flow with electrical resistors, that measure the resistance between electrodes, starting from 1mm above the ground, and the voltage drop when overland flow occurs. These detectors measure the time-to-start of surface runoff and the water depth. starting from 1 mm above ground and the respective voltage drop at overland flow occurrence. Another method using electrical resistance sensors and small V-notch weirs is was used by Srinivasan et al. (2000). Several studies measured overland flow on bounded plots and hillslopes (Sidle et al., 2007; Badoux et al., 2006; de Moraes et al., 2006; Feyen et al., 1996). Overland flow that reached the bottoms of these profiles or plots was collected by plastic plates and pipes and routed into gullies or gutters. The volumes are measured by tipping buckets (Badoux et al., 2006), or by water level loggers in reservoirs or weirs (Sidle et al., 2007; de Moraes et al., 2006). By digging a profile, it is possible to collect surface flow, interflow, and flow in deeper horizons in sand filled runoff gutters and measure each flow separately (Feyen et al., 1996). However, the logistical demands for these methods are large, so that overland flow can only be measured on few plots in the catchment. Additionally, the area is disturbed by the constructions of the bounded plots.

Overland flow traps, plastic pipes of different shapes, diameters, and perforation were also used in various studies (Dehotin et al., 2015; Zimmermann et al., 2014; Godsey et al., 2004; Vertessy and Elsenbeer, 2000). This method was used mostly in the rainforest of South-America and allows measurements with a large number of overland flow detectors. The overland flow trapped in the pipe can be sampled and serves as a ON/OFF indicator. Therefore, the frequency of overland flow occurrence can be calculated and spatial and inter-event analyses can be performed. No intra-event data can be collected since an overland flow trap is a cumulative water sampler.

The design of the overland flow collecting devices by Zimmermann et al. (2014) suited the objectives of this study the most, since the frequency of overland flow occurrence can be calculated and samples can be taken easily. The low-cost (eight Swiss francs per collector) plug system is an ideal solution for building a large number of devices without a long construction period. Due to this plug system, no glue was used that could have contaminated the sample.

4.1.2. Overland flow collector (OFC)

An overland flow collector (OFC, modified after Zimmermann et al. 2014) consists mainly of a pipe with holes to collect overland flow and a pipe junction to store the overland flow (Figure 6). The components of an OFC are a pipe, a T-junction, a pipe coupling and three lids. A sanitary pipe connector system of 50 mm diameter pipes (polypropylene, Valsir S.p.A., Italy) was chosen to build the OFCs. The pipe of the OFC is 500 mm long and has 88 boreholes of 3.8 mm diameter in two rows along one side. The two rows are placed 10 mm apart, so that overland flow on an uneven surface will also be collected. Different spacing between the holes and number of rows were tested with artificial overland flow (Figure 6; Figure 30). Very shallow subsurface flow (0-25 mm) can be blocked by the pipe and also flow into the pipe. The pipe is connected at an angle of 87° to the T-junction. To place the holes at the surface level, the pipe can be turned in the junction to fit the slope. The bottom of the junction has a pipe coupling with a lid, where approximately 0.3 liters of overland flow can be stored. If the storage in the OFC is completely filled, the overland flow has to flow over or around the OFC. The top of the junction is closed by with a removable lid to be able to sample and empty the OFCs easily. The samples were taken with a syringe, that was flushed before taking the sample. All collectors were emptied before a rainfall event.

The pipe junction of OFCs were fully emptied with a sponge on a stick after visually determining the presence of water and taking a sample. Insects and spiders that were occasionally found trapped in the OFCs in the forest were freed. It is assumed that they did not affect water quality or contaminate the sample. The pipe was not emptied and cleaned in the field to avoid a frequent reinstallation that influences the measurements. However, drops of water and sediment residues potentially remained in the pipe.

Figure 6: Prototypes of OFCs with one and two rows of holes in the 50 cm long pipe. T-Junction pipe and coupling for storage attached on the left side. See Figure 8 and Figure 9 for the correct installation in the field.

4.1.3. Site selection, site description and assessment of characteristics

The occurrence and chemical variability of overland flow was compared for four land cover types: bare land (B), meadow (M), wetland (W) and forest (F). 3 to 6 OFCs were installed at each of the three sites (A-C) per land cover type in catchment WS41 (Figure 7).

For the bare land sites (Figure 9), locations were chosen where the bedrock is exposed by natural landslides. These sites have a steep slope. These bare land sites cover a small area of the catchment (ranging from 15 m^2 (BB) up to 450 m^2 (BA)). The upslope area of the bare land is covered by either forest or meadow.

The location of (dry) meadow (Figure 8) and wetland (fens or bogs; Figure 8) depends on the slope and on the curvature. These factors as well as soil wetness sensed with boots (cf. Rinderer et al. 2012) and typical vegetation helped to distinguish meadow and wetland sites. Meadow sites were identified in steeper parts with mostly dry topsoil and short grass (< 0.1 m). Heath spotted-orchid (Dactylorhiza maculata) is common on these sites. Wetland sites (WA and WC) have a mostly wet topsoil and are located in flatter areas of the catchment. A dominant species in these areas is the marsh-marigold (Caltha Palustris) of the Calthion Palustris alliance, indicating eutrophic fen meadows. These Eutrophic fens are usually fed by groundwater or mineral-rich surface water (Klimkowska et al., 2007)

Wetland site WB (Figure 30, Appendix A) has a different vegetation and is probably a different wetland type than the two other sites. At WB, sphagnum mosses dominate. That indicates that WB is probably a bog. Bogs are fed by acidic groundwater that is low in minerals or by water coming entirely from precipitation.

For the forest (Figure 9), sites were chosen with sparse understory vegetation. The ground at site FA is only vegetated with mosses, and at site FB, ferns are the only ground vegetation. The ground at the forest site is covered by an up to 10 mm thin litter layer composed of fir needles. The topsoil is loose also due to the rooting of the fir trees.

Upslope of every OFC, the soil and topographic characteristics were determined in the field to analyze their influence on overland flow occurrence. The Topographic Wetness Index (TWI) and the local slope were additionally determined based on a TWI raster data by Rinderer et al. (2014) and a local digital elevation model (DEM) using a geographic information system (GIS).

The slope was determined in the field with a digital inclinometer (Pieps, Austria). Distances of the OFC to the stream and to the next tree were measured with measuring tape. The closest distance to the stream was noted. The distance to the trees was measured from the OFC location to the tree crown. The distance to a tree was set to zero where the OFC location was under the crown of a tree. The error of the distance measurements is probably 0.5 m. Distances over 5 m were estimated and distances over 10 m were set to 10 m. The curvature and the roughness were estimated in the field and categorized into three classes uniform, convex, and concave, and high, medium, and low, respectively. The location of the OFCs was measured with a GPS device (Garmin, USA) and imported into a GIS (ArcMAP, Esri, USA). The mean accuracy of the GPS is 4 m (root mean square error; U.S. Department Of Defense, 2008); the locations were checked in the GIS and if necessary remeasured. The TWI values from raster data by Rinderer et al. (2014) were assigned to the point location data. However, the slopes, that were calculated based on a local DEM, corresponded only roughly to the measured slope due to the relative coarse resolution of the resampled DEM (6x6m).

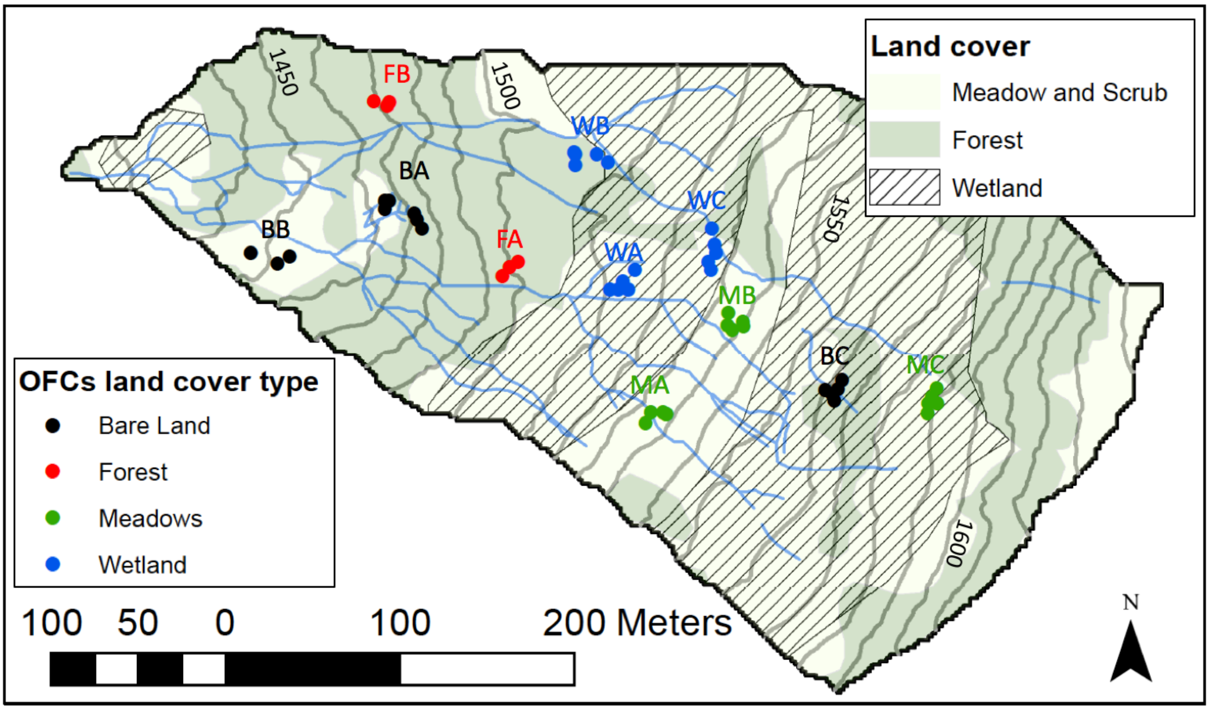


Figure 7: Map of catchment WS41 with the OFC locations (the different land cover types are indicated with the circle fill color). The dominant land cover is indicated by the background map. Hatched areas are wetlands (Federal inventory of wetlands of national importance, Swiss Federal Office for Environment, Bern). The land cover was automatically mapped by aerial imagery (Rinderer et al., 2016), therefore, they do not always agree with the field observations, which was used to determine the land cover of the OFCs. The 10 m contour lines are indicated in grey.

Figure 8: Pictures of OFCs MC3 on meadow (left) and WC5 on wetland(right). Portable conductivity meter to measure EC and field book (left).

Figure 9: Pictures of OFCs on bare land site BC (BC3-5, left) and in the forest (FA1; right). The three OFCs on bare land have electrical resistance sensors with time measurements included (white Arduino box and red wire).

4.1.4. Installation of the OFCs

In total, 50 OFCs were installed in locations with at least one meter of undisturbed and homogeneous area above the OFC. The locations at a site were chosen such that the OFCs represent the variability of the site (e.g. slope, topography, vegetation, distance to trees) are represented. The OFCs were placed at soil surface level, but the installation of the OFCs was slightly different for every land cover type (Figure 7). The soil surface starts at the organic matter layer with plant residue. At the meadow and wetland sites, the roots of the vegetation had to be removed locally to place the OFCs at the surface level. While at meadow sites and at WA and WC the OFCs were installed at the level of the thin partly decomposed litter horizon rich of muck humus, the OFCs were installed on the horizon less rich in humus of dead Spaghnum mosses at the WB site. In the forest, the OFCs were placed on the mor humus topsoil at the litter horizon. On the Flysch bedrock at the bare land sites, the OFCs were installed on the loose clay surface by digging and removing bigger sandstone pebbles. For all sites, the two rows of holes in the OFC pipe were placed on the upslope side so that one was located above and one just under the surface level. Therefore, no precipitation fell directly into the pipe.

4.1.5. Time of onset of overland flow

The timing of onset of surface runoff was determined with resistance sensors in nine overland flow collectors on three sites (BC, Figure 9, MC, and WB, Figure 29, Appendix A). The centerpiece of the self-built measurement devices consists of an Arduino microcontroller for measuring the resistance between two electrodes and logging the data. The design of the device and the script for the code was created by Rick Assendelft. The electric resistance is measured by two wires attached at the bottom of the OFCs. One OFC per site has two additional wires attached at the lid to measure when the OFC fills completely. The electrical resistance is measured every five minutes. If the empty OFC fills with water, the value for the electrical resistance drops. The time of the first drop in electrical resistance is then the time of onset of overland flow with a precision of 5 minutes. However, the devices were not calibrated to measure volumes and EC in standard unit Siemens. It is possible that the OFC only filled a little at the onset-time and filled completely later. With the additional resistance sensor in the lid, we can only estimate the filling behavior. The calibration is also difficult due to the variability in the electrical resistance and temperature in overland flow. These measurements were only taken in October because of long construction time and technical failures in the field beforehand.

4.1.6. Sample Collection and Chemical Analysis

The response to overland flow was checked for every OFC after every rainfall event. Dry OFCs were noted a 0 in the measuring protocol, full OFCs with a 1. For partially filled OFCs, the proportion of the water was estimated by the small grooves in the pipe junction. At responding OFCs, EC was measured with a portable conductivity meter (Profiline Cond 3310, WTW, Germany).

Samples of the overland flow were taken during three sampling campaigns from all responding OFCs within 30 hours after the event in the sampling weeks in July, August, September and October. All responding OFCs were sampled on the 30.08. (event no. 6), 03.10. (event no. 10), and 27.10. (event no. 14) in 2016 (see Table 1 for rainfall characteristics of the events; sampled events are shown with a dotted border). Bulk rainfall samples were collected after every measured event. A 50 ml sample was taken for the ion chromatography (IC; 861 Advanced Compact IC, Metrohm, Switzerland) and inductive-coupled plasma mass-spectrometer (ICP-MS; 7900 ICP-MS, Agilent Technologies, USA) and stored in the fridge until analyse. The samples were frozen if the analyse was not within 24 hours. In the laboratory the samples were filtered by 0.45 µm syringe filters (Simplepure, Membrane-Solutions, USA) and divided into subsamples (2 ml for IC). The 14 ml subsamples for the ICP-MS were acidified with 50 µl of ultrapure HNO_3 65 %. The IC analyzed the concentration of anions (F, Cl, Br, P, S). The ICP-MS analyzed a series of cations (Li, B, Na, Mg, Al, K, Ca, Mn, Fe, Co, Zn, Cd, Ba, Pb, Bi, Y, In, Ho, Lu). Sample treatment and the IC and ICP analysis were performed in the laboratory of the department of environmental systems science at ETH Zurich. For the water stable isotope analysis, the overland flow was sampled separately in 20 ml glass bottles and stored at room temperature. The samples for stable isotopes were filtered and analyzed with a

Picarro L2130-i analyzer (Picarro, USA) at the chair of hydrology at the University of Freiburg, Germany, for the stable isotopes ^{18}O (oxygen) and ^{2}H (Deuterium). The measurement error is ± 0.16 ‰ and ± 0.6‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively.

4.2. Additional instrumentation and measurements

Rainfall volumes and intensities were measured by a tipping bucket rain gauge at the meteo station (Figure 10). Rain water was sampled with a bulk rainfall sampler. Pre-event soil water was sampled at six sites with soil suction lysimeters at 15, 30 and 50 cm depth (SL03-SL06; Figure 10). Soil moisture, soil temperature and EC (at 5, 15, 30 and 50 cm depth) were measured at two sites (near SL03 and SL04, Figure 10) with time-domain reflectometer probes (TDR) and recorded on a Em50G wireless cellular logger (Decagon Devices, USA).

Groundwater levels were measured every five minutes at 52 wells by Odyssey Capitance water level data loggers (Dataflow Systems, New Zealand). Additionally, EC was measured at some ground water wells. Every month, ground water wells were sampled by Leonie Kiewiet (PhD student).

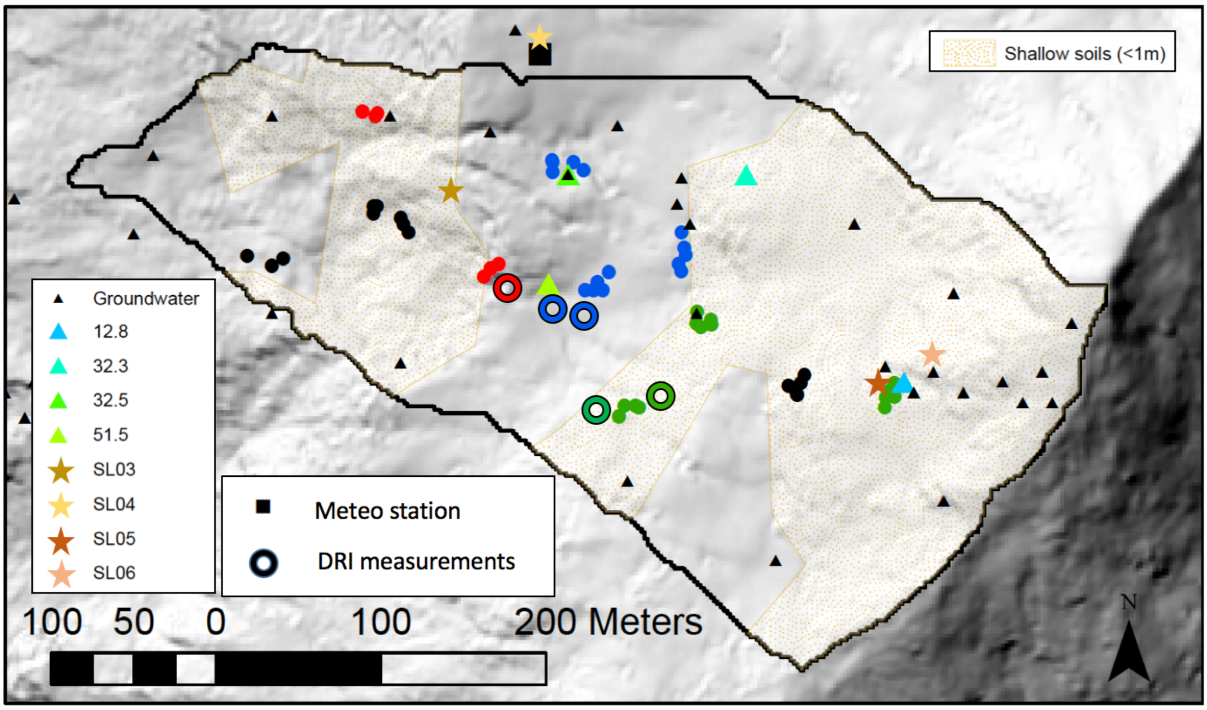


Figure 10: Map of the instrumentation and measurements in the catchment WS41. Black triangles are the groundwater wells in the area. Colored triangles are the groundwater wells used for the calculation of the event water fraction. Stars indicate the location of the suction lysimeters (in 15, 30, and 50 cm per location). Double ring infiltrometer (DRI) measurements are conducted near the OFC sites of the same color. The dotted area indicates shallow soils with less than 1 m depth (Fischer et al., 2015).

Infiltration measurements were conducted with a double ring infiltrometer (DRI; Figure 10) at the forest (one measurement at site FA), meadow (two measurements at site MA), and wetland sites (two measurements at site WA). At the bare land sites, the measurements were not feasible like at the other land cover types due to the steep slope and scree accumulation in flatter parts. The DRI was pushed 50 to 100 mm into the topsoil. The inner and the outer ring were filled with water. In the inner ring, the water level was measured with a water level indicator, while the outer ring was regularly refilled. The water level and the respective time were noted at different time intervals relatively to the water level drop rate, and infiltration rates were calculated for these intervals once saturated conditions established.

4.3. Statistical Analysis

The statistical software package R (R Core Team, 2016) was used for data handling, statistical analysis and visualization. All the rain characteristics were calculated from the tipping data. Linear Regression and Spearman's rank correlation were performed for interval variables, for example, precipitation amounts and intensities, soil moisture and characteristics of OFCs locations like the slope. Analysis of Variance (ANOVA) was used for nominal data, for example, frequency of overland flow occurrence per OFC, land cover, and site. Tukey's honest significant difference (HSD) test was used after ANOVA to find significantly different means. For the boxplots, the first and the third quartiles bound the box, the median is marked by a line inside the box, and the mean is marked by a cross. Whiskers complete the boxplot and show the minimum and the maximum value, if located in 1.5 interquartile ranges from the quartiles. Otherwise, all the points outside this area are plotted individually as outliers.

5. Results

5.1. Studied events

5.1.1. Rainfall event characteristics

In the study period from August to October 2016, overland flow was measured with all 50 OFCs installed in the field for 14 events. In Table 1 the rainfall characteristics are listed for each event. Overland flow was also measured for four events in the test period in July 2016 (events T1-T4.2, Table 1), but at that time only 6 to 16 OFCs were already installed. Therefore, the data from the events in July were excluded from the analysis, unless explicitly stated otherwise. The characteristics of the test events are included at the end of the Table 1 for completeness.

Total precipitation was less than 20 mm for 6 events, between 20 and 40 mm for 4 events, and more than 40 mm for 4 events with a maximum of 76 mm (Table 1). These three categories are in the remainder of the text referred to as small (S), medium (M), and large (L) events. The maximum 1 hour rainfall intensities ranged between 2 and 21 mm h^{-1} (medium event). The small events have a maximum 1 hour rainfall intensity below 5 mm h^{-1} except for event no. 6 with a maximum 1 hour rainfall intensity of 9 mm h^{-1}. All large events have a maximum 1 hour rainfall intensity larger than 5 mm h^{-1}. Precipitation amount and the maximum 1 hour rainfall intensity were non-linearly correlated (Spearman's rank correlation r_s=0.776, p=0.002; linear regression not significant, p>0.05). Similarly, precipitation amount and the maximum 10 min rainfall intensities were non-linearly correlated (r_s=0.611, p=0.02; linear regression not significant, p>0.05). The maximum 10 min rainfall intensities ranged from 5 to 77 mm h^{-1}. The maximum 10 min rainfall intensity was higher than 30 mm h^{-1} for only two events. The maximum 1 hour and 10 min rainfall intensities were positively correlated (linear regression r^2=0.890, p<0.001). The average intensity was non-linearly correlated with total precipitation volume (r_s=0.679, p=0.01; linear regression not significant, p>0.05).

5.1.2. Antecedent wetness conditions

The antecedent (i.e. pre-event) wetness conditions are represented by the soil moisture at 5 cm below the soil surface at the forest and the meadow at the start of precipitation events and by the number of days without rainfall since the last event (Table 1). The soil moisture, that was measured 1 h before event started, ranged from 0.325 to 0.517 m^3 m^{-3} at the meadow site and from 0.499 to 0.552 m^3 m^{-3} at the forest site. The antecedent soil moisture conditions were categorized as wet above 0.440 m^3 m^{-3} and as dry below 0.400 m^3 m^{-3} for the soil moisture on meadow (5 cm depth; Table 1). The soil moisture data and the days without rain data were significantly linearly correlated with a negative slope for meadow (r^2=0.75, p<0.002) and forest (r^2=0.78, p<0.001). The soil moisture content was therefore lower after longer dry periods. However, the higher temperatures in August led to faster decreasing of the soil moisture, while in October, dry periods over 4-5 days were not enough to result in dry pre-event conditions.

Table 1: Rainfall characteristics, antecedent soil moisture conditions, and frequency of overland response for the studied events. The background color of the rows represents event size (total rainfall; white (S) to dark grey (L)). Sampled events are shown with a dotted border. The characteristics of the test events (T_1-T_4) are shown at the end of the table.

No.	Event size	Date of measuring	Precip. [mm]	Duration of rainfall [h]	Average intensity [mm h^{-1}]	Max. 1 h int. [mm h^{-1}]	Max. 10 min int. [mm h^{-1}]	Pre-event cond.	Soil moisture meadow; forest [m^3 m^{-3}]	Days without rain [d]	Freq. all OFCs	Freq. bare Land; forest; meadow; wetland
1	M	02.08.16	30	5.2	5.7	20.6	76.8	-	-	1.1	0.71	0.79; 0.10; 0.73; 0.87
2	L	08.08.16	73	19.6	3.7	13.0	25.2	-	-	4.0	0.79	1.00; 0.12; 0.80; 0.87
3	M	15.08.16	26	15.0	1.7	7.6	14.4	dry	0.388; 0.514	1.7	0.40	0.74; 0.00; 0.19; 0.47
4	L	19.08.16	48	13.4	3.6	18.4	60.0	dry	0.380; 0.512	6.3	0.87	0.96; 0.15; 0.93; 1.00
5	S	23.08.16	3	2.3	1.5	2.0	4.8	wet	0.448; 0.528	1.6	0.20	0.32; 0.00; 0.07; 0.29
6	S	30.08.16	19	4.6	4.3	9.4	30.0	dry	0.326; 0.499	8.3	0.40	0.88; 0.00; 0.09; 0.43
7	L	07.09.16	76	25.6	3.0	6.2	12.0	dry	0.394; 0.521	2.1	0.78	0.96; 0.08; 0.75; 0.93
8	M	19.09.16	35	21.4	1.6	5.6	8.4	dry	0.325; 0.500	9.6	0.67	0.86; 0.00; 0.55; 0.87
9	S	29.09.16	17	10.9	1.6	3.8	15.6	wet	0.467; 0.543	0.4	0.34	0.74; 0.03; 0.07; 0.35
10	S	03.10.16	15	11.9	1.3	3.4	7.2	med.	0.414; 0.524	4.3	0.34	0.73; 0.00; 0.07; 0.40
11	S	17.10.16	14	15.4	0.9	2.2	4.8	med.	0.433; 0.530	5.7	0.31	0.70; 0.00; 0.07; 0.31
12	M	18.10.16	28	19.2	1.5	4.0	10.8	wet	0.445; 0.533	3.0	0.62	0.69; 0.05; 0.56; 0.83
13	S	24.10.16	12	16.9	0.7	1.6	4.8	wet	0.517; 0.552	0.2	0.38	0.49; 0.00; 0.21; 0.60
14	L	27.10.16	54	28.6	1.9	11.6	25.2	wet	0.458; 0.538	1.6	0.85	1.00; 0.08; 0.93; 0.94
T1	S	01.07.16	14	3.1	4.5	3.8	10.8	-	-	2.7	0.23	1.00; 0.00; 0.10; 0.10
T2	L	13.07.16	109	32.7	3.3	15.4	68.4	-	-	1.0	0.80	1.00; 0.80; 0.50; 0.10
T3	M	15.07.16	23	9.1	2.5	6.0	12.0	-	-	0.5	0.66	1.00; 0.00; 0.50; 0.90
T4.1	L	26.07.16	60	20.9	2.9	10.6	56.4	-	-	5.7	0.59	- ; 0.30; 0.50; 0.75
T4.2	S	27.07.16	12	1.7	7.1	5.8	27.6	-	-	0.4	0.82	0.95; 0.00; - ; 0.86

5.1.3. Sampled Events

Samples for isotope and chemical analysis of overland flow overland flow samplings were collected on the 30.08.16 (event no. 6, small), 03.10.16 (event no. 10, small) and 27.10.16 (event no. 14, large; see (Table 1). Small events preceded the first two samplings dates. The average intensity was highest for the event no. 6 (4.3 mm h^{-1}) and low for event no. 10 (1.3 mm h^{-1}). The antecedent soil moisture conditions were dry for event no. 6 and relatively wet for the event no. 10. The event no. 14 was large, had high maximum 1 hour rainfall intensities of 11.6 mm h^{-1} and low average rainfall intensities of 1.9 mm h^{-1}. The antecedent soil moisture conditions were wet.

5.1.4. Infiltration rates

The five double ring infiltrometer (DRI) measurements showed that topsoil infiltration rates, or saturated hydraulic conductivity (K_{sat}), differed for the three land cover types meadow, wetland and forest (Table 2). The lowest infiltration rate was measured on wetland; the highest was measured in the forest. On wetland, two measurements at the site WA with the DRI resulted in infiltration rates of 1 to 2 mm h^{-1}. On the steeper meadow site MA (Figure 30, Appendix A), the infiltration rate varied between 2 and 40 mm h^{-1}. An infiltration rate of more than 500 mm h^{-1} was measured near the forest site FA. Bare land was not measured because of installation problems of the DRI caused by the steep and pebbly slopes.

<table>
<tr><th>No.</th><th>Site</th><th>Land cover</th><th>Infiltration rate [mm h⁻¹]</th></tr>
<tr><td>1</td><td rowspan="2">MA</td><td rowspan="2">meadow</td><td>2</td></tr>
<tr><td>2</td><td>40</td></tr>
<tr><td>3</td><td rowspan="2">WA</td><td rowspan="2">wetland</td><td>2</td></tr>
<tr><td>4</td><td>1</td></tr>
<tr><td>5</td><td>FA</td><td>forest</td><td>>500
saturation not reached</td></tr>
</table>

Table 2: Infiltration rates of the DRI measurements for the three sites MA, WA, and FA.

5.2. Frequency of overland flow occurrence

The frequency of overland flow occurrence per location is the fraction of events with responding OFCs. If a OFC was only partly filled, the amount of water in the OFCs is considered to calculate the mean frequency of overland flow occurrence per location. For the seasonal analysis, the frequency of overland flow occurrence per site and land cover are calculated based on the mean frequency per OFCs. For the event-based analysis, the frequency of overland flow occurrence is the mean of the all OFCs responses of a site or land cover for a specific event.

5.2.1. Seasonal frequency of overland flow occurrence at each site and per land cover

The frequency of occurrence of overland flow for the 14 events was dependent on land cover (Figure 11): The OFCs on the bare land collected water for most events and were often completely filled. The OFCs in the forest collected water for fewer events and were never fully filled. Two of the three OFCs that never collected water (FA2, FB2, MB1) were located in the forest. Some OFCs (BA6, MA2, WA4, WA5) had different response than the other OFCs of the same land cover type. Bare land OFC BA6 responded similar frequent than the other bare land OFCs, but BA6 was for over 40 % of the events only partially filled. Meadow OFC MA2 was completely filled for every event, while all the other meadow OFCs had a frequency of overland flow occurrence of less than 60 %. On generally frequent responding wetlands, WA4 and WA5 were filled for less than 30 % of the events.

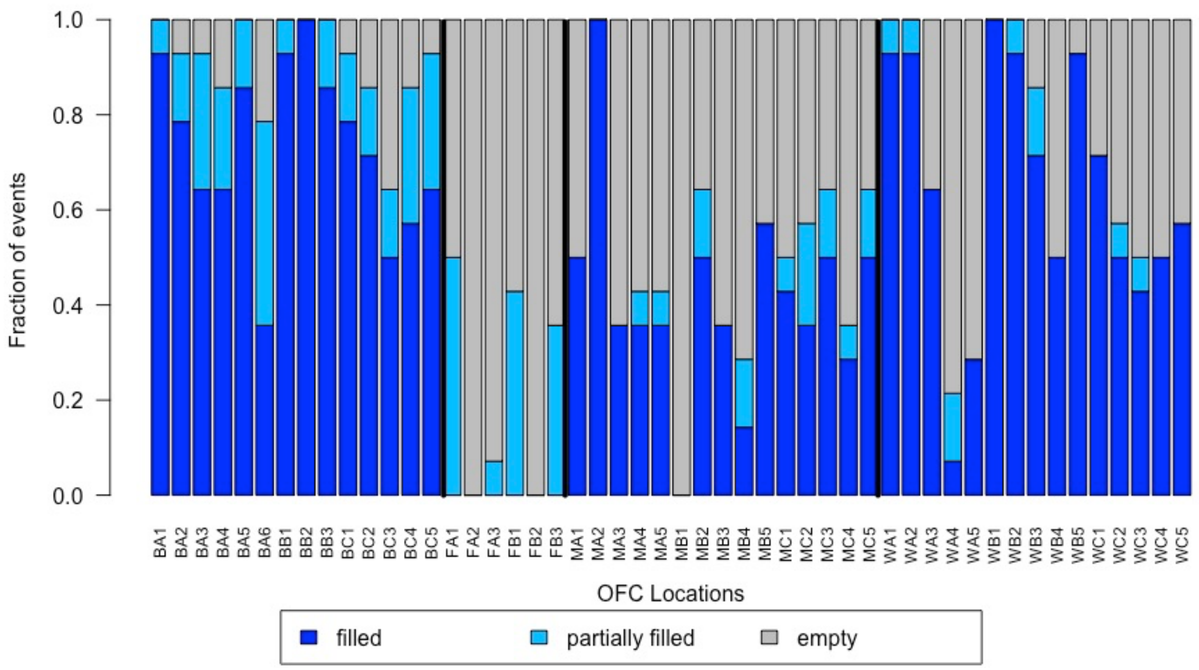


Figure 11: Stacked barplot of response frequencies (i.e. fraction of events that OFC was completely filled (dark blue), partially filled (light blue), or empty (grey)) for the 50 OFCs.

The frequencies of overland flow occurrence aggregated per land cover types (Figure 12) were compared with an analysis of variance (ANOVA) and Tukey's HSD test. The analysis suggests that the mean frequencies of overland flow occurrence were significantly different ($p<0.05$) for the different land cover types, except for bare land and wetland. Overland flow occurred most frequent on bare land (mean frequency of 0.78, 11 out of 14 events; standard deviation sd=0.15), followed by wetland and meadow with means of 0.66 (9 of 14 events; sd=0.27) and 0.42 (6 out of 14 events; sd=0.22), respectively. The mean frequency for forest was 0.05 (1 out of 14 events; sd=0.05).

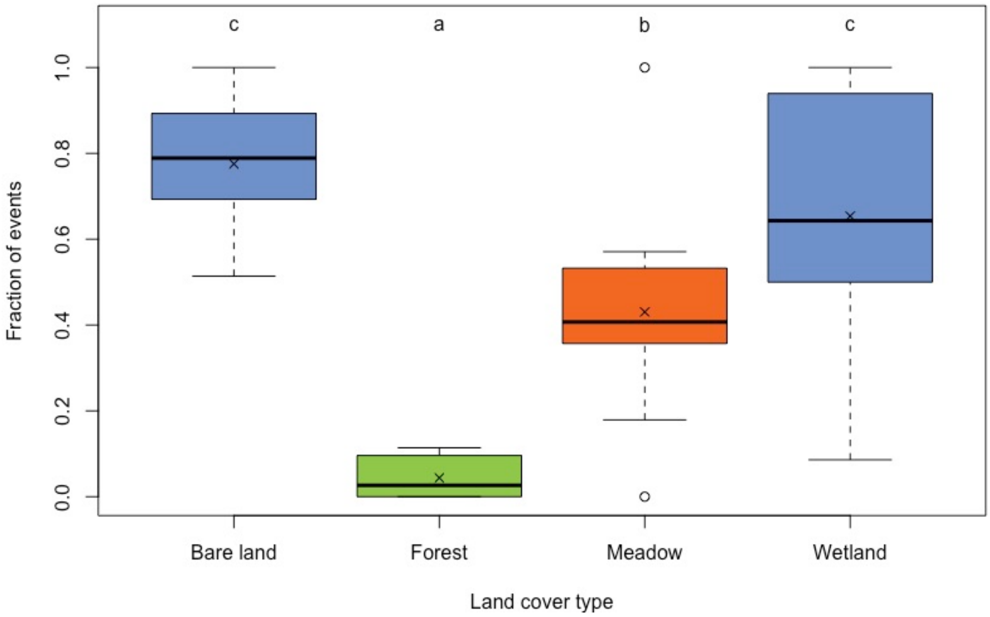


Figure 12: Boxplot of means of frequency of overland flow occurrence per OFC location for the different land cover types. Different letters indicate statistically significant different mean overland flow occurrence.

There was no significant relation between the mean frequency of overland flow occurrence and TWI, local slope (field measurements; Figure 13), estimated contribution area, distance to stream, distance to nearest tree, or soil roughness. The vertical curvatures are not equally distributed over the land cover types and therefore nothing can be stated on this characteristic. When only the wetlands are considered, overland flow occurs less frequent at sites with steeper slopes ($r^2=0.28$, $p=0.04$; Figure 13). If the distance to tree is categorized into "close to tree (<2m)" and "further away (>2m)" and bare land is excluded from the analysis, then overland flow occurs less frequently close to a tree than further away (ANOVA, $p<0.001$; Figure 14). However, OFCs in forest sites, with low frequencies of overland flow occurrence, are more often located "close to tree" than the other land cover types (OFCs per site in "close to tree" category: six forest, six meadow, three wetland). Bare land sites were excluded from the tree proximity analysis because no roots, that could lead to higher infiltration, were found on bare land site.

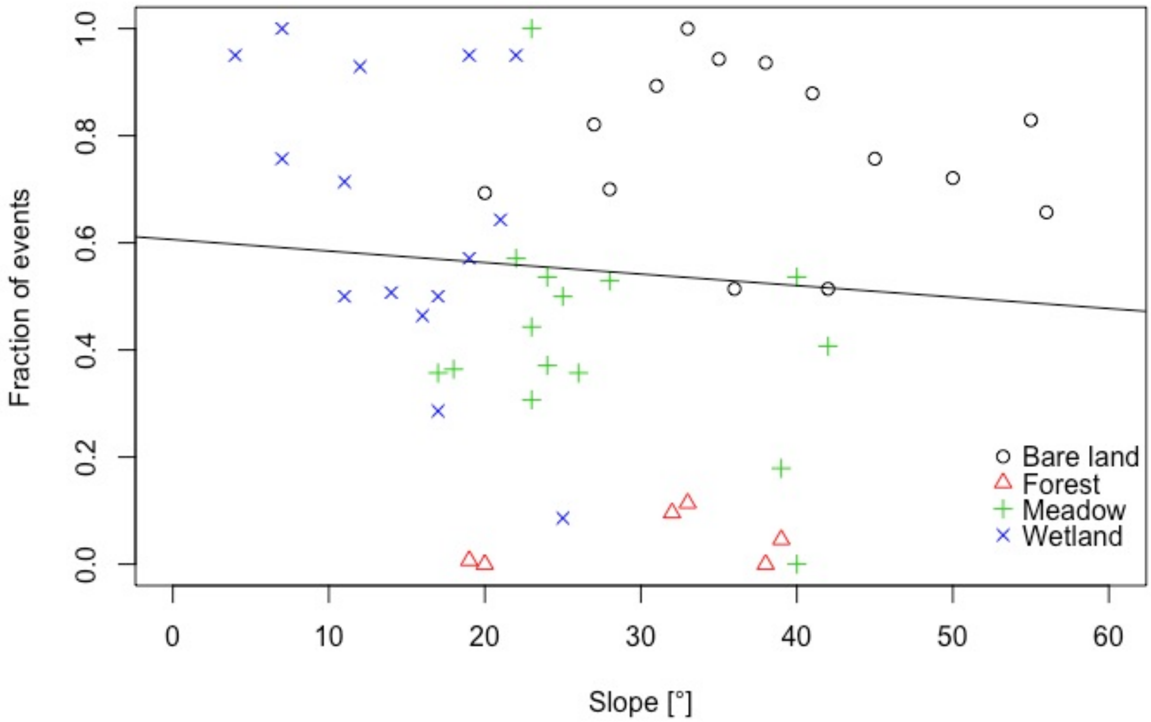


Figure 13: Fraction of events with overland flow occurrence as a function of local slope for the 50 OFCs. Different colors and symbols indicate different land cover types. Regression line (solid line) is not significant (p>0.05).

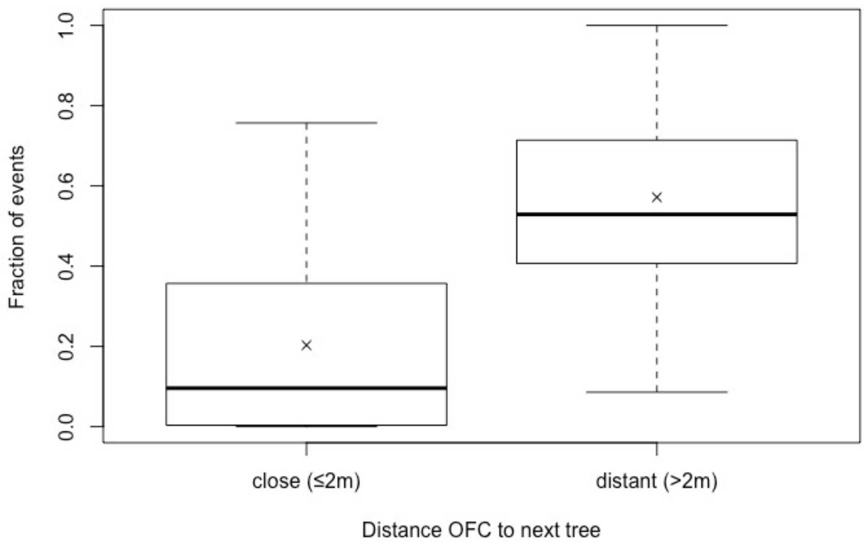


Figure 14: Boxplot of frequency of overland flow occurrence categorized per distance of OFCs to the next tree (close ≤2 m and nearby >2m). Bare land sites are excluded for this boxplot.

5.2.2. Event-based frequency of overland flow occurrence per land cover

On an event scale, we analyzed how rainfall characteristics control the occurrence of overland flow frequency. Figure 15 gives an overview of all the 14 events measured in August, September and October with frequency of occurrence per land cover type. There was a significant correlation between the frequency of overland flow occurrence and the rainfall characteristics (rainfall amount, maximum 1 hour rainfall intensity, maximum 10 min rainfall intensity and average rainfall intensity). The correlation for total rainfall amount was stronger than for the different rainfall intensities for each land cover type (except for the average rainfall intensity for wetland; Table 3; Figure 15). The frequency of overland flow occurrence was not correlated with antecedent wetness conditions (Table 3). Low antecedent wetness conditions led to a wider spread of overland flow (i.e. higher frequencies of occurrence) at the bare land and wetland sites, but the relation was not significant. Even though longer dry periods also lead to lower antecedent wetness conditions, overland flow occurrence was higher at bare land and wetland sites after longer dry periods, but the relation is not significant.

*Table 3: Spearman's rank correlation coefficients and significance (p<0.0001 '***'; p<0.001 '**'; p<0.01 '*'; p<0.05 '.') for the relations between the frequency of overland flow occurrence per OFC and the rainfall characteristics and antecedent wetness conditions. The coefficients are indicated for all OFCs and separately for each land cover type.*

	Rainfall amount		Max 1 hour rainfall intensities		Max 10 min rainfall intensities		Average intensities		Soil moisture Meadow		Soil moisture Forest		Days without rain	
All OFCs	**0.920**	***	**0.827**	**	**0.694**	*	**0.673**	*	-0.391		-0.309		0.172	
Bare land	**0.870**	***	**0.804**	**	**0.721**	*	**0.769**	*	-0.433		-0.396		0.271	
Forest	**0.749**	*	**0.739**	*	**0.703**	*	**0.608**	.	0.045		0.089		-0.115	
Meadow	**0.871**	***	**0.740**	*	**0.637**	.	**0.586**	.	-0.156		-0.083		-0.020	
Wetland	**0.869**	***	**0.684**	*	**0.553**	.	0.521		-0.309		-0.218		0.130	

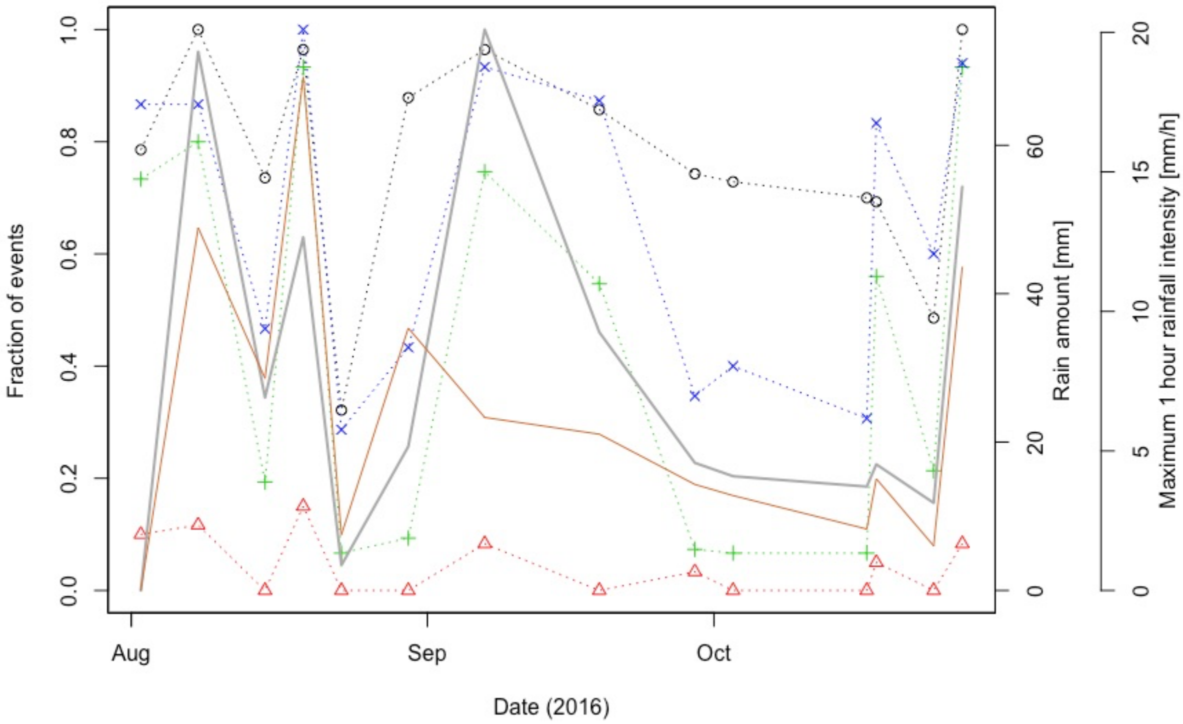


Figure 15: Relative numbers of responding OFCs for each event per land cover type. The grey line indicates the rainfall amount, the brown line the maximum 1 hour rainfall intensity. For the correlation between rainfall characteristics and the frequency in overland flow occurrence see Figure 16 and Figure 17.

For the wetland and meadow site, the relative frequency in the occurrence of overland flow changed after 27 mm of rainfall (dashed vertical line in Figure 16). At this threshold, the frequency increases sharply by more than 20 percentage points. For bare land, the relative frequency in overland flow occurrence increased after 13 mm of precipitation. There was no clear break in the relation between the relative frequency in the occurrence of overland flow and total rainfall for the forest sites (Figure 16).

Higher maximum 1 hour rainfall intensity (averages per event and per land cover) generally led to higher frequency of overland flow occurrence for all land cover types (Figure 17). No clear threshold, with an increase in frequency of overland flow occurrence like for the rainfall amount, was found for the maximum 1 hour rainfall intensity. For meadows, the frequencies of overland flow occurrence increased the most for increasing maximum 1-hour rainfall intensities, but also had a high variation in the medium range, for example, two events (no. 6 and no. 14) had maximum 1-hour rainfall intensities of around 10 mm h^{-1} with frequencies of 9 % and 93 %, respectively. However, the rainfall amount for event no. 6 and no. 14 were also different with 19 mm and 54 mm, respectively. For bare land, the maximum 1-hour rainfall intensities of less than 5 mm h^{-1} had lower frequencies of overland flow occurrence than maximum 1-hour rainfall intensities over 5 mm h^{-1}.

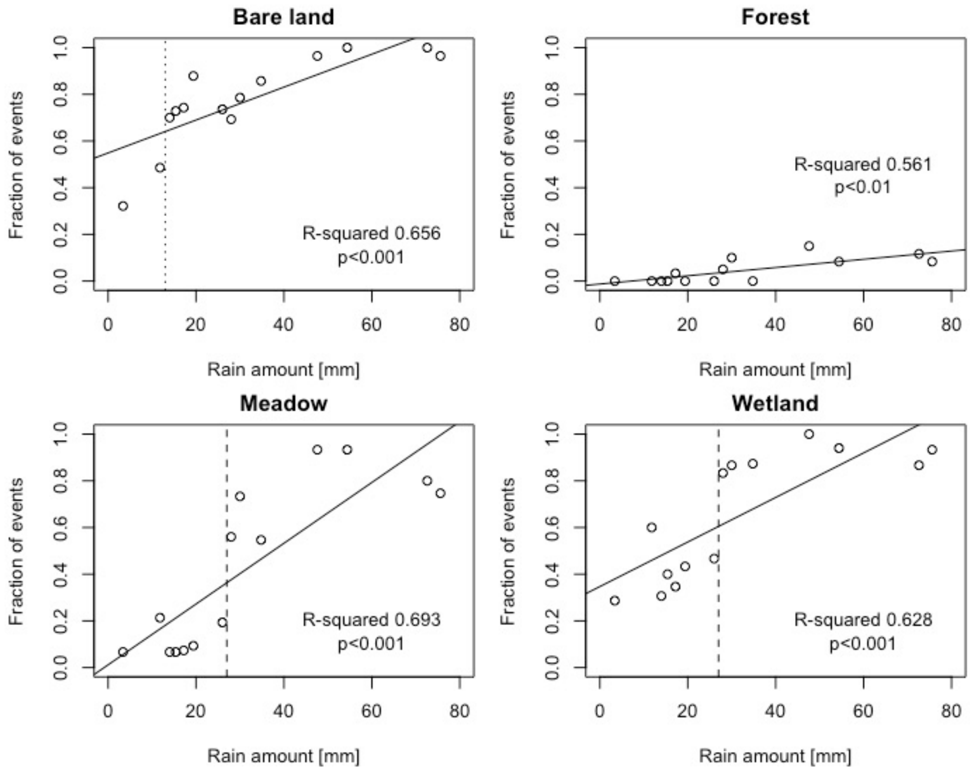


Figure 16: Relation of rainfall amount and frequency of overland flow occurrence per land cover. Every dot reflects an event. Solid line shows the regression (r^2 and p-values indicated). Vertical dashed and dotted lines indicate thresholds of rainfall amount where the relative frequency in the occurrence of overland flow changes more sharply.

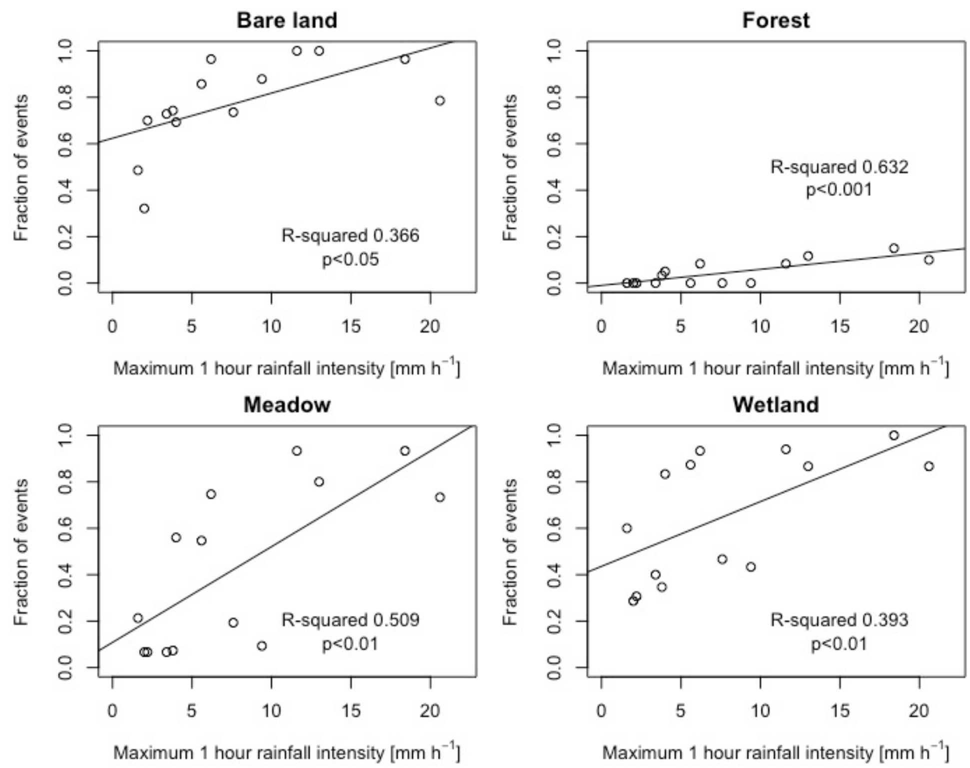


Figure 17: Relation of maximum 1 hour rainfall intensity and frequency of overland flow occurrence per land cover, every dot reflects an event, solid line shows the regression (r^2 and p-values indicated).

5.2.3. Onset of overland flow

Valid Measurements of the onset-time of overland flow were available for three events: two small events on October 1 (15 mm; no. 10) and October 15 (14 mm; no. 12), and a large event (54 mm, no. 14) on the 25th of October 2016. The maximum 1 hour rainfall intensities were 3 mm h^{-1} and 2 mm h^{-1} for the small events and 12 mm h^{-1} for the large event. The antecedent soil moisture was highest for the large event no. 14 (0.46 m^3 m^{-3} at the meadow, at 5 cm depth); it was lowest for the small event no. 10 (0.41 m^3 m^{-3}; second small event 0.43 m^3 m^{-3}).

The time of the onset of overland flow was compared to the time of the onset of the rain and the amount of rain that fell before the overland flow started. Figure 18 shows the cumulative precipitation over time and the onset time of overland flow for the different OFCs. Table 4 indicates the duration of rainfall before the onset of overland flow, the volume of rainfall in this time period, and the maximum 10 min rainfall intensity in the hour before the onset of overland flow for each event.

The amount of rainfall before the start of overland flow varied from site to site and also between the events (Figure 18). BC4 and BC5, of the bare land OFCs, required the longest lag time and the most rainfall before the onset of overland flow for the small event no. 10 (>16 h and >9 mm). For the large event, only 4 mm during less than 2.5 h was enough to produce overland flow on bare land. Bare land OFC BC3 only responded for the large event after 25 mm of rain. An inverse relation between antecedent soil moisture conditions on the amount of rainfall needed before the onset of overland flow was also found for OFCs in the wetland. Lower soil moisture conditions therefore led to shorter lag time of overland flow onset. At the meadow site, overland flow was measured only during the second small and the large event. The rainfall amount and the lag time do not seem to correspond to antecedent soil moisture condition, but correspond rather with the maximum 10 min rainfall intensities. No statistical analysis was performed due to the small number of measurements. For WB2, only 0.2 mm of additional rainfall (in less than 20 min) was needed to fill the collector completely for event no. 12 and no. 14. The OFC at MC2 filled almost immediately after the late onset of overland flow by high rainfall intensities (Figure 18). On bare land, the OFC BC3 was only partly filled after the first onset of overland flow for the large event; 11.6 mm of additional rainfall and high rainfall intensities were needed to fill the OFC BC3 completely.

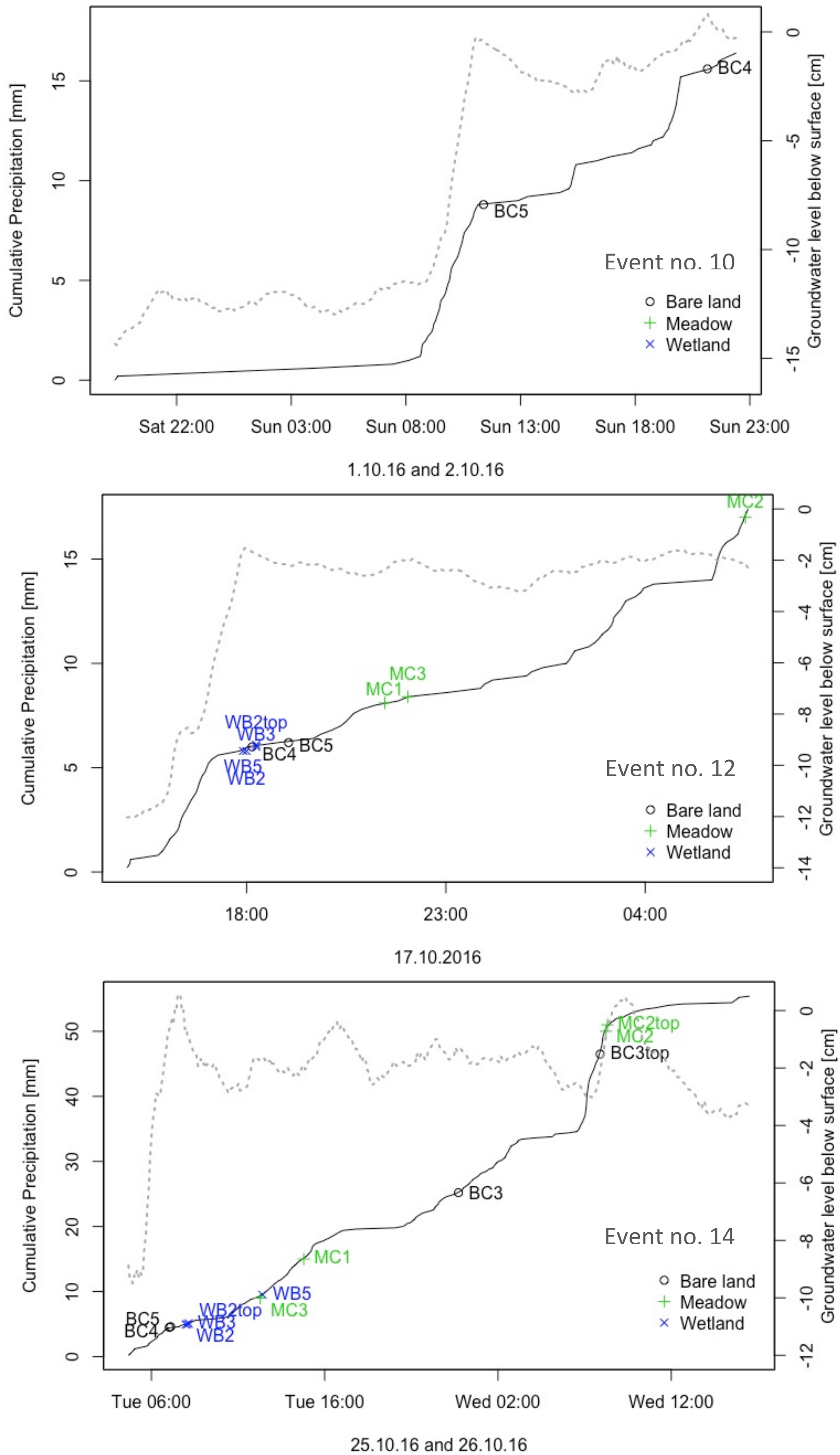


Figure 18: Time series of cumulative precipitation (solid black line) for event no. 10 (top), event no. 12 (middle) and event no. 14 (bottom), together with the time of the onset of overland flow at the different OFCs (labeled points). The dotted line is the groundwater level below the surface for groundwater well 32.5 (close to site WB; Figure 30, Appendix A). See Table 4 for the details on rainfall characteristics before the onset of overland flow.

Table 4: Lag time between the onset of rainfall and the onset of overland flow, total rainfall before the start of overland flow, and the maximum 10 min rainfall intensity in the hour before the onset of overland flow for each OFC for the three events. Time Measurement of onset of overland flow. The overland flow response is indicated in the interval 0 (empty) to 1 (full), the EC is given in µS cm^{-1}.

Events	Characteristics	BC3 (top)	BC4	BC5	MC1	MC2 (top)	MC3	WB2 (top)	WB3	WB5
01.10.2016, S event 10 Total rainfall: 15 mm Soil moisture: medium	**Response**	0	1	0.1	0	0	0	No data		
	EC	-	84.1	-	-	-	-			
	Lag time [h]	-	25.8	16.1	-	-	-			
	Rainfall amount [mm]	**-**	**15.4**	**8.8**	**-**	**-**	**-**			
	Max 10 min int [mm h^{-1}]	-	7.2	4.8	-	-	-			
17.10.2016, S event 11 Total rainfall: 14 mm Soil moisture: medium	**Response**	0	0.2	0.2	1	0.3	1	1	1	1
	EC	-	58.5	27.5	30.9	39.1	28.8	17.0	18.9	19.5
	Lag time [h]	-	3.1	4.1	6.5	16.0 (-)	7.0	3.0 (3.3)	3.2	2.9
	Rainfall amount [mm]	**-**	**5.8**	**6**	**7.8**	**17.2 (-)**	**8**	**5.6 (5.8)**	**5.8**	**5.6**
	Max 10 min int [mm h^{-1}]	-	4.8	4.8	4.8	6 (-)	4.8	4.8 (4.8)	4.8	4.8
25.10.2016, L event 14 Total rainfall: 54 mm Soil moisture: wet	**Response**	1	1	1	1	1	1	1	1	1
	EC	81.8	56.7	71	32.8	24.7	31.5	11.2	46.9	14.9
	Lag time [h]	19.1 (27.2)	2.4	2.4	10.1	27.6 (27.6)	7.6	3.3 (3.5)	3.4	7.7
	Rainfall amount [mm]	**25.0 (46.6)**	**4.2**	**4.2**	**14.8**	**50.2 (50.6)**	**9**	**4.6 (4.8)**	**4.8**	**9.4**
	Max 10 min int [mm h^{-1}]	4.8 (25.2)	2.4	2.4	3.6	25.2 (25.2)	2.4	2.4 (2.4)	2.4	2.4

5.3. Spatiotemporal variability in overland flow chemistry

5.3.1. Electrical Conductivity (EC)

The Electrical Conductivity (EC) of overland flow varied for the different events and between land cover, sites and locations. At some OFC locations, the EC did not vary a lot over time, while for others the variability in the EC of overland flow was high. The variation in EC for the forest OFCs was particularly high (Figure 19). Location BA5 is an outlier with low EC, compared to the generally high median EC of the other bare land OFCs. For meadows, the EC was generally lower and the variation in EC was small for many OFCs (MA3, MB2, MB3, MC4). However, the variation between the OFCs was high for the meadow sites. While the wetland OFCs at the sites WA and WC have a high EC, the OFC at WB are characterized by low EC of overland flow. The Tukey's HSD test shows that for WB and WA, and WB and WC the mean EC is significantly different ($p<0.0001$), while WA and WC have a similar mean in EC ($p \approx 1$). If the aggregated EC values are compared for the different land cover types, overland flow has significantly different EC on bare land, meadow, and wetland ($p<0.0001$, Tukey's HSD test). The EC of overland flow in the forest is only significantly different from overland flow on the meadow ($p>0.001$), but similar to bare land and wetland.

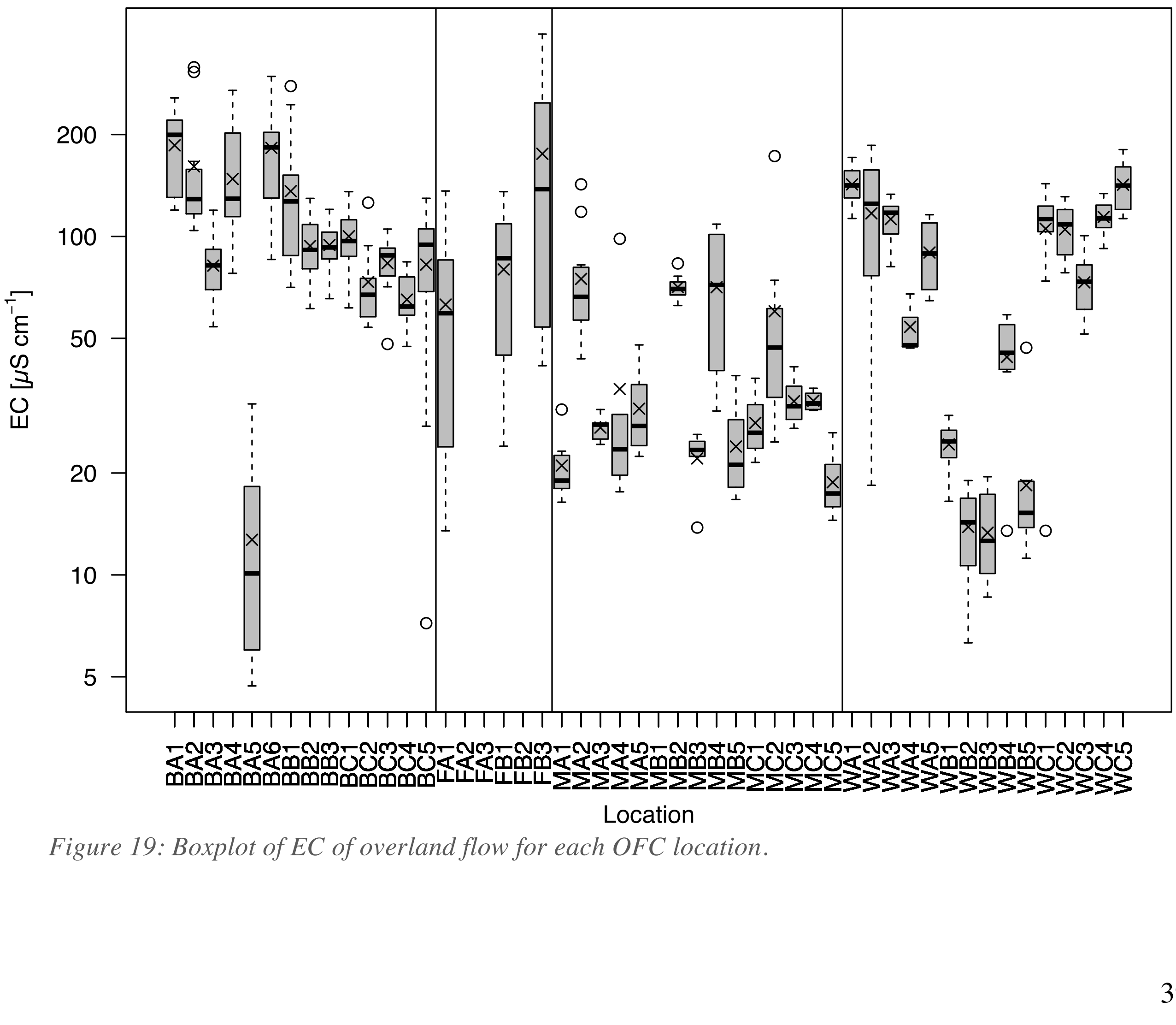


Figure 19: Boxplot of EC of overland flow for each OFC location.

The frequencies of overland flow occurrence were compared to the mean EC per location. There was no significant linear slope for bare land and meadow, but there was a significant positive slope for the wetlands WA and WC (locations in these wetlands with a high frequency of overland flow occurrence are likely to have high EC; $r^2 = 0.6475$, $p<0.01$). For the three responding OFC in the forest, the trend seems to be the other way around, but a significance analysis could not be performed due to the small number.

On an event scale, relations between the EC values and rain characteristics were analyzed on significant positive or negative slope of the regression ($p<0.05$, $r^2>0.50$). No significant slopes different from 0 were found for sites and land cover. Significantly decreasing EC values for increased rain volumes were found for three OFCs (BC1, WA1, MC4), and an opposite effect for OFC BB1. High maximum 10 min rainfall intensity resulted in a low EC for four OFCs (BC3, MB3, WB1, WC2). There was also a negative correlation between the maximum 1 hour rainfall intensity and the EC of overland flow for these OFCs (BC3, MA5, WB1, WC2, WC5). For OFC BA1, the EC was positively correlated to the antecedent soil moisture.

5.3.2. Chemistry of overland flow

Concentrations of the main cations and anions in overland flow were highly variable for the different land cover types and the different sites. In this section, the results for the anions and the cations that differed significantly between sites (Tukey's HSD test) are described first, other anions and cations with extreme values or poor distribution are mentioned at the end for completeness. Only three overland flow samples were taken in the forest for event no. 14, therefore, they are not included in the statistical analyses.

Calcium (Ca) had the highest concentrations in overland flow, up to 34 mg l^{-1}. Differences between sites even of the same land cover were large (Figure 20). The location BA5 was excluded from Figure 20 because it had significantly lower concentrations (<2 mg l^{-1}) than the other BA OFCs. Wetland site WB had significantly lower Ca concentrations than sites WA and WC. This pattern was also observed for potassium (K) and many other cations. Ca concentrations for bare land were similar to wetland sites WA and WC, while the concentrations of the meadow sites were lower and similar to wetland site WB. K concentrations were low on bare land and high for meadows, but wetland site WA and WC had even higher K concentrations.

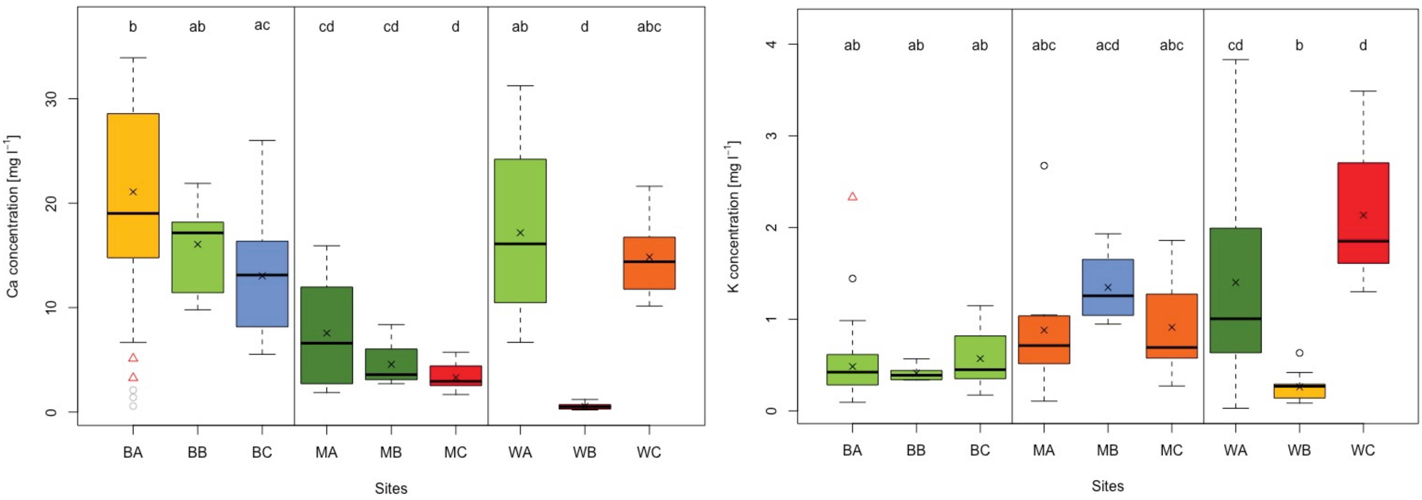


Figure 20: Boxplots of Ca (left) and K (right) concentrations (mg l^{-1}) for the different sites. The boxplot for Ca for site BA are shown without the data for BA5 (Ca concentrations below 2.5 mg l^{-1}; grey circles). The two samples from the forest are indicated with a red triangle. The second forest sample has a K concentration of 7.53 mg l^{-1}(not in the boxplot). Sites without the same letter have significantly different mean concentrations (Tukey's HSD test). Sites with the same combination of letters are colored with the same color.

Natrium (Na) and magnesium (Mg) concentrations did not show differences between land cover types as for the Ca and K concentrations. For Na, the highest concentrations were observed for the sites BA and WA, the lowest on the site MB. Similarly, Mg concentrations were high for site BA. Like for Ca and K, the concentrations of Na and Mg were higher for the wetland site WA and WC than for WB.

Concentrations of aluminum (Al; Figure 21), manganese (Mn), and iron (Fe) were high for the wetland site WB, and concentrations of Al were low for the wetland sites WA and WB. The high Al concentrations for the site BA were from location of BA5. Outliers with high Mn concentrations were samples from BC1, BA5 and WA2. The two forest samples had high Mn concentrations, similar to site WB. Also the Fe concentrations were, except from the site WB, the highest in the forest. For copper (Cu), the patterns are similar, but a contamination of the samples has to be suspected because all locations with Arduino resistance measurements (wires and thus copper) had extremely high Cu concentrations. The results for cobalt (Co) are similar to Al, Fe and Mn, with high concentrations at the site WB.

Concentrations of zinc (Zn; Figure 21) and cadmium (Cd) were not significantly different between the WB site and all other sites because the meadow sites MA, MB and MC had high concentrations as well. The wetland sites WA and WC have medium concentrations, while bare land has only low concentrations. Forest location FB1 had extreme high concentrations for Zn and Cd.

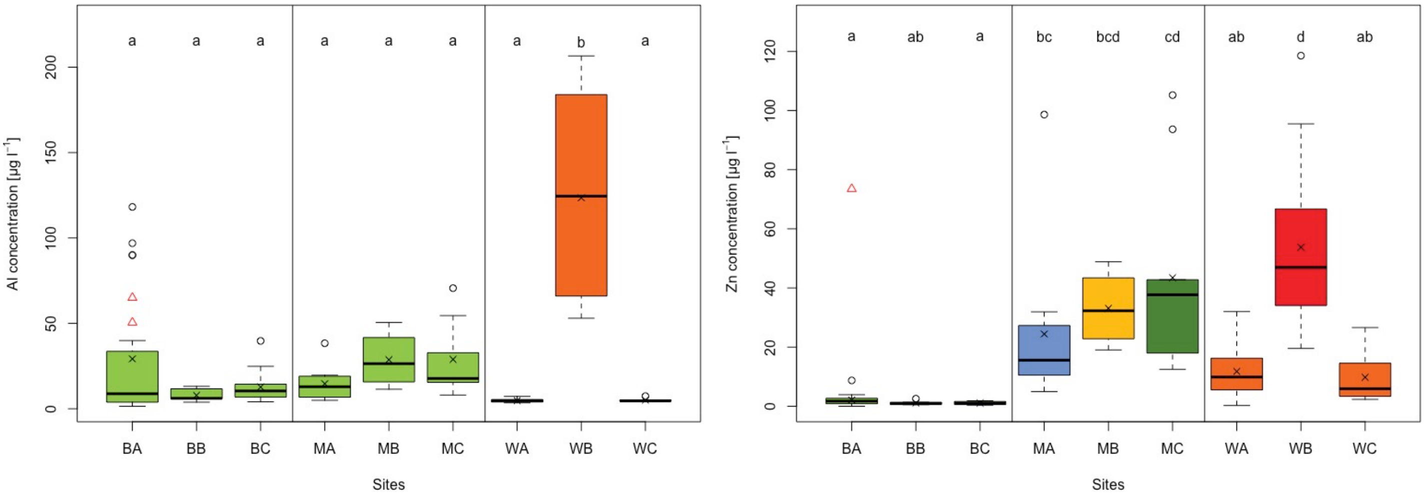


Figure 21: Boxplots of Al (left) and Zn (right) concentrations (µg l^{-1}) for the different sites. The two samples from the forest are indicated with a red triangle. The second forest sample has a Zn concentration of 153 µg l^{-1}(not in the boxplot). Sites without the same letter have significantly different mean concentrations (Tukey's HSD test). Sites with the same combination of letters are colored with the same color.

There were no significant differences between the sites in mean for fluoride, bromide, nitrate, and chloride concentrations. Nitrate concentrations were higher on bare land for the two small events no. 6 and no. 10 than on meadow, where nitrate concentrations were higher for large event no. 14. Sulphate concentrations for the location BA6 were three times higher than the next value. Phosphate was only detected in six samples. The phosphate concentration in the sample from MA2 (event no. 10) was more than ten times higher than the concentrations in the other samples.

Hereafter, element concentrations with minor importance and poor distribution are stated. Lithium (Li) concentrations were low for the bare land site BA and was not detected in many other samples. Boron (B) had outliers for all land cover, while the concentrations were low in the rest of the samples. Nickel (Ni) concentrations were lower for bare land than for meadow and wetland sites. Barium (Ba), bismut (Bi), and titan (TI) concentrations were not significantly different between the sites, while Ba and Bi had outliers for all land cover types. Lead (Pb) concentrations were highest for the MA site followed by the WB site.

5.3.3. Isotopic composition of overland flow

Isotopic composition of precipitation changes with the season and the origin of the water, therefore affects also the isotopic composition in overland flow. In a δ^{18}O-δ^{2}H plot, the isotope samples of the precipitation usually lie on the global meteoric water line (GMWL). Deviations from the GMWL are caused by the aridity or humidity of the vapor source area or by evaporative loss. The GMWL is a linear regression of the global relationship between δ^{18}O and

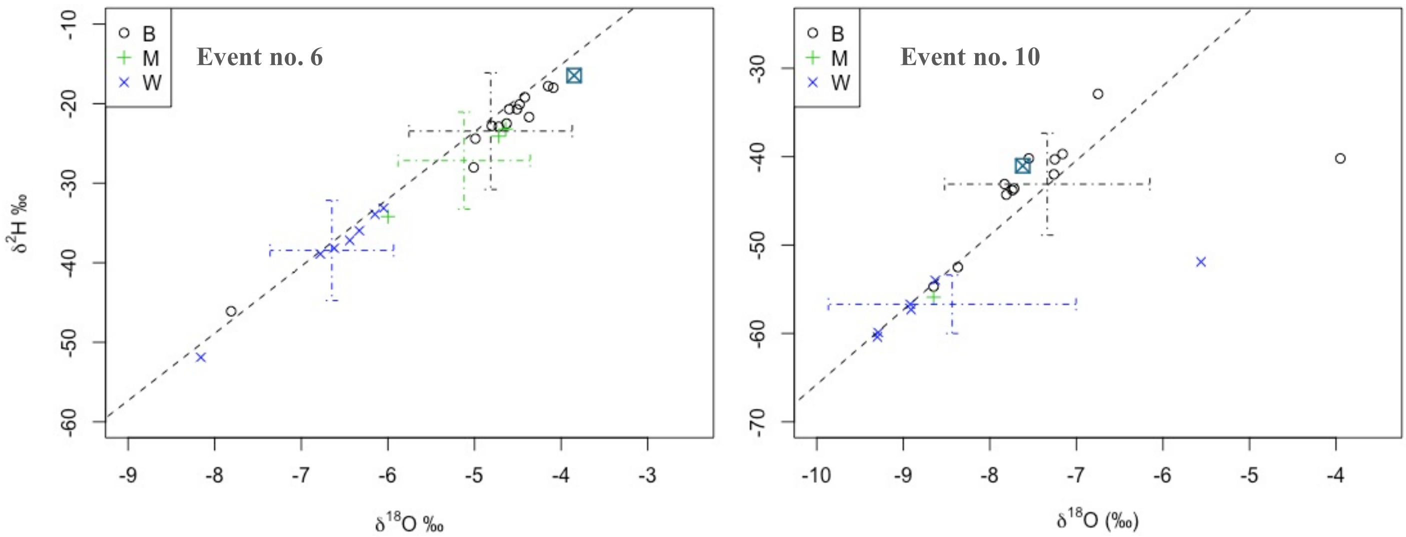
δ^2H for natural meteoric water ($\delta^2H = 8 * \delta^{18}O + 10$ ‰; Craig, 1961). The local meteoric water line for the catchment (LMWL) was determined by the bulk precipitation samples over the sampling season ($\delta^2H = 8.45 * \delta^{18}O + 18.7$ ‰; r^2=99.5, $p<0.0001$) and differs insignificantly from the GMWL for the given range.

Overland flow samples from the different land cover types were found clustered by the isotope data (Figure 22). For the three sampling events, overland flow from bare land generally had an isotopic composition close to the bulk rainfall sample, while overland flow from wetlands differed more in isotopic composition. The isotopic composition of overland flow on meadows ranged between bare land and wetland. However, differences in the isotopic composition varied also for the three sampled events.

For the sampled event no. 6 (Figure 22, top left), the isotopic composition of overland flow differed largely for the wetland and bare land sites, while two meadow samples (MC3 and MC5) were similar to the samples from the bare land and another meadow sample (MA2) was similar to the wetland samples. The samples from bare land were similar to the bulk precipitation sample. The isotopic composition of BA6 and WA1 differed the most from the bulk precipitation sample.

The results for sampled event no. 10 (Figure 22, top right) were similar to event no. 6, but only one sample (MA2) was available for the meadow. Bare land samples clustered around the rainfall sample, that did not mark an extreme value of isotopic composition. Wetland samples were clearly distinguishable from bare land samples in δ^2H. The two samples (BA5 and WB1) that did not fall on the LMWL might indicate an evaporative effect.

For event no. 14 (Figure 22, bottom left), the rainfall sample marked the most negative ratios of $\delta^{18}O$ and δ^2H. This indicated that the rain water of the event no. 14 came from a different region than the rainfall for event no. 6 and no. 10, probably from a cooler, high-altitude or inland region due different large-scale weather and wind patterns. However, the sequence on the LMWL stayed the same for mean isotopic composition of the land cover: bare land (closest to the bulk rainfall sample), then forest, meadow, and wetland. The bare land samples were not clustered near the rainfall sample, but wider scattered along the LMWL. The meadow and the wetland samples were also wider scattered along the LMWL.



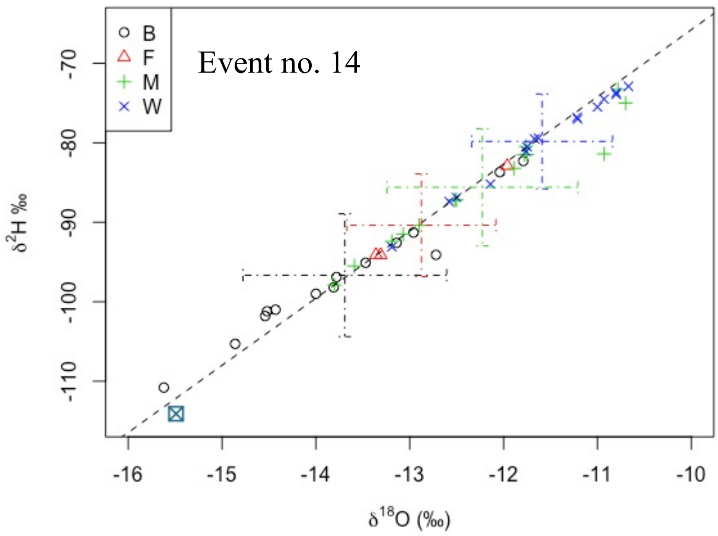


Figure 22: Relation between $\delta^{18}O$ and $\delta^{2}H$ for event no. 6 (top left), event no. 10 (top right), and event no. 14 (bottom left). The crossed box is the bulk precipitation sample. The LMWL is given by the dotted line. Error bars indicate the mean and the range of two standard deviations (same color than the land cover).

That overland flow is a mixture of rainfall, soil water and groundwater, can be seen in Figure 23 for the three events no. 6, no. 10 and no. 14. Figure 23 shows the relations between $\delta^{18}O$ and $\delta^{2}H$ (left), and EC and Ca concentrations (right) for bulk rainfall, overland flow, soil water, and groundwater samples. The means of the isotopic ratios fell on the LMWL in the order of bulk rainfall, overland flow, soil water, and groundwater, except for event no. 14 where the mean isotopic ratios of groundwater was closer to the rainwater than the soil water. Soil water and overland flow were widely scattered on the LMWL, while groundwater had rather short error bars (1 sd). The relation between EC and Ca concentrations shows the same order of rainfall, overland flow, soil water and groundwater. However, the sample points did not fall on a line like for the isotopic composition. The regression line was significant for all three events ($p<0.001$), but especially soil moisture deviated considerably from the regression and had the largest standard deviations. Also groundwater samples were scattered over a wide range, while overland flow samples were clustered close to the rainfall sample.

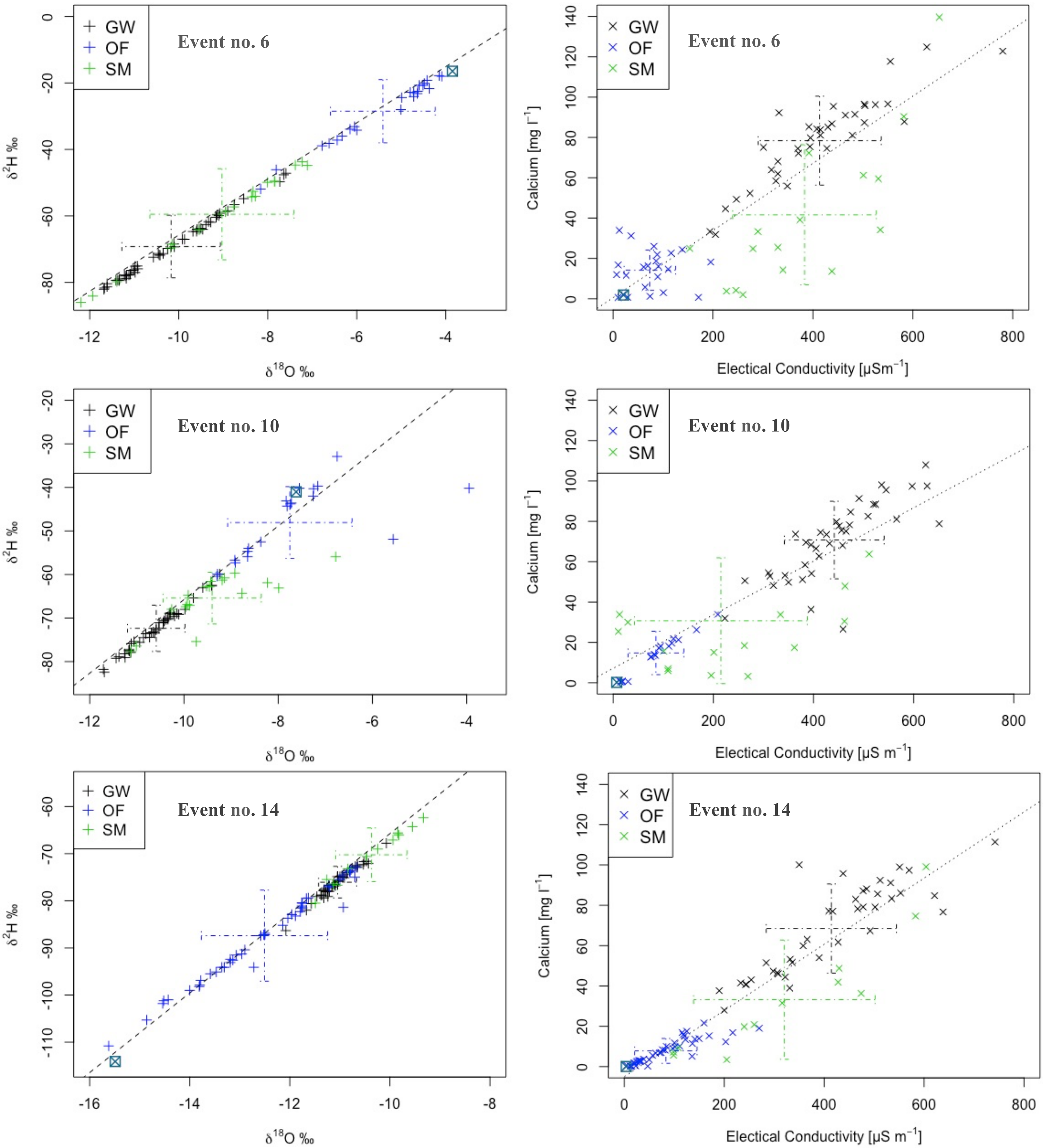


Figure 23: Relation between $\delta^{18}O$ and δ^2H (left) and EC and Ca concentrations (right) of groundwater (GW), overland flow (OF), and soil water (SM) samples (different color) for event no. 6 (top), event no. 10 (middle), and event no. 14 (bottom). Error bars are indicated in the same color than the samples. The dashed line (left) represents the LMWL. The dotted line (right) is the regression line (event no. 6, r^2=0.73, p<0.0001; event no. 10, r^2=0.60, p<0.0001; event no. 14, r^2=0.89, p<0.0001).

5.4. Fractions of event water in overland flow

The fractions of event water in overland flow were calculated for every OFC and every sampling campaign based on a rain water sample and a nearby soil water (Table 5) or groundwater sample (Table 6). The soil water and the groundwater sample are considered to represent the pre-event water, but were sampled after the event together with the overland flow collectors because the suction lysimeters at 15 cm and some shallow groundwater wells were mostly dry before the event. Therefore, the event water fraction in overland flow is generally underestimated. In this sub-chapter, the event water fraction means always the event water fraction in overland flow. Events no. 6 and no. 10 were small, with dry and medium dry soil moisture conditions, respectively. Event no. 14 was a large rainfall event with wet antecedent soil moisture conditions. Some OFC only responded to the large event no. 14, therefore their fractions of event water are separately indicated in Table 7. Event water fractions based on different traces should be similar for the same event and for the same OFC if event water fractions are based on conservative tracers and no other processes than mixing influence the concentration.

The event water fractions for $\delta^{18}O$ and $\delta^{2}H$ are similar in most cases. The event water fractions were largest for bare land, followed by the meadow sites. On wetland sites, overland flow contained less than 40 % event water. For wetland sites, the mean event water fraction decreased with higher antecedent soil moisture content (Figure 25). For meadows, the event water fraction was highest for event no. 6 with dry antecedent soil moisture condition. On bare land, the high antecedent soil moisture conditions for event no. 14 led to the lowest fraction of event water (Figure 25). Most event water fractions based on isotopes for wetland sites WA and WB were under 0 (which is not possible (NP)).

Event water fractions based and Ca concentrations are within a similar range as those for EC for the meadow and wetland sites (generally above 75 %). For the bare land site, the event water fractions based on Ca concentrations were negative (NP) because of the high Ca concentrations in overland flow for bare lands (Table 5 and 6). On the other hand, Ca concentrations in overland flow for the wetland site WB were lower than the Ca concentration of the rainfall sample, which led to calculated event water frictions over 1 (NP).

The use of isotope ratios resulted in different event water fractions than for EC and Ca concentrations data (Table 5-7), except for bare land location BA5, where overland flow consists mainly out of event water, and high event water fractions were calculated based on isotope ratios, Ca concentrations and EC data. Event water fractions based on EC and Ca concentrations were higher than isotope ratios based fractions for the wetland site WB and lower for site WA and WC. For bare land sites, especially the BA site, lower event water fractions were obtained based on the EC and the Ca concentrations data than based on the isotope ratios.

The event water fractions based on δ^2H and EC data are compared in Figure 24. If the δ^2H-based fractions are considered conservative and the event water fractions based on EC are not in the same range (dotted line in Figure 24), then the event water fractions based on EC under- or overestimate the event water contribution. The EC data led to an underestimation of the event water contribution for bare land. For wetland and meadow, the event water fraction is mostly overestimated by EC data. The biggest overestimation occurred for site WB for which the EC-based fractions were larger than 0.8, while the δ^2H-based fractions were less than 0.5. The EC-based fractions for wetland site WB were high for the small event no. 6, while the δ^2H-based event water fractions were less for event no. 10 with higher antecedent soil moisture conditions and for the large event no. 14. For the wetland sites, the trend is similar as for site WB for δ^2H-based fractions, but low EC-based event water fractions of sites WA and WC led to a high the variability of event water fractions for event no. 10 and 14 (Figure 25). For the bare land sites, both event water fractions based on δ^2H and EC data decreased from event no. 6 to event no. 14, while event no. 10 had the highest mean event water fractions for bare land (Figure 25).

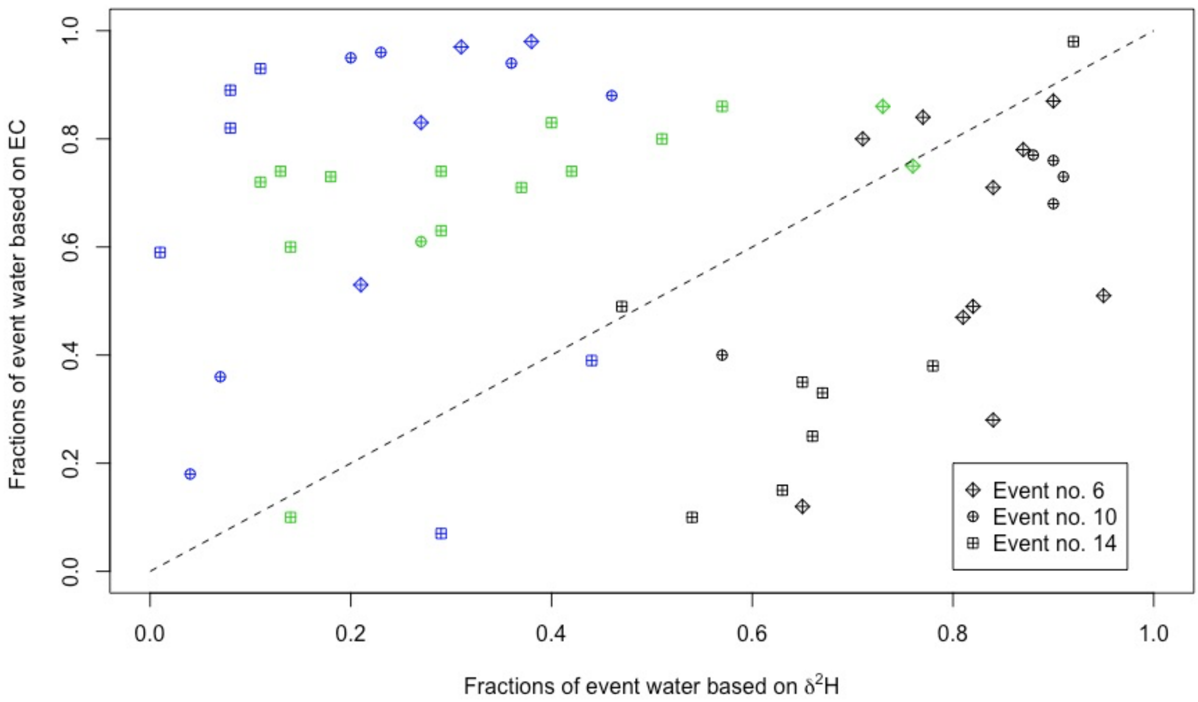


Figure 24: Comparison of event water fractions based on δ^2H and on EC data. The colors indicate the land cover (bare land (black), meadow (green), and wetland (blue)). The symbols represent the different events. The dotted line represents the 1:1 line

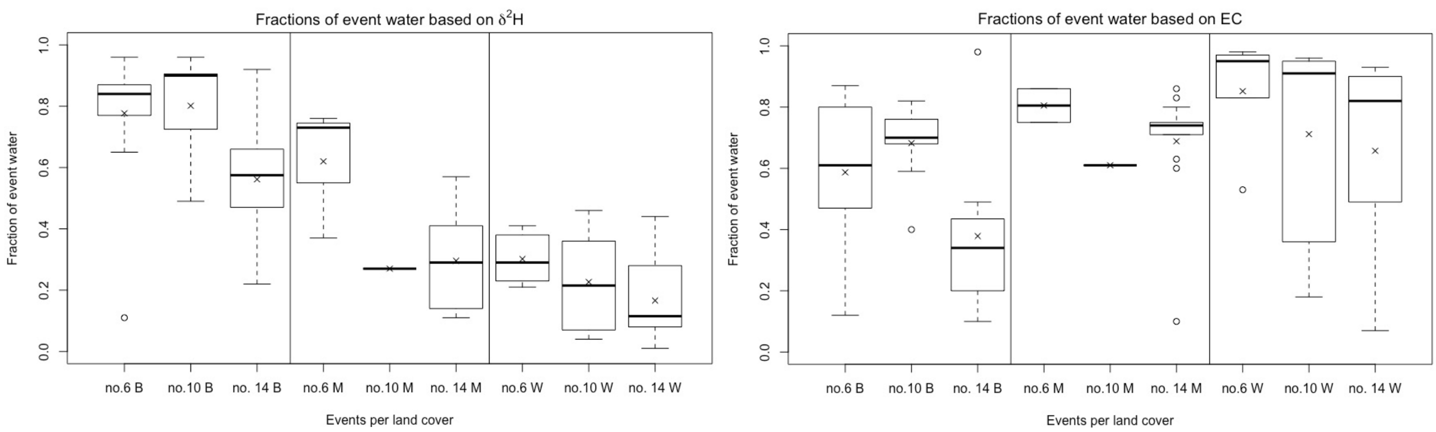


Figure 25: Boxplots of event water fractions based on δ^2H (left) and on EC (right) for the three different events per land cover type.

Table 5: Fractions of event water based on δ^2H, $\delta^{18}O$, EC, and Ca concentrations data where the pre-event water composition was based on soil water samples for each sampling location and campaign. Cell colors vary from light blue (event water) to ocher (pre-event water). Not responding OFCs are colored in grey. NP indicates that the calculation was not possible (event water fractions >100 % (light blue) or <0 % (ocher)).

Pre-event sample		δ^2H			$\delta^{18}O$			Ca			EC		
	OFCs	No. 6	No. 10	No. 14	No. 6	No. 10	No. 14	No. 6	No. 10	No. 14	No. 6	No. 10	No. 14
Soil water SL03_15	BA1	65%	49%	47%	72%	61%	49%	2%	NP	NP	12%		NP
	BA2	84%	NP	61%	88%	NP	64%	10%	NP	NP	28%	69%	NP
	BA3	95%	NP	78%	94%	NP	86%	27%	NP	8%	51%	82%	38%
	BA4		57%	22%		72%	20%		NP	NP		40%	NP
	BA5	96%	NP	92%	93%	NP	NP	99%	82%	93%	NP	103%	98%
	BA6	11%		44%	5%		46%	NP		NP	NP		NP
	BB1	87%	90%	26%	84%	96%	26%	29%	NP	NP	NP	68%	NP
	BB2	82%	88%	63%	81%	93%	68%	13%	NP	NP	49%	77%	15%
	BB3	81%	90%	54%	79%	95%	57%	38%	NP	NP	47%	76%	NP
Soil water SL06_15	BC1	71%	NP	54%	66%	NP	61%	NP	2%	3%	80%	59%	10%
	BC2	84%	91%	67%	78%	91%	78%	46%	32%	25%	71%	73%	33%
	BC3	77%		66%	72%		78%	39%		12%	84%		25%
	BC4	87%	NP	47%	81%	NP	36%	62%	27%	41%	78%	70%	49%
	BC5	90%	96%	65%	83%	NP	76%	41%		26%	87%		35%
Soil water SL05_15	WA1	NP	7%	NP	NP	NP	NP	NP	NP	NP	95%	36%	NP
	WA2	38%	4%	NP	29%	NP	NP	22%	NP	NP	98%	18%	NP
	WB1	21%	46%	8%	38%	NP	12%	NP	97%	97%	53%	88%	82%
	WB2	27%	36%	11%	45%	36%	14%	NP	96%	97%	83%	94%	93%
	WB3	31%	20%	8%	47%	18%	11%	NP	99%	98%	97%	95%	89%
	WB5	41%	23%	1%	53%	17%	2%	NP	99%	98%	NP	96%	59%
	WC1	23%		NP	15%		NP	NP		NP	NP		NP
	MA2	37%	27%	NP	34%	34%	NP	19%	7%	NP	NP	61%	NP
	MC3	73%		18%	73%		17%	69%		73%	86%		73%
	MC5	76%		40%	76%		44%	91%		82%	75%		83%

Table 6: Fractions of event water based on δ^2H, $\delta^{18}O$, EC, and Ca concentrations where the pre-event water composition was based on groundwater and deep soil water for each sampling location and campaign. Cell colors vary from light blue (event water) to ocher (pre-event water). Not responding OFCs are colored in grey. NP indicates that the calculation was not possible (event water fractions >100 % (light blue) or <0 % (ocher)).

Pre-event sample		δ^2H			$\delta^{18}O$			Ca			EC		
	OFCs	No. 6	No. 10	No. 14	No. 6	No. 10	No. 14	No. 6	No. 10	No. 14	No. 6	No. 10	No. 14
Deep soil water SL03_50	BA1	59%	37%	56%	67%	44%	62%	2%	NP	NP	55%		NP
	BA2	81%	NP	67%	85%	NP	74%	10%	NP	NP	63%	NP	NP
	BA3	95%	NP	82%	93%	NP	94%	27%	NP	NP	75%	33%	38%
	BA4		47%	34%		59%	36%		NP	NP		NP	NP
	BA5	95%	NP	93%	92%	NP	NP	99%	79%	91%	100%	95%	98%
	BA6	NP		53%	NP		58%	NP		NP	103%		NP
	BB1	85%	88%	37%	81%	95%	41%	29%	NP	NP	33%	NP	NP
	BB2	79%	85%	69%	78%	90%	78%	13%	NP	NP	74%	17%	15%
	BB3	77%	87%	61%	75%	93%	68%	38%	NP	NP	73%	14%	NP
Groundwater 12.8	BC1	87%	NP	52%	85%	NP	64%	74%	80%	89%	87%		81%
	BC2	93%	94%	66%	90%	94%	83%	86%	86%	91%	81%		86%
	BC3	90%		64%	87%		83%	85%		90%	90%		84%
	BC4	94%	NP	44%	92%	NP	37%	90%	85%	93%	86%		89%
	BC5	96%	97%	64%	92%	NP	81%	85%		91%	92%		87%
GW 51.5	WA1	45%	45%	NP	8%	51%	NP	65%	71%	82%	96%	68%	69%
	WA2	73%	44%	NP	51%	51%	NP	88%	65%	81%	99%	58%	64%
GW 32.5	WB1	41%	51%	12%	38%	NP	14%	NP	99%	99%	47%	98%	94%
	WB2	46%	41%	14%	45%	49%	16%	NP	99%	99%	78%	NP	98%
	WB3	49%	26%	12%	47%	35%	13%	NP	100%	100%	92%	NP	96%
	WB5	56%	29%	5%	53%	34%	4%	NP	100%	100%	98%	NP	86%
GW 12.8	WC1	55%		2%	52%		1%	70%		71%			54%
GW 32.3	MA2	60%	49%	1%	60%	62%	2%	85%	62%	75%			68%
GW 12.8	MC3	88%		14%	88%		14%	97%		91%			94%
	MC5	89%		37%	89%		43%	98%		83%			97%

Table 7: Fractions of event water based on δ^2H, $\delta^{18}O$, EC, and Ca concentrations where the pre-event water composition was based on soil water (left), and on groundwater and deep soil water (right) per OFC, that were only responding for event no. 14. Cell colors vary from light blue (event water) to ocher (pre-event water). Not responding OFCs are colored in grey. NP indicates that the calculation was not possible (event water fractions >100 % (light blue) or <0 % (ocher)).

Pre-event sample		Event no. 14				Pre-event sample		Event no. 14			
	OFCs	δ^2H	$\delta^{18}O$	Ca	EC		OFCs	δ^2H	$\delta^{18}O$	Ca	EC
Soil water SL03_15	FA1	51%	54%		NP	Deep soil water SL03_50	FA1	59%	62%		NP
	FB1	51%	53%	29%	NP		FB1	59%	61%	9%	NP
	FB3	24%	24%		NP		FB3	36%	38%		NP
Soil water SL05_15	WA3	2%	2%	NP	NP	GW 51.5	WA3	NP	NP	78%	74%
	WA4	44%	47%		39%		WA4	37%	41%		86%
	WA5	NP	NP	NP	NP		WA5	NP	NP	78%	76%
	WB4	NP	NP	98%	91%	GW 32.5	WB4	NP	NP	97%	100%
	WC2	23%	25%	NP	NP	GW 32.6	WC2	27%	28%	78%	65%
	WC3	29%	36%	NP	NP		WC3	32%	38%	75%	68%
	WC4	28%	34%	NP	NP		WC4	31%	36%	67%	61%
	WC5	12%	16%	NP	NP		WC5	16%	19%	54%	49%
	MA1	57%	66%	80%	86%	Groundwater 32.3	MA1	61%	69%	97%	96%
	MA3	13%	NP	72%	74%		MA3	21%	5%	96%	93%
	MA4	NP	NP	67%	75%		MA4	6%	0%	95%	93%
	MA5	42%	51%	71%	74%		MA5	48%	56%	96%	93%
	MB2	14%	14%	30%	10%		MB2	21%	24%	87%	80%
	MB3	37%	41%	79%	71%		MB3	43%	49%	96%	94%
	MB4	29%	32%	56%	63%		MB4	35%	41%	95%	87%
	MB5	14%	15%	66%	60%		MB5	21%	24%	94%	90%
	MC1	11%	14%	69%	72%	GW 12.8	MC1	7%	11%	96%	94%
	MC2	51%	56%	77%	80%		MC2	48%	59%	97%	96%
	MC4	29%	31%	73%	74%		MC4	25%	29%	97%	95%

For six events (no. 3, 4, 5, 6, 10, 14), EC of soil water from the suction lysimeter SL04 at 15 cm depth was measured after the events. Event water fractions based on EC data of overland flow and pre-event water sample SL04 were analyzed to determine a relation to rainfall amount and maximum 1 h rainfall intensity. The rainfall amount did not influence the event water fraction based on EC (regression lines not significant, $p>0.05$; Figure 26). Higher maximum 1 hour rainfall intensities led to higher event water fractions in overland flow for bare land and meadows with significant regression lines of $r^2=0.77$ and $r^2=0.70$, respectively (both $p<0.05$; Figure 27). Lower antecedent soil moisture content generally led to higher event water fractions, but the regression was not statistically significant ($p>0.05$, Figure 28). However, the variations in the event water fractions per event and per land cover was rather high, especially for the wetlands (see error bars of 1 sd, Figure 26-28). Over all six events, the differences in the mean event water fractions were also high for the different sites, especially for the wetland sites. Wetland site WB had a high mean event water fraction of 0.95, while the mean event water fraction of WA was 0.55 (WC, 0.73). Bare land sites BA, BB, and BC had mean event water fractions in the low range with 0.58, 0.62, and 0.70, respectively. The meadow sites MA, MB, and MC had mean event water fractions in the high range of 0.78, 0.84, and 0.91.

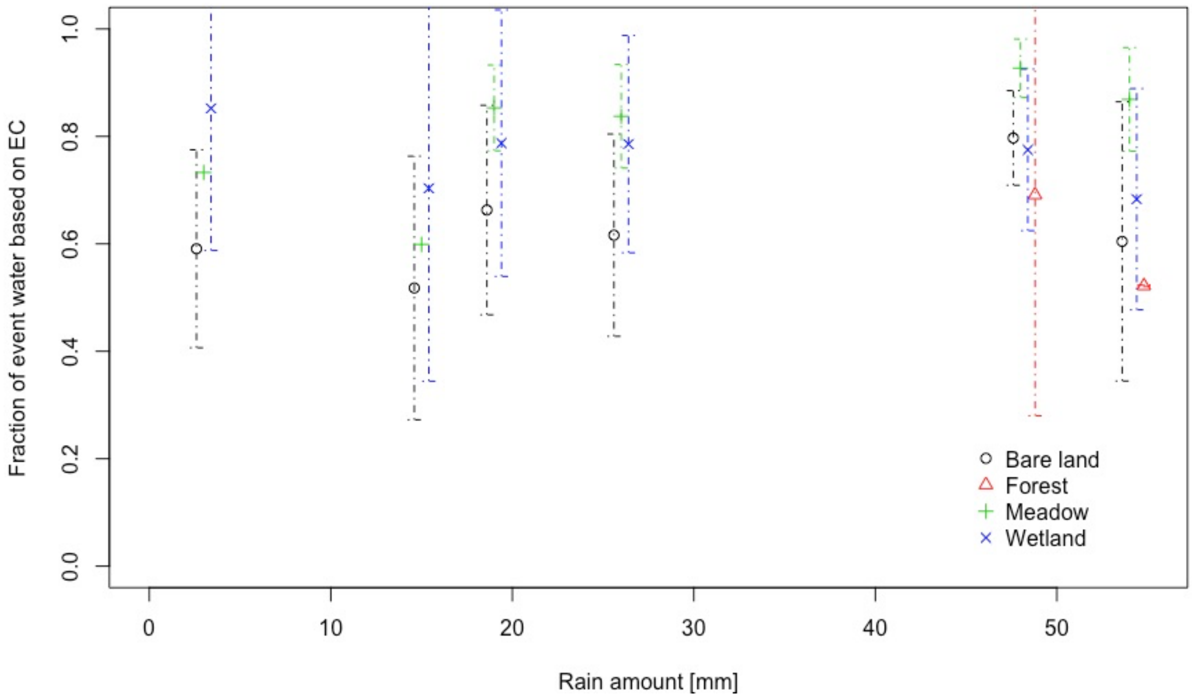


Figure 26: Relation between rainfall amount and mean fraction of event water in overland flow based on EC measurements for each land cover. The error bars indicate the range of two standard deviations (68 %).

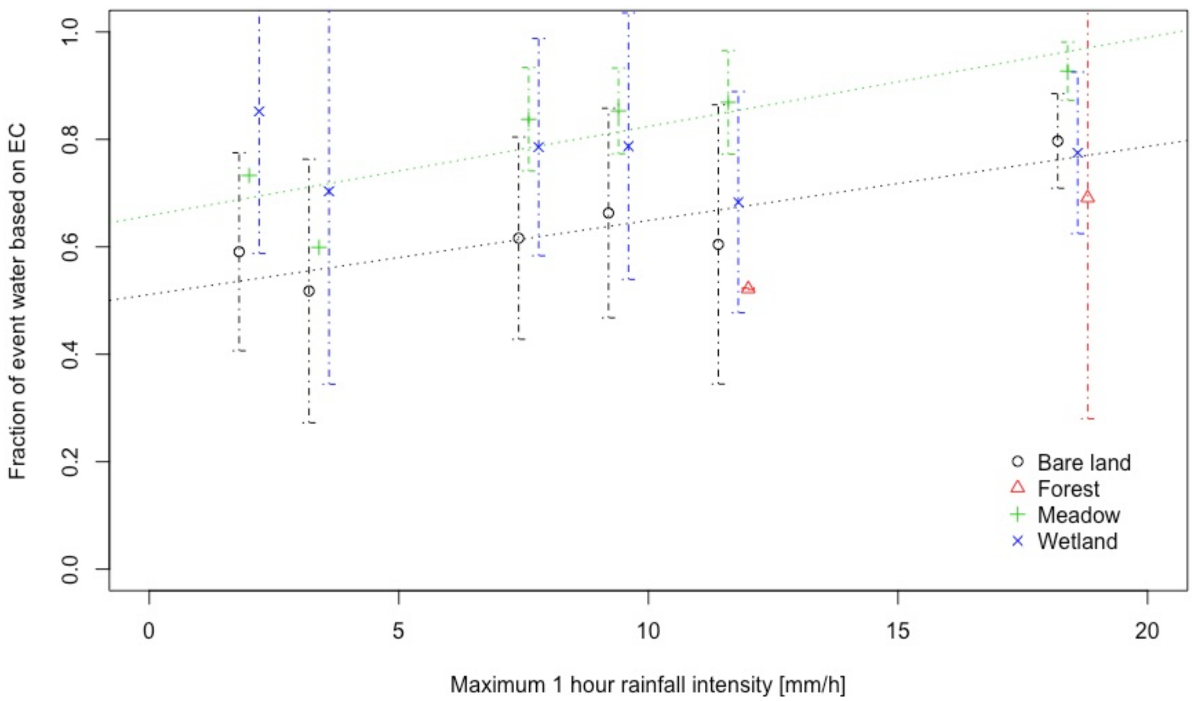


Figure 27: Relation between maximum 1 hour rainfall intensity and mean fraction of event water in overland flow based on EC measurements for each land cover. The regression lines are significant for bare land and meadow (p<0.05). The error bars indicate the range of two standard deviations (68 %).

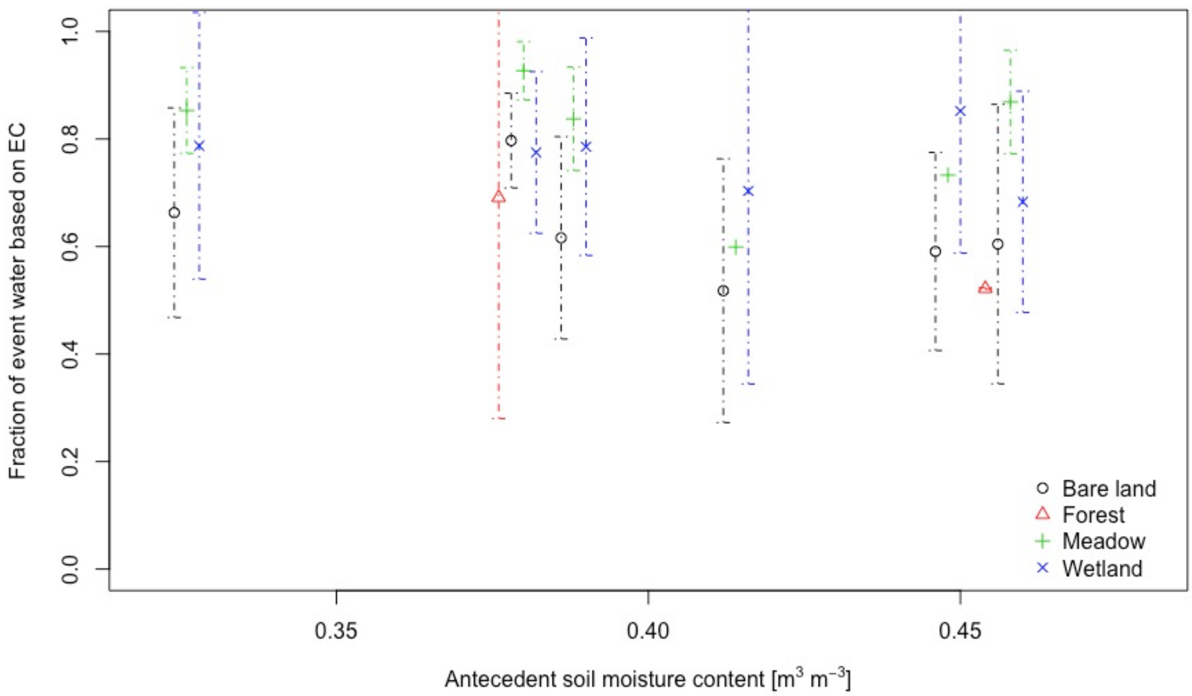


Figure 28: Relation between antecedent soil moisture content and fraction of event water in overland flow based on EC measurements per land cover. The error bars indicate the range of two standard deviations (68 %).

6. Discussion

6.1. First Research Question: During which conditions (rainfall amount, rainfall intensity, and antecedent soil moisture condition) does overland flow occur and how does the land cover (bare land, forest, meadow, and wetland) affect the frequency of occurrence of overland flow?

To answer the first research question, the occurrence of overland flow was measured at 50 locations on different land cover surfaces in the Studibach catchment for 14 events between August and October 2016 on the basis of ON-OFF-measurements with simple overland flow collectors.

6.1.1. The effect of rainfall characteristics and antecedent soil moisture conditions on overland flow occurrence

There is a linear process relation between rainfall amount and overland flow. Larger rainfall amounts lead to higher soil moisture and to higher rising groundwater levels. When the saturation of the soil reaches the soil surface, additional rainfall will contribute to SOF. After reaching saturation, the SOF volume increases the more rain falls. For meadows and wetlands, the frequency of overland flow occurrence increased by 20 % after 27 mm rainfall. This means that after the threshold of 27 mm of rainfall is exceeded, overland flow gets activated at locations with usually not responding OFC to smaller rainfall amounts. For bare land, the increase in the frequency of overland flow occurrence appeared after 13 mm of rainfall. The Flysch bedrock is an almost impermeable layer, but the rain could be needed to saturate the loose gravel and loamy surface and fill the rills, before overland flow starts. However, the found thresholds may not be clear and disappear if more rainfall events would be measured and included in the analysis.

The frequency of overland flow occurrence is shown to be correlated to rainfall conditions. (rainfall amount and rainfall intensities). No significant correlations were found between frequency of overland flow occurrence and antecedent soil moisture conditions. However, time measurement showed that larger rainfall amounts were needed to start overland flow with dry pre-event soil moisture conditions. In this study, the soil moisture was derived from the volumetric water content on meadow and on forest in 5 cm depth, where the variation in the water content is the highest due to direct solar radiation and evaporation. “Days without rain between events” was not the best estimator for the antecedent soil moisture conditions because also the temperature and the direct solar radiation for these days had an impact on the actual antecedent soil moisture conditions. These challenges can be addressed with more sophisticated methods to describe the antecedent soil moisture conditions. For example, Haga et al. (2005)

introduced an antecedent soil moisture index that includes the depth of the surface soil and averages over soil moisture measurements in the surface soil.

Dynamic runoff connectivity of overland flow, as described by Gomi et al. (2008), could be another explanation for the found threshold. The rainfall amount leads to saturation and rising water tables that lead to SOF connectivity after the water level rises to the surface at some places. In Tromp-van Meerveld and McDonnell (2006), a threshold of 55 mm was found for subsurface stormflow increase in terms of two magnitudes. Their fill and spill hypothesis is built for the soil-bedrock interface and subsurface stormflow and implies that a certain volume of rainfall is needed to fill the microtopographic relief of the topography (Tromp-Van Meerveld and McDonnell, 2006). An analogue hypothesis could hold for the surface and overland flow as Appels et al. (2011) found it for agricultural fields. After saturating the soil and filling the microtopographic depressions on the surface, the water spills over the surface as overland flow. If this hypothesis holds, the rain threshold is an indicator for SOF as dominant process.

6.1.2. Spatial variability in frequency of overland flow occurrence

There were significant differences in frequency of overland flow occurrence for the different land cover types. Land cover determines the infiltration capacity and the hydraulic conductivity of the topsoil and possibly subsoil, and therefore, influences overland flow occurrence. The highest frequency of overland flow occurrence was found on bare land and wetlands, followed by meadows. Overland flow rarely occurred in the forest. Feyen et al. (1996) investigated runoff processes in the neighboring Erlenbach catchment, including overland flow on wetlands. Fast-rising groundwater tables in the wetland sub-catchment led to saturation during rainfall and may have started the SOF. Their water balance calculation suggested upward flow into the closed sub-catchment, but it is not reported if the return flow reached the surface or only fed shallow interflow (Feyen et al., 1996). Overland on muck (wetland locations) and mor (forest locations) humus was compared in another study in the same catchment by Feyen et al. (1998). They reported higher overland flow runoff on muck (1.9 mm) than on mor humus (0.7 mm). For both humus types, the amount of overland flow corresponds to less than 1 % of total rainfall in fall 1996 (Feyen, 1998). In the Brazilian Amazon rainforest, Moraes et al. (2006) investigated overland flow on forest and a meadow on former forest. On 60 % of the days, overland flow occurred on both land cover types, but a larger fraction of the rainfall turned into overland flow on the meadow (17 %) than in the forest (2.7 %; de Moraes et al. 2006). In the Studibach catchment, the frequency of overland flow occurrence is also rather high (over 60 % for bare lands and wetlands, 42 % for meadows), except for the forest sites (5 %). Since the small storage of the OFCs was filled frequently, overland flow can be assumed as a frequent and significant contributor to stormflow for the bare land and wetland sites. However, overland flow volumes were not measured in this study.

Correlations were not significant for frequency of overland flow occurrence and topography (slope and TWI) or site characteristics (distance to tree and distance to channel), but, for example, overland flow occurred significantly more often on flatter slopes at wetland sites. However, topography and site characteristics influence the land cover, and significantly different means of frequency of overland flow occurrence were found for the different land covers. Rinderer et al. (2016) found that in the Studibach catchment, groundwater rise is controlled by topography. Moreover, a functional relation between the topographic wetness index (TWI) and the time to rise was found. Rainfall was a second-order control on the time of groundwater level rise and affects the relation between TWI and time to rise by determining the time to overcome the soil moisture deficit (Rinderer et al., 2016). For overland flow, the results in this study suggest other dominant effects, that control the frequency of overland flow occurrence in the catchment. While no significant topographic effect on overland flow frequency was found, rainfall characteristics (precipitation amount and intensity) and land cover seem to dominate overland flow occurrence. According to the time measurements, antecedent soil moisture conditions seems to play a minor role for overland flow. Antecedent soil moisture conditions may only increase or decrease the threshold for the rainfall amount to overcome the soil moisture deficit until SOF occurs. The hypothesis, that site characteristics can explain the frequency of overland flow occurrence, has to be rejected. For wetlands, it was found that overland flow occurs most often in flat areas, whereas this relation does not seem to hold for the other land cover types. A strong variation in overland flow frequency was found by Loos and Elsbeer (2011) in a tropical rainforest. They analyzed the frequency and terrain attributes (3 non-digital and 17 digital ones based on DEMs of different resolution) with a random forest ensemble tree approach. Their analysis results suggest that the variability of overland flow occurrence is best explained by microtopography, terrain slope, and distance to channel. Additionally, the frequency of overland flow dropped at a certain slope (5-6°, for a 5x5 m resolution DEM) and at a certain distance to the stream (>20 m; Loos and Elsenbeer, 2011). These finding do not correspond to the results in this study. No change in frequency of overland flow was found for these parameters. Distance to tree was the only parameter that led to an increase in frequency of overland flow occurrence if the distance exceeded 2 m. Comparing the results, it has to be considered, that the locations in this study were chosen based on land cover, and that land cover is already correlated with slope and distance to stream in the Alptal catchment. Loos and Elsbeer (2011) only measured overland flow in the rainforest. The effect of microtopography on overland flow occurrence was not determined in this study.

6.1.3. Type of overland flow

One objective of this study is to determine the main processes of overland flow generation. The results do not show a clear dominant overland flow generation process for each land cover, and interactions between the processes are possible. However, tendencies can be inferred from the relations between frequency of overland flow occurrence and rainfall amount or antecedent soil moisture, from the time of onset of overland flow, and from the fractions of event water (Table 8). The high correlation between the rainfall amount and frequencies of overland flow occurrence indicates that SOF is the dominant process for all land cover types. A lower, but still significant correlation was found for the maximum 10 min rainfall intensities and the frequencies for all land cover types. This correlation indicates that HOF could also have contributed to generate overland flow. No trend was found for antecedent soil moisture conditions. Time of onset of overland flow points SOF as overland flow generation process. Overall, it seems that SOF is probably the dominant overland flow generation process. However, SOF and HOF are not necessary contradictory processes, but rather depend on the rainfall characteristics and antecedent soil moisture conditions. Overland flow areas and the saturated areas only overlap partially in a study by Srinivasan et al. (2002), such that not all saturated areas produce overland flow, which is also produced on areas without saturation.

Table 8: Summary of indication for overland flow processes. Weaker indications for overland flow processes are in brackets.

Land cover	Rainfall amount	Rainfall intensity corr.	Infiltration rate	Onset of overland flow	Pre-event soil moisture	Chemical variability (see 6.2.)	Event water fractions (see 6.3.)
Bare land	SOF	HOF	No data	SOF	No trend	HOF	HOF
Forest	(SOF)	HOF	SOF	No data	HOF, Hydrophobicity (observation)	SOF	SOF
Meadow	SOF	(HOF)	SOF, HOF	SOF	No trend	SOF	SOF
Wetland	SOF	(HOF)	SOF, HOF	SOF	No trend	SOF, return flow	SOF, return flow

A study by Scherrer et al. (1996) compared overland flow and subsurface runoff generation for different soil types in Switzerland using high intensity irrigation experiments. Scherrer et al. (1996) found for shallow (<1m) Gleysols in Bilten and Willerzell (distance to the Alptal catchment < 30 km) that overland flow occurs shortly after the irrigation started and accounted for up to 80 % of the total irrigation water during the experiment. Similar high runoff coefficients (>50 %) for overland flow were only measured for a Podsol and loamy Cambisols. The other soil types (Cambisol, Regosol) had lower overland flow runoff coefficients. Surprisingly, the land cover type at Bilten was a sparsely vegetated forest of green alder and Norway spruce. Similar high runoff coefficients for overland flow can be excluded for the Norway spruce forest in the Studibach catchment because of the low frequency of overland flow occurrence on the forest sites. The other land cover types in the study of Scherrer (1996) were meadow with intensive or extensive use. The slopes of the study sites were between 10° and 55°. These characteristics are comparable to the extensive used meadows in the Studibach with slopes between 17 to 42°. However, the results of Scherrer (1996) cannot be compared directly to the results of this study because they used high sprinkling rates of up to 100 mm h^{-}

^{1}. Such high precipitation rates are rare; the maximum 1 hour rainfall intensity during the study period was a bit less than 30 mm h^{-1}. However, the quick on-set of overland flow can give information about the overland flow type. Scherrer (1996) reported for the overland flow generation in Bilten that, HOF is more likely than SOF. Return flow was observed from mouse holes. No subsurface runoff was measured in Bilten. The onset of overland flow occurred in less than 8 minutes during wet conditions. For the colored Gleysol in Willerzell, the overland flow started after 7 minutes on average and absolute HOF was the dominant process because of the low infiltration rate. SOF occurred only on some surfaces of the plot, where the shallow groundwater level reached the surface (Scherrer, 1996). Considering the low infiltration rates on the meadow (K_{sat} between 2 and 40 mm h^{-1}), the response of the Gleysol in the Alptal catchment may be similar for such a high intensity storm. Absolute HOF is probably dominant under such conditions, whereas for large events with lower intensities saturation of the soil and SOF is more likely.

The infiltration rate for the wetland was low and less than 2mm per hour, which was exceeded during the most events. On meadow, the measured infiltration rates indicate a large range of infiltration rates and more water was needed to reach saturated condition, also because the soil moisture was lower at the beginning. In the forest, the infiltration rates of around 400 mm h^{-1} were so high that saturated conditions were not reached during the experiment. Rainfall intensities that exceed the measured infiltration are unrealistic in Switzerland. An explanation for the measured overland flow in the forest can be a hydrophobic surface (which is no measured with the double ring infiltrometer). Another explanation could be that the infiltration rates vary depending on the macropore density due to spatial variability in the density of roots and soil organisms.

The lack of a correlation between the frequency of overland flow and antecedent wetness condition suggests a limited influence of hydrophobicity. However, hydrophobicity was observed during a rain event in the forest in the litter layer above the topsoil, but it led to only a small volume of overland flow. The place where the hydrophobic reaction occurred was covered for 2 weeks by a plastic sheet because field material was stored there. Scherrer (1996) measured overland flow caused by hydrophobicity on alpine meadow on Podsols on the Gotthardpass, but for the meadow in this study no hydrophobicity was observed.

Additional information on the overland flow processes is given by the timing of the onset of overland flow. The onset of overland flow points to SOF as the dominant process. There were no high rainfall intensity bursts before overland flow started, and when the soil moisture conditions were dry, a higher rainfall amount was needed until overland flow started. Generally, overland flow did not start within the first two hours of a rainfall event (average intensity did not exceed 2 mm h^{-1}), not even on bare land. Moody and Martin (2015) measured time to runoff on a burned forest area with an overland flow detector, that detects already a very small amount of overland flow. The times to overland flow was often less than 10 min and for cumulative rainfall less than 1 mm, but with a high spatial variability on the hillslope. The high rainfall intensities and the short times to start indicated HOF (Moody and Martin, 2015). Neither such high rainfall intensities nor short onset times of overland flow were reached in the Studibach catchment and therefore points to the exclusion of HOF for the bare land sites in this study. However, a distinction of SOF and HOF for bare land is maybe not that meaningful because of only a very shallow and hydrological active horizon.

6.1.4. Limitations

Despite its preliminary character, this study provided insights into the spatiotemporal dynamics of overland flow generation in the Alptal catchment and led to the identification of SOF as the dominant overland flow generation process. However, limitations apply for the generalization of the findings and the application of these findings in models.

The OFCs were not designed to measure the volume and magnitude of overland flow. Therefore, overland flow runoff coefficients and contributions to streamflow could not be calculated for the different land cover types. Once an OFC is filled, overland flow has to flow around (and over) it, which will eventually result in rills and erosion. OFCs were reinstalled, when rills and erosion under the OFCs, mostly on bare land, were observed. The OFCs have also not been tested for overland flow on a hydrophobic litter or humus horizon. Overland flow may then not find the way into the OFCs because hydrophobicity could be reduced in front of the OFC pipe by the pooling of water. The upslope contribution area of OFCs were not bound. Especially for bare land, return flow from other land cover types could possibly influence the frequency of occurrence and the chemical composition of overland flow.

The variation in overland flow occurrence between land cover types cannot be directly transferred to catchments of other soil types, as different overland flow processes can occur for other soil types. For example, sealing and swelling of the topsoil can lead to HOF. The results of this study are only valid for Gleysols, as Gleysol was the only soil type in the catchment. However, the findings can be transferred to other catchments with shallow Gleysols. For other soils, overland flow generation is different in response time and magnitude as described in Scherrer (1996). Overland flow may have similar characteristics as in the Studibach catchment on shallow and poorly permeable soils, for example, on loamy Cambisols and Podsols (Scherrer, 1996).

Processes in the soil were not studied and therefore nothing can be said about air entrapment or macropore flow near the surface. Blue dye experiments could show flow paths of overland flow and lead to the identification of return flow (Schneider et al., 2014).

6.1.5. Outlook

The next study on overland flow in the Alptal would need to measure the volume of overland flow for the land cover types to calculate overland flow runoff coefficients. This can be done with the measurement of overland flow runoff volumes for bounded plots. Bounded plots are required, so that the overland flow volume can be referred to an area, and that no additional overland flow can flow into the measured plot. This method requires more material and interference with nature than the ON/OFF measurement method in this study. With a new, small and low-cost instrument to measure plot scale runoff volumes by Stewart et al. (2015; Upwelling Bernoulli Tube), overland flow can be accurately measured in timing and amount across a range of flow magnitudes (up to 300 l min^{-1}). The flow rate, through a slot with a calibrated geometry in the vertical pipe, is derived from the water level, measured by a pressure sensor with ±7 mm accuracy. Long-term overland flow studies from plots can be conducted with this robust and reliable instrument without emptying the overland flow collectors periodically after rainfall events (Stewart et al., 2015). However, bounded plots result in further challenges for the study design. For example, the choice of the plot size can influence the overland flow runoff coefficients (Joel et al., 2002) and the depth of insertion of the border into the soil can influence subsurface flow and therefore the occurrence of return flow.

Alternatively, the contribution of overland flow to stream flow can be estimated by isotopic and chemical hydrograph separations (Barthold et al., 2017), but it is probably challenging to assign the land cover types to fractions of stormflow contribution(Fischer et al., 2015, 2017).

6.2. Second research question: What is the spatiotemporal variability in the chemistry and the isotopic composition of overland flow?

The second research question focuses on the spatiotemporal variability in the chemistry and the isotopic composition of overland flow. Chemical concentrations are significantly different for the land cover types. Special patterns were found by comparing sites of the same land cover type and by comparing the concentrations measured at the OFC locations individually. Finally, the isotopic composition, EC and Ca concentrations of overland flow were compared to the chemical composition of rainwater, soil water, groundwater, and streamflow.

6.2.1. Spatiotemporal variability in overland flow chemistry

In the Studibach catchment, overland flow of the different land cover types differs in the chemical composition. The stable isotope values showed a clear distinction between bare land and wetland. While the values for bare land cluster around the precipitation values, the wetland samples have an isotope signal closer to the groundwater samples. A different mixing of pre-event water and event water can therefore be assumed. The spatiotemporal variation in stable isotopes and the fractions of event and pre-event water will be further discussed in chapter 4.3. In Figure 22 the two points of BA5 and WB1 showed a high deviation from the GMWL. This deviation is probably caused by evaporation of pre-event water due to the special locations of the OFCs WB1 and BA5 (see Figure 30 in Appendix A) or measurement errors.

The isotopic composition, EC and concentrations in overland flow varied mostly between rainwater and soil water, and groundwater, except for the Ca concentrations of overland flow, which were in the same range as soil water. This indicates that overland flow is a mixture of rainwater and soil water or groundwater and that overland flow dissolves the available elements from the surface ground or the vegetation quickly, but does not reach the same concentrations as groundwater that has more time to dissolve elements. Barthold et al. (2016) compared overland flow (bulk sample of first flush and sequential intra-event samples at three different sites in dry channels) to rainfall, troughfall, stormflow and base flow in a rainforest in Panama. They found that Ca concentrations of overland flow ranged between rainfall and groundwater (baseflow). One overland flow sampler reached similar high Ca concentrations as baseflow, which was explained by a high contribution of groundwater by return flow. Other element concentrations (K, ammonium and nitrate) were higher in overland flow than in baseflow (Barthold et al., 2017). We have also measured higher K concentrations in many overland flow samples than in some groundwater samples.

A recurring pattern in the analysis was the different behavior of the wetland sites WA and WC, and WB for many chemical concentrations. WA and WC had higher concentrations in nutrients and higher EC; WB had higher concentrations in metal and is only fed by precipitation. This supports the hypothesis, that these sites are two different types of wetlands. Based on chemical, hydrological and plant data WA and WC can be classified as eutrophic fens, WB as a bog. During events, water levels rise to the surface and lead to overland flow at wetland WB. At wetland sites WA and WC, mineral-rich return flow from (perched) groundwater leads to overland flow. This corresponds to the observations in the field, where overland flow velocities on WA and WC were higher than for WB. Holden et al. (2008) mention higher hydraulic roughness to overland flow by Sphagnum than by peatland grasses, and therefore lower velocities. Wetlands are often used as areas for water treatment and can retain, for example, phosphate and nitrate (Huttunen et al., 1996). Species occurring in wetland WA and WC particularly the marsh-marigold or sedges (e.g. Carex lasiocarpa) favor nutrient removal (Huttunen et al., 1996).

The EC of overland flow on bare land was higher than for the other land cover types. On bare land, the absence of the vegetation and the topsoil layer lead to direct interaction between the rainfall and the exposed bedrock. Sediment is more easily detached by raindrop splash erosion on bare lands than on vegetated areas. Splash erosion and erosion rills explain the higher erosion rate that is often found on intershrub plots than on meadow plots (Wainwright et al., 2000). The sediment in overland flow could lead to a higher EC due to dissolving salts. The concentrations of overland flow on meadows was generally in between those for wetlands and bare lands. Rather low EC values could mean a low interaction of the rainfall with the soil and limited mixing with the soilwater (see chapter 4.3. for event water fractions). The higher nitrate concentration in overland flow on bare land than on the meadow, except for the event no. 14, may be caused by the mobilization of cow dung on meadows during large event no. 14. Kurz et al. (2004) studied the effects of grassland management on overland flow and the phosphate and nitrate concentration. They found that grazing animals led to overland flow with elevated nitrate and phosphate concentrations (Kurz et al., 2005). The ten times higher concentration in phosphate and the high nitrate concentration for the meadow location MA2 could therefore be influenced by cow dung in the upslope area.

6.2.2. Limitations

The OFCs are designed to take only a bulk sample until the OFC is filled. This leads to uncertainties in the chemistry in overland flow, that is expected to change during the event. The filling of the OFC could happen with the first flush of overland flow or by several small flushes. The OFC are not designed to measure volumes and take intra-event samples. Element concentrations of intra-event samples may show changes of overland flow processes particularly the mixing of precipitation and soil water during a rainfall event. Further, the concentrations could then be compared to the volume of overland flow. The dilution of overland flow and total export can then be addressed. This was not possible for this study. For example, the overland flow volumes were only small in the forest (partially filled OFCs). Even if high element concentrations were measured, the total export of this element in overland flow is still small because only small volumes of overland flow occurred.

Only a few samples were collected in the forest during the sampling campaigns because of a smaller number of OFCs, the few responding OFCs and the small amounts of overland flow in the collectors. Therefore, the land cover forest was underrepresented in the analysis and excluded from the statistical analyses. To sample the overland flow variability in the forest, extra samples should have been taken every time overland flow occurred in forest, not only during the sampling campaigns.

The chemistry of the heterogeneous Flysch bedrock was not taken into account for the chemical analysis. The influence of the Flysch bedrock on overland flow chemistry can be estimated as low for the land cover forest, meadow and wetland, and could only influence return flow from ground water. However, the Flysch bedrock layers at the ground surface have an effect on chemistry of overland flow on bare land, but the different bedrock layers at the surface were not analyzed on their respective chemistry and the effect on overland flow was not quantified

6.2.3. Outlook

These results show that it is interesting to study the spatial and temporal variability in the chemical composition of overland flow. With a relocation of the OFCs in a new sampling season in the catchment, the OFCs could be placed in different hydrological zones (e.g. riparian zones, or areas distant from streams) to study them selectively. Additionally, the OFC design could be adapted, to measure the volumes of overland flow and take intra-event samples

The chemical data set of water samples (rainfall, overland flow, groundwater, soil water, and stream water) would allow further analysis of the chemistry. Depending on the research question, it could be interesting to look at ratios of two or more element concentrations. For example, the ratio of K SiO_2^{-1} was used by Elsenbeer and Lack (1996) in the rainforest to distinct rainfall, throughfall and overland flow from soil water, groundwater and stream water. We did not take a closer look at concentration ratios as SiO_2 was not analyzed. However, the variation in element concentrations between land covers types can be used to identify the contribution to the stream, and hereby ratios of element concentrations could be helpful, for example, in a hydrograph separation. A hydrograph separation is a way to estimate the contributions of different processes and areas of a specific land cover type to runoff. However, a hydrograph separation of the stormflow was not possible with this data for the sampled event due to technical failure and errors in the programming of the sequential ISCO samplers. With the experience of these failed stormflow sampling campaigns, (sequential) samples should be taken (from precipitation, overland flow, soil water, groundwater and stormflow) and a streamflow hydrograph separation could be performed successfully in another season.

The impact of the cattle grazing in the upper catchment can only be approximated for this study. Periods and number of cows in the upper catchment area should be recorded for several years to analyze of the impact of trampling on soil hydraulic conductivity and cattle dung on overland flow chemistry. The movement of the cattle could be tracked by GPS. Cow dung can be mapped, but this would need a lot of field work for the large areas in the upper catchment. However, more exemplary catchments can be found for impact analysis of cattle on overland flow in Switzerland than the remote Studibach catchment with low cattle density.

Overland flow in the forest occurred less frequent than for the other land cover types, and we were only able to take a few overland flow samples in the forest. For forests, overland flow variation in chemistry is not well understood. A study that prioritizes overland processes in the forest should therefore last over a longer season to capture enough events. However, the relevance of such a study is not so high because of the probably small contribution of overland flow in forests to the stream, even if forests cover a large proportion of the catchment.

6.3. Third Research Question: How does the fraction of event (rainfall) and pre-event (soil) water in overland flow vary for different rainfall conditions and how is it affected by land cover?

The event water fractions were calculated based on the ratios of $\delta^{18}O$, $\delta^{2}H$, Ca concentrations, and the EC in overland flow, rain water (bulk sample), and soil water or groundwater. A high variability in the calculated event water fractions was found for the different elements and for the different land cover types. Even within a land cover type, the event water fraction differed considerably for some events.

6.3.1. Mixing of event and pre-event water

The fractions based on different concentrations showed significant differences. Different event water fractions based in isotopes were generally found for different land cover types, despite of the large variability within a land cover type. Event water fractions based on isotopes were high for bare land and low for most wetland sites. Therefore, we can assume that return flow of soil water and groundwater contributes largely to overland flow for wetland site WA and WC. The same process is possible for some OFCs on the meadow, for example, MA2, MA3, MA4, MC1, and MC3. At least, event water fractions under 50 % for the other meadow OFCs point to SOF as dominant process for event no 14. However, some meadow OFCs (e.g. MA1, MC2) had higher event water fractions (over 50 %), such that both processes HOF and SOF could have contributed to overland flow. For the smaller event number 6, MC3 and MC5 had high event water fractions of 73 % and 76 %, which indicates less mixing of rainwater with soil water, even though it is not a clear indication for HOF. For the forest, the three calculated event water fractions for event no. 14 of around 50 % (FA1, FB1) and of 23 % point to SOF.

At bare land site BA, the occurring overland flow was HOF according to the high fractions of event water except for one location (BA6), where the fraction of event water was only 10 %. At the location BA6, return flow from intercepted subsurface flow is probably dominant, but cannot be excluded for other OFCs on bar land. Even if bare land covers only a very small part of the catchment, its influence on stream flow may be high because they are probably highly connected to the stream by overland flow. With higher rainfall intensities maybe less mixing with pre-event water in the soil occurs. Since the EC is not a conservative tracer, another possible explanation could be a water film that forms on the surface, so less interaction with the soil takes place. A study of Ziegler et al. (2001) on overland flow on unpaved road in Thailand showed with stable water isotopes that the dominant process leading to overland flow is infiltration excess (HOF) and not intercepted subsurface flow (which in a way is a similar process to return flow). The intra-event samples of overland flow were all closer to rainwater in $\delta^{18}O$ than to the soil water. However, intercepted subsurface flow was observed on roads near this catchment (Ziegler et al., 2001).

Fractions of event water were generally lower for the large event no. 14 with a high antecedent soil moisture content compared to the smaller events no. 6 and no. 10. A larger contribution of pre-event water is likely, caused by the higher water content in the soil and the larger rainfall amount, which would lead to Faster saturation and mixing with pre-event water, even return flow. The comparison of the EC-based fractions indicated further that higher intensities lead to higher event-water fractions.

The results of Fischer et al. (2017) for different catchments in the Zwackentobel showed that the contribution of pre-event water was high for small events, while it became more event water dominated during large events. The limited storage of pre-event water in the shallow soils of the catchments was used to explain the increased importance of event water (Fischer et al., 2017). However, the results of this study show that overland flow generally has a higher fraction of event water for small event and higher fractions of pre event water for large events. This could be caused by the limited storage of the OFC and by increasing event water fractions in overland flow during the large events. Therefore, it seems possible that overland flow (SOF) during large events can explain the change from pre-event to event water after saturation of the soils.

The stable water isotopes $\delta^{18}O$ and $\delta^{2}H$ are conservative tracers (McGuire and McDonnell, 2008). In this overland flow study, both stable water isotopes resulted in similar fractions. An evaporations effect can be identified for BA5 and WB1 for event no. 10. Calcium and EC cannot be regarded as conservative tracers. On bare land, negative event water fractions were calculated based on Ca concentrations. Reactions on the bare surface may have led to the higher Ca concentrations. For wetland site WB, the ponding effect on this wetland seems to prevent the precipitation water to interact with the soil, since the water level is above the surface. The dense vegetation even lowered Ca concentrations of wetland site WB by uptake through the roots and the high cation exchange capacity of the peat.

The event water fractions based on EC should be handled with care. The EC of overland flow increases on bare lands due to interaction with the Flysch bedrock and stays low on wetland sites WB because rainwater falls onto standing water and cannot interact with the soil. This leads to different event water fractions based on EC. The EC-based event water fractions for meadows are closer to the isotope-based fractions, but overestimate isotope-based event water fractions. Considering the underestimation of isotope-base event water fraction due to the sampling of pre-event water, EC-based event water fractions are probably more accurate for meadows than this study suggests.

6.3.2. Limitations

The pre-event samples was taken from suction lysimeters and groundwater wells after the event. This is not an ideal situation because the soil water sample then also contained some event water. The calculated event water fractions in overland flow are therefore likely underestimated at least for the isotope-based fractions. The uncertainties of the event water fractions were not quantified, neither the over- or underestimation. This sampling set-up was chosen to reduce the logistical effort and the field days. Because of uncertainty of predicting the actual start and the size of rainfall events, a lot of flexibility is needed to capture a large rainfall event for a sampling campaign with pre-event samples. Another challenge of sampling soil water before the rainfall events are the suction lysimeters in 15 cm depth that often fell dry before rainfall events. The set-up for pre-event sampling should be rethought for subsequent studies to get more accurate event water fractions.

6.3.3. Outlook

A follow-up study could analyze the change of fractions of event water in overland flow during an event. Intra-event samples could be taken from the overland flow collectors with a sequential sampler. Sequential rainfall samplers were installed and sampled for this study. An assignment of the overland flow samples to the respective rainfall based on the overland flow onset times was not performed, but would lead to further insights of processes during the events. To be able to take samples of the pre-event water (soil water) without dilution through event water, suctions lysimeter could also be installed in the two different wetland sites, where sampling should be possible also after longer dry periods, due to the relatively high water table. The high variation in soil water can be addressed by installing more suctions lysimeters and taking mean concentrations of stable water isotopes of shallow soil water samples at different depths per land cover to calculate the event water fractions in overland flow.

The calculated event water fractions based on EC should only be used as a rough estimation. Processes of increasing (bare land) and decreasing (site WB) EC values in overland flow are examples for the non-conservativeness of EC as base for calculating event water fraction.

7. Conclusion

Determination of the timing of overland flow, combined with land cover data, collected rainfall and soil moisture data has provided insight in the spatiotemporal factors controlling the overland flow process in the study area. The collection and chemical analysis of overland flow has furthermore provided information of the sources of overland flow and therefore understanding into the dominant overland flow processes. In general, overland flow was found to be a frequent and spatiotemporally variable runoff component in occurrence and in chemistry.

Land cover is found to be the most important spatial factor controlling overland flow. The highest frequencies for overland flow occurrence were found for bare land (78 %) and for wetland (66 %). Overland flow occurred on meadow on average only in 42 % of events, even less in forests (5 %).

Rainfall amount is found to be the most important temporal factor controlling overland flow. Rainfall intensity is found to be a second-order control of overland flow. Antecedent soil moisture is a minor factor in controlling overland flow and most likely only affects the threshold of rainfall amount initiating overland flow.

Determined event water fractions based on stable water isotopes indicate that SOF is the dominant overland flow generation process for the land cover types meadow, wetland, and forest in the Studibach catchment. The onset times of overland flow also point to SOF as overland flow generation process for meadow, wetland and forest. On bare land, high fractions of event water point to HOF, while overland flow onset time measurements point to SOF. Event water fractions based on EC and Ca concentrations over- or underestimated the event water contribution compared to fractions based on conservative stable water isotopes ^{18}O and ^{2}H because of interaction with the soil and uptake of Ca by plants on wetlands, that are low on nutrients.

This study overall points to the relevance of overland flow as a fast contributor to stormflow runoff for the Alptal. The shallow and low-permeable Gleysol facilitates SOF as the dominant overland flow process. Different land cover types are significantly different in overland flow occurrence, chemical composition and event water fractions. High rainfall amounts led to generation of overland flow at most locations, except for some forest sites. The event water fractions in overland flow tend to decrease for higher rainfall amounts and to increases for higher rainfall intensities.

7.1. Recommendation for further field work

In the following, field experiences are shared as a recommendation for further studies to avoid similar mistakes:

- OFCs on steep bare land are prone to slide with the eroded loose material and need regular maintenance to stay connected to the bedrock with overland flow. The locations on bare land should be chosen after rainfall, so that activated flow lines can be excluded or chosen on purpose.
- The use of copper wire for the electrical resistance sensor can influence the chemistry of sampled water. Metal clamps for attaching the OFCs to the soil showed erosion marks and can contaminate samples as well.
- The pre-event water sample from the suctions lysimeter are highly variable in space and time and difficult to sample before events (they fall dry). Averages over many lysimeters or continuously measured groundwater are alternatives.
- The ISCO sampler program need close attention and probably a full test run of the program, not only a test of functionality. We equipped the ISCO sampler with an additional battery. Cold temperatures can shorten the durability of the batteries. Changing of a battery after an event sampling was necessary.

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Appendix A: Pictures from the sites and the field work

Figure 29: Bare land site BA with OFC BA5 (left), taking a sample from BA5 with a syringe (right, photo by Lukas Bossart), and the samples of sampling campaign for event no. 14 (below).

Figure 30: Meadow site MA with OFC MA4 and double ring infiltrometer with the Mythen in the background (top), wetland site WB with wrapped Arduino sensor and Groundwater well 32.5 behind small tree (bottom left), and overland flow reaching an OFC during test run with artificial irrigation in the Irchel park (bottom right).

Appendix B: Personal Declaration

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

Zurich, 20.04.2017 Tobias Sauter