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Spatial and temporal variation in the flowing stream network and saturated areas in a boreal watershed in Northern Sweden

GEO 511 Master's Thesis

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26 January 2018
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Abstract

Temporary streams are common in headwaters. A shift from a flowing stream to standing water or dry stream can have significant consequences for the ecosystem and therefore highlights the importance of understanding the variations in stream network contraction and expansion. This thesis contributes to a better understanding of flowing stream network dynamics and spatial and temporal variability in saturated areas in a boreal environment. This knowledge can be used to ensure high water quality and appropriate water management by protecting certain areas. Investigations of this thesis were done in the well-studied Krycklan catchment in Northern Sweden from mid-May to mid-September 2017. Several field methods were applied to gather data about the spatial and temporal patterns in flowing stream network dynamics and soil saturation. Water presence and flow were detected with four stream sensors at 12 selected sites. Data about the electrical resistance, temperature, flow, water level switch and groundwater table were collected, analysed and interpreted. Each measurement cluster was additionally equipped with a time lapse camera to check the results of the sensors. In addition, field surveys were conducted by mapping the stream network and classifying the flow on six different dates. Saturated areas were also mapped on six different dates. The highest soil saturation was observed in May with varying conditions until August. Precipitation could partly explain the number of saturated soil areas. The field observations revealed that variations in the flowing stream network are rather small after the snowmelt until June, but increased with more dry sections and sections with standing and ponding water in August. Processes of downward contraction and disintegration were observed. The quality of the data varied for the different sensors. The temperature sensor was the most reliable for the detection of water presence. For a boreal environment, and therefore many locations of barely flowing or standing water, the installed flow sensor is too imprecise and cannot detect low flow velocities. It has to be adjusted for an unbiased result in areas with little variation in topography. The collected data on the length of the flowing stream network were compared to precipitation and discharge, which showed similar patterns on a temporal scale. Furthermore, a 5 m DEM to relate topographic indices such as upstream distance, local slope, accumulated area and topographic wetness index were related to the state of the stream. For this study site in a boreal watershed, the upstream distance and accumulated area could best explain where water was flowing, standing and where dry channels occur.

1. Introduction

1.1. Context

Water is one of the most important resources on earth. Not only humans, but also ecosystems depend on the quantity and quality of water (Grabs, 2010). Where does the journey of this essential flowing water begin and where does it go? Headwaters are the source and origin of small-order streams. Once running water has formed a stream, it is not certain that it continues as a perennial stream. In fact, temporary streams play a considerable role, particularly in headwater streams (Godsey and Kirchner, 2014). The ecosystem services provided by these headwaters are vast, such as the supply of water and nutrients for the downstream environment and many more services. But the knowledge about the hydrological processes in headwaters is limited (Bishop et al., 2008) and research is needed to better understand low-order streams and their processes and dynamics.

The combination of human activities in the natural environment, the demand for fresh water and climate change lead to more frequent and more extreme floods and droughts in the future. At a smaller scale, a change in the stream network regime from flowing to standing to dry can have serious consequences for an ecosystem. Moreover it can influence the quality and diversity of services they provide (Datry et al., 2016). This highlights the importance of understanding the variations in the flowing stream network dynamics. This thesis aims to contribute to a better comprehension of the variations in the flowing stream network and saturated areas of headwaters in a boreal environment.

In boreal environments, the temporal variability of the flowing stream network is high. Many streams are missing on current maps, especially temporary streams (Ågren et al., 2015). Wet soils, especially in mires, have a low load-bearing capacity and already little traffic with cars or forestry machinery can cause compaction or rutting of the soil (Ågren et al., 2014). Hence, the soils are very vulnerable but at the same time also represent an essential resource for many ecological habitats and vegetation.

Therefore, a proper management and policy for forest and water resources in a boreal region requires better insights into soil moisture patterns and stream network dynamics. With the knowledge of the occurrence of ephemeral streams and saturated soils, the impacts of forestry on the water can be reduced. This can be done, for example, by avoiding driving over these saturated areas or through dry temporary streams. It is expected that the pressure on water quality increases in the future due to the effects of climate change, particularly in boreal regions (Ågren et al., 2015). Therefore, a better understanding of the flowing stream network is required to protect the riparian zone. With this knowledge, we can delineate areas where a special treatment or conservation is important to ensure high water quality.

1.2. Ephemeral streams

Temporary streams are common particularly in headwaters. Temporary streams, include ephemeral or intermittent streams, are streams where flow ceases periodically. The streams can dry out naturally or as a consequence of human impacts (Datry at al., 2016). The latter can also occur due to ditching. This has consequences for the stream network dynamics since the natural path of flowing water is interrupted by human made stream channels.

Ephemeral streams are highly dynamic ecological ecosystems and are complex with varying durations, frequencies, timing of flow as the network expands and contracts. In addition to providing aquatic habitats, they are important for the transport of nutrients and organic matters. Knowledge and understanding of the wet-dry cycle in an intermittent stream ecosystem contributes to a better understanding of the chemical processes and ecological habitats (Datry et al., 2016). During a dry period, leaf litter and sediment accumulate in the channel and when the stream starts to flow again, the accumulated sediments and organic matters are transported downstream (Datry et al., 2014). Therefore, the variability of flow influences the biogeochemical processes, e.g. microbial activity and thus water quality.

Despite the profound hydrological relevance of intermittent and ephemeral streams, there is a lack of monitoring of the variation in the flowing stream network (Wigington et al., 2005). This lack of monitoring, particularly in ephemeral streams, is connected to the episodic flow and low predictability of the flow (Bishop et al., 2008). One reason for the missing data is the technical challenge of monitoring them, due to the high spatial and temporal variation of flow in the stream network as it expands and contracts (Bhamjee et al., 2016).

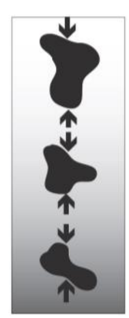
1.2.1. Expansion and contraction of ephemeral streams

When flow occurs in an ephemeral stream channel, the flowing stream network expands and in turn contracts when flow ceases. The control of how a flowing stream network expands and contracts is dependent on different factors such as in-channel characteristics, i.e. channel geometry, longitudinal profile, roughness and modification. In addition, catchment characteristics are closely related to the way of how a stream network responds. These are the topography of the catchment, land cover and use, and anthropogenic activities such as drainage of the catchment. Due to many involved factors, it is challenging to monitor the expansion and contraction of flowing streams with high temporal and spatial resolution (Bhamjee et al., 2011).

Patterns

There are three different models for a stream network expansion and two models for contraction pattern (see table 1). Coalescene expansion occurs when small water pools form independently from each other and create a flowing stream when they connect (Bhamjee et al., 2011). High intensity of rainfall combined with a low water infiltration capacity of the soil, often lead to downstream expansion of the stream network due to surface flow from precipitation (Ward and Robinson, 2000). Headward expansion is based on soil saturation and represents the growth of the stream network towards the head of the channel. Contrary, downward contraction appears when the stream dries out at first from the channel heads. The second model of contraction is disintegration when local pools of water remain after the flow ceased and disappear due to drainage or evaporation. (Bhamjee et al., 2011).

Table 1. Patterns of stream network expansion and contraction (from Bhamjee et al., 2011).

Expansion patterns			**Contraction patterns**	
Coalescene	Downstream expansion	Headward expansion	Disintegration	Downward contraction
				

Relation to discharge and stream length

Processes of expansion and contraction also affect the length of the flowing stream network. Variations of stream length are big, especially in first-order streams. One control of the length of the flowing stream network is precipitation (Blyth and Rodda, 1973). Nevertheless, the understanding of stream length variations on different spatial and temporal scales is still limited (Wigington et al., 2005). Moreover, intermittent streams are often not mapped but account for the total stream length of a catchment. They also show different temporal patterns, as some ephemeral streams only flow during or after heavy rainfall or snowmelt, some only flow during wet periods and some occur episodically (Meyer et al., 2007).

1.3. Saturated soil

In order to understand the expansion and contraction of an intermittent stream network, not only the surface flow but also variations of the groundwater level are important (Stanley et al., 1997). When the soil is saturated, the additional precipitation leads to surface flow, thus it affects the flowing stream network. Saturated areas and groundwater level are closely linked to variations in stream network; where soils are wet, the stream is more likely to be flowing.

Spatial patterns of soil moisture help to investigate soil water redistribution (Rinderer et al., 2012). It also suggests areas of soil saturation and flow processes on the surface, particularly in soils with low load-bearing capacity (Western et al., 2004; Western et al., 2005). It is known that compaction of these wet soils, for example due to traffic, can increase surface flow. Especially soils near streams exhibit a low load-bearing capacity and are therefore vulnerable to soil disturbance. It is therefore important to map the change and extent of these saturated areas to understand the variations in soil moisture and develop an adequate protection of these areas (Ågren et al., 2014).

1.4. Aims and research objectives

This thesis aims to contribute to a better understanding of expansion and contraction of the flowing stream network in the Krycklan catchment in Northern Sweden. Since there is little empirical evidence of the distribution and variation of the flowing stream network (Goulsbra et al., 2014), the approach in this study combines data loggers and visual observations to ensure the quality of the data on both the temporal and spatial variation in the flowing stream network. In particular, this thesis addresses the following five research questions (RQ).

The first question concerns the collection of data with the use of certain data loggers from the University of Zurich.

> ***RQ1****: Can the measurement clusters with four different sensors be used to determine whether there is flowing/standing/no water in the boreal environment?*

The second research question addresses the monitoring of the flowing stream network in a certain study area.

> ***RQ2****: How does the flowing and connected stream network change in a boreal catchment in Northern Sweden from snowmelt until the end of August/September and during rainfall events?*

As a third question, the collected data is to be analysed regarding the state of the stream and the length of the flowing stream sections.

> ***RQ3****: What is the relation between the length of flowing stream channel and streamflow?*

Since the occurrence of flow is related to the saturation of the soil (Goulsbra et al., 2014), empirical data of the saturated soil is important as well and is addressed in this study.

> ***RQ4****: How does the saturated area change in a boreal catchment in Northern Sweden from snowmelt until the middle of August?*

Furthermore, the collected data regarding the state of the stream are analysed in relation to topographic information in order to predict where the stream may be flowing or has standing water.

> ***RQ5****: Can topography predict the locations of flowing and standing water?*

1.5. Structure of the thesis

The first part of this thesis describes the study site in terms of location, climate, topography, vegetation and history. After this, the methods are introduced, starting with the four different sensors, time lapse photography, stream network mapping, saturated area mapping, groundwater wells and the visualisation of the data in a geographic information system (GIS). The results of these measurements and surveys are shown in the next chapter and are interpreted, compared and embedded in the framework of existing literature in the discussion. In the conclusion, the individual research questions are addressed again.

2. The Krycklan catchment – A study site description

2.1. Location

The study site is in the Krycklan catchment. It is located in the northern part of Sweden, approximately 50 kilometers northwest from the city Umeå (red dot in figure 1). The whole catchment has a size of 67 km^2 and is divided in 18 different sub catchments (Laudon et al., 2013).

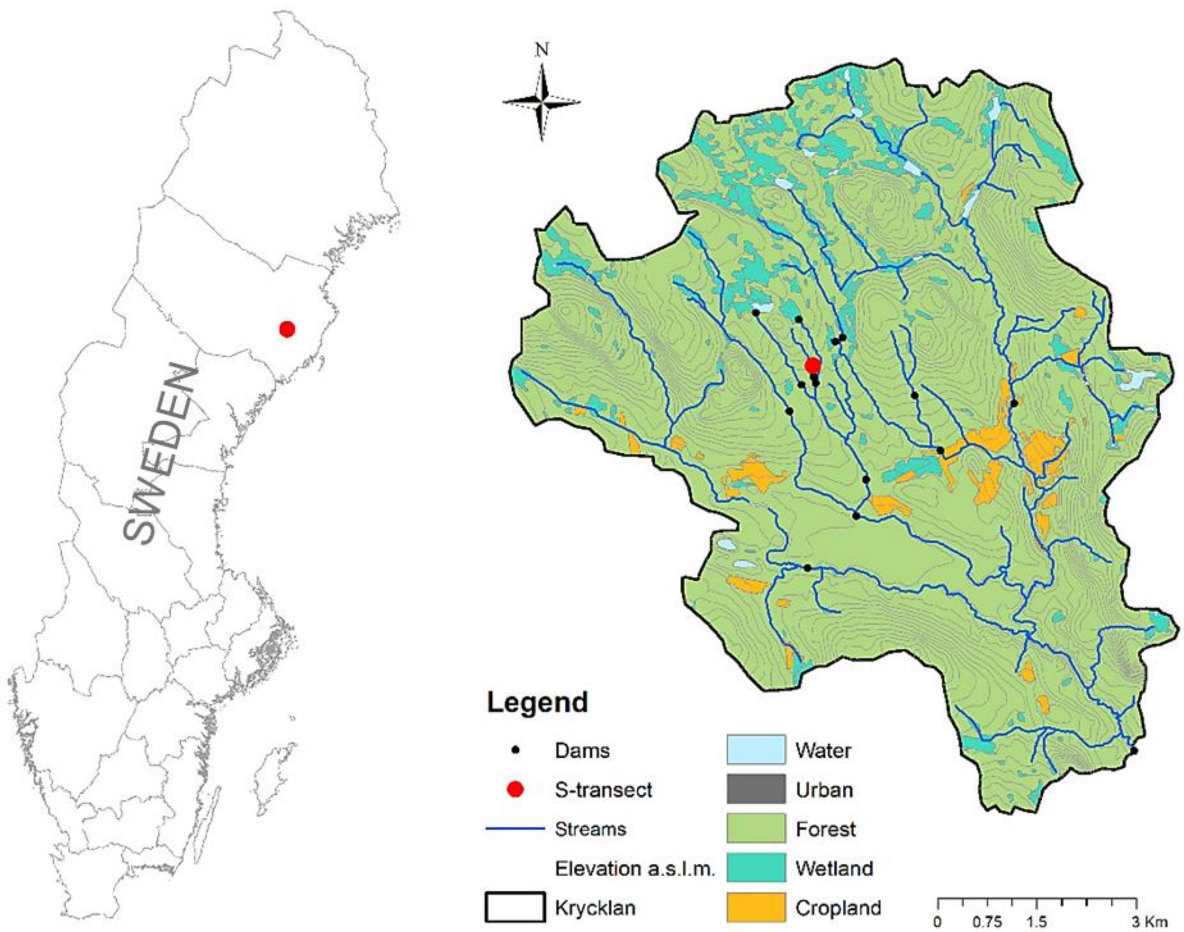


Figure 1. Map of the Krycklan catchment and location of the study site in northern Sweden (adapted from Zanchi et al., 2016).

Krycklan belongs to the Swedish University of Agricultural Sciences (SLU) and forms part of the Svartberget field research infrastructure (Laudon, 2017). The Krycklan catchment provides an optimal study area for hydrology, biogeochemistry and climate research in a boreal region. The area contains all typical landscape features for a boreal region, i.e. forests, soils, mires, lakes and streams. Furthermore, the infrastructure for doing research is already available and various data is being collected in this area since 1981, particularly hydrological data. Therefore, many data records exist which can be a useful gain for further research to compare the data (Laudon et al., 2013). Most of the data is available for the public which constitutes a further advantage. For this research the discharge and precipitation data is particularly valuable, as well as detailed maps of the area.

2.2. Climate

The Krycklan catchment has a cold temperate humid climate, with a mean annual temperature of 1.8 °C. The mean annual precipitation is 614 mm from which slightly more than the half results in runoff and the other half is used in evapotranspiration (Laudon et al., 2013).

Figure 2 shows the climate diagram from Vindeln, the village next to the Krycklan catchment. It can be seen that most precipitation falls during the summer and autumn period, particularly from July to November. The winter and spring months, on the other hand, are rather dry. The field investigations for this research were conducted in May, June and August.

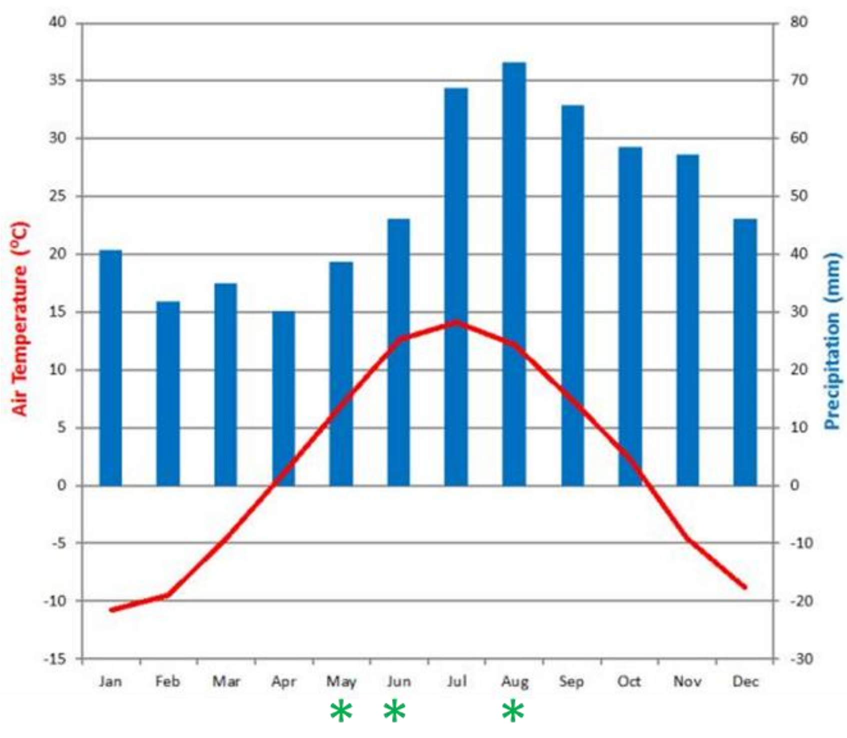


Figure 2. Climate diagram 1961-1990 Vindeln (adapted from ICOS Sweden, 2017).

As a typical boreal landscape, the spring and early summer period is characterized by the snowmelt. The total amount of the meltwater can contribute up to 50% of the whole annual water sum (Barnett et al., 2005). Snowmelt in the Krycklan catchment generally starts in the middle of April

(Laudon et al., 2007). However, in 2017, the snowmelt process slightly shifted seeing the temperature was close to 0°C at the beginning of June. That discharge is strongly related to the snowmelt can be shown by the fact that the highest discharge in the Krycklan catchment in 2013 was on 14 May, only few days after the peak of snowmelt. In contrast, the lowest discharge that year was measured after a drought period on 30 October 2013 (Ågren et al., 2015).

2.3. Physical environment and history

The Krycklan catchment is glacial shaped and consists of quaternary deposits including 51% of till and 30% of sorted sediments. The bedrock underneath the Krycklan catchment consists of Svecofennian metasediments (Laudon et al., 2013), and is mainly made up of gneiss (ICOS, 2017).

The entire catchment ranges from its lowest point at 114 up to 405 m above sea level. As shown in figure 1, 88% of the land is covered with forest. The 100 years old mixed forest mostly consists of Scots pine with 63% and 26% Norway spruce. Furthermore, in the upper part of the catchment are many wetlands (visualised blue in figure 1), covering 9% of the entire catchment area (Laudon, 2013).

Well-developed iron podzols can be found in the till soils, but with a shorter distance to the streams, the content of organic material increases (figure 3), which is also known as the riparian peat zone (Laudon et al., 2013).

Figure 3. Example of the soil near the streams.

The Krycklan catchment has been actively investigated since 1923 with several research activities, particularly forest research and soil frost, having been conducted (ICOS, 2017). The Svartberget field station, which is located in the center of the Krycklan catchment, was built in 1970 (Laudon et al., 2013). Climate and hydrology monitoring programs have been active since 1980 and benefit from this unique infrastructure (ICOS, 2017). Today, the Krycklan catchment has become an experimental platform for scientific projects (Laudon et al., 2013).

The land use in the Krycklan catchment is mainly forestry. However since 1922, 25% of the catchment has been protected (Laudon et al., 2013). As an effect of the forestry and timber production, close to 25% of the Fennoscandian forests have been artificially drained by ditches. The estimation of the length of these ditches in Sweden is 1 million km, which is double the length of the natural stream network (Skogssällskapet, 2017). An example of these former ditching activities, located in one of the study sites, can be seen in the photography figure 4.

Figure 4. Example of measurements in a location with former ditching activities.

3. Methods

In this thesis, several methods are used to address the five research questions mentioned above. The methods are qualitatively described in this chapter. At the beginning, the methods are all different and address different aims, but in a next step their results are set in context and in relation to each other in order to obtain the best results to answer the research questions.

3.1. Stream sensors

One method to monitor the seasonal change of the flowing and connected stream network is the use of 12 measurement clusters, each of them with four different sensors from the University of Zurich. The aim is to determine, with the data out of these 12 clusters, whether there is flowing, standing or no water in the streams. There are four sensors attached to a data logger device. These sensors measure different variables such as the ER (electrical resistance), the flow, a water level switch and the temperature (figure 5). A detailed description of each sensor follows in the next paragraph.

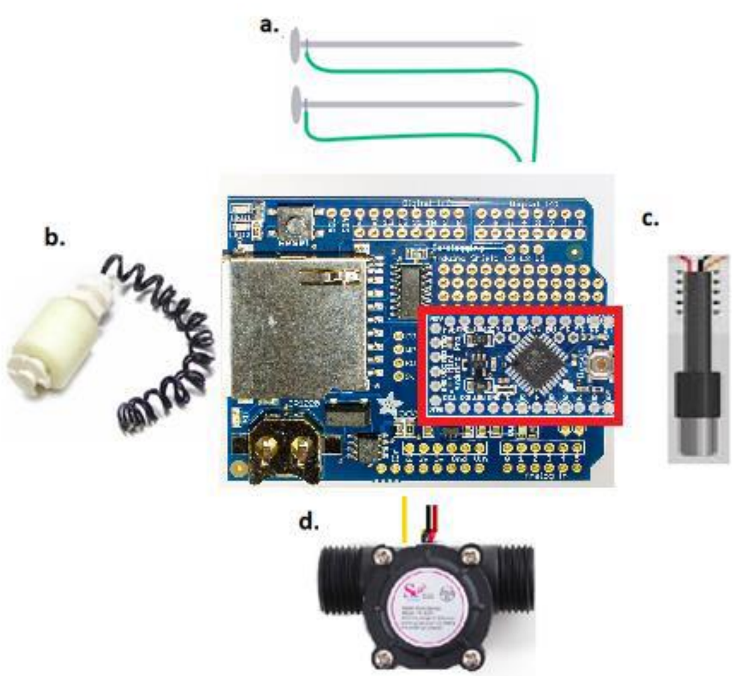


Figure 5. Different sensors: a. ER, b. water level switch, c. temperature, d. flow sensor and the Arduino logger (from: Assendelft, 2016).

Electrical resistance

The ER sensor is shown in figure 5 as letter a. Two electrodes measure the conductivity of the environment in which they are embedded in. These two electrodes are located in the stream channel slightly above the channel ground. Based on the given signal of the ER sensor, it can be determined whether there is water in the channel or not. The analog signal is the amount of voltage from 0 to 5 V and fits into a discreet value between 0 and 1023. The outcome number thus represents the amount of voltage drop which is applied to the electrodes. The higher the resistance, the higher also the voltage drop. For example: when there is no water in the channel, the voltage drop is high. When comparing absolute values to other ER sensors it must be mentioned, that this outcome number depends on how far the two electrodes are installed form each other and how much wire is exposed. However it is not calibrated that means, absolute values of the ER sensor are not be compared to other independent sites, since water chemistry and temperature may also affect the electrical resistance.

Flow

The second sensor attached to the logger is the flow sensor (marked as letter d in figure 5). A plane is placed as deep as possible onto the channel ground, to make sure that the water does not flow underneath the plane. A funnel attached to the end of the plane will guide the water to the flow sensor which has a wheel that begins to rotate when there is flowing water. The unit of the outcome data is liter per hour. The gradation from one flow level to the next is always in steps of 12 l/h. In case of high water level, the attached funnel is not able to guide all the flowing water, and it flows over the funnel. Therefore, the aim of this flow sensor is not to get discharge data, but to detect whether the water in the channel is flowing or standing.

Water level switch

The third sensor concerns the water level (seen as letter b in figure 5). It is a water level switch, which starts to float when it is in the water. Therefore the outcome is a binary signal of 0 if there is no water and 1 if the water is present. In the latter illustration of the results, the signal of 1 is turned into a 5 to make the visualisation clearer. To keep the water level sensor steady, it is installed in a plastic tube with holes which allow the water to get through. Furthermore, this tube is protected with a sock to avoid sediments blocking the water level switch, which could falsify the signal. In the second fieldtrip in this study, in August, these water level switches were also additionally fixed with a wooden stick, to ensure that the switch remains stable when there is water and that the attached wire does not jam in the tube.

Temperature

The fourth sensor measures the temperature (letter c in figure 5). It is installed just above the channel ground. In contrary to the other sensors, the temperature sensor does not give an explicit result about the presence of water, but has to be compared to the data of a longer period. To detect whether there is water or not, the variation of the data has to be interpreted. Usually, a small diurnal variation in temperature is a hint of the presence of water. However, the interpretation of the temperature output data can be difficult due to sudden changes in the surrounding temperature such as a cold front or the presence of snow and ice (Ronan et al., 1998; Constantz et al., 2001; Constantz, 2008).

All these sensors are attached to an Arduino pro Mini computer hardware which is based on an open source platform and is used as an all-in-one measurement cluster. The Arduino runs with four AA 1.5 V batteries. Every five minutes a measurement is taken with all the four sensors and is stored. To store the collected data, each logger has a SD card inside which saves all the data gathered. An example of a properly installed measurement cluster is shown figure 6.

The results of the sensors can be compared among themselves to interpret whether there is water or not, for example the water level switch and temperature sensor of A1. When comparing the results of the sensors between the measurement clusters, e.g. ER sensor of A1 and ER sensor of A12, the results should be compared as relative values. This is due to various conditions at different locations, for example the amount of sediment and therefore different values for the ER sensor. For the interpretation of water presence, particularly the temporal changes of the sensors are relevant.

Locations of the measurement clusters

The measurement clusters are installed at the 12 locations seen in figure 7. All locations were selected by taking ditches and temporary streams into account. It is well known, that some of these old, human made ditches dry out during the summer season due to the fact that most of them do not flow as the topography would predict. By installing the measurement clusters in these ditches or downstream in the channels, data will be gathered about whether there is water or not and whether it is standing or flowing. Basically, three different sub catchments are investigated and named in this thesis, in west-east direction, as Area 1 (with cluster A9), Area 2 (with clusters A1 to A8) and Area 3 (with clusters A10 to A12). In Area 1, the stream is not following a clearly defined stream channel, but is rather diffuse. Due to the small variation in topography at certain areas, the water is flowing over a wide area instead of a clear channel. Additionally, the thick moss layer with its high water holding capacity prevents the water from flowing on the surface. Due to the spatially diffuse flow, the stream network was mapped only in a small section. Area 2 is investigated in particular, since in this stream network many ditches are present and it sometimes dries out relatively far downstream (second stream network section in figure 7). The section between A7 and A8 is an area monitored with highly sensitive instruments (S-Transect, see figure 1), and is therefore not included in this study, to not disturb these measurements. Area 3 is dominated by former ditches. This implies that the “streams” are more parallel rather than perpendicular to the contour lines. This means that the gradient of topography is smaller and therefore streams are less likely to flow.

Figure 6. Picture of the measurement cluster installed at location A11.

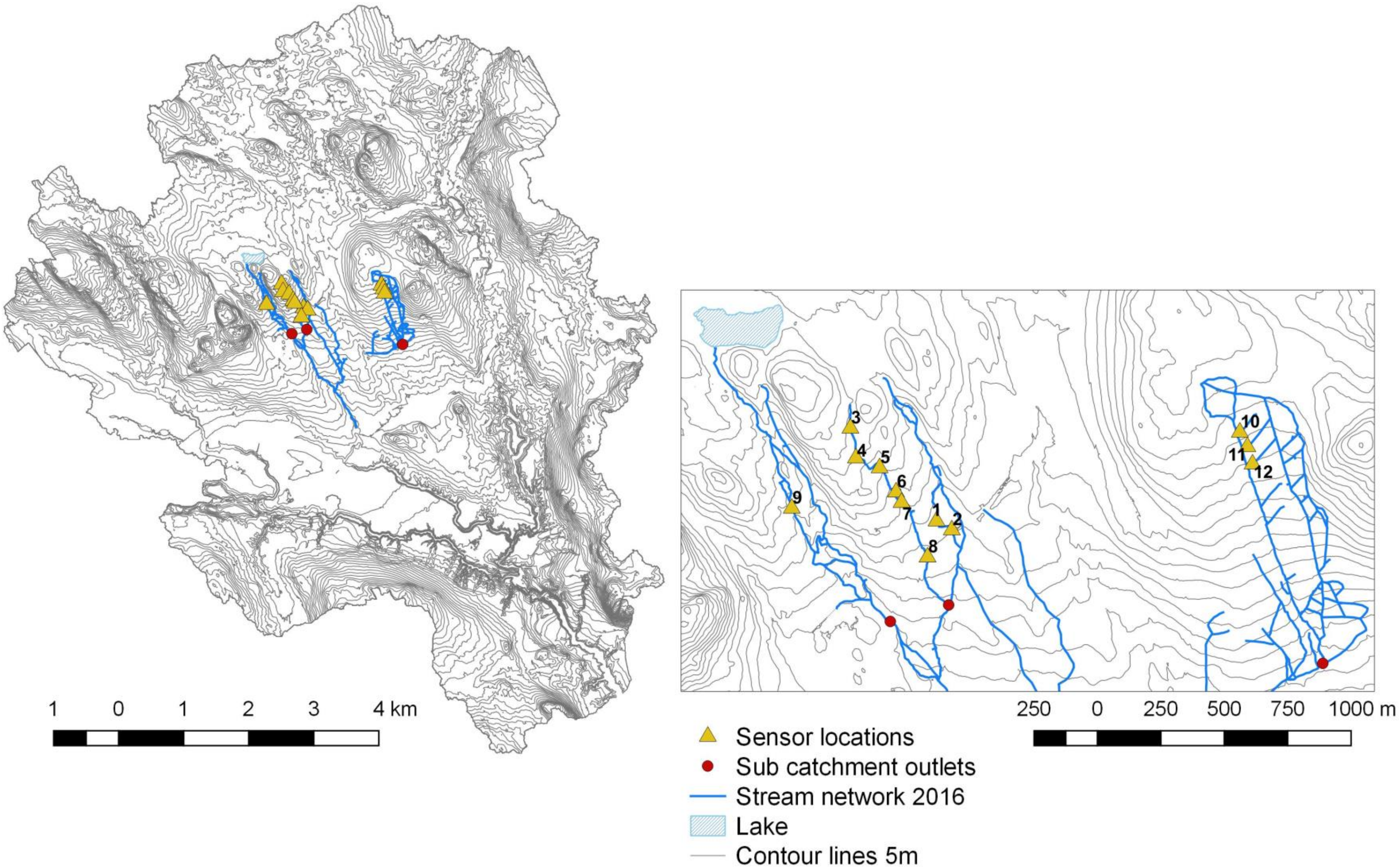


Figure 7. Location of the measurement clusters in the Krycklan catchment.

3.2. Time lapse photography

At every location with measurement clusters installed, a camera is placed in a spot with a clear view over the sensors and the concerning stream channel. The cameras were originally intended for the observation of wild animals, an example can be seen in figure 8. Therefore, the motion sensor on the front is taped to prevent the camera from reacting to any motion in the environment. All the cameras are configured to take one picture every 15 minutes. During nighttime, the cameras work with infrared. In the post processing procedure, the data of the time lapse cameras is combined with the data of the measurement clusters. The time lapse photography supports the interpretation of whether there is water in the stream channel and whether it is flowing or standing.

Figure 8. Picture of the Bushnell time lapse camera installed in the field (site A3).

3.3. Flowing stream network mapping

A further method to address temporal and spatial changes of the flowing stream network is mapping the stream network in the field. This monitoring takes place in the three sub catchments mentioned above (figure 7). The network of those four streams is mapped four times in May and June and twice in August with an interval of approximately one week. The interval of the observations varies and is adjusted to the weather conditions, as there is special interest regarding steam network changes after rainfall events.

The observation results of the flowing stream network are illustrated in maps of which each of them represents a different date. To show the current state of the stream, each stream section is classified into a class from 1 to 5. The different classes are shown in table 2 below.

Table 2. Stream network classification used in this study.

Class	State of the stream
5	**Flowing** water
4	**Barely flowing** water (v < 1m/min)
3	**Standing** water (> 2cm deep)
2	**Ponding** water (< 2cm deep)
1	**Dry** channel

Class 1 means that there is no water in the stream channel. Class 2 represents ponding water, which means that the present water is standing and has a depth of less than 2 cm measured from the water surface to the cannel ground. In contrary, the third class, named standing water, measures a greater depth than 2 cm. The flowing water is further divided into class 4, which represents barely flowing water, and class 5, named flowing water. The stream is defined as barely flowing water when the velocity of the water is less than 1 m/min.

Due to the difficulties of visual observation to distinguish between the classes of flowing, barely flowing or standing water, a fluorescent dye tracer is used. The clearly visible tracer is injected into the water and meets the flow dynamic of the stream. The distance which the tracer has travelled within a certain time helps to estimate the velocity of the water, and therefore allows to classify the stream section into an appropriate flow class. For addressing the third research question, the area of standing water and the length of the flowing stream channel, as well as the connected stream length, are compared to each other. These data are also set in relation to the discharge measured at the outlet of the sub catchments.

3.4. Saturated soil mapping

To evaluate the area of saturated soil and the wetness distribution, a qualitative evaluation of the saturated area along the stream network can be done. In combination with the flowing stream network mapping, it helps to identify the spatial and also temporal distribution of water presence above and below the surface. For a qualitative evaluation, the classification scheme from Rinderer et al. 2012 is applied (seen in table 3). It is an inexpensive and efficient qualitative method to assess the variability of soil moisture with no requirement of measuring instruments (Rinderer et al., 2012). The sampling soil spots are graded in an appropriate moisture class. The classes rise from 1, which represents the driest state of the soil, up to class 7, which means that the soil is saturated, thus water can be seen on the soil surface.

Table 3. Qualitative wetness classes (Rinderer et al., 2012; Icons from Mueller, 2015).

Class	Qualitative indicator criteria
1	The trousers of a person sitting on the ground would stay **dry**
2	The trousers of a person sitting on the top would get **moist after some minutes**
3	The trousers of a person sitting on the top would get **wet after some minutes**
4	The trousers of a person sitting on the top would get **wet immediately**
5	**Squelchy noise** can be heard when stepping on the ground but no water is visible
6	**Water squeezes out** of the topsoil when stepping on it with a boot
7	**Water** can be seen on the soil surface

The saturated soil is mapped along the stream network in the same three sub catchments where the measurement clusters are installed. The measurements are taken across the streams in east-west direction. The transect route in the field is marked with ribbons at the trees, to ensure that further measurements are taken at the same positions. The width of the transect lines varies from approximately 15 to 25 m. The start and endpoints of each transect line are stored in a hand-held GPS for the later investigations and illustrations in the GIS. A qualitative assessment of the soil wetness is taken with an interval of 2 to 3 m to the next measurement. In the field, each position is classified into one of the 7 wetness classes from Rinderer et al. 2012. As a result, every measurement gets a colored classification in the maps.

The saturated area is mapped every week. Four maps are created in May and June, and two in August. In addition, the weather data, basically precipitation and temperature, is collected for further comparisons and interpretations of the saturated area. To ensure unbiased data, the qualitative measurements are taken in the afternoon to avoid the influence of dew on the vegetation, particularly in August. Moreover, the measurements are not taken during and directly after rainfall events.

3.5. Groundwater wells

In addition to the sensors and the qualitative evaluation of the saturated soil area, groundwater wells are installed. Close to each measurement cluster, one groundwater well is set up in the same channel. The tubes have a length of approximately 1 m and a diameter of 1.5 cm. With the help of an iron core, they are hammered into the channel ground as deep as the channel subsoil allows. To get the most accurate data, it is important that the tube is placed in a vertical position. After the installation, the distance from the top of the tube to the channel ground is measured (marked as A in the figure 9). Additionally, the water level within the tube is measured (marked as B in figure 9). This is done by inserting a thin pipe into the groundwater well while blowing air into this thin pipe. The inserting is stopped as soon as the water in the tube is bubbling due to the air coming from the pipe. A mark is noted at this point of the pipe, and after removing the pipe out of the tube, the distance of this mark to the end of the pipe is measured. With the tube height (A) and the water depth in the tube (B), the water depth above or below the surface can be calculated. By repeating this procedure on different days, groundwater level variations can be monitored and a rise or fall of the groundwater can be detected.

In this study, the groundwater levels are measured at the beginning of June and in August. The results are compared to each other and set into context with the results of the measurement clusters. It helps to get an idea of water level variations and water distributions below the surface.

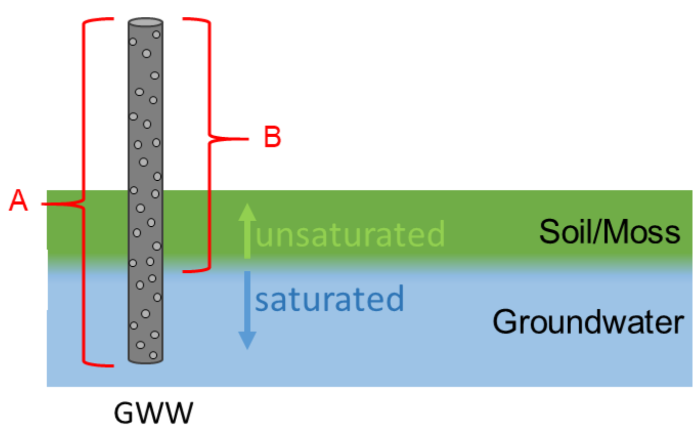


Figure 9. Installation of groundwater wells.

3.6. Analyses with the digital elevation model

To analyse the terrain of the catchment with the results from the classification of standing or flowing water, a high resolution digital elevation model (DEM) of the Krycklan catchment is used. The DEM is based on light detection and ranging measurements (LIDAR) and has a resolution of 5 m (Laudon et al., 2011).

The aim is to examine whether the topography can predict locations of standing or flowing water, and how the threshold waters change under different conditions. In particular, the upstream distance, the accumulated area, the topographic wetness index (Beven and Kirkby, 1979), and the slope are taken into account for the analyses.
The upstream distance concerns the distance between the sub catchment outlet and the stream segments which are classified by the flow state, where the outlet represents the smallest distance, thus 0 m. A further analysed topographic indices is the local slope which is calculated in QGIS based on the DEM.

The accumulated area, also named contributing area, is the upslope area which contributes its flow to a certain downslope cell. The calculation of the accumulated area is based on the digital elevation model with the method of the multiple triangular flow direction (Seibert and McGlynn, 2007).

The topographic wetness index (T_{WI}) is finally calculated by taking the accumulated area and the local slope into account, $T_{WI} = \ln(\alpha/\tan\beta)$. Where α is the accumulated area per unit contour length and β the local slope (Beven and Kirkby, 1979). The topographic wetness index was calculated with the Whitebox Geospatial Analysis Tools (Whitebox GAT), which is an open source GIS software package (University of Zurich, 2017). After the calculation, the data was analyzed in the geographic information system application of QGIS.

Later, the results of these topographic indices are combined with the state of the streams (flowing water, standing water or dry channel) as provided by the measurement clusters. This is done by the analysis of the variance (ANOVA), to detect whether there is a significant difference between the indices for flowing water, standing water or dry channel. In a next step, the detected difference can be located with a t-test.

4. Results

4.1. Measurement clusters and time lapse photography

The following chapter describes the results for three of the 12 measurement clusters because they show especially interesting results. The graphs for measurement clusters from all 12 sites can be seen in appendix 9.1.

Site A2

Figure 10a visualises the collected data of the four different sensors at site A2. The location of site A2 can be seen in figure 7. The data was collected from 18 May 2017 until 13 September 2017 although there is a data gap between 11 and 16 August due to empty batteries in the logger. Figure 10b gives information about the stream state at site A2 according to the time lapse camera. The lack of camera data between 14 June and 8 August is due to requirement of this camera in other field investigations elsewhere.

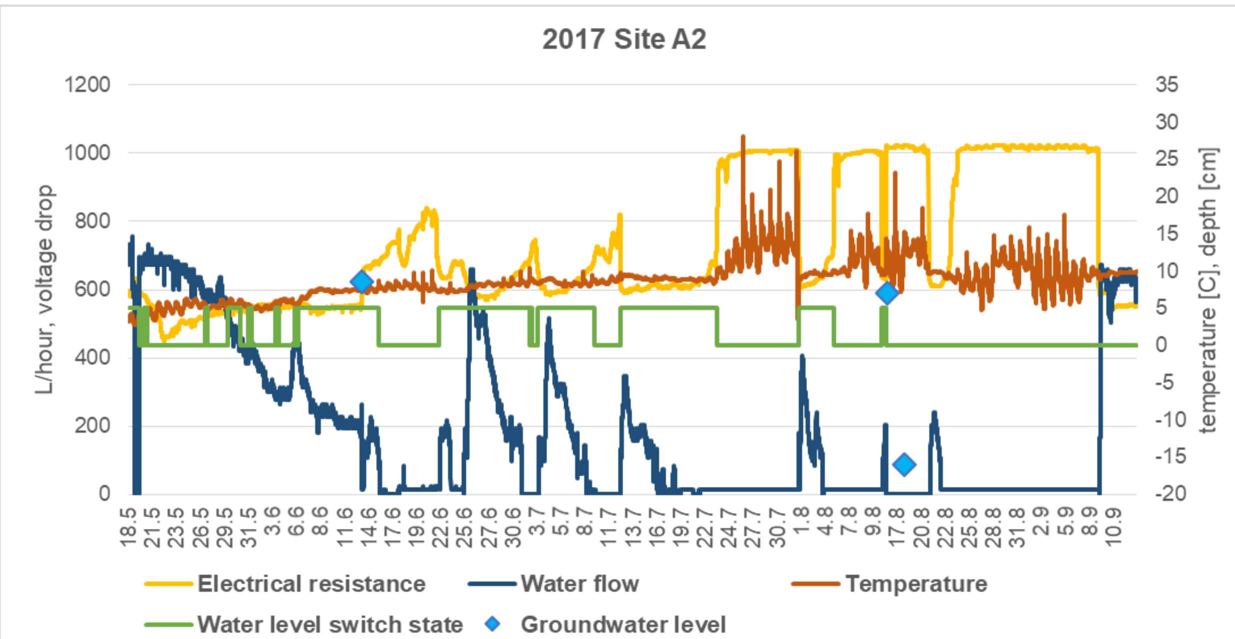


Figure 10a. Collected data from the measurement cluster at site A2. The electrical resistance is illustrated in yellow, the water flow in dark blue, the temperature in red and the water level switch in green. In addition, the groundwater levels are shown as light blue dots.

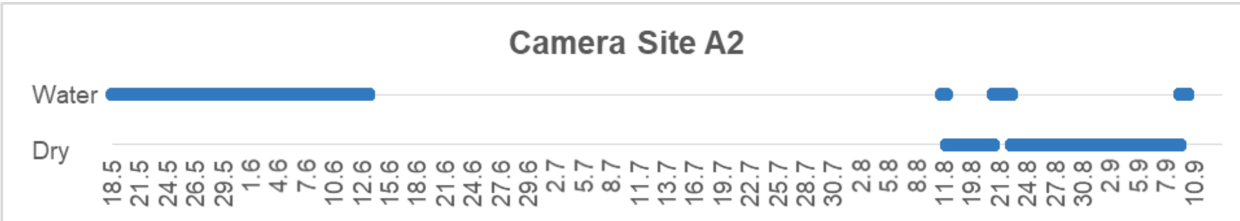


Figure 10b. Stream sate according to the time lapse camera at site A2.

The dark blue curve shows a sudden decrease in the flow on 18 May. From the time lapse photography, it can be detected that a large amount of precipitation caused a shift of the funnel and moved the flow sensor out of the water. After the reinstallation on May 19, the flow decreases almost evenly until middle of June. At the same time the electrical resistance rises and the water level switch state goes down to 0. During the same period, the diurnal variation in the temperature is slightly bigger than before. Therefore, all four sensors indicate slow drying of the channel at this location. The same process occurs two additional times in beginning of July. After a period of approximately 10 days of flowing water, the four sensors show the same change on 23 July, although the changes in temperature and electrical resistance are clearly larger. This indicates that the stream is dry during this period. Until 13 September, the flowing water and absence of water alternate seven times according to the measurement cluster.

Figure 11 illustrates the shift of the flow dynamic at site A2 from the installed time lapse camera on for four different days. The photographs of the camera were analysed for all days regarding state changes and can be seen in figure 10b and 12. The following photographs give an example of state changes. The first photo was taken on 19 May and shows that the stream is flowing. A bit more than two weeks later, the water level is lower but the stream is still flowing. On 17 August, the stream has ceased to flow and the channel is dry. Finally, three weeks later, the water runs again. These interpretations from the camera agree with the results of the sensors.

Figure 12 visualises the agreement of the four installed sensors on the photographs from the time lapse camera at site A2. The figures for the other sites can be found in appendix 9.2. The analysis at site A2 revealed that the ER and flow sensors are very reliable for detecting water presence with 99 and 97% of agreement.

Figure 11. Examples of time lapse camera images for site A2.

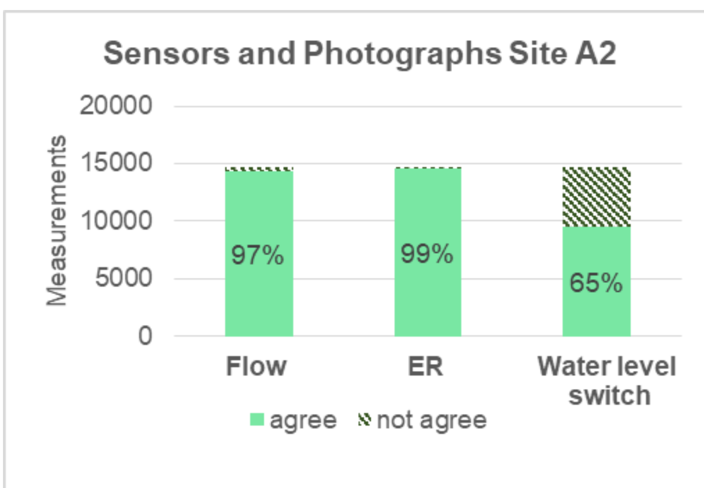


Figure 12. Statistics on how often the flow sensor, ER sensor and water level switch agreed with the images of the camera at site A2.

Site A5

Site A5 is located in Area 2 (see figure 7). All the four sensors, i.e. ER, water flow, temperature and water level switch, consistently indicate flowing water until 25 July. After this, the water level switch drops to 0, the ER increases, the temperature variations increase and the flow sensor goes down to 0. After a short period of rewetting on 29 and 30 July, the sensors indicate the same dry out process of the stream. This alternation repeats another four times with a coherent result of all four sensors until the end of the measurement period. However, the ER varies more than the other curves, particularly at the end of August (figure 13a). All measurements of the groundwater level show that the water level was above the surface during the time of the measurement. But it decreases from the first to the last measurement from 18 cm to 2.5 cm.

The diagram in figure 13b represents the states of the stream observed by the camera. In general, the observed states by the camera match the data from the sensors. However between 27 and 30 August, the camera data agrees with the ER and temperature data, but disagrees with the flow sensor and water level switch.

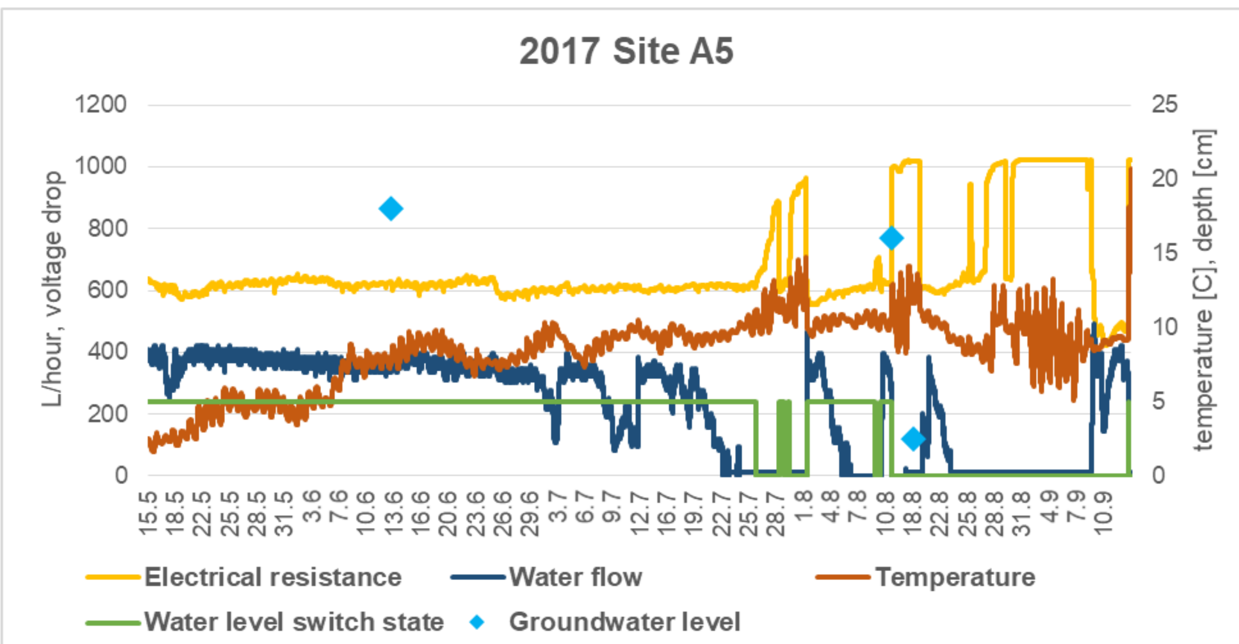


Figure 13a. Collected data from the measurement cluster at site A5.

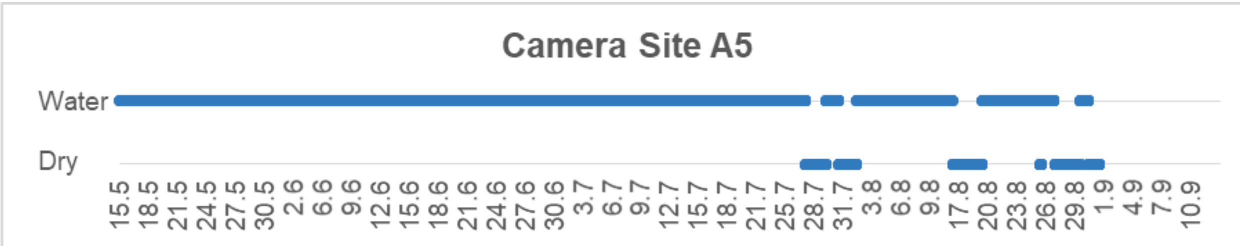


Figure 13b. Stream sate according to the time lapse camera at site A5.

The photographs in figure 14 visualise two shifts from a stream with water (16 May and 21 August) to a dry channel (16 and 31 August). The four example states match the data of the sensors. How the sensor data of the other days match the images from the time lapse camera can be seen in figure 15. The reliability of the ER sensor is at 99%, whilst the flow sensor and water level switch less agree on the photographs (86% and 90%).

Figure 14. Examples of time lapse camera images for site A5.

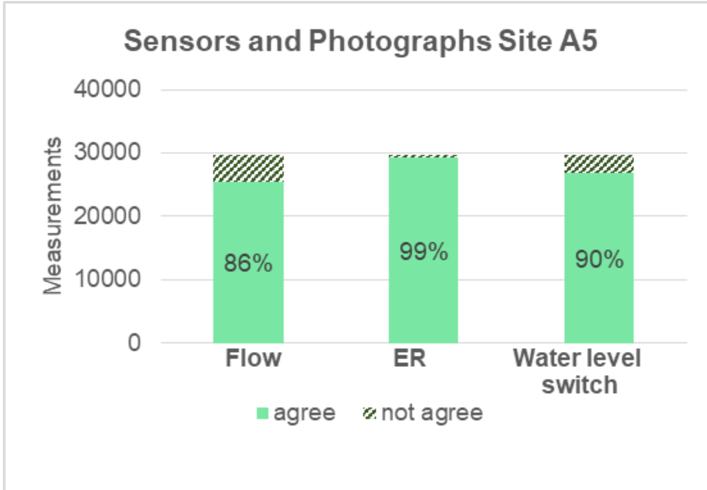


Figure 15. Statistics on how often the flow sensor, ER sensor and water level switch agreed with the images of the camera at site A5.

Site A9

The third example is from site A9, located in the western part in Area 1 (figure 7). From the beginning of the measurements on May 17 until 2 June, the combined results of the four sensors indicate that the water is flowing (figure 16a), before the state shifts to standing water or barely flowing for three days. After an increase in flow, the ER sensor rises while the temperature variations increase as well and the water level switch drops to 0. The flow also lowers to 0 (figure 16a). This suggests a dry period until 24 June. The stream changes from dry to flowing three more times, before the sensors show an ambiguous signal between 16 and 19 July. According to the electrical resistance and the water level switch, the stream is dry twice, while the flow sensor only shows flow on 19 July and the temperature variations do not suggest a dry state during the mentioned period. These incoherent results indicate a state of standing or ponding water. The photographs cannot be consulted for this period due to a lack of data based on a technical issue. For the remainder of the measuring period, the four sensors show coherent data regarding the state of flowing or dry channel, with an exception of a wrong signal of the ER on 30 August. On the photographs can be seen that water is not present.

The pre-installed groundwater well was located approximately 15 m further downstream. Due to this distance, a discrepancy might have occurred between the groundwater level and the water presence in the stream above on 18 August (figure 16a).

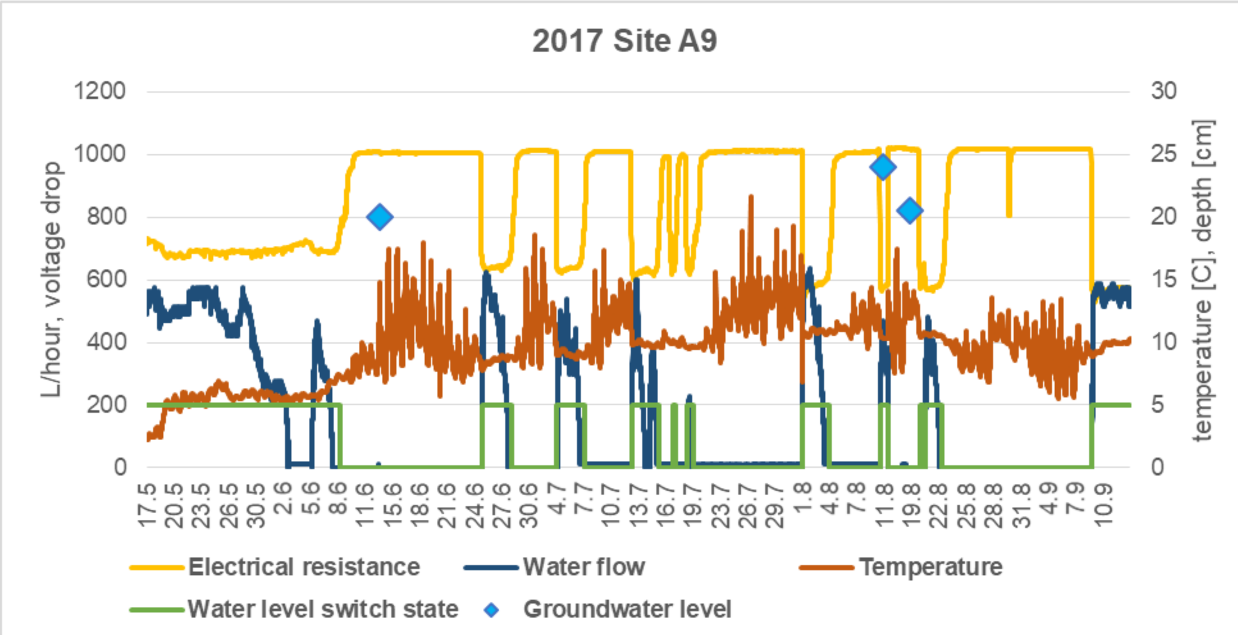


Figure 16a. Collected data from the measurement cluster at site A9.

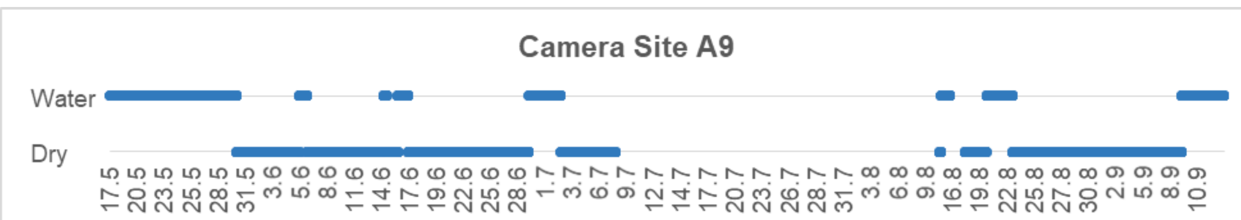


Figure 16b. Stream sate according to the time lapse camera at site A9.

The four photos in figure 17 represent four different states of the stream at site A9. In the first picture (22 May), water is present in the channel while it is dry on 18 August. Four days later on 22 August, the stream has a little amount of water in comparison to the distinct presence of flowing water on 9 September. The stream states according to these four example photos are in agreement with the state indicated by the sensors. The statistic in figure 18 shows the agreement of the sensors with the photographs over the whole measurement period. The photographs suggest that for site A9 the flow sensor performs best with 79%, but also the ER sensor and water level switch reveal almost equal percentage of agreement (76% and 74%).

Figure 17. Examples of time lapse camera images for site A9.

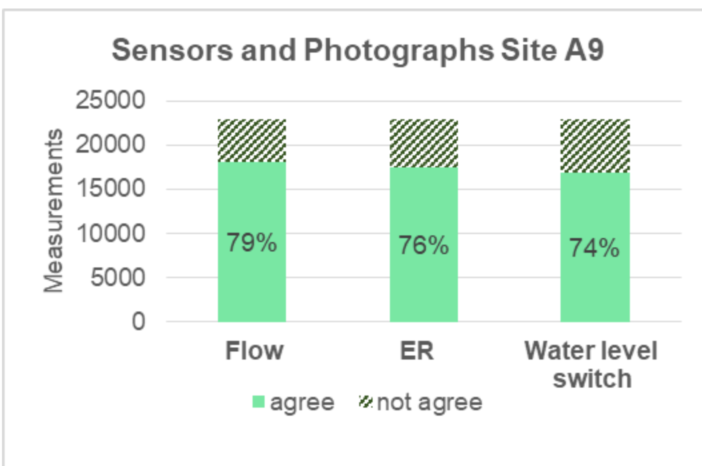


Figure 18. Statistics on how often the flow sensor, ER sensor and water level switch agreed with the images of the camera at site A9.

Other sites

In appendix 9.1. with graphs of the other measurement clusters, it can be seen that the results of the sensors at site A1 suggest standing water until 27 July, after which the stream dries out three times. On the camera photos, however, the first drying out is not recognizable as a completely dry channel. The graph of site A3, which is located close to the stream head, shows that the amount of the flow varies until 20 July, after which ponding water occurs and the stream dries out on 18 August. Sites A4 and A6 have similar dynamics. The two measurement clusters indicate standing water over the whole measurement period, with an exception of flow at site 6 on 18 May. The measurement clusters of site A7 and A8 both suggest flowing water during the entire measurement period, although based on observations, the stream at site A8 is barely flowing.

Sites A10, A11 and A12 also have similar dynamics. At the beginning of the measurement period all the sensor indicate that there is flowing water and later from 20 May, respectively 24 May for A11 and A12, until 30 May, standing water. After this, the stream channels stay dry except for two short exceptions: there is standing water at the end of May and beginning of June. At the end of the measurement period (9 September), all the sensors suggest the return of flowing water in these three channels.

4.2. Flowing stream network maps

Area 1

The flowing stream network was mapped on six different days to monitor the network dynamics. As seen in figure 19, there is one survey stream in Area 1. At the first three surveys on 19 May, 30 May and 6 June, water was flowing everywhere in the stream network. On 12 June, however, there is no water observed at the surface in the upper part of the stream. Some meters upstream of sensor 9, limited surface flow was observed (a velocity smaller than 1 m/min), and was classified as barely flowing (light blue in figure 19). In August, the lower part of the stream changed from flowing to barely flowing and on 18 August, the upper parts were characterised by standing and ponding water, and also dry sections.

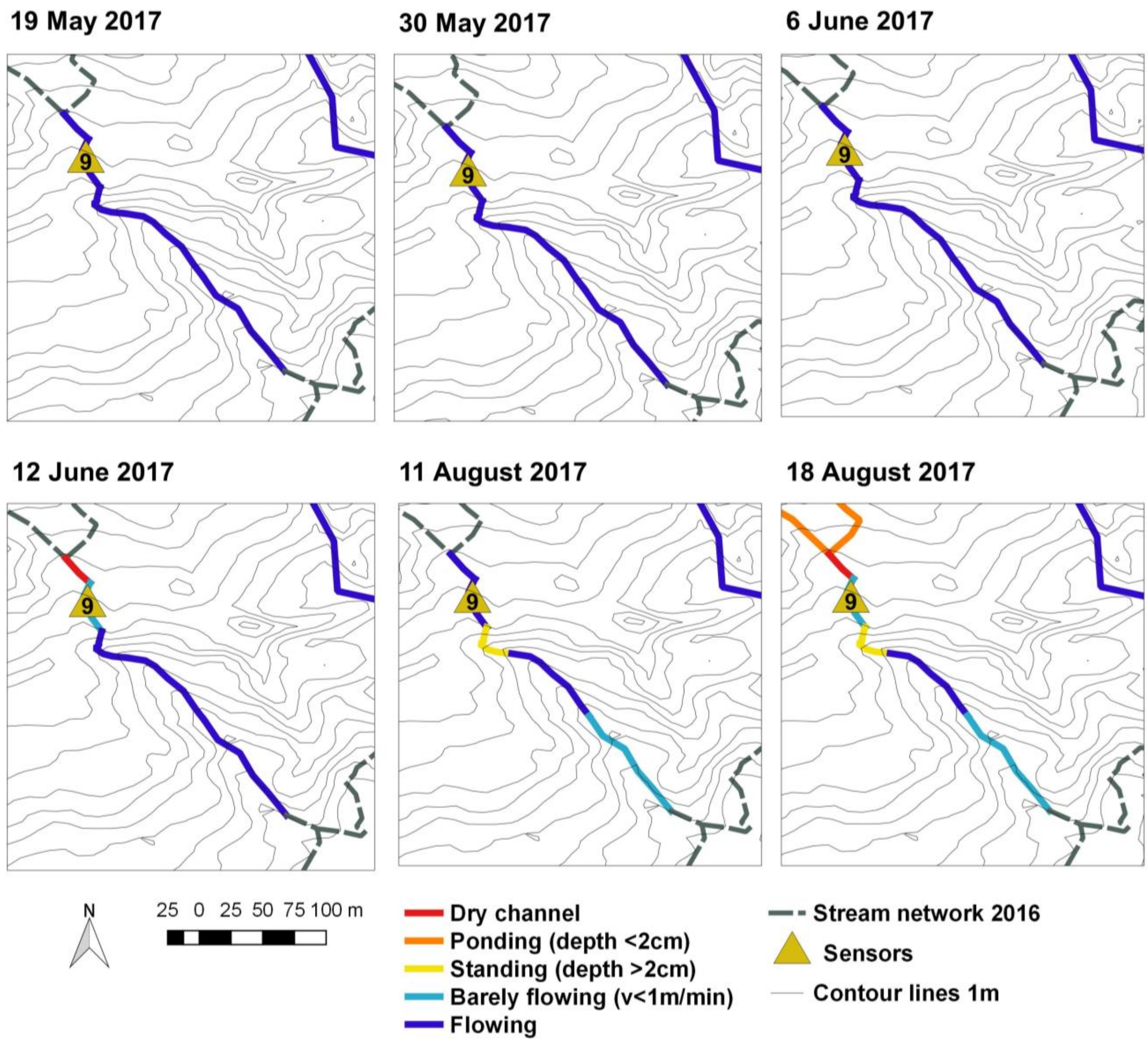


Figure 19. Changes in channel state along the stream network in Area 1.

Area 2

Area 2 includes two streams. Over all, a shift of the rather wet and flowing dynamic to a drier state was observed. As in Area 1, the flowing stream network does not change between the surveys conducted from 19 May to 6 June (figure 21). There are two ditches that drain to the main stream channel, where sensors 4 and 6 are located. These two sections are in contrast to the flowing stream barley flowing. The stream branch with sensors 1 and 2 changes from standing to barely flowing to flowing water where it joins the stream again on the eastern side. In the middle of June and in the middle of August, the same mentioned sections shift from barely flowing to standing water and from standing water to ponding with a stream depth less than 2 cm. On 18 August, several segments, particularly on the upper part of the stream had dried. The sections where sensors 2 and 5 are installed even ceased to flow.

Area 3

At the beginning of the survey, (19 and 30 May), all the stream branches carry water, although not in all of them there is flowing water, but rather standing or barely flowing water (figure 20). The two observations in June reveal that two of the side branches went completely dry and the one with sensor 10 had little ponding water. Comparing the situation in June to the ones on 11 and 18 August, the main stream begins to change its state from flowing to barely flowing. The survey on 18 August even shows that there is no section classified as flowing water, and the area is dominated by standing water and dry channels (yellow and red in figure 20).

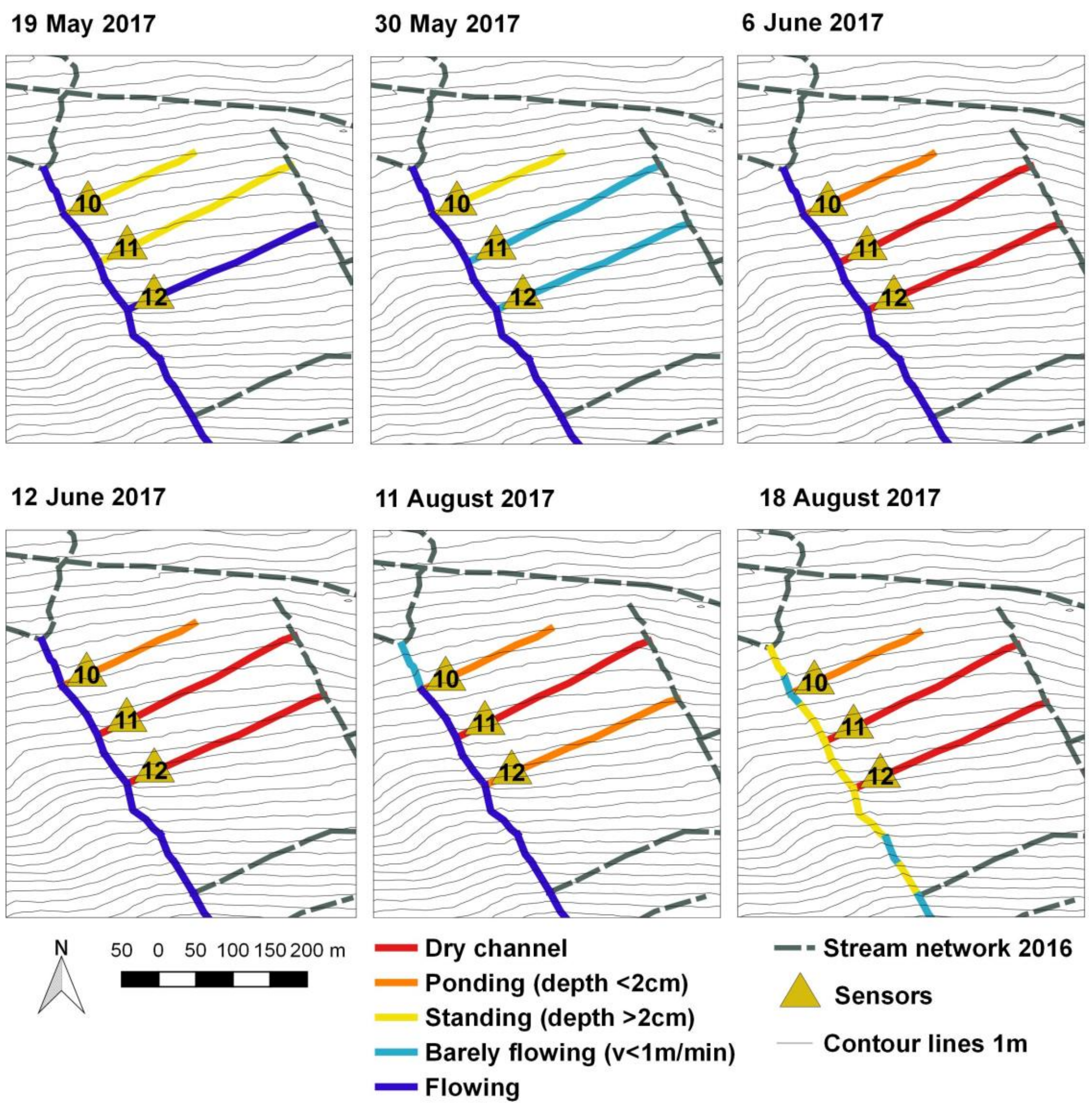


Figure 20. Changes in channel state along the stream network in Area 3.

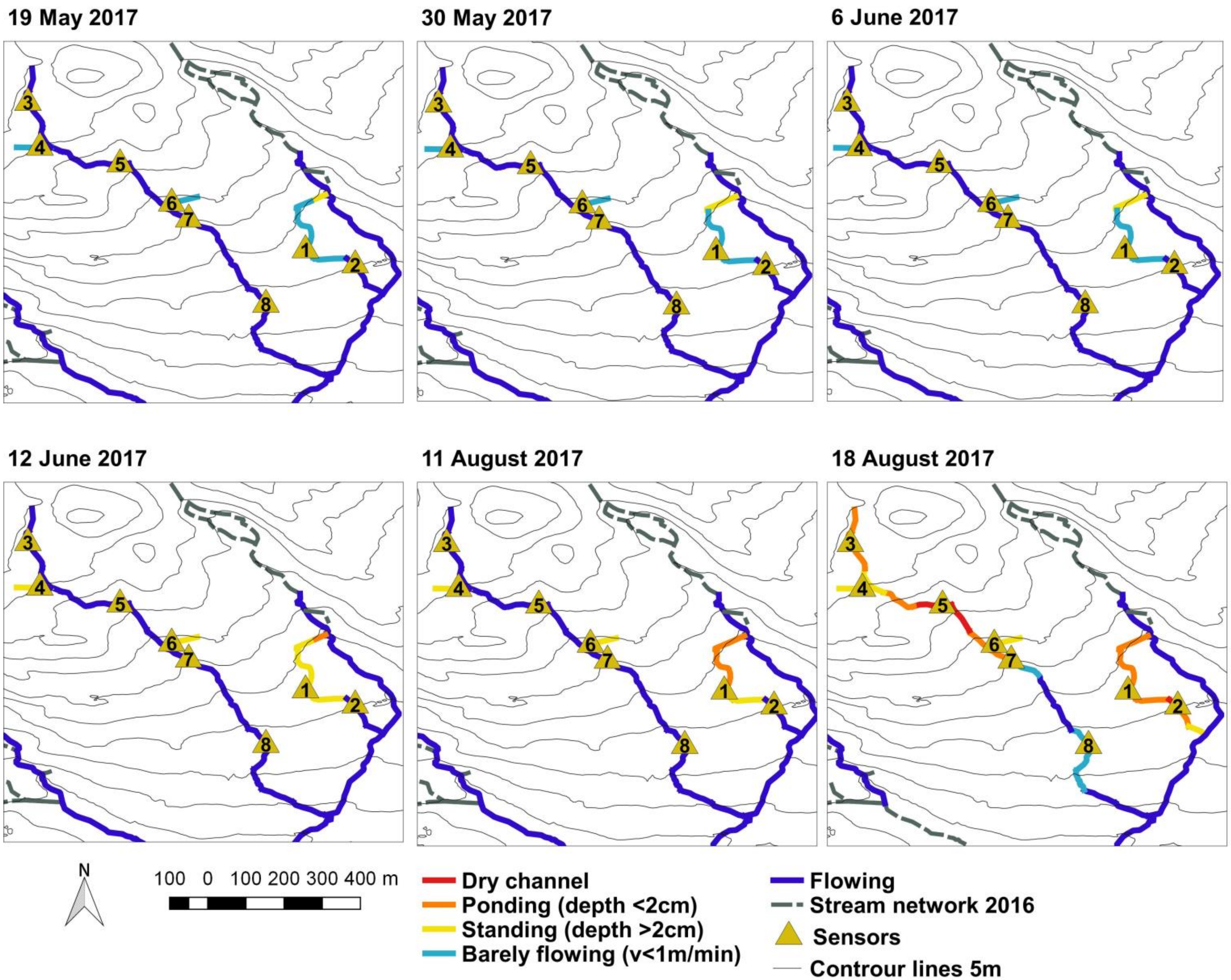


Figure 21. Changes in channel state along the stream network in Area 2.

4.3. Temporal variation in flowing stream length, discharge and precipitation

4.3.1. Temporal variation in number of sensors with flow

The state of the stream was defined based on the given signals of the sensors and the combination of those. For the category flowing, the velocity must be at least 36 l/h and the water level switch had to give the signal of 1. Standing water was defined by a signal of 1 for the water level switch, but flow was less than 36 l/h. A dry channel was defined as the flow sensor showing 0 l/h, while the ER was higher and the level switch is indicating 0.

In figure 22a, it can be clearly seen that the number of measurement clusters with flow was high at the beginning of the measurement period. As the number of sensors in flowing stream conditions decreased until 2 September, the total number of sensors in dry channel conditions increased. During the very last days of the measurement period, the distribution is changed again. The total number of sensors in standing water remained more or less at the same level with small fluctuations in the beginning and end of the measurement period. Figure 22b shows the number of sensors with flow in Area 2 related to discharge in Area 2 on a logarithmic scale. It can be seen that at maximum discharge, six out of eight sensors showed flow, the remaining two sensors are A4 and A6 which were located in standing water.

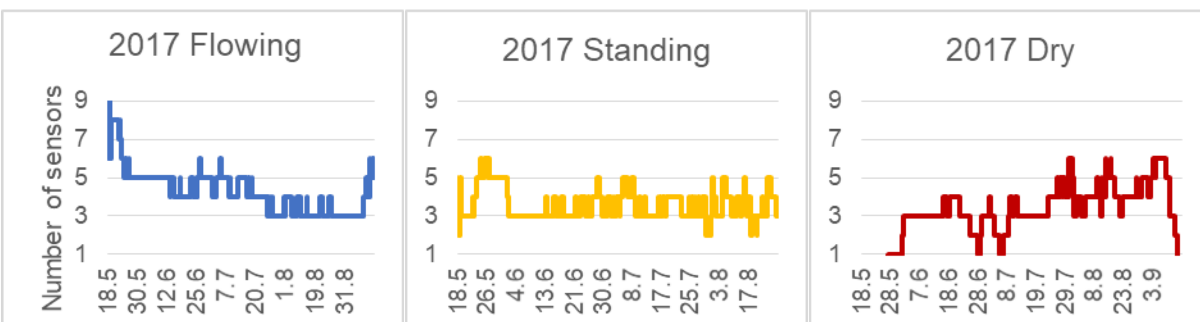


Figure 22a. Number of sensors with the indicated stream state.

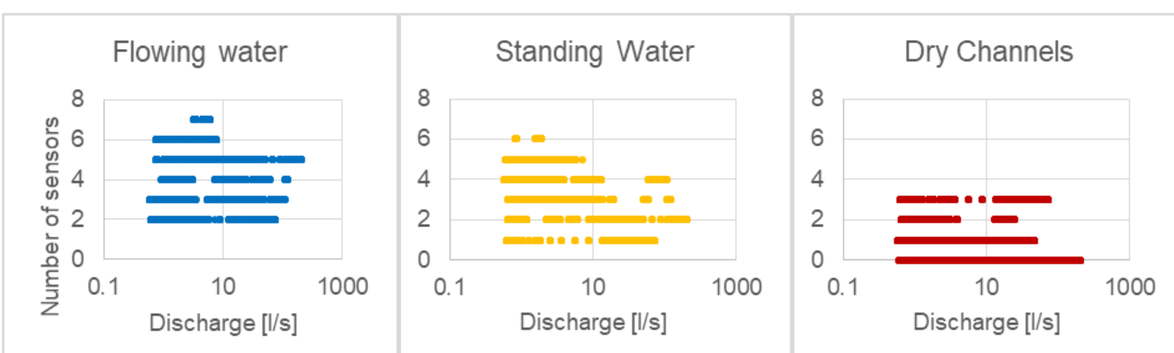


Figure 22b. Number of sensors with the indicated stream state related to discharge. Discharge data and the number of sensors only include Area 2 (Discharge data from ICOS Sweden national infrastructure, Svartberget)

4.3.2. Relation between the flowing stream length and discharge

The discharge for Area 2 from 1 April until 26 September is illustrated in figure 23 on a logarithmic scale. The first two distinct peaks were in May with the highest flow of 201 l/s on 19 May. With 72 l/s, the peak in September is the second highest one.

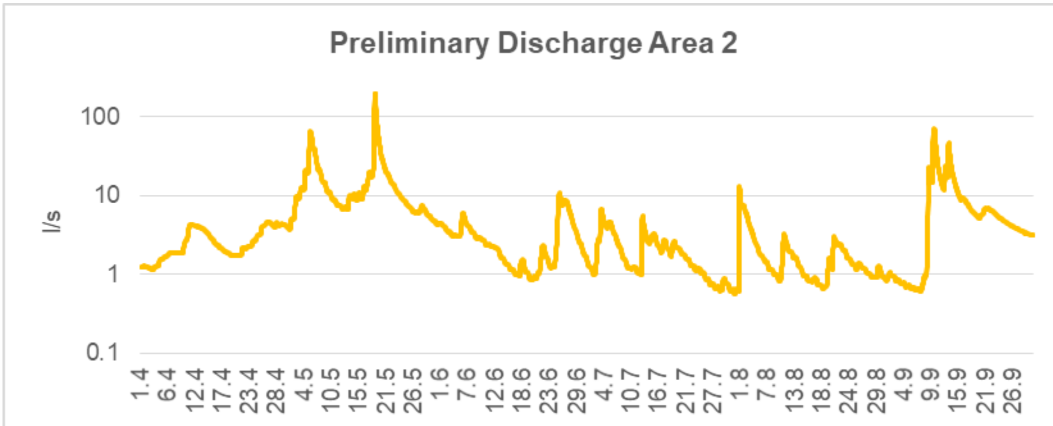


Figure 23. Preliminary discharge for Area 2 from the beginning of April to the end of September 2017 (Data from ICOS Sweden national infrastructure, Svartberget).

To analyse the length of the flowing stream network, the six surveys from the stream network mapping were analysed. For this analysis, the classes flowing and barely flowing were both defined as flowing. Figure 24a shows the length of the flowing stream network in Area 1 during six observations. At the first observation on 19 May, the flowing stream network of Area 1 was 296 m long and does not change until a small decreasing on 12 June and reaches its minimum on 11 August with 182 m. Figure 24b shows the same, analog for Area 3. The peak of the flowing length in Area 3 is on 30 May with 1’850 m. After this peak, the flowing length decreases until it reaches its shortest length of 868 m on the last survey on August 18.

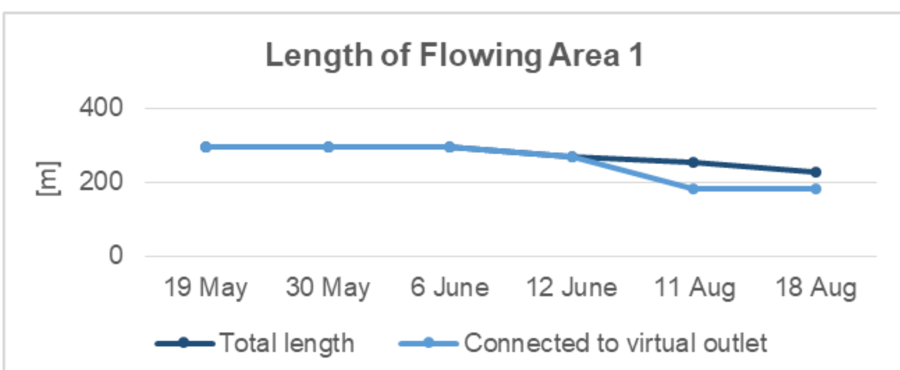


Figure 24a. Flowing plus barely flowing stream network length in Area 1.

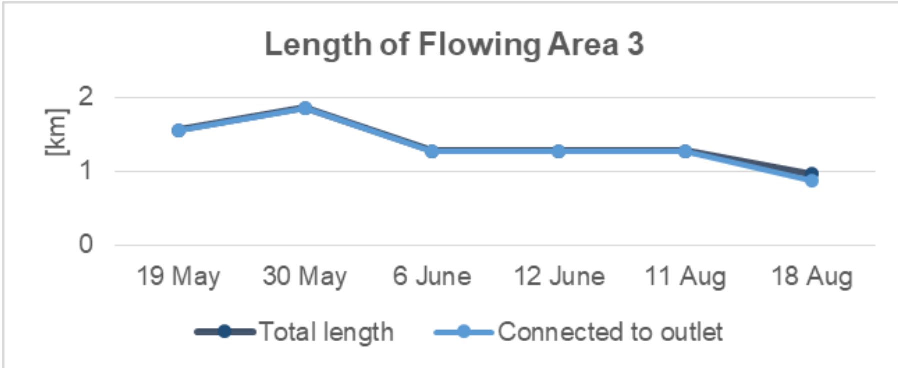


Figure 24b. Flowing plus barely flowing stream network length in Area 3.

Figure 25 illustrates the temporal change of discharge and analog to this the change in the flowing stream network length. In general, it can be seen that both graphs show a similar pattern, when the connected stream length is shorter, the discharge decreases as well. However, this pattern is not observed at the beginning of the survey on 19 May. Between this point and 30 May, the discharge decreases relatively steep in comparison to the level of the next survey. While the length of the flowing stream network only drops from 2’825 to 2’771 m.

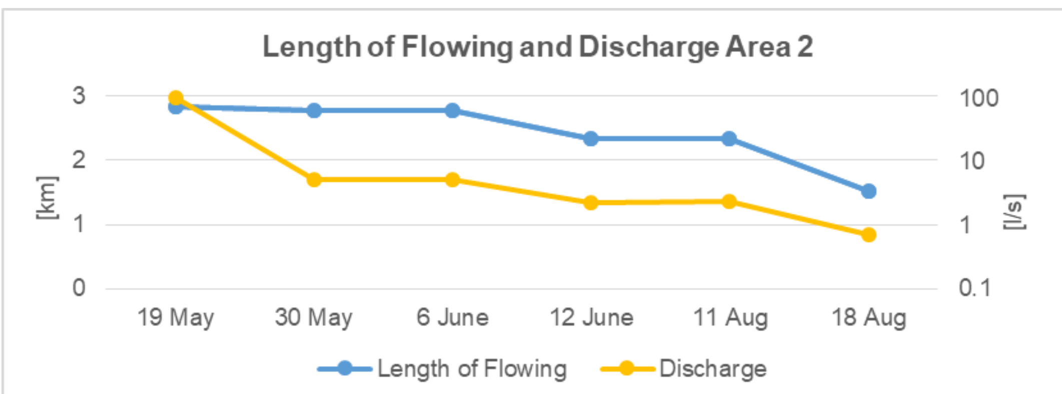


Figure 25. The length of flowing stream network connected to the outlet and discharge on the six survey dates (discharge data from ICOS Sweden national infrastructure, Svartberget).

In addition to the temporal scale, the relation between the length of flowing stream sections and discharge is analysed and shown in figure 26 on a log-log scale. The resulted β-value is 0.1857 and therefore indicates little connection between the flowing stream length and measured discharge. However, there are only six points of stream length surveys available and taken into account.

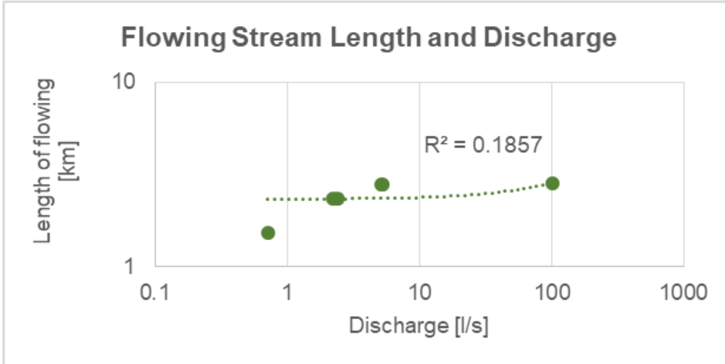


Figure 26. Relation of the length of flowing stream network connected to the outlet and discharge in Area 2 on the six survey dates with linear trendline and R-squared value (discharge data from ICOS Sweden national infrastructure, Svartberget).

4.3.3. Relation between discharge and flow at individual sensor locations

As already mentioned in the methods, eight measurement clusters, namely A1 to A8 are located in Area 2. In the following section, the results of these sensors are compared to the discharge data. The results of site A2 and A5 are discussed here, the other six graphs are located in the appendix 9.4.

Site A2

Figure 27 shows the combination of discharge and data from the sensors at site A2. The graph over the entire measurement period can be found in the appendix 9.4. After an increase in discharge at the end of June, the sensors switch to a flowing state and go down to dry as the discharge decreases (figure 27). The signal of the sensors at site A2 indicate that the channel at this location is dry while the stream is still flowing little at the outlet. The same pattern occurs every time the sensor suggests a dry channel. On 11 July the sensor signal goes up to standing water without a big change in the discharge.

Site A5

The measurement cluster of site A5 is installed in the western part of Area 2 (see figure 7). Contrary to site A2, the discharge at the outlet and the measurement cluster graphs of site A5 do not follow a similar pattern (figure 28). The first observation is that at the end of July, when the discharge stays at a minimum, the sensor signal shifts twice from standing to dry. Furthermore, the sensor reacts to the peak in discharge in the beginning of August with a delay of four days until it alters to the flowing signal. The second observation is that during the second small discharge peak on 10 August, the discharge clearly increases and the sensors change from a dry to a standing signal but remain static before it goes down to dry again.

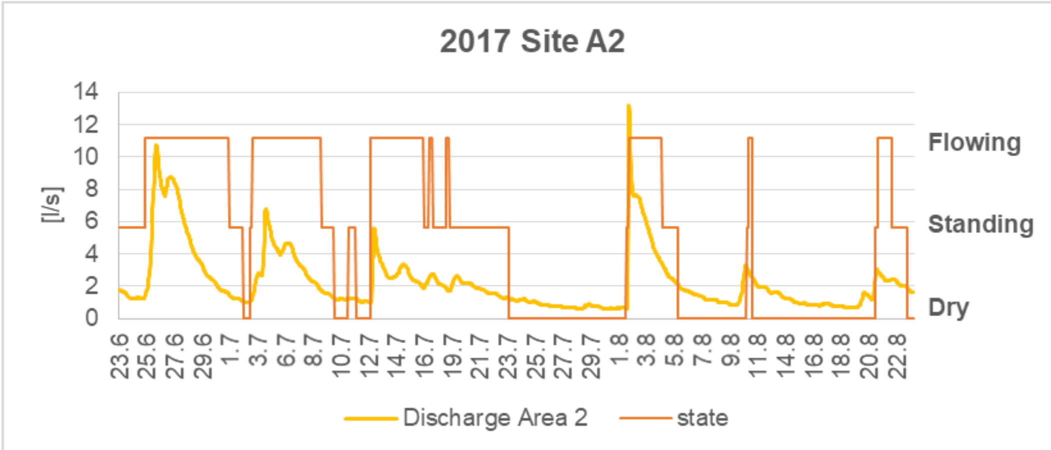


Figure 27. Combination of the discharge and interpretation of the data from the measurement cluster at site A2 for the period from the end of June to the middle of August. The red curve is the result from sensors described in chapter 4.1., whilst the yellow curve represents the discharge of Area 2.

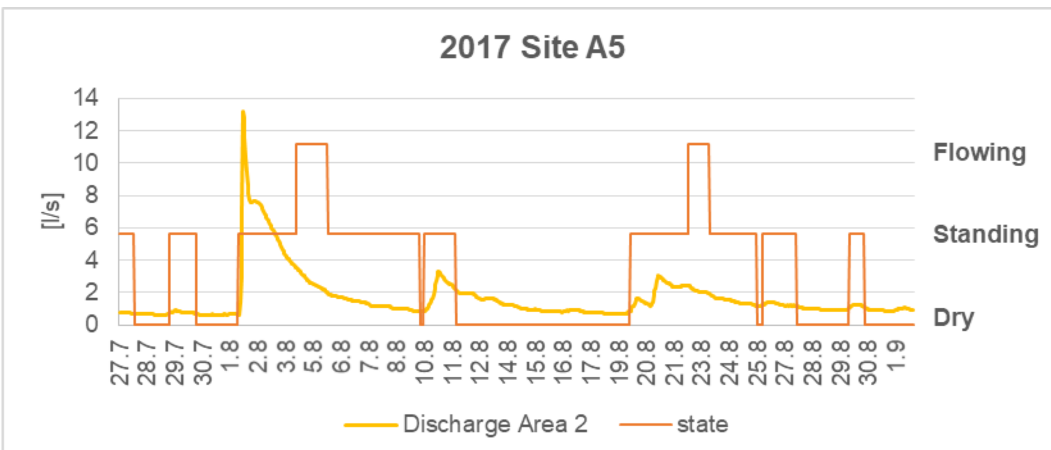


Figure 28. Combination of the discharge and interpretation of the data from the measurement cluster at site A5 for the period from the end of July until the end of August. The red curve is the result from sensors described in chapter 4.1., whilst the yellow curve represents the discharge of Area 2.

4.3.4. Relation between precipitation and flow at individual sensor locations

The state of the streams based on the given signals of the measurement clusters were also related to precipitation data. All the combined graphs of the 12 sites can be seen in appendix 9.5.

Figure 29 shows the 30 min precipitation intensity and the state of the stream according to the sensors at site A10 (location see figure 7) and illustrates that the channel state is not very sensitive to precipitation intensity. Thereby, over the period from 12 July to 7 September, the sensors indicate a dry channel although there are several rainfall events.

The sum of precipitation in the last 24 hours (figure 30) better explains the changes in channel state. There has to be a certain amount of precipitation for flow to occur in the channel.

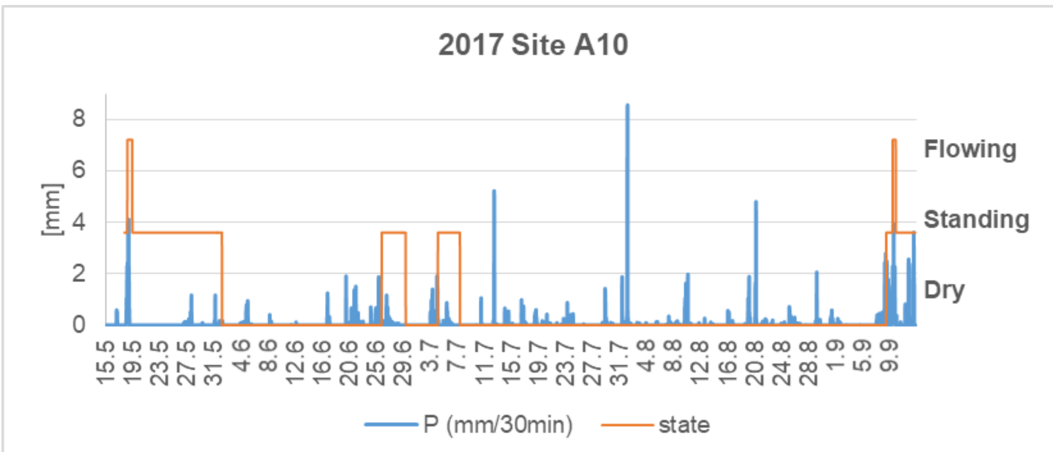


Figure 29. Time series of precipitation and stream state at site A10 (precipitation data from ICOS, Svartberget).

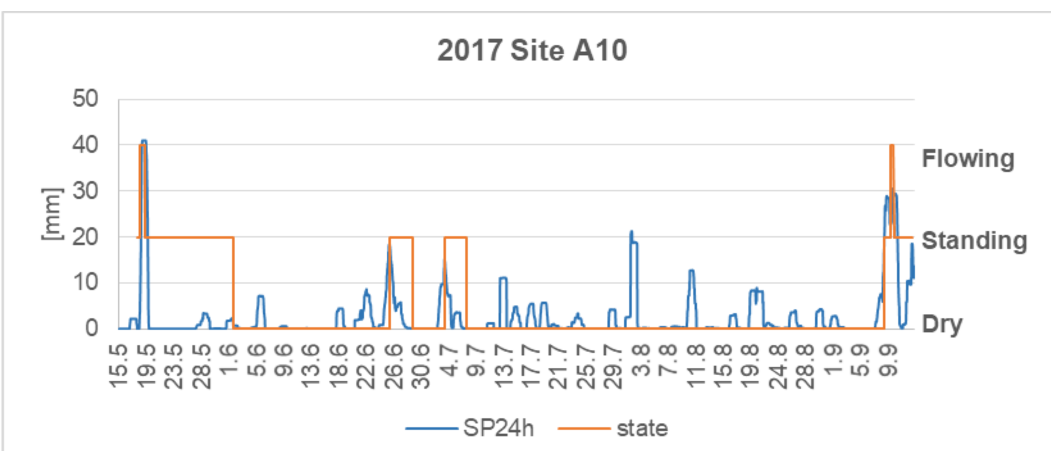


Figure 30. Time series of 24 h precipitation and stream state at site A10 (precipitation data from ICOS, Svartberget).

Figure 31 shows the sum of precipitation in the last three days. It can be seen that the first rainfall event on 18 May brings the sensor to indicate a flowing state although only at the first moment. After this time, water is standing while the sum of precipitation is still 40 mm. The increase of the precipitation on 18 June caused a shift to standing water at the last part of the event. In contrary, on 4 July, the stream sate already changes the signal at the beginning of the event. The last rainfall event during the measurement period is also big enough to shift the stream from dry to flowing although the flowing state does not last as long as the rainfall event.

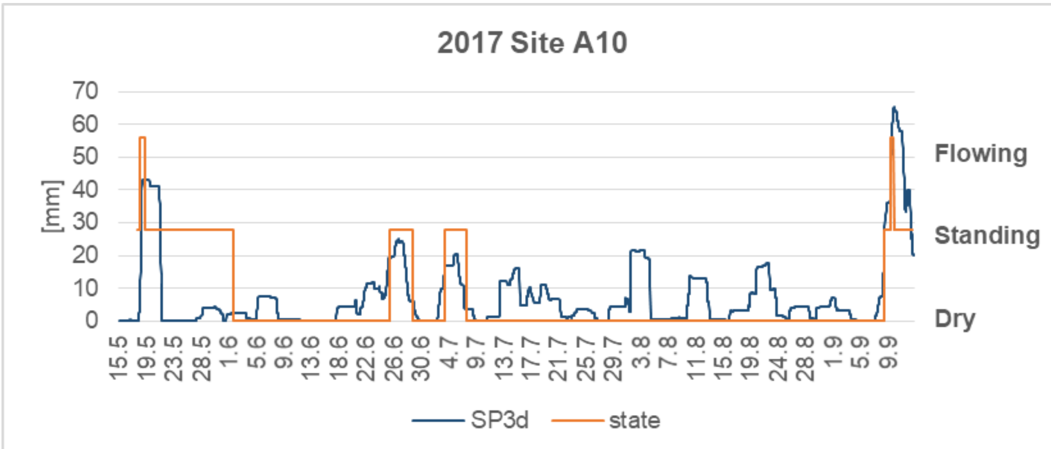


Figure 31. Time series of three day total precipitation and stream sate at site A10 (precipitation data from ICOS, Svartberget).

There are big differences in the relation of the stream state and precipitation between site A5 and A10 (figure 32). There is a clear pattern of the relation between precipitation and the state of the channel for site A5. But not for site A10 for which there is no clear graduation of the flowing and standing state. It can be seen that the stream at site A5 has flow until 22 July, and from then on shows dynamics in state changes related to precipitation. The main difference to site A10 is that the response at A5 is the shift to flowing water, whilst the stream at A10 reacts less frequent and rather with standing water. These differences may be caused due to a lower gradient in topography at site A10 and thus greater amount of precipitation is required for the water to flow. Furthermore, a higher water holding capacity of the soil at site A10 can prevent small amounts of precipitation to contribute to surface flow.

The sensors located at sites A2, A3 and A9 react similar to precipitation as the discussed example of A5 (seen in appendix 9.5.). Contrary, the stream state at site A1 is standing water or dry channel during the whole measurement period, and therefore no reaction of flow based on precipitation can be seen. Site A4 had all the time standing water with no reaction to precipitation, while site

A6 with similar conditions responds with a change from standing water to flowing water but remained in standing water until the end of the measurement period. The stream sections monitored at site A7 and A8 show flow all the time and therefore reactions based on precipitation cannot be seen. Sites A11 and A12 are due to similar locations comparable to A10. The pattern of relation to precipitation is also similar. It can be seen that even during rainfall events the sites do not react with present water in the channels. However, the graphs which take the temporal change into account, show that certain amount of precipitation, i.e. 40 mm of the three day total, is required to shift a dry channel to standing water or flow.

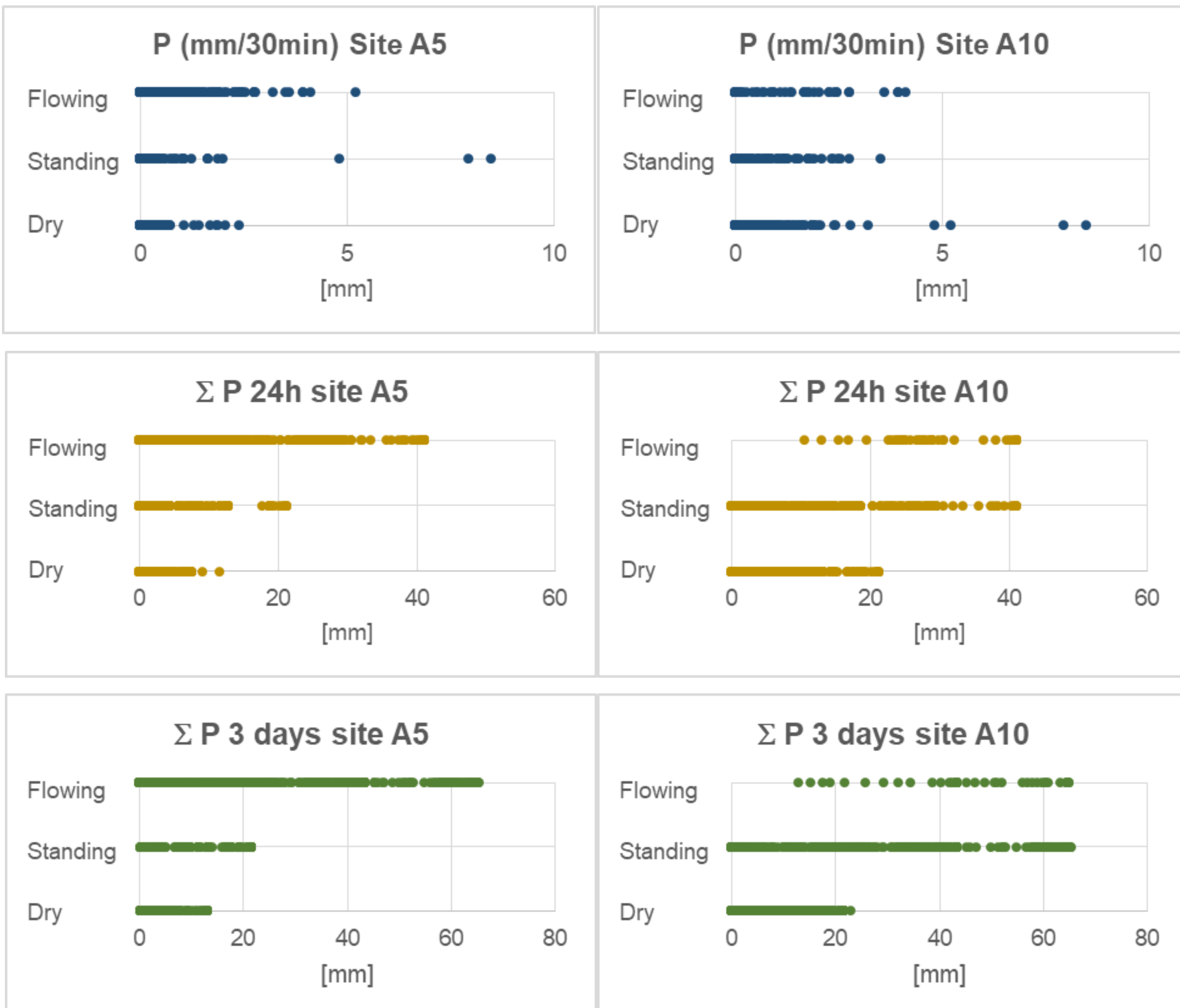


Figure 32. Relation between 30 min, 24 hour and three day total precipitation and state of the stream at site A5 and A10.

4.4. Relation between topography and stream state

This chapter describes the results from the topographic analyses. The DEM is based on the technology of LiDAR measurements and has a resolution of 5 m. All three areas with the different outlets are combined in the analyses. All the generated scatter plots derived from the analysed data can be found in appendix 9.6. to 9.9.

4.4.1. Upstream distance

The boxplots in figure 33 show the distance between the outlet and the monitored stream segment for the sites that are flowing, have standing water, or were dry on the six survey dates. Therefore, a stream branch in the upper headwater, e.g. measurement cluster A3 (figure 7), has a greater upstream distance compared to the measurement cluster A8 which is close to the outlet.

Figure 33. Boxplots of the upstream distance for sites with flowing water (F), standing water (S) and a dry channel (D). Statistically significant differences in mean upslope distance for the three different stream states are indicated by a star and different letters.

For four field observations there was a significant difference in the mean upstream distance of flowing stream sections and the upstream distance of standing stream sections or sections without water. In all the surveys with a significant difference, the upstream distance of the flowing state was different to the upstream distance of dry channels. With dry channels occurring in the upper parts of the streams, while the sections close to the outlet are rather flowing.

As the letters a and b signalise in figure 33, the location of the significant difference between the stream states varies over time. At the first survey in August, the upstream distance of dry channels are significantly different from the upstream distance of flowing and standing water sections. While at the second survey in August, the upstream distance of flowing sections are significantly different from the upstream distance of channels without or standing water.

In conclusion, it can be said that for four out of six field surveys, the upstream distance of the flowing stream sections is significantly different from those with standing water or a dry stream.

4.4.2. Slope

In general, the western part of the area has steeper slopes (figure 34). Furthermore, for Area 2, the channel of the stream is clearly visible in figure 34, due to steep slopes at the stream borders and therefore higher elevation compared to the channel bed. This derives from the shape of the ditches as seen in figure 4. In Area 3, which is located in the eastern part, stream channels can barely be distinguished based on the slope map. In general, the local slope in Area 3 does not vary much.

Contrary to the upstream distance, there was no significant difference in the mean slope of the flowing stream sections, sections with standing water and dry stream sections (figure 35). However, it can be seen that the degree of slope does not vary much in dry channels and dry channels occur mainly in areas with low slopes, i.e. 2° to 4°, with an exception of the last survey on 18 August.

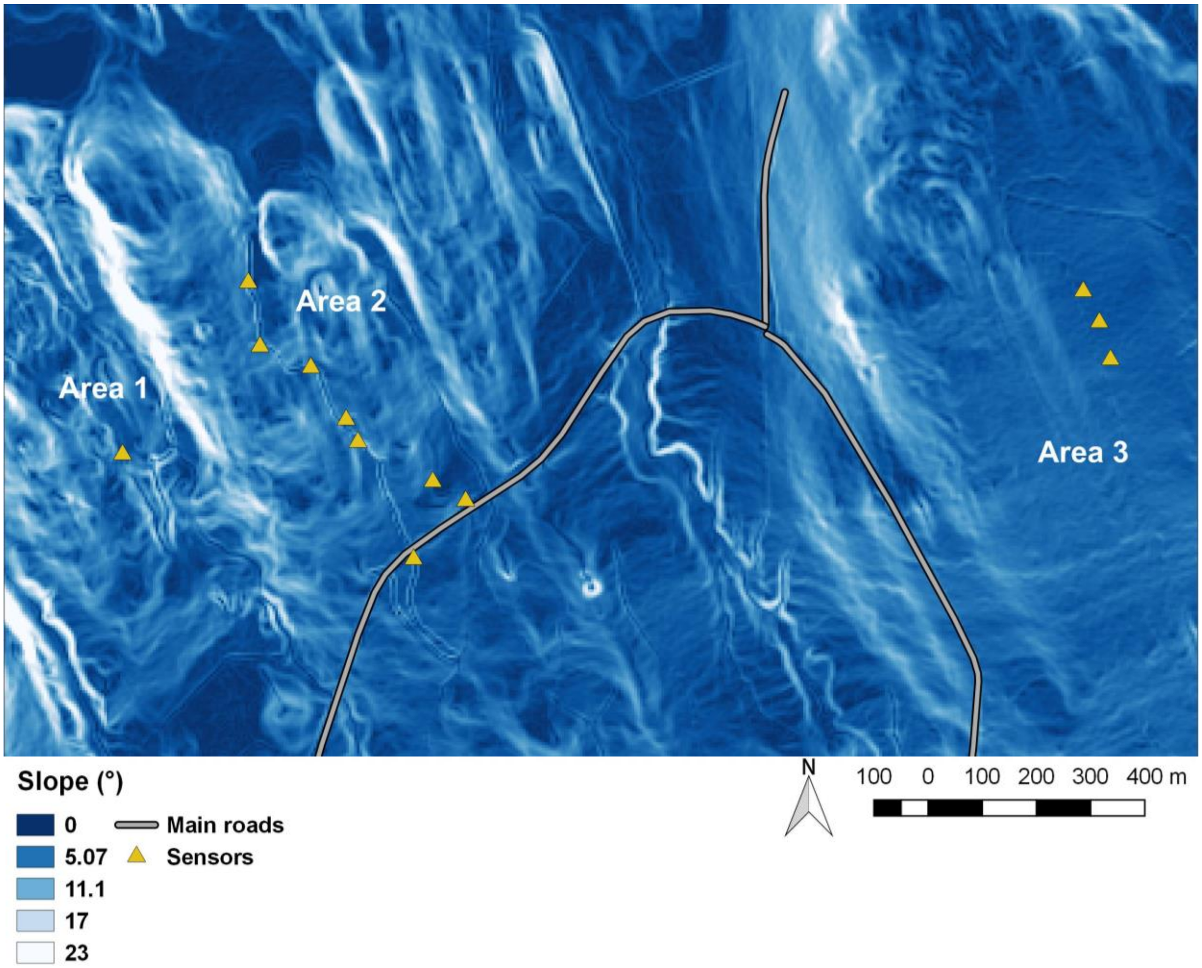


Figure 34. Map of the study area with the local slope.

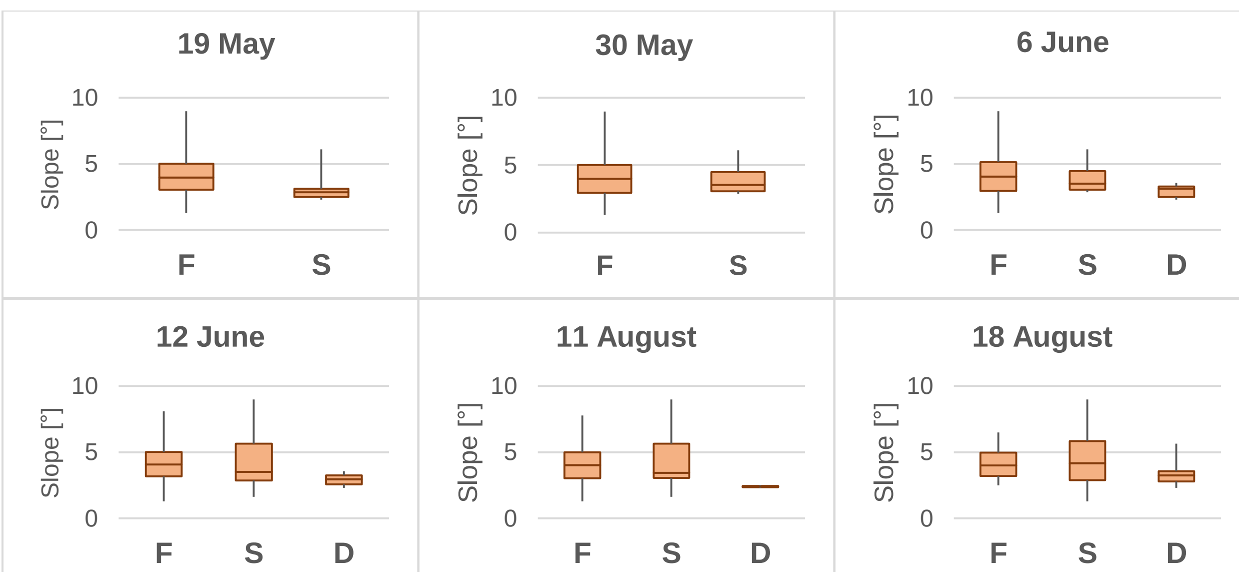


Figure 35. Boxplots of the local slope for flowing sections (F), sections with standing water (S) and dry sections (D) on the six survey dates. There were no statistically significant differences.

4.4.3. Accumulated area

Most of the monitored streams are clearly visible in the map of the accumulated area (figure 36), but in the eastern part of Area 2 and also Area 3, the accumulated catchment area does not correspond with the observed stream channels. According to this map, the accumulated area is small in the discussed areas. During the field observations, however, water was visible in these channels. Further downstream of the sensor in Area 1, the water flow is, also according to the DEM, very diffuse, with it flowing without a distinct channel.

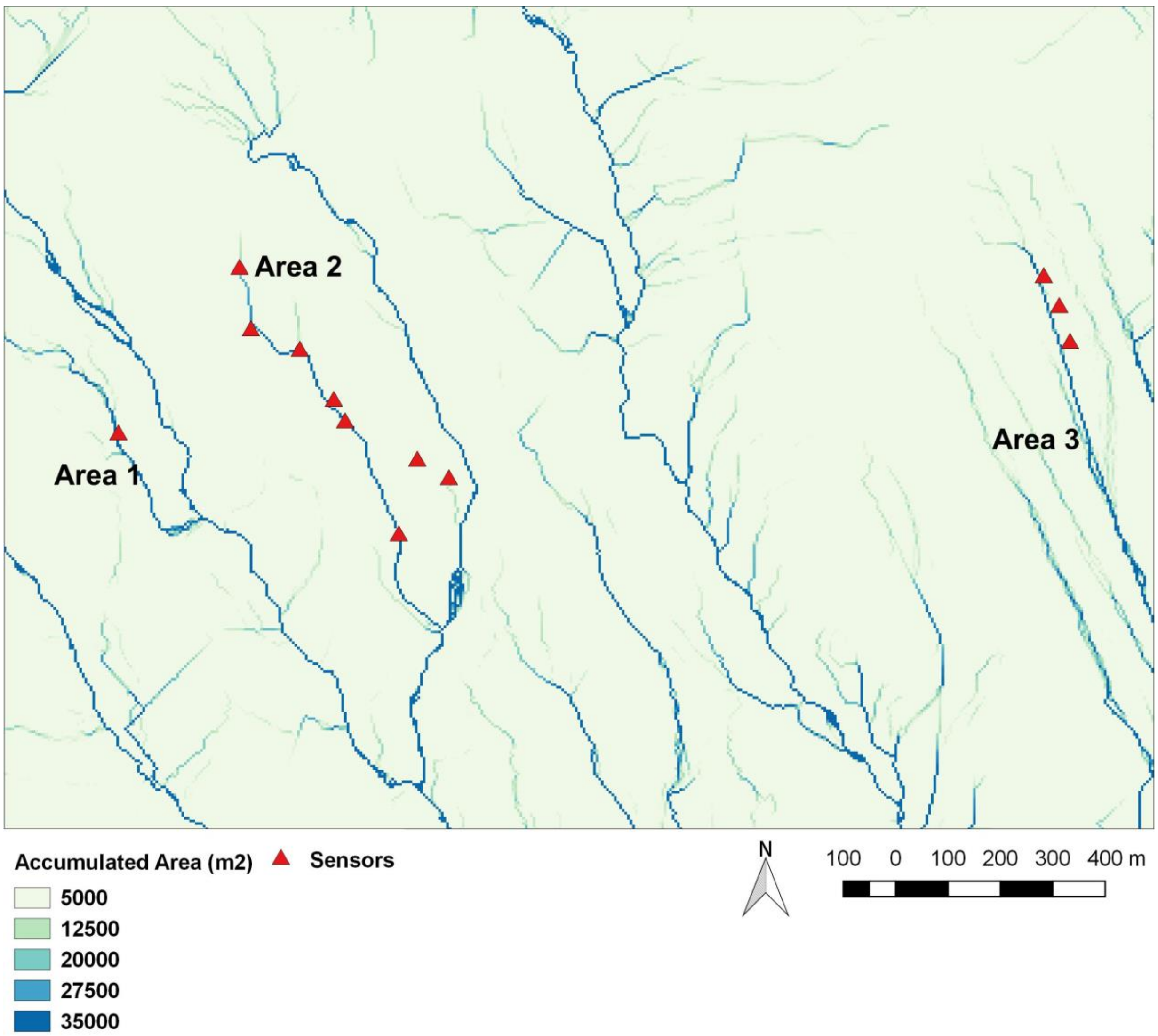


Figure 36. Map of the study area with the accumulated area.

In all of the surveys, the flowing stream sections had the largest contributing area (figure 37). The analysis revealed a significant difference in the mean accumulated area of the flowing sections, sections with standing water and dry sections for three out of six surveys, namely the last three field surveys. In all the three surveys, the accumulated area of sections with flowing water is different from the accumulated area of sections with standing water and dry channels.

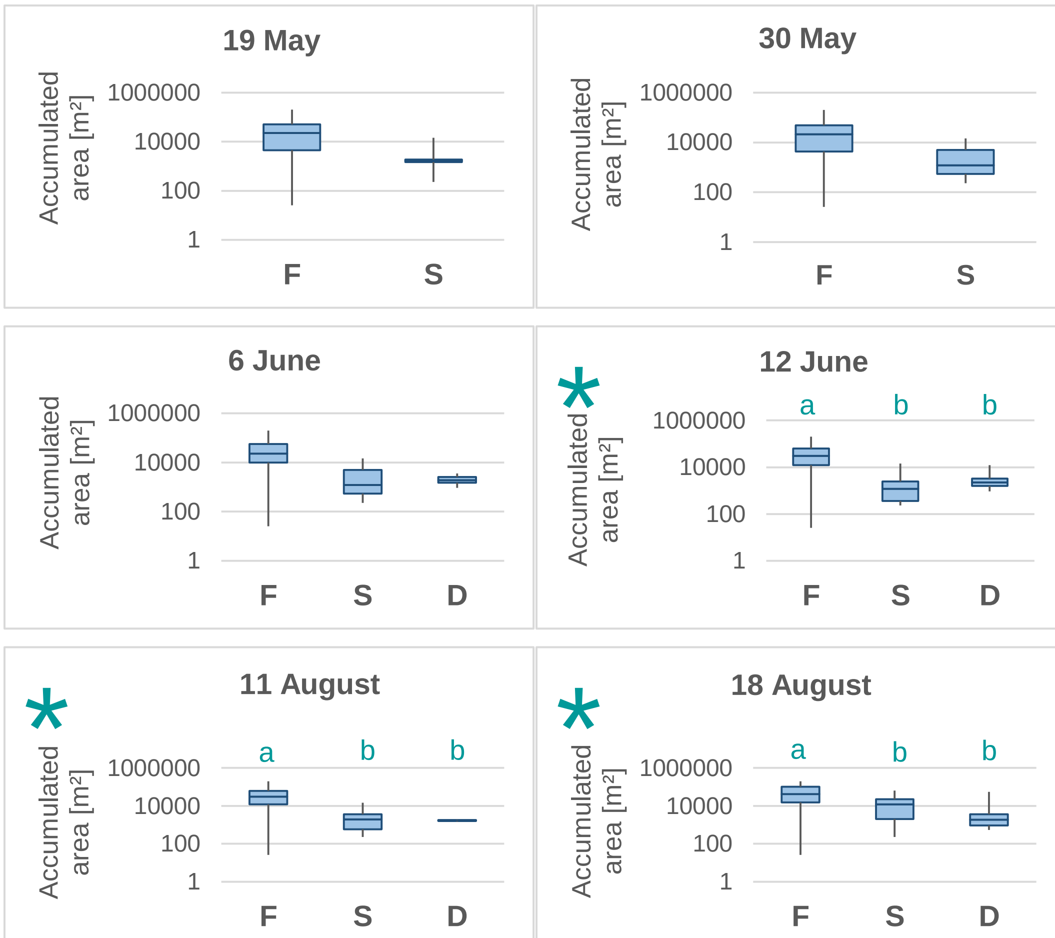


Figure 37. Boxplots of the accumulated area for flowing sections (F), sections with standing water (S) and dry sections (D) on the six survey dates. In order to provide for a better visualization, the accumulated area is drawn on a logarithmic scale.

4.4.4. Topographic wetness index

Figure 38 shows the map of the calculated topographic wetness index (T_{WI}) for the study area. Since the topographic wetness index is calculated with the local slope and contributing area, high values for T_{WI}, and therefore darker colors, mean the slope is low and it is, thus, an area where much water accumulates (Ågren et al., 2014). Values for the T_{WI} are higher in locations of the observed stream channels, although less distinctively in the eastern part of Area 2 and 3. According to the T_{WI} map, Area 3 has more places where water accumulates, since the colors are mainly dark.

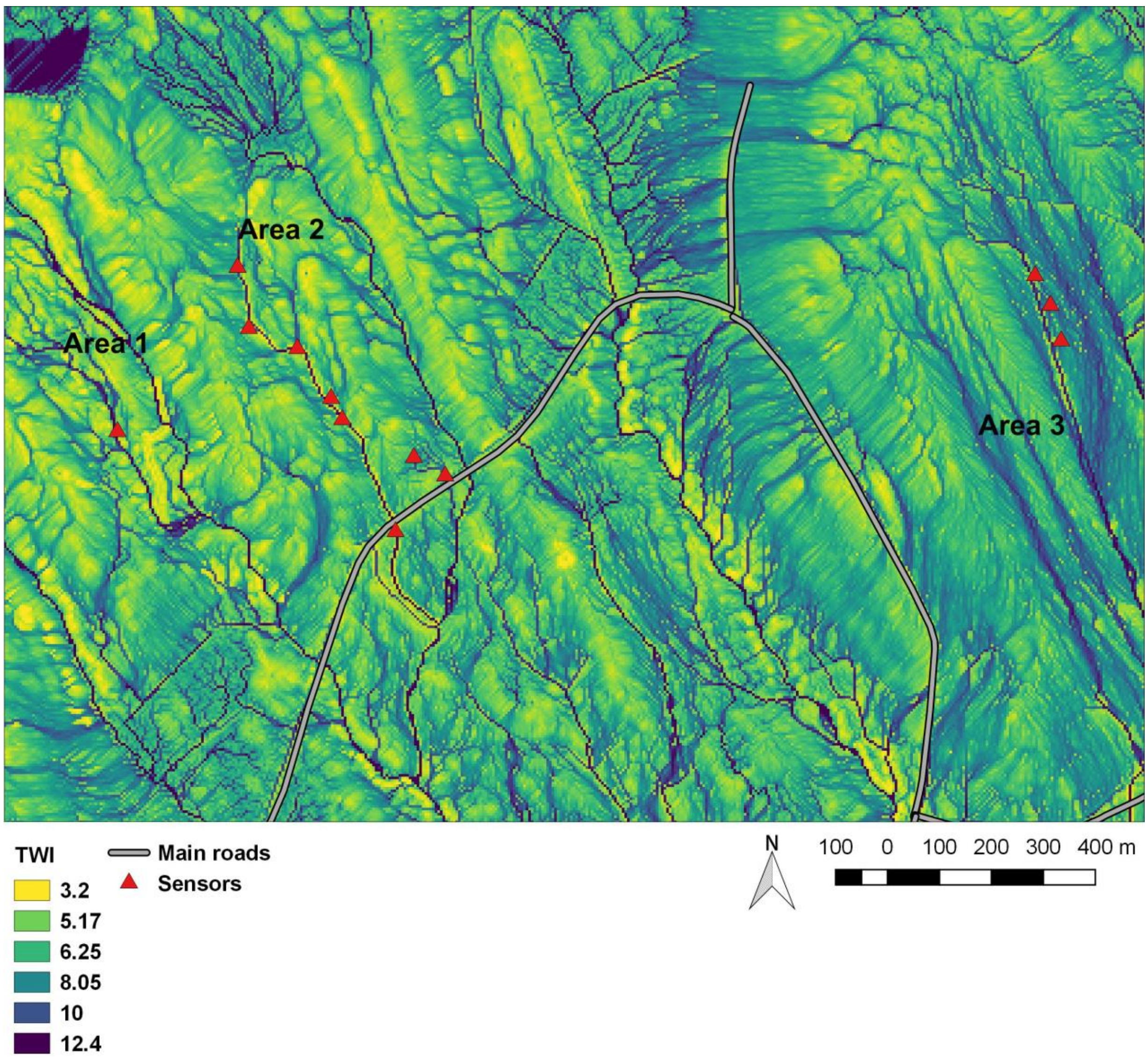


Figure 38. Map of the Topographic Wetness Index in the study area.

The statistic relation between T_{WI} and the stream state is shown for the six surveys in the boxplots of figure 39. There was no significant difference in the mean T_{WI} for the flowing, standing water or dry stream sections on any of the six survey dates.

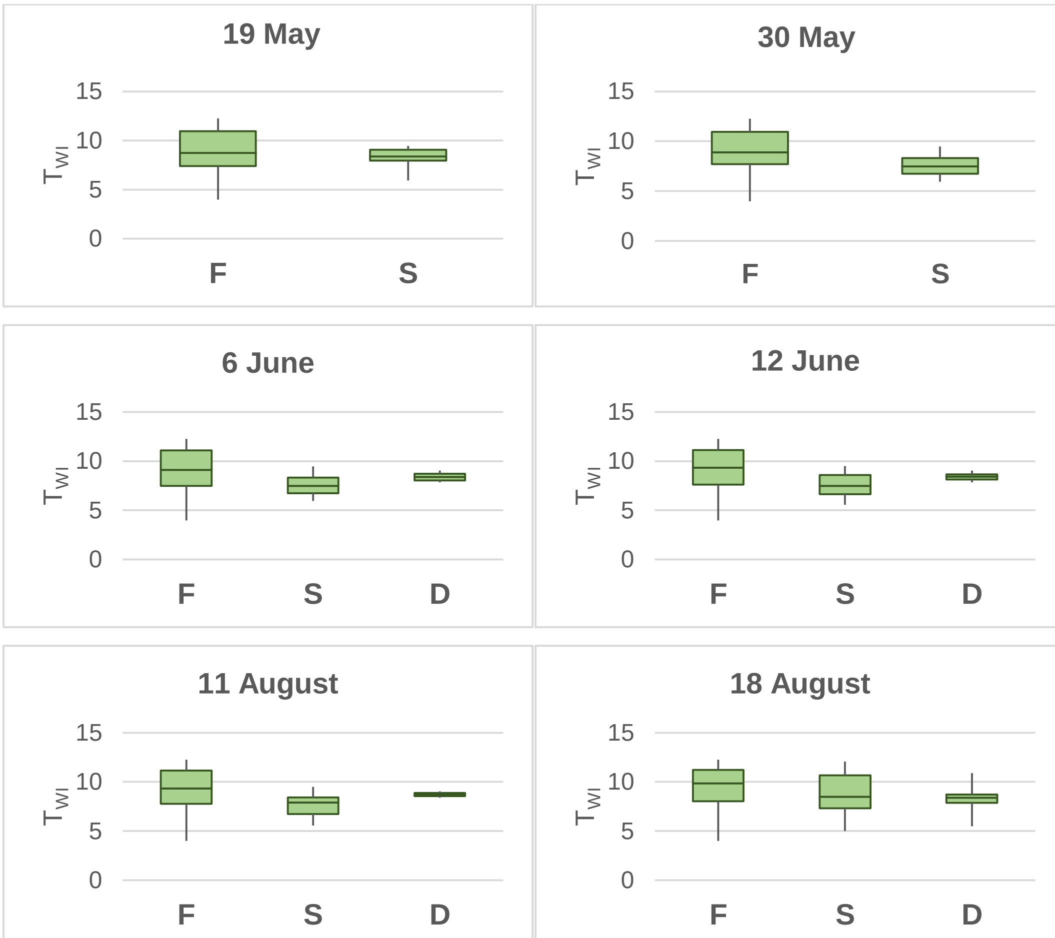


Figure 39. Boxplots of the Topographic Wetness Index (T_{WI}) for flowing sections (F), sections with standing water (S) and dry sections (D) on the six survey dates. There were no statistically significant differences.

4.5. Saturated soil area

4.5.1. Saturated soil maps

Area 1

In addition to the flowing stream network dynamic, the spatial and temporal variation in the saturated soil area was observed. Figure 40 shows the soil moisture status on six different days in Area 1.

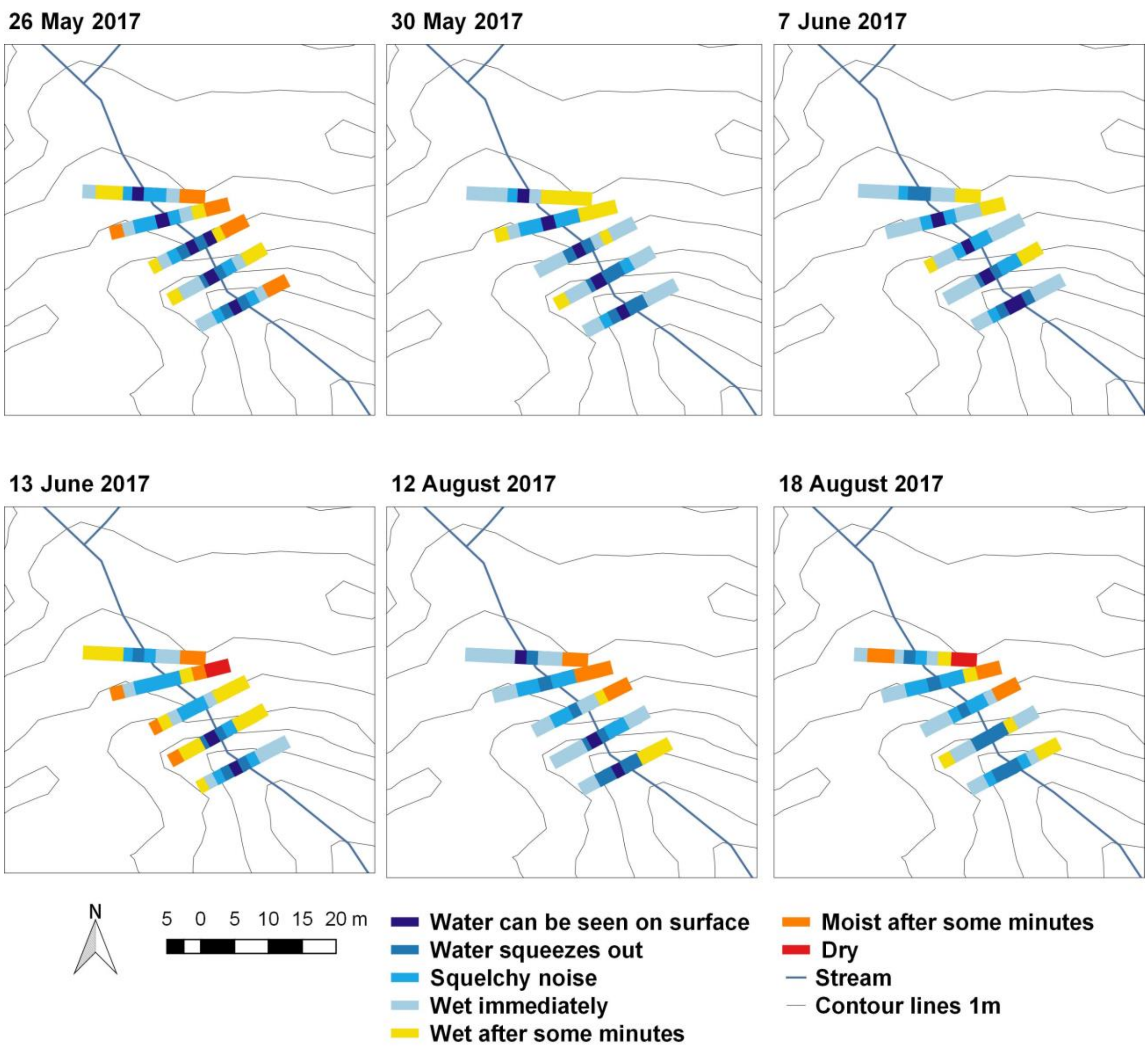


Figure 40. Soil moisture patterns in Area 1 on six different dates.

At the first two observation days, water was seen on the surface, where the stream flows and the soil became drier with increasing distance from the stream. However, in the end of May and beginning of June, this distinction seems to decrease. The map of 13 June represents the driest state of the soil in Area 1. Based on the two surveys in August, the driest parts are located on the eastern side of the area, where also the topography is slightly steeper than on the western side. The map of August 18 indicates that water cannot be seen in the stream channel anymore but rather squeezes out of the soil when stepping on it. Surveys of 30 May, 7 June and 12 August are observations with rainfall events two days earlier. All these three observations show surface water in or close to the stream channel.

Area 2

The six different maps in figure 41 represent the observations of the soil moisture status in Area 2. The soil was mapped along the stream, with a gap in the lower part, due to not affect the measurement instruments in the S-Transect (see figure 1). The main difference between the first and second survey is that many parts of the soil shifted to a drier state, with an exception of the lower parts with less variable topography. At the beginning of June, the soil saturation in the eastern area had increased. Later, on 13 June, the saturated soil in Area 2 is in general rather small in comparison to the other surveys. The two surveys in August reveal a rewetting process of the soil. However, the last map shows again a shift to drier conditions, especially in the upper part of Area 2.

Area 3

Figure 42 illustrates how the saturated area changed between six different days between May and August in Area 3. The soil on 26 May was more saturated in the northern part with less differences in topography than in the southern areas (Figure 42). The two observations from the end of May and the beginning of June indicate rewetting of the soil, and a shift to drier conditions in the middle of June. On 12 August, many parts of the soil are classified as “wet immediately” (light blue in figure 42). Meanwhile, no water is visible on the surface. The last map from 18 August reveals again a shift to drier conditions, including also sections which are classified as dry (red in figure 42). In general, in comparison to the other observation areas, Area 3 rather represents soil with a low saturation, since there are not many surveys where water could be seen on the topsoil.

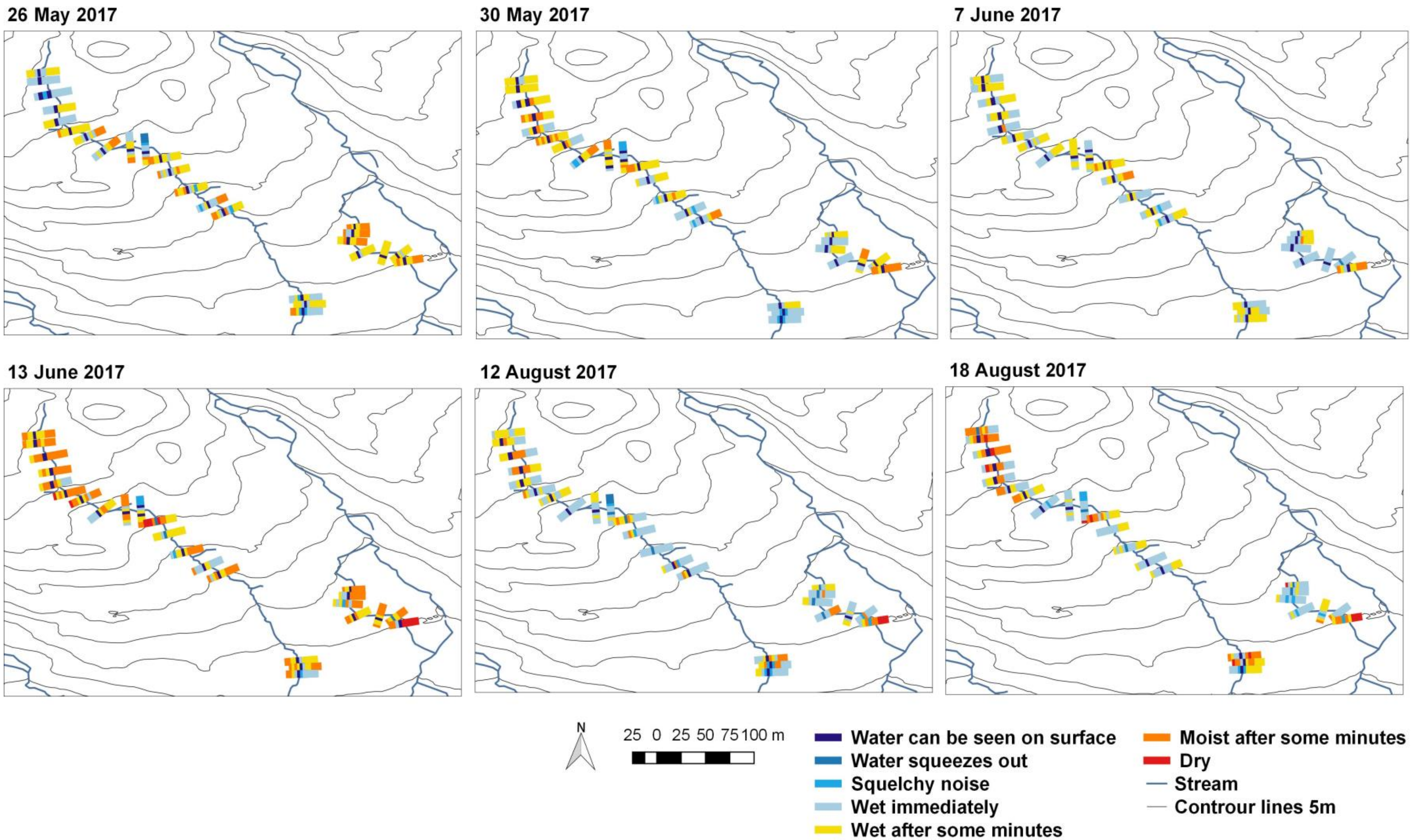


Figure 41. Soil moisture patterns in Area 2 on six different dates.

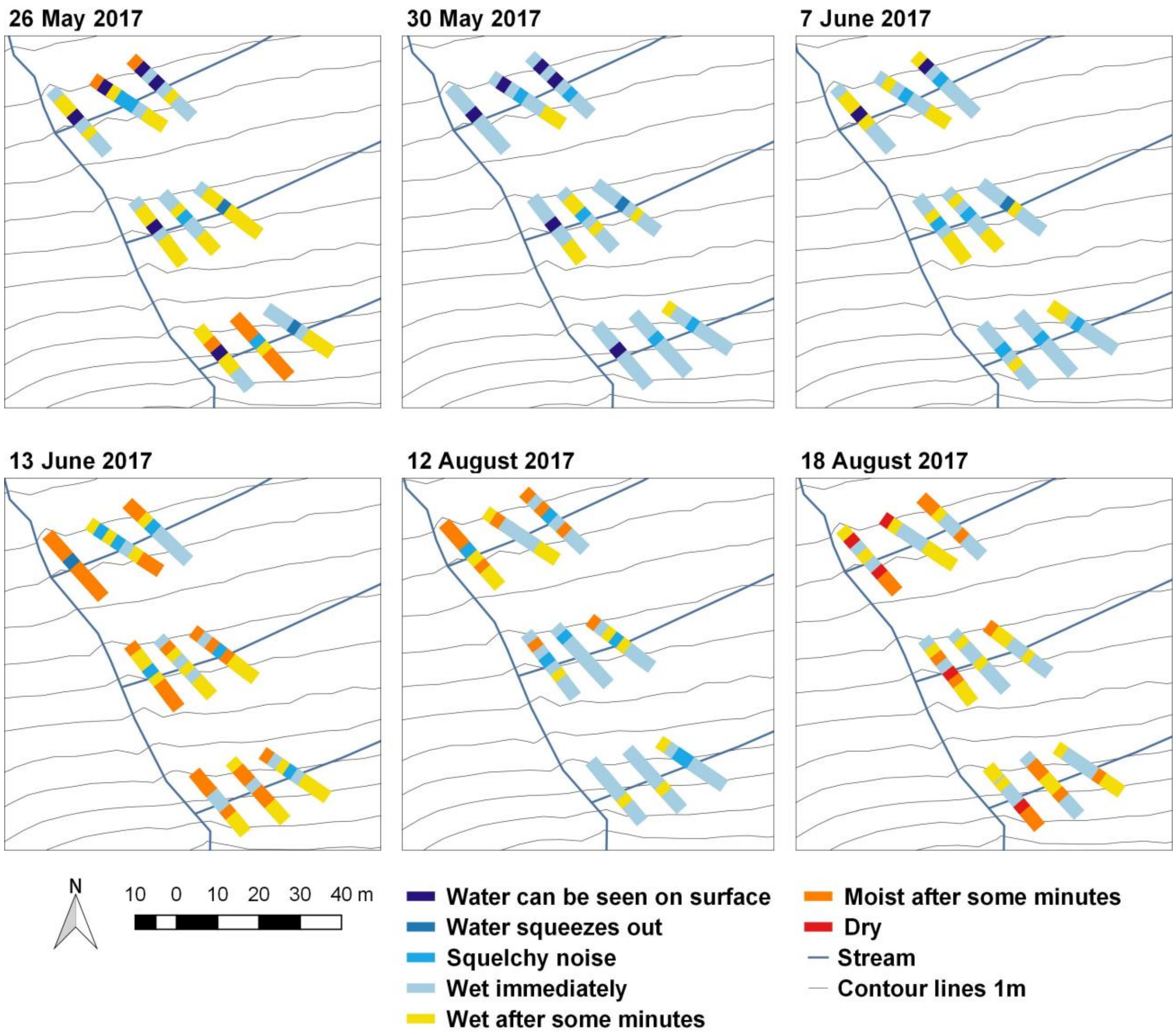


Figure 42. Soil moisture patterns in Area 3 on six different dates.

4.5.2. Relation between saturated area and discharge

Soil spots which were classified in classes 5-7, i.e. Squelchy noise, water squeezes out and water can be seen on surface, were defined as a saturated areas. Figure 43a shows the temporal change of the saturated soil related to discharge on the six field surveys in Area 2. It can be seen that on the first two surveys (26 and 30 May) the observed numbers of saturated areas is at its maximum (35 and 38 monitored spots) and also discharge is high during this period, affected by snow melt processes. From the first survey to the last one (26 May until 18 August), discharge decreases with a factor of 7, whilst the amount of saturated areas decreases with a factor of 1.3.

Figure 43b expresses the relation between the amount of these saturated soil spots and discharge. The dashed line represents the trendline with a R^2-value of 0.55. It is clearly visible that the highest two numbers of saturated soil areas are related to the highest two discharge values and smaller numbers of saturated areas are linked to days when discharge is smaller.

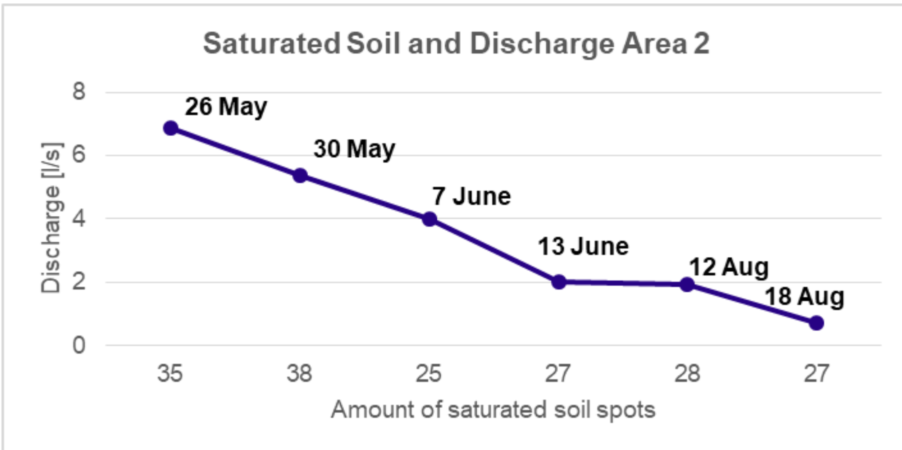


Figure 43a. Temporal variation between saturated areas (classes from 5-7 based on the field surveys) and discharge in Area 2.

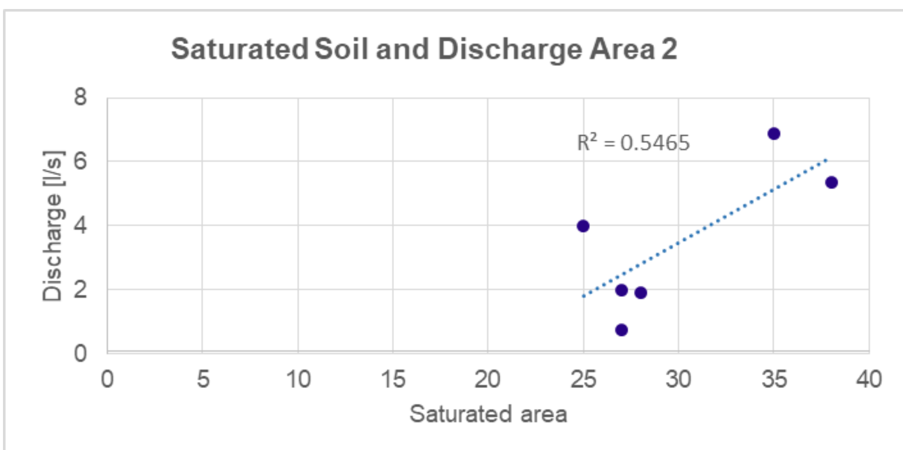


Figure 43b. Relation between saturated areas (classes from 5-7 based on the field surveys) and discharge in Area 2.

5. Discussion

5.1. Flowing stream network expansion and contraction

5.1.1. Observed patterns

Referring to the expansion and contraction patterns (Bahmjee et al., 2011 see table 1), Area 1 showed a downward contraction and first beginnings of a disintegrating contraction pattern. The disintegrating model can be observed in the upper part of the area where variations in topography are low. Although the stream section is not completely disintegrated as it was the most common model in the case study in an agricultural catchment in Southern Ontario (Bahmjee et al., 2011), but disintegrated with a section of standing water. Similar processes could be observed in Area 2, where also downward contraction dominated, similar to the study in a mountainous catchment in Sierra Nevada, California (Godsey and Kirchner, 2014). Furthermore, there were locations of disintegrating pools of standing and ponding water on 18 August. Completely fragmentation with dry channels could be observed on the survey of 18 August at locations A5 and A2. Area 3 showed downward contraction as well, in particular the main stream. Side branches and former ditches dried out relatively soon (in June) and in one piece with no fragmentation. The main stream showed prevalence of standing water and thus disintegrating sections of barely flowing water.

Controls on the pattern of expansions and contractions are catchment characteristics as well as in-channel characteristics, described in chapter 1.2.1. These factors are relatively stable and normally do not change in one season. It would be interesting to see rewetting processes and thus expansion patterns of the three observed areas, since under similar conditions, flowing stream networks are expected to react and thus expands in a similar way (Bahmjee et al., 2011).

Hydrological changes in the catchment cause stream network expansion and contraction and not inverse (Godsey and Kirchner, 2014). It is therefore important to understand the change of hydrological processes in the catchment and take them into account for this study.

5.1.2. Difference in connected flowing

Interruptions of the connected flowing network could be observed in all three areas. In particular, Area 1 and 2 exhibited dry channel sections in between flowing stream sections and this in turn leads to fragmentation of the flowing stream network. Contrary, field observations in Area 3 revealed predominantly sections of standing water which interrupt the connected flow.

The connected flow of a stream network can be strongly affected by the rearrangement of bedload and debris deposits, i.e. collected sediment behind a fallen tree (Godsey and Kirchner, 2014). Analog to bedload rearrangement, in this study the fast growing moss within the channels in can affect the flowing stream network since the moss has a high water holding capacity and therefore acts like a buffer for water pools and prevent the water to flow. This fragmentation and disconnection of the flowing stream network can cause serious ecological consequences for the regarding stream habitat (Godsey and Kirchner, 2014).

5.1.3. Relation with precipitation and discharge

The data was analysed regarding the question: *When is water flowing?* The analysis of the sensors revealed that flow is present in particular in the beginning of the measurement period and thus during, and also periods after the snowmelt. Shifts from flow to dry channels occurred mainly at the end of July and during August. Precipitation played an important role, especially rainfall events on several days in a row.

On the temporal scale, the pattern of the length of the flowing stream network on the six field surveys is similar to the pattern of discharge. In the analysis can be seen that discharge decreases in a similar manner as the flowing stream length decreases over time. The analysis of correlation between flowing stream length and discharge (log-log scale), revealed a β-value of 0.186 and therefore rarely indicates a strong statistical correlation. In a mountainous catchment in Sierra Nevada, California, the relation of the flowing stream network and discharge exhibited β-values between 0.18 and 0.4 and therefore represent vary correlations. Nevertheless, there were only small numbers of points available (Godsey and Kirchner, 2014). In this study, the relation between discharge and flowing stream length was, due to limited data availability, only investigated in Area 2 and therefore limits concluding states of the general correlation. Furthermore, the weirs where discharge is measured, are in general located close to the highest limit of the connected network also during low flows and can therefore lead to a biased results when the connected network is compared to discharge (Godsey and Kirchner, 2014).

5.1.4. Relation with topography

In addition to the temporal scale, analysis of spatial dynamics aim to answer the question: *Where is water flowing?* Analysis with topographic indices revealed that the upslope accumulated area and upstream distance of a stream segment correlate with its state, i.e. whether there is flow or not. A study in a Swiss pre alpine headwater catchment also showed that accumulated area and additionally T_{WI} can be used to explain flow occurrence (Sjöberg, 2016). The size of the upslope contributing area was also significant with the occurrence of flow in a peatland catchment study in the United Kingdom (Goulsbra et al., 2014). Contrary, in this study the relation of flow occurrence and T_{WI} was not statistically significant. Moreover, local slopes were also not significantly correlated with flow occurrence.

5.2. Saturated soil area

The analysis of relation between saturated areas and discharge suggest that there is a pattern in correlation. A further question is whether decreasing discharge causes decreasing saturated areas or rather is a result of decreasing saturated areas. The survey on 7 June revealed 25 spots of saturated areas while discharge was still at 4 l/s, and thus compared to the other observations relatively high. This small number of observed saturated areas combined with high discharge could be caused by vegetation growth and therefore increasing evapotranspiration, since vegetation patterns can also be used as indicators of saturated areas (Kulasova et al., 2014).

5.3. Sensor performance

Considering that the flow sensor collects data with an interval of only 12 l/h, it should be more sensitive for the use in slowly flowing boreal streams. However, the flow sensor is a nice tool to interpret the streams with flowing water or ephemeral streams. An improved method for further research could be to install more sensitive flow sensors in selected areas of standing or barely flowing water. However, the flow sensor is important for monitoring the flowing stream network, since it is the only one which indicates the occurrence of flow, while the ER, water level switch and temperature sensors can only provide information of wet or dry states (Bhamjee et al., 2011).

An additional issue is the flow dynamic of some streams. For example at site A8 with a high channel and water depth. The flow occurred particularly in the middle of the water column or at the surface due to the wind, whilst the flow sensor, installed at the bottom of the channel, indicated no flow or very low values (figure 44). To prevent this issue, the flow sensor should be installed at locations where the water depth is not too deep, i.e. smaller than 30 cm.

At the beginning of the measurement period, some ER sensors showed rather high values, despite the presence of water. This could be due to narrow stream channels and therefore a relatively high probability of the electrodes touching the channel soil. The sediment plays an important role as well, since leafs or other sediments flowing in the water can touch or hang on the electrodes. This leads to a biased result because water and sediments do not have the same electrical resistance. This is the case, in particular, in streams with slow flow due to low water depth. To avoid issues like this, the two electrodes should be installed in flow direction of the flow. With this, the probability of the electrodes to touch the channel soil is minimized. In addition, a small grid in front of the electrodes could prevent sediments to hang on the ER sensor. However, the electrodes should be cleaned at every field inspection.

Figure 44. Flow dynamic highlighted with a tracer.

The water level switch was a useful component in the measurement cluster to detect whether there is water or not. Nevertheless, it must be ensured that the switch is correctly installed, i.e. the switch is fixed and the connected wire cannot jam the tube, and that there is a protection, for example a thin sock, to prevent that sediment blocks the switch. One possibility to keep the switch vertical, is to attach the connected wire to a stable stick.

The temperature sensors turned out be very reliable for further analyses, since the error source is comparatively small. This is also due to the simple installation. However, it must be said that the application of a temperature sensor only makes sense when the measurements are conducted over a longer time period. This is because the data has to be analysed in relation with the whole period to detect how the diurnal variations alter.

Time lapse cameras are a nice tool to verify data collection of the sensors. The use of cameras particular makes sense when the sensors are in a test phase. However, the devices are sensitive, e.g. batteries are drained quickly in a cold climate and humid air negatively influences the functioning of the camera. Moreover, the data analysis requires a lot of time and the interpretation can be difficult, since it is sometimes hardly visible whether water is present or absent and where the threshold is. Additionally, since the vegetation grows fast in the boreal summer, the data collection should be checked in situ from time to time, also to ensure that there is a good view of the observation site without any vegetation in the way.

5.4. Limits of the research and suggestions for future directions

The study sites are three areas and four different stream branches. The results of the measurement clusters installed in these four stream branches were related to the discharge at the outlet. Due to limited availability of discharge data, this could be done only for one study area (Area 2). However, it would be interesting to see how the measurement clusters match the discharge data of the other areas as well. Moreover, the mapping could be focused on one area instead of three, but in a larger scale and a connected area. This means, the result of the mapping of the channel states in the stream network would be comprehensive. With this, also the change in connected and disconnected stream sections could be observed and analysed. A limitation of the qualitative assessment of the saturated soil is the subjectivity of the classification (Rinderer et al., 2012). Therefore, to obtain a more accurate assessment, the classification can be evaluated by several persons. These persons do not have to be experts to achieve a reliable results of the assessment (Rinderer et al., 2012).

Field surveys

The mapping of saturated soils and stream networks was done with a hand-held GPS. Therefore, the start and endpoints of the transect lines are inputs from a hand-held GPS. Due to the limited accuracy of the GPS, the wettest areas (dark blue boxes in the figures) do not always occur at the actual stream channel. For a more precise spatial resolution, a higher accuracy of the GPS inputs is required. The presence of a thick moss layer at some sites was an issue regarding the stream network mapping. Due to the high water holding capacity of the moss, a lot of water is required to form a surface flow. Particularly Area 1 and 3 are examples for this case. A further issue is the diffuse flow of water when no distinct channel exists, as this is the case at site A9.

Analyses with the DEM

The accumulated area and upstream distance values for a dry channel and flowing water sections are significantly different. The number of dry channel sections was small in all six surveys and varied from zero to nine. On the contrary, the number of observed flowing stream sections varied from 26 to 56. In order to intensify the analysis and review the relation between topography and state of the stream, it is suggested that an area with a larger number of dry sections is observed. The resolution of the used DEM affects the results (Sørensen and Seibert, 2007), thereby the resolution should be adjusted depending on the scale of the feature of interests. Since this study is rather on a small scale, it makes sense that the DEM is not too coarse. Topographic indices as slope, accumulated area, topographic wetness index and upstream distance may all be affected by the resolution and quality of the DEM.

Outlook on open research questions

The results of this thesis revealed that further and detailed investigations of long term stream network dynamics would be interesting. It would be interesting to monitor the expansion and contraction of the flowing stream network over several seasons and compare them also regarding climate conditions. A possible research question in that sense would be:

> *How does the flowing stream network change on a long term scale and how are these changes affected by varying climate conditions?*

The groundwater level has been measured three times for this thesis in order to compare it with the results of the sensors. The change in groundwater level combined with the change of the stream network would be interesting to investigate. Moreover, it could be analysed how groundwater changes are affected by snowmelt processes or rainfall events. Areas could be defined, where groundwater does not change much and thus the soil acts as a buffer, and on the other hand areas, where groundwater level varies much and contributes to surface flow.

> *How does groundwater level change seasonally and how does it affect the flowing stream network?*

Different soil types and their water holding capacity regarding saturation would be interesting to investigate. It could be analysed which soil characteristics benefit a short- and long term soil saturation with also taking the role of vegetation into account. A possible question would be:

> *What is the relation of vegetation, soil type and saturated areas? Can the water holding capacity of a soil be changed, and when yes, how?*

6. Conclusion

The investigations in this thesis have demonstrated that a lot of data can be collected concerning flowing stream network dynamics, and linked to the distribution of soil saturation, groundwater level variations, and discharge and precipitation. The results and interpretation of these analyses allowed answering the individual research questions.

> ***RQ1****: Can the measurement clusters with four different sensors be used to determine whether there is flowing/standing/no water in the boreal environment?*

The measurement clusters with the ER sensor, water level switch, flow and temperature sensor yielded reliable but imprecise results to determine whether there is flowing, standing or no water in the channel. The flow sensor (reliability of 60%) is not sensitive enough for use in the boreal environment with barely flowing water. More reliable data were obtained from the ER sensors (reliability of 94%), but the proper installation and field inspections for cleaning the electrodes are essential to get useful data. The water level switch (reliability of 88%) is an advantageous tool in data collection, since it delivers a distinct signal whether there is water or not. On the other hand, the signal can easily be disturbed by jamming of the wire and therefore a wrong position of the switch. In this study, this happened at three locations in the beginning of the measurement period. With an adjusted case, a higher reliability of the data collection may be reached. The temperature sensor is also a useful sensor to determine whether there is water or not. The potential of errors and disturbance of the signal is rather small and for longer periods of data, it can be clearly seen when the diurnal variations change and therefore indicates the presence or absence of water.

> ***RQ2****: How does the flowing and connected stream network change in a boreal catchment in Northern Sweden from snowmelt until the end of August/September and during rainfall events?*

The flowing stream network in the study area changes throughout the summer with a decrease in flowing stream sections from May to August in 2017. Locations with limited variation in topography are characterised by barely flowing stream sections. Changes in the flowing stream network from May to the beginning of June are small, but the clearest shift to a drier state was observed in mid-August. The connected stream network changed after the snowmelt in June, whilst the upper parts of the streams shifted to ponding water or went dry. The flowing stream network changes in response to rainfall events from 1 to 4 mm last for only short term. On three field surveys, the flowing stream network was mapped one day after a rainfall event and no big changes due to these events could be detected. A suggestion for future investigations is to map during these events. In particular, sections of former ditching activity exhibit a quick shift to dry states after snowmelt and do not react to small rainfall events. In August and September the precipitation amount threshold was to change from standing water to a flowing stream was higher.

RQ3*: What is the relation between the length of flowing stream channel and streamflow?*

According to the installed measurement clusters, the number of flowing stream sections was largest during snowmelt and decreases until the minimum at the beginning of September. Due to big rainfall events over several days, the number of flowing stream segments increased again. The temporal variability in the number of sites with a dry channel was opposite. The numbers of locations with standing water reached the maximum during snowmelt and remained similar after. The maximum of the total length of flowing stream channel in the study area was seen during snowmelt on 30 May. During the summer the length continuously declined to the minimum of 8’560 m on 18 August. At the temporal scale, the pattern of discharge is similar to the pattern of the length of flowing stream network and are therefore affected by each other.

RQ4*: How does the saturated area change in a boreal catchment in Northern Sweden from snowmelt until the middle of August?*

The soil in general shifts from a rather wet state in May to a drier sate in June. After this, the saturation slightly increased in response to precipitation until August. The major difference is the change in the area with visible water on the surface in May, whereas in August most surface water had disappeared. Moreover, it was observed that flat areas with less variability in topography are more saturated than steeper areas. Furthermore, areas close to the stream are in general more saturated compared to areas further away from the channel. Snowmelt processes affected the soil saturation in May and the beginning of June whereas small rainfall events do not result in big changes in saturation.

RQ5*: Can topography predict locations of flowing and standing water?*

The upstream distance and upslope accumulated area could partly explain where water is flowing or standing. In contrast, information on slope and topographic wetness index were not useful to predict locations of flowing and standing water. Dry stream channels were in each survey the most upstream while water flows in the closest parts to the outlets.

7. References

ÅGREN, A., LIDBERG, W., AND RING, E. (2015) Mapping Temporal Dynamics in a Forest Stream Network - Implications for Riparian Forest Management, Forests, 6, 2982.

ÅGREN, A., LIDBERG, W., STRÖMGREN, M., OGILVIE, J., AND ARP, P. A. (2014) Evaluating digital terrain indices for soil wetness mapping – a Swedish case study. Hydrology and Earth System Sciences, 18, 3623-3634.

ASSENDELFT, R.S. (2016) Stream network expansion and contraction- monitoring, patterns and controls. PhD Proposal, Geography Department, University of Zurich.

BARNETT, T. P., ADAM, J. C., AND LETTENMAIER, D. P. (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303-309.

BEVEN, K. J., KIRKBY, M. J. (1979) A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin, 24:1, 43-69.

BHAMJEE, R., AND LINDSAY, J. B. (2011) Ephemeral stream sensor design using state loggers. Hydrology and Earth System Sciences, 15, 1009-1021.

BHAMJEE, R., LINDSAY, F. B., AND COCKBURN, J. (2016) Monitoring ephemeral headwater streams: a paired-sensor approach. Hydrological Processes, 30(6): 888-898.

BISHOP, K., BUFFAM, I., ERLANDSSON, M., FÖLSTER, J., LAUDON, H., SEIBERT, J., AND TEMNERUD, J. (2008) Aqua Incognita: the unknown headwaters. Hydrological Processes, 22, 1239 – 1242.

BLYTH, K., AND RODDA, J. C. (1973) A Stream Length Study. Water Resources Research. 9, 1454-1461.

CONSTANTZ, J. (2008) Heat as a tracer to determine streambed water exchanges. Water Resources Research, 44.

CONSTANTZ, J., STONESTORM, D., STEWART, A. E., NISWONGER, R., SMITH, T. R. (2001) Analysis of streambed temperatures in ephemeral channels to determine streamflow frequency and duration. Water Resources Research, 37, 317-328.

DATRY, T., FRITZ, K., AND LEIGH C. (2016) Challenges, developments and perspectives in intermittent river ecology. Freshwater Biology. 61, 1171-1180.

DATRY, T., LARNED, S. T., AND TOCKNER, K. (2014) Intermittent Rivers: A Challenge for Freshwater Ecology. BioScience. 64, 229-235.

GOULSBRA, C., EVANS, M., AND LINDSAY, J. (2014) Temporary streams in a peatland catchment: pattern, timing, and controls on stream network expansion and contraction. Earth Surface Processes and Landforms 39, 790-803.

GODSEY, S. E., AND KIRCHNER, J. W. (2014) Dynamic, discontinuous stream networks: hydrologically driven variations in active drainage density, flowing channels and stream order. Hydrological Processes 28, 5791-5803.

GRABS, T. (2010) Water quality modeling based on landscape analysis: importance of riparian hydrology. Dissertations from the Department of Physical Geography and Quaternary Geology No 24. Stockholm University, Sweden.

ICOS NATIONAL NETWORK SWEDEN 2017 <http://www.icos-sweden.se/station_svartberget.html> (access: 12.11.2017)

KULASOVA, A., BEVEN, K. J., BLAZKOVA, S. D., REZACOVA, D., CAJTHAML, J. (2014) Comparison of saturated areas mapping methods in the Jizera Mountains, Czech Republic. Journal of Hydrology and Hydromechanics. 62, 2, 160-168.

LAUDON, H. (2017) The Krycklan Catchment Study. A unique infrastructure for field based research on hydrology, ecology and biogeochemistry. A Hitcher's Guide 3.1.

LAUDON, H., BERGGREN, M., ÅGREN, A., BUFFAM, I., BISHOP, K., GRABS, T., JANSSON, M., KÖHLER, S. (2011) Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: The role of processes, connectivity, and scaling. Ecosystems 14, 880-893.

LAUDON, H., SJOBLOM, V., BUFFAM, I., SEIBERT, J., AND MORTH, M. (2007) The role of catchment scale and landscape characteristics for runoff generation of boreal streams. Journal of Hydrology. 344, 198-209.

LAUDON, H., TABERMAN, I., ÅGREN, A., FUTTER, M., OTTOSSON-LÖFVENIUS, M., AND BISHOP, K. (2013) The Krycklan Catchment Study - A flagship infrastructure for hydrology, biogeochemistry, and climate research in the boreal landscape. Water Resources Research. 49, 7154-7158.

MEYER, J., STRAYER, D., WALLACE, J., EGGERT, S., HELFMAN, G., AND LEONARD, N. (2007) The contribution of headwater streams to biodiversity in river networks. Journal of the American Water Resources Association. 43, 86-103.

MUELLER, D. (2015) Interrater Reliability of a Qualitative Soil Moisture Assessment Scheme – Case studies from Tanzania and Switzerland. MSc-Thesis at the Department of Geography, University of Zurich, Switzerland.

RINDERER, M., KOLLEGGER, A., FISCHER, B.M. C., STÄHLI, M. AND SEIBERT, J. (2012) Sensing with boots and trousers - qualitative field observations of shallow soil moisture patterns. Hydrological Processes. 26, 4112-4120.

RONAN, A. D., PRUDIC, D. E., THODAL C. E, CONSTANTZ, J. (1998) Field study and simulation of diurnal temperature effects on infiltration and variably saturated flow beneath an ephemeral stream. Water Resources Research. 34, 2137-2153.

SEIBERT, J., AND MCGLYNN, B. L. (2007) A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models. Water Resources Research, 43, W04501.

SJÖBERG, O. (2016) The Origin of Streams – Stream cartography in Swiss pre alpine headwater. MSc-Thesis at the Department of Earth Sciences, Uppsala University, Sweden.

SKOGSSÄLLSKAPET (2017) When do we ditch the ditch? A field test of the “DitchFlowTracker” to prioritize forest drainage ditch maintenance for sustainable forest management. <https://www.skogssallskapet.se/forskning/alla-projekt/projekt/2017-04-24-when-do-we-ditch-the-ditch---a-field-test-of-the-ditchflowtracker-to-prioritize-forest-drainage-ditch-maintenance-for-sustainable-forest-management.html> (access: 5.12.2017).

SØRENSEN, R., SEIBERT, S. (2007) Effects of DEM resolution on the calculation of topographical indices: TWI and its components. Journal of Hydrology 347, 79-89.

STANLEY, E. H., FISHER, S. G., GRIMM, N. B. (1997) Ecosystem expansion and contraction in streams. BioScience 47. 427-435.

UNIVERSITY OF ZURICH (2017) Whitebox Geospatial Analysis Tools <http://www.geo.uzh.ch/en/units/h2k/Services/Whitebox-GAT.html> (access: 16.12.2017).

WARD, R., AND ROBINSON, M. (2000) Principles of hydrology (4th edition). McGraw Hill, London. 450.

WESTERN, A., ZHOU, S. L., GRAYSON, R. B., MCMAHON, T.A., BLÖSCHL, G., WILSON, D. J. (2004) Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. Journal of Hydrology 286 1-4. 113-134.

WESTERN, A. W., ZHOU, S. L., GRAYSON, R. B., MCMAHON, T. A., BLÖSCHL, G., WILSON, D. J. (2005) Reply to comment by Ilja Tromp van Meerveld and McDonnell on Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. Journal of Hydrology 303 1-4. 313-315.

WIGINGTON, P., MOSER, T. J., AND LINDEMANN, D.R. (2005) Stream network expansion: a riparian water quality factor. Hydrological Processes, 19(8). 1715-1721.

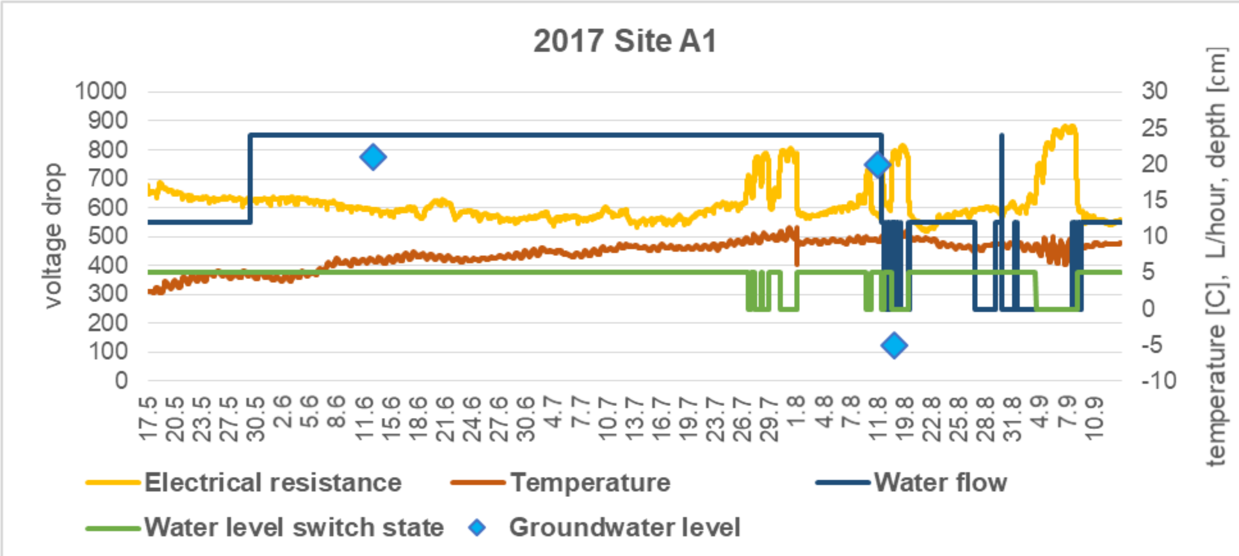
ZANCHI, G., BELYAZID, S., AKSELSSON, C., YU, L., BISHOP, K., KÖHLER, S. J., AND GRIP, H. (2016) A Hydrological Concept including Lateral Water Flow Compatible with the Biogeochemical Model ForSAFE. Hydrology, 3 (1), 11.

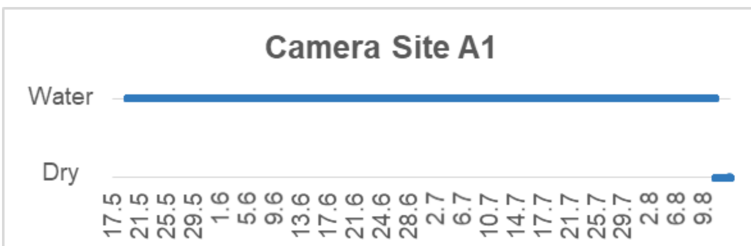
8. Acknowledgement

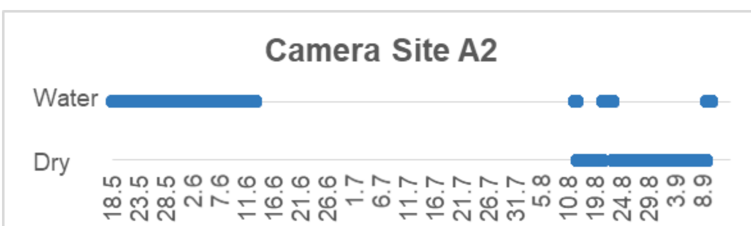
I wish to thank my supervisors Ilja van Meerveld and Jan Seibert for the very professional supervision with constructive, inspiring and motivating discussions. I thank Jana Erdbrügger, Rick Assendelft and Itziar Aginaga for excellent assistance in field work, helpful discussions and for wonderful moments in the beautiful Northern Swedish wilderness. Further, I want to thank the Krycklan- and SLU-Team, in particular Reinert Huseby Karlsen, Thomas Grabs and Kevin Bishop for interesting and helpful talks. Last but not least, I also thank my friends for the support and those who reviewed my thesis for their valuable comments, which have greatly improved this thesis.

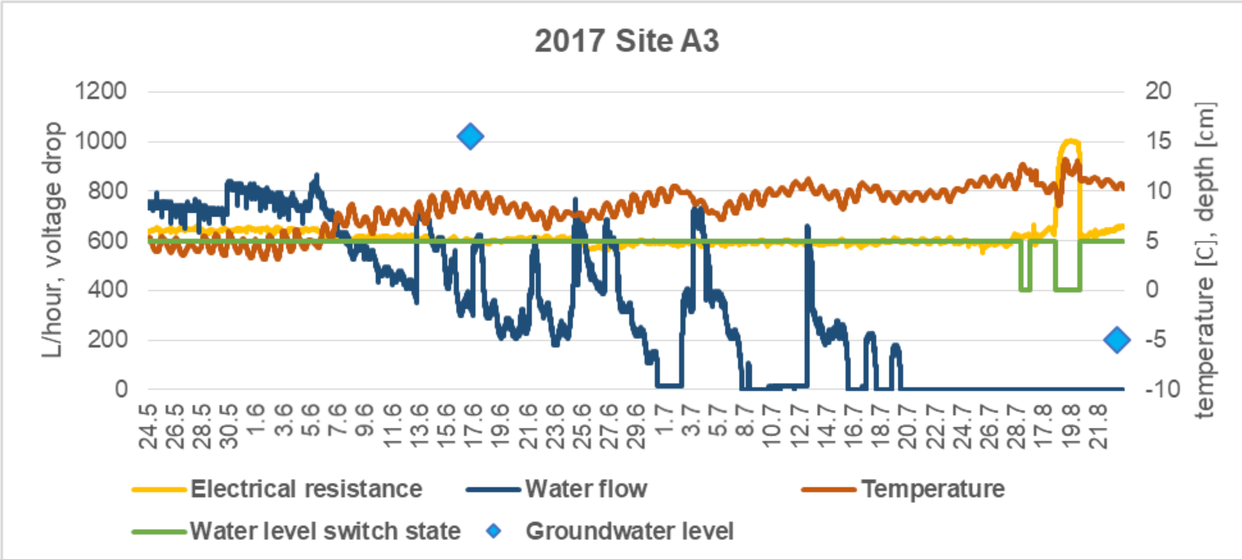
9. Appendix

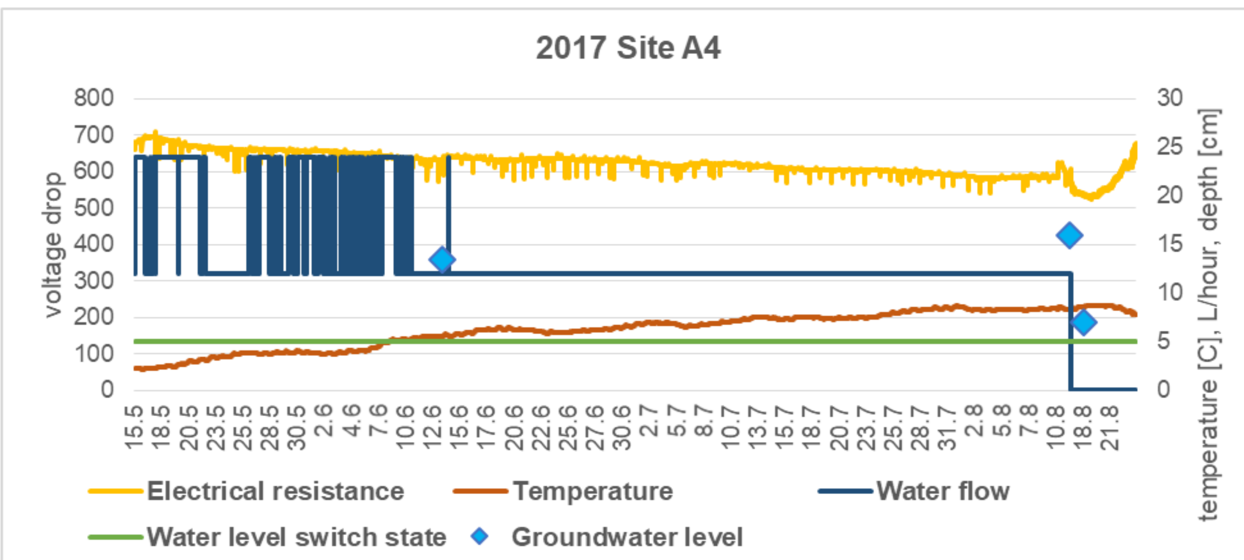
9.1. Measurement clusters and time lapse photography

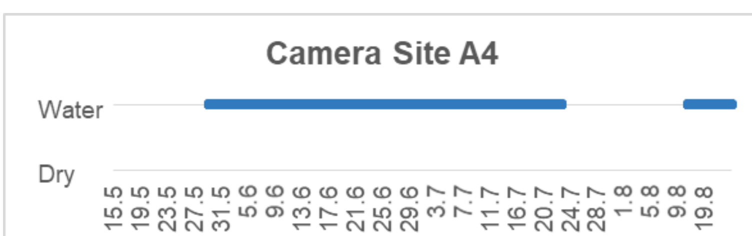


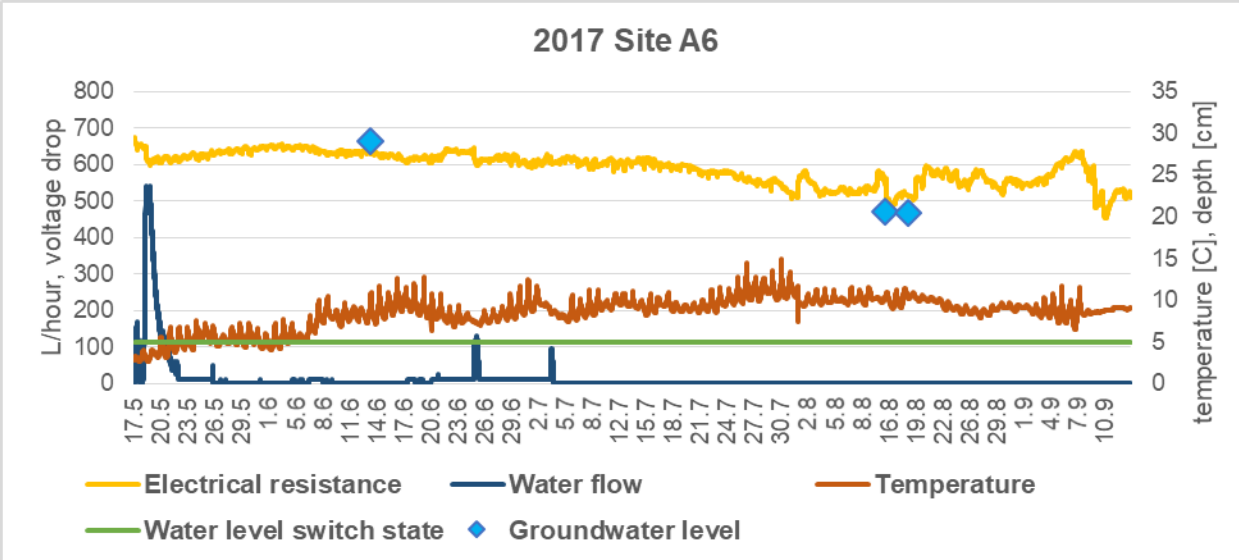


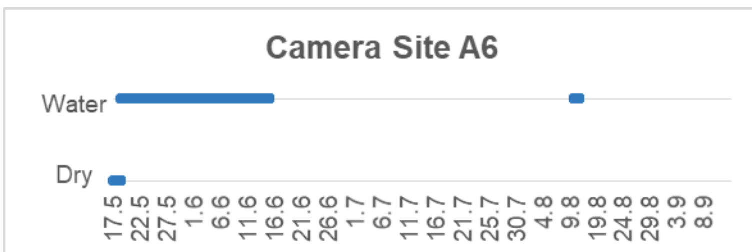


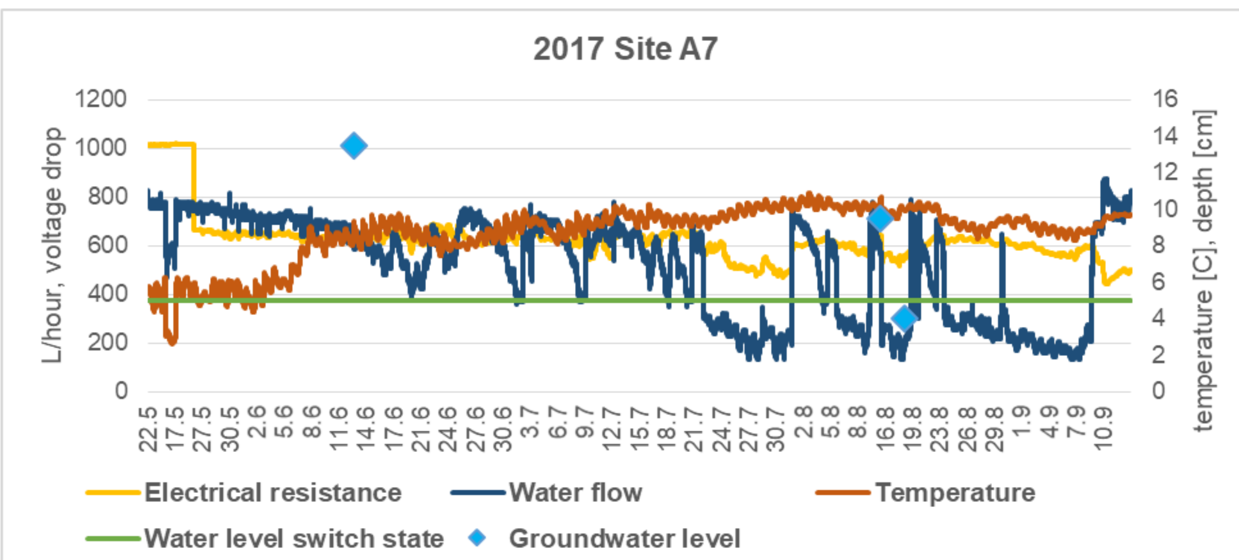

2017 Site A3
L/hour, voltage drop
1200
1000
800
600
400
200
0
20
15
10
5
0
-5
-10
temperature [C], depth [cm]
24.5 26.5 28.5 30.5 1.6 3.6 5.6 7.6 9.6 11.6 13.6 15.6 17.6 19.6 21.6 23.6 25.6 27.6 29.6 1.7 3.7 5.7 8.7 10.7 12.7 14.7 16.7 18.7 20.7 22.7 24.7 26.7 28.7 17.8 19.8 21.8
Electrical resistance
Water flow
Temperature
Water level switch state
Groundwater level

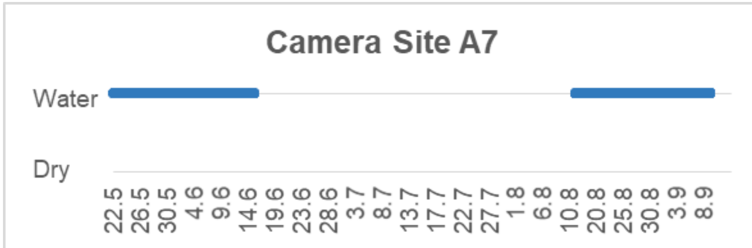

2017 Site A4
voltage drop
800
700
600
500
400
300
200
100
0
30
25
20
15
10
5
0
temperature [C], L/hour, depth [cm]
15.5 18.5 20.5 23.5 25.5 28.5 30.5 2.6 4.6 7.6 10.6 12.6 15.6 17.6 20.6 22.6 25.6 27.6 30.6 2.7 5.7 8.7 10.7 13.7 15.7 18.7 20.7 23.7 25.7 28.7 31.7 2.8 5.8 7.8 10.8 18.8 21.8
Electrical resistance
Temperature
Water flow
Water level switch state
Groundwater level

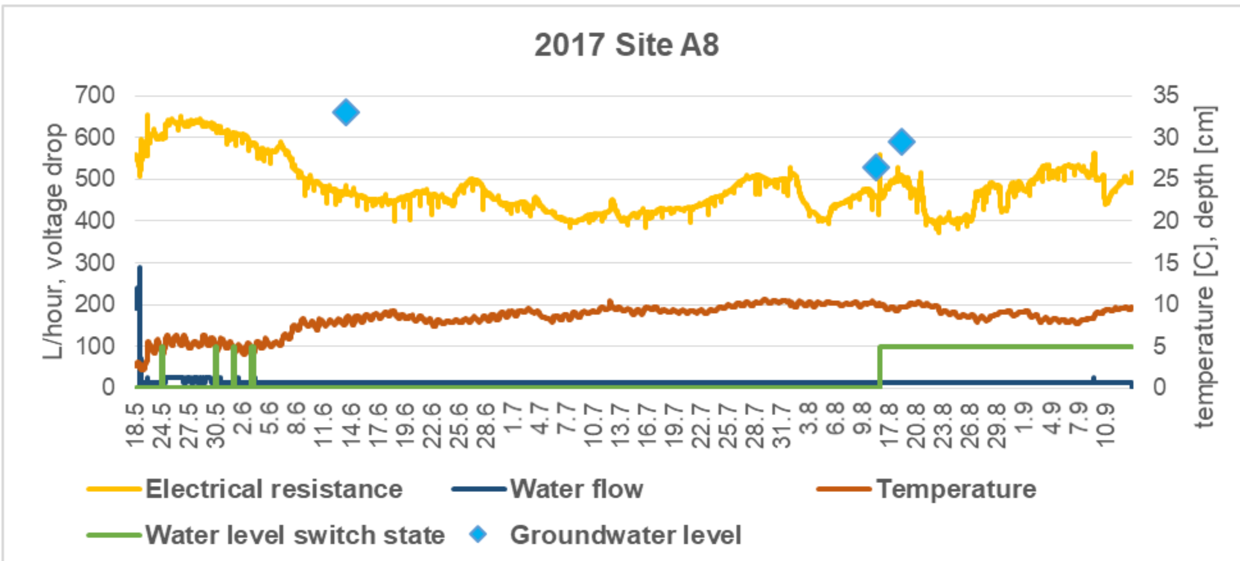

Camera Site A4
Water
Dry
15.5 19.5 23.5 27.5 31.5 5.6 9.6 13.6 17.6 21.6 25.6 29.6 3.7 7.7 11.7 16.7 20.7 24.7 28.7 1.8 5.8 9.8 19.8


2017 Site A6
L/hour, voltage drop
temperature [C], depth [cm]
Electrical resistance
Water flow
Temperature
Water level switch state
Groundwater level

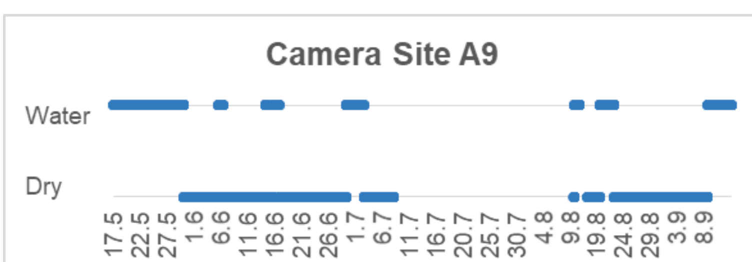

Camera Site A6
Water
Dry

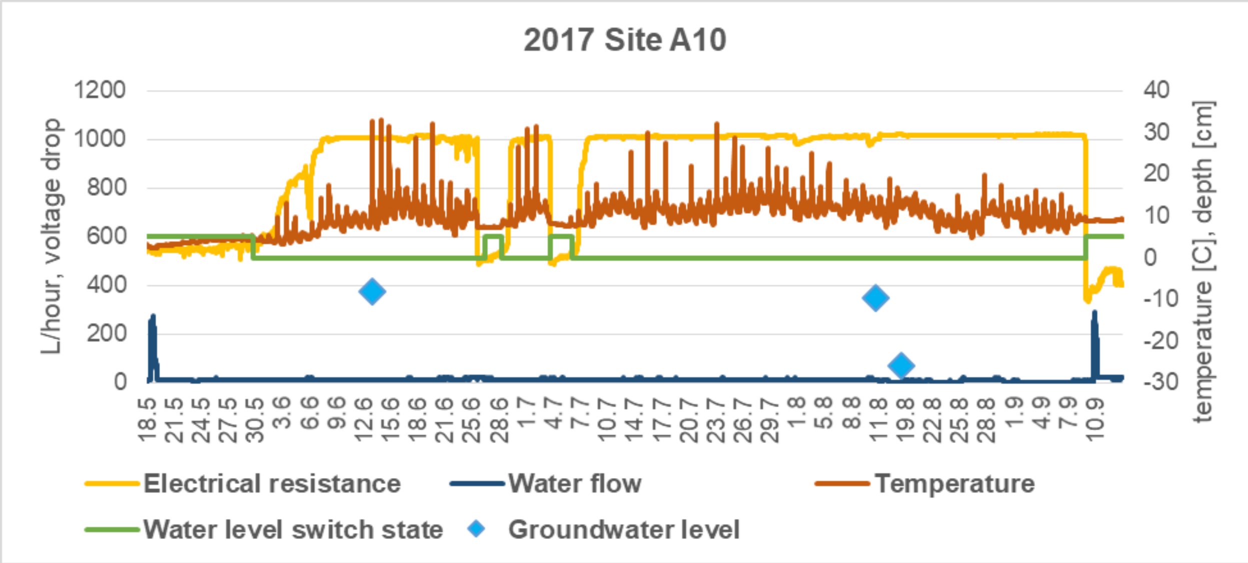

2017 Site A7
L/hour, voltage drop
temperature [C], depth [cm]
Electrical resistance
Water flow
Temperature
Water level switch state
Groundwater level

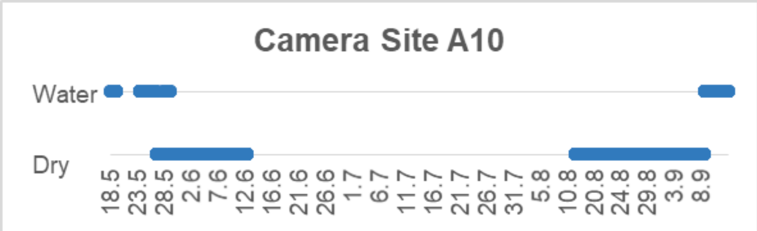

Camera Site A7
Water
Dry
22.5 26.5 30.5 4.6 9.6 14.6 19.6 23.6 28.6 3.7 8.7 13.7 17.7 22.7 27.7 1.8 6.8 10.8 20.8 25.8 30.8 3.9 8.9

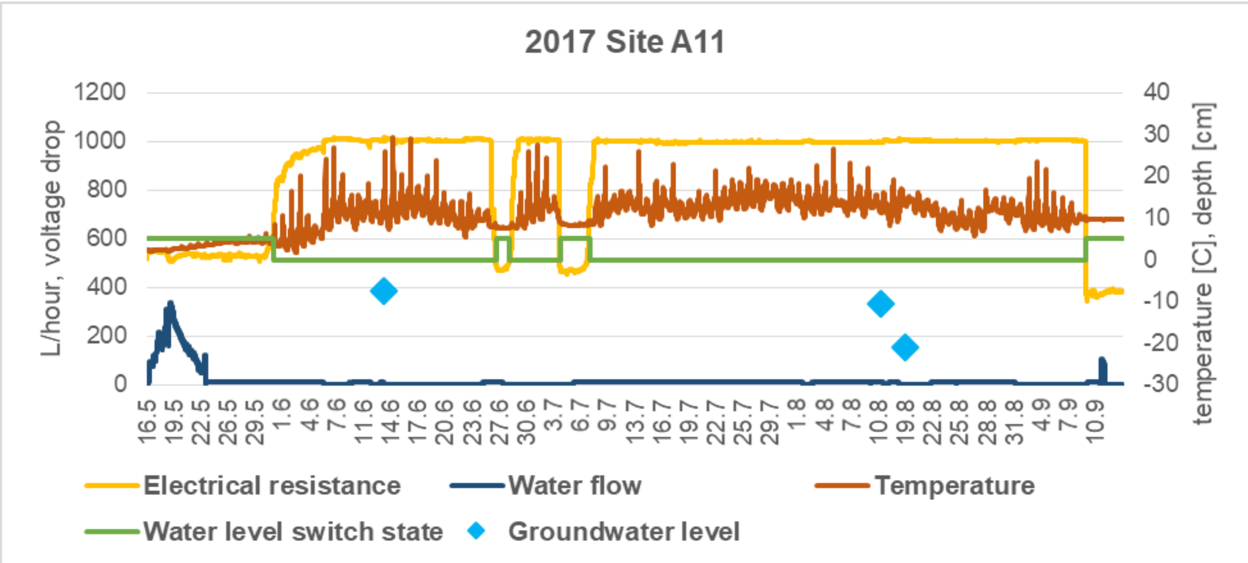

2017 Site A8
L/hour, voltage drop
0 100 200 300 400 500 600 700
temperature [C], depth [cm]
0 5 10 15 20 25 30 35
18.5 24.5 27.5 30.5 2.6 5.6 8.6 11.6 14.6 17.6 19.6 22.6 25.6 28.6 1.7 4.7 7.7 10.7 13.7 16.7 19.7 22.7 25.7 28.7 31.7 3.8 6.8 9.8 17.8 20.8 23.8 26.8 29.8 1.9 4.9 7.9 10.9
Electrical resistance
Water flow
Temperature
Water level switch state
Groundwater level

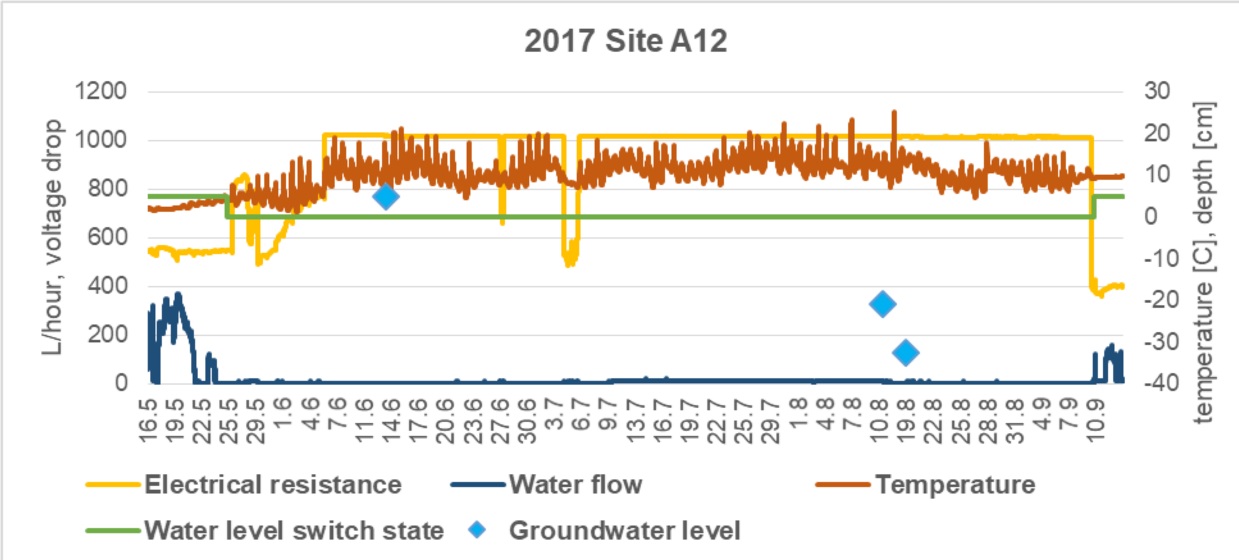

Camera Site A8
Water
Dry
18.5 25.5 30.5 4.6 9.6 14.6 18.6 23.6 28.6 3.7 8.7 12.7 17.7 22.7 27.7 1.8 5.8 10.8 20.8 25.8 30.8 3.9 8.9

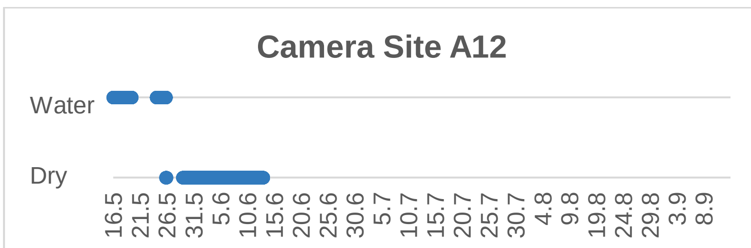

Camera Site A9
Water
Dry
17.5 22.5 27.5 1.6 6.6 11.6 16.6 21.6 26.6 1.7 6.7 11.7 16.7 20.7 25.7 30.7 4.8 9.8 19.8 24.8 29.8 3.9 8.9


2017 Site A10
L/hour, voltage drop
temperature [C], depth [cm]
Electrical resistance
Water flow
Temperature
Water level switch state
Groundwater level

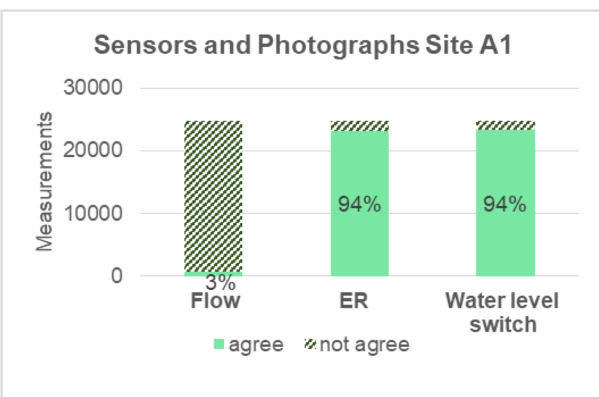

Camera Site A10
Water
Dry

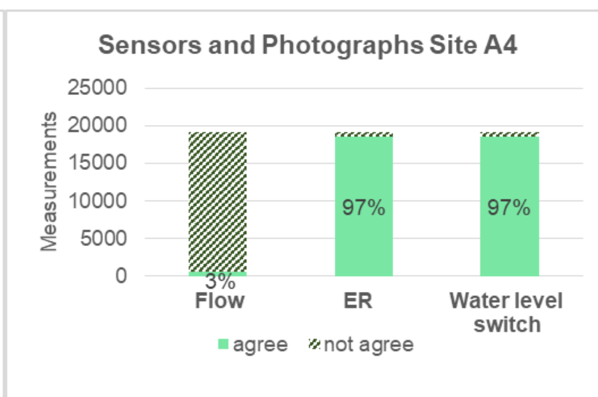

2017 Site A11
L/hour, voltage drop
temperature [C], depth [cm]
Electrical resistance
Water flow
Temperature
Water level switch state
Groundwater level

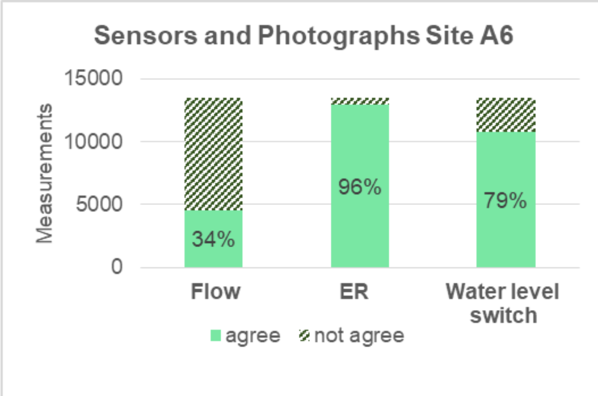


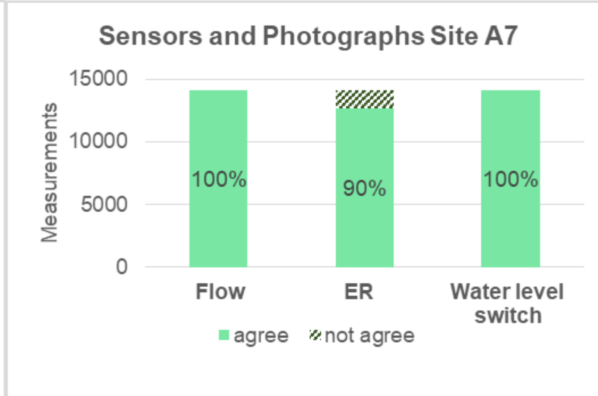


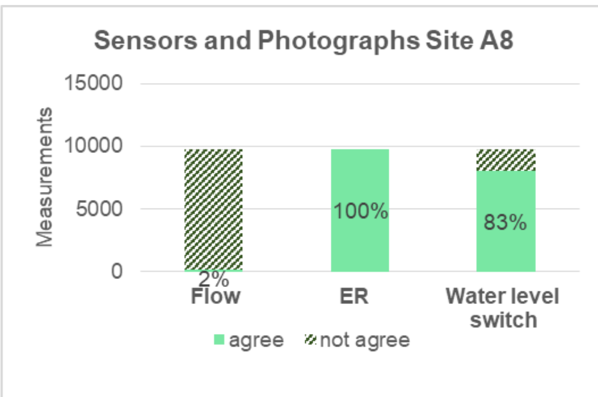
9.2. Agreement of sensors and photographs

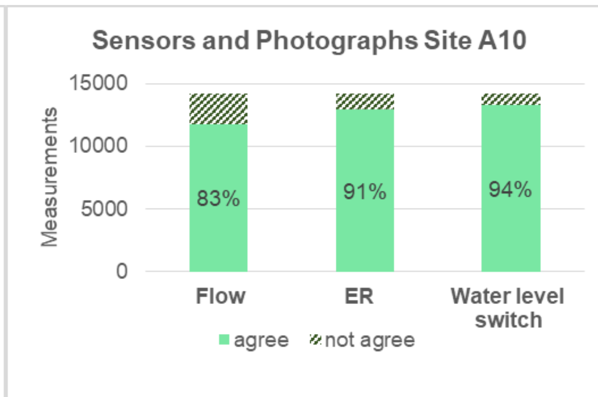


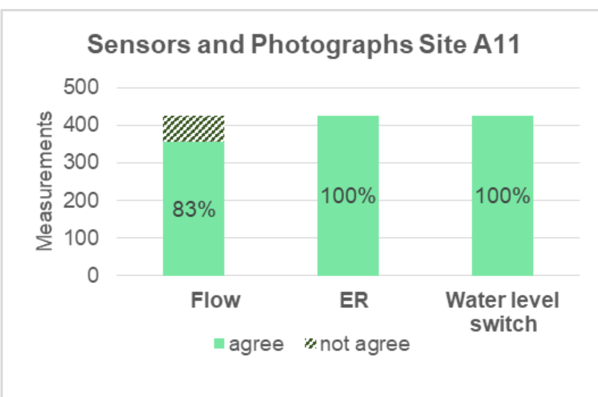


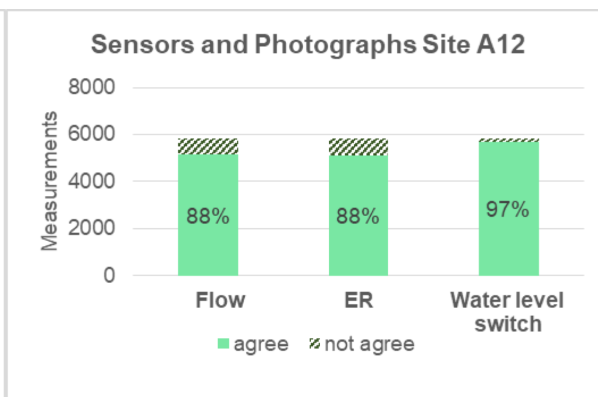

Sensors and Photographs Site A6
15000
10000
5000
0
Measurements
34%
96%
79%
Flow
ER
Water level switch
agree
not agree


Sensors and Photographs Site A7
15000
10000
5000
0
Measurements
100%
90%
100%
Flow
ER
Water level switch
agree
not agree

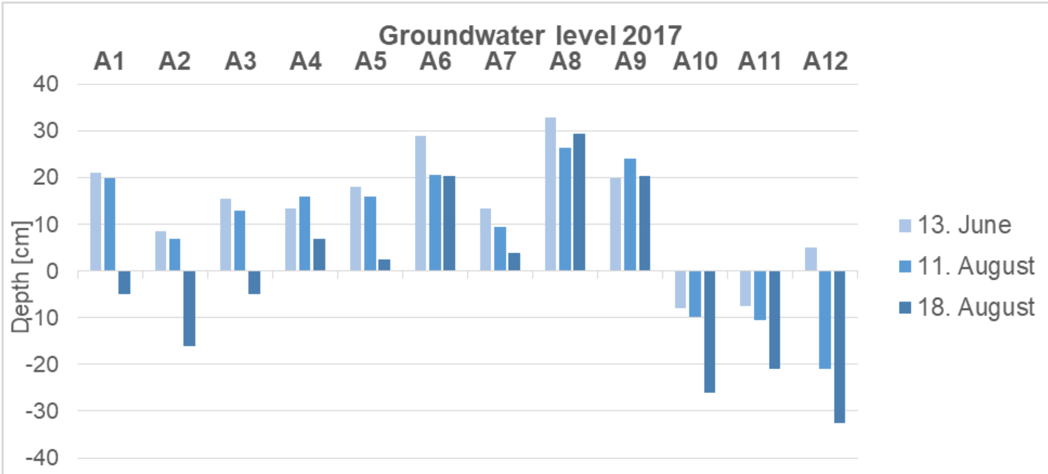

Sensors and Photographs Site A8
15000
10000
5000
0
Measurements
2%
100%
83%
Flow
ER
Water level switch
agree
not agree


Sensors and Photographs Site A10
15000
10000
5000
0
Measurements
83%
91%
94%
Flow
ER
Water level switch
agree
not agree

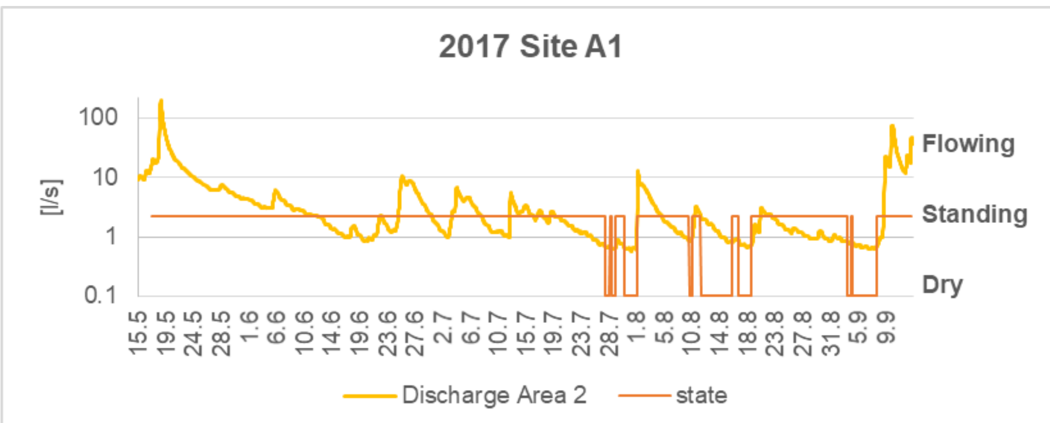

Sensors and Photographs Site A11
500
400
300
200
100
0
Measurements
83%
100%
100%
Flow
ER
Water level switch
agree
not agree

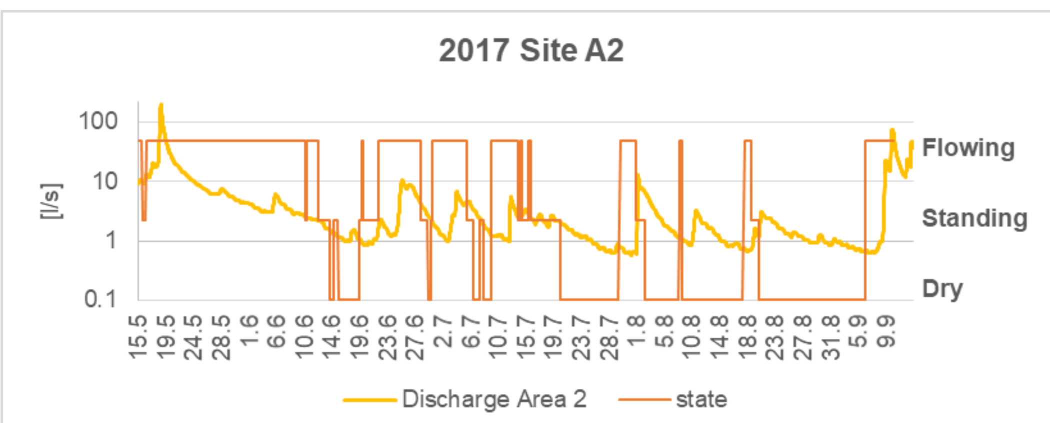

Sensors and Photographs Site A12
8000
6000
4000
2000
0
Measurements
88%
88%
97%
Flow
ER
Water level switch
agree
not agree

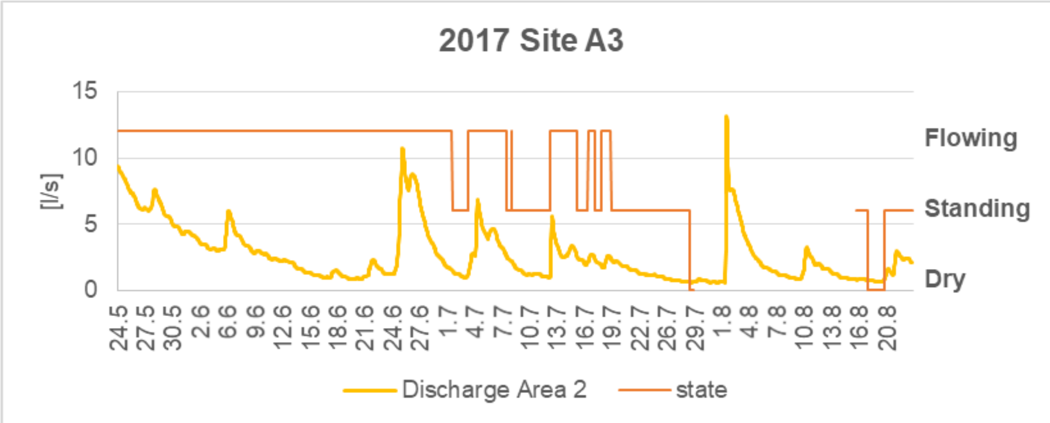
9.3. Groundwater wells

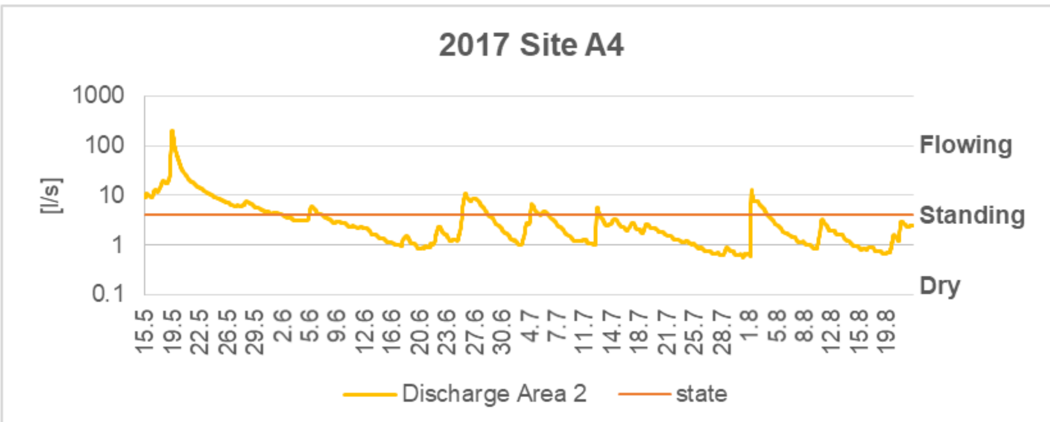


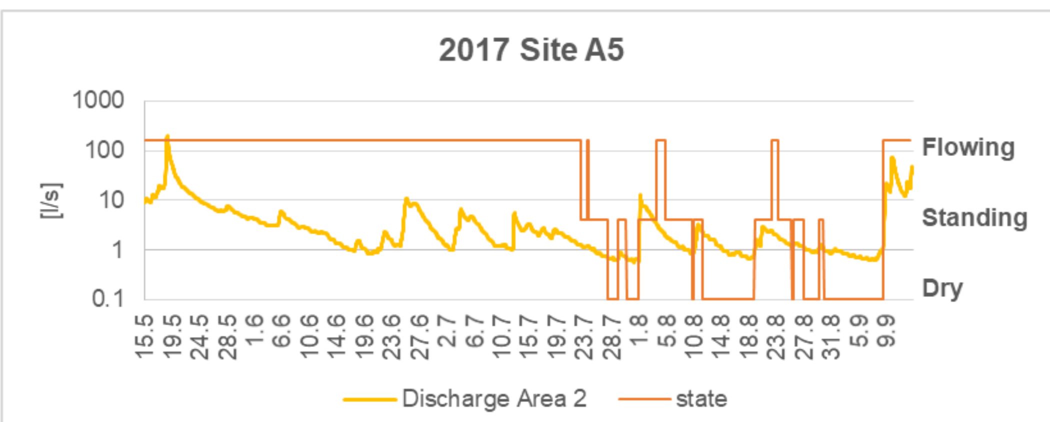
9.4. Relation to discharge

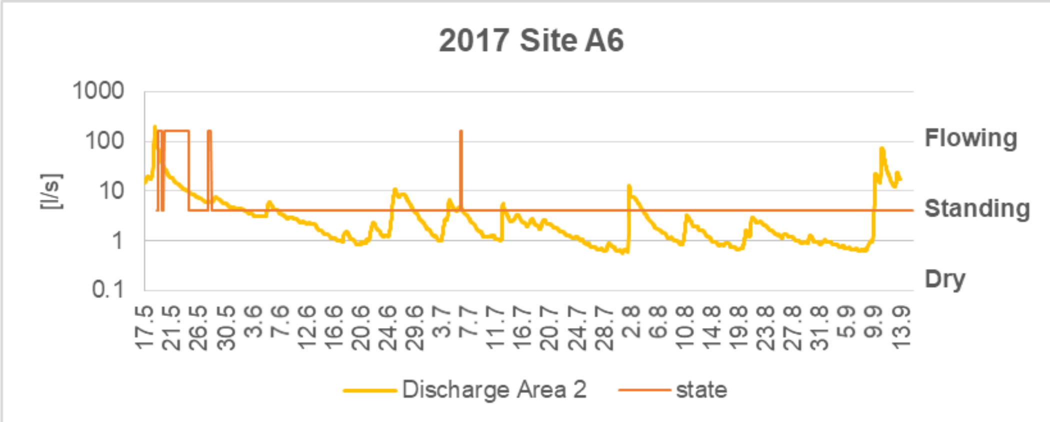


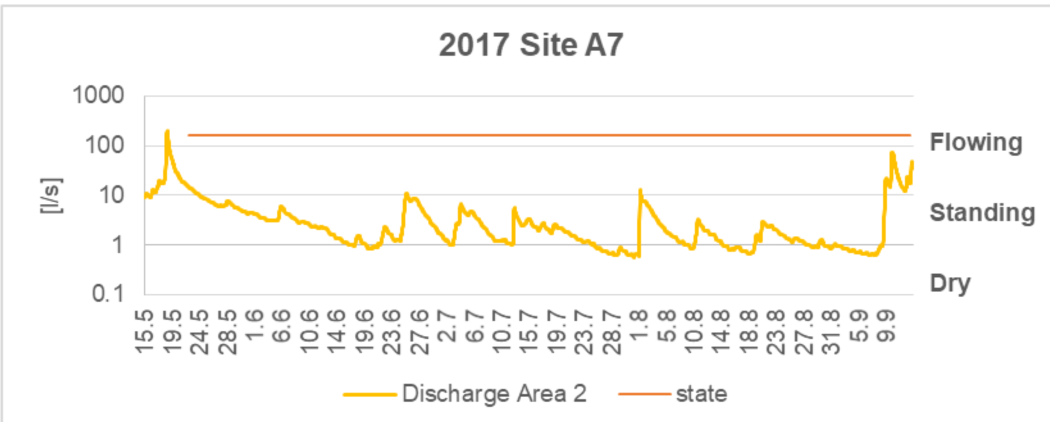


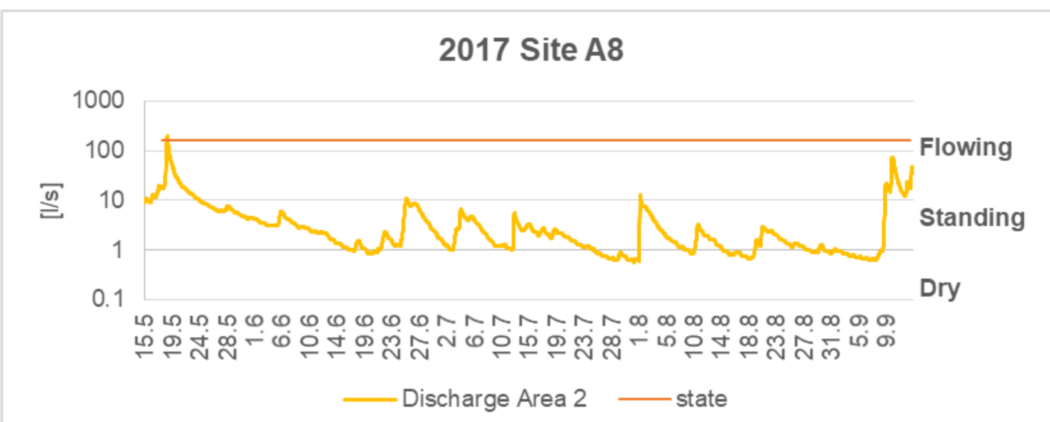

2017 Site A3
15
10
5
0
[l/s]
Flowing
Standing
Dry
24.5 27.5 30.5 2.6 6.6 9.6 12.6 15.6 18.6 21.6 24.6 27.6 1.7 4.7 7.7 10.7 13.7 16.7 19.7 22.7 26.7 29.7 1.8 4.8 7.8 10.8 13.8 16.8 20.8
Discharge Area 2
state


2017 Site A4
1000
100
10
1
0.1
[l/s]
Flowing
Standing
Dry
15.5 19.5 22.5 26.5 29.5 2.6 5.6 9.6 12.6 16.6 20.6 23.6 27.6 30.6 4.7 7.7 11.7 14.7 18.7 21.7 25.7 28.7 1.8 5.8 8.8 12.8 15.8 19.8
Discharge Area 2
state

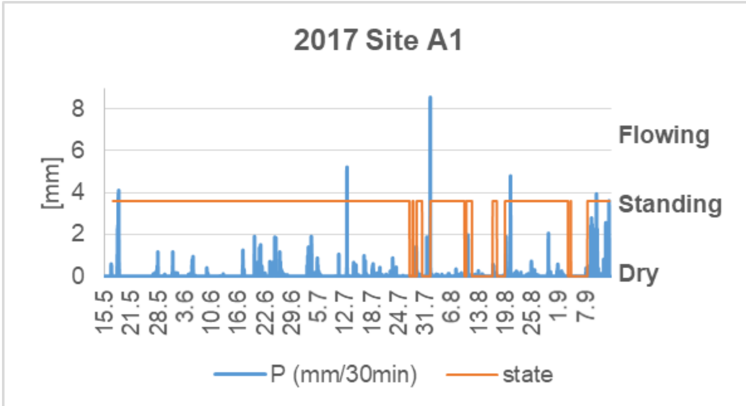

2017 Site A5
1000
100
10
1
0.1
[l/s]
Flowing
Standing
Dry
15.5 19.5 24.5 28.5 1.6 6.6 10.6 14.6 19.6 23.6 27.6 2.7 6.7 10.7 15.7 19.7 23.7 28.7 1.8 5.8 10.8 14.8 18.8 23.8 27.8 31.8 5.9 9.9
Discharge Area 2
state

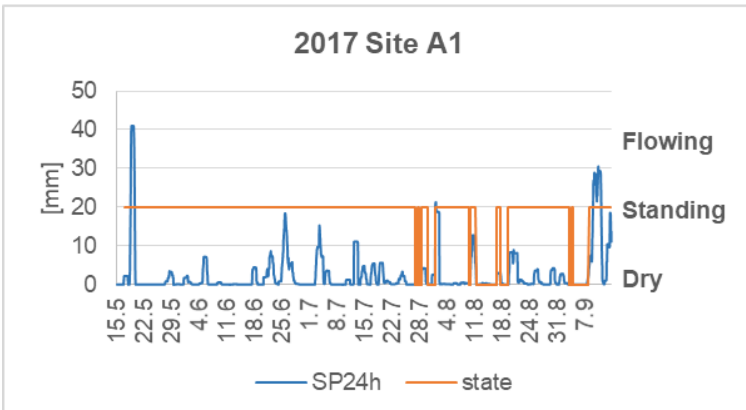

2017 Site A6
1000
100
10
1
0.1
[l/s]
Flowing
Standing
Dry
17.5
21.5
26.5
30.5
3.6
7.6
12.6
16.6
20.6
24.6
29.6
3.7
7.7
11.7
16.7
20.7
24.7
28.7
2.8
6.8
10.8
14.8
19.8
23.8
27.8
31.8
5.9
9.9
13.9
Discharge Area 2
state

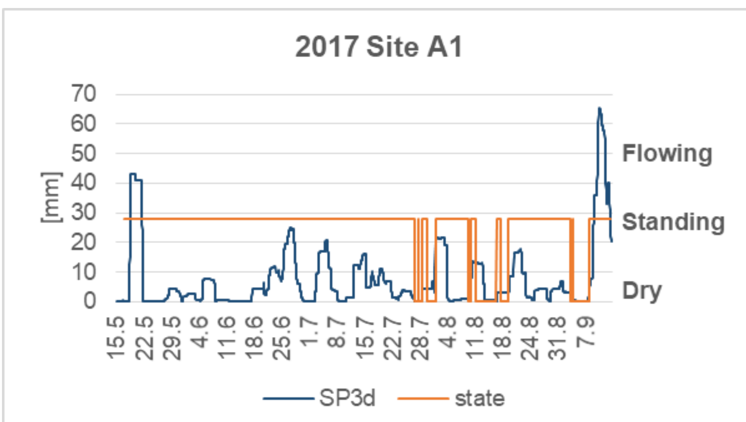

2017 Site A7
1000
100
10
1
0.1
[l/s]
Flowing
Standing
Dry
15.5
19.5
24.5
28.5
1.6
6.6
10.6
14.6
19.6
23.6
27.6
2.7
6.7
10.7
15.7
19.7
23.7
28.7
1.8
5.8
10.8
14.8
18.8
23.8
27.8
31.8
5.9
9.9
Discharge Area 2
state

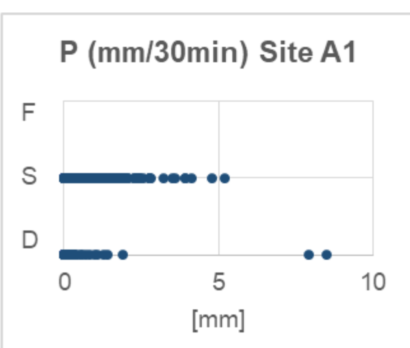

2017 Site A8
1000
100
10
1
0.1
[l/s]
Flowing
Standing
Dry
15.5
19.5
24.5
28.5
1.6
6.6
10.6
14.6
19.6
23.6
27.6
2.7
6.7
10.7
15.7
19.7
23.7
28.7
1.8
5.8
10.8
14.8
18.8
23.8
27.8
31.8
5.9
9.9
Discharge Area 2
state

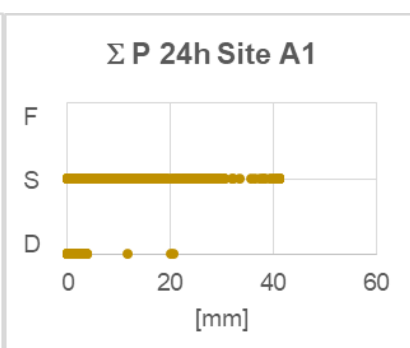
9.5. Relation to precipitation

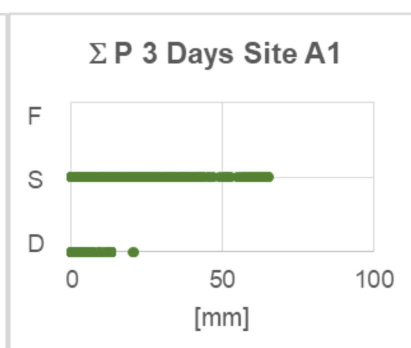


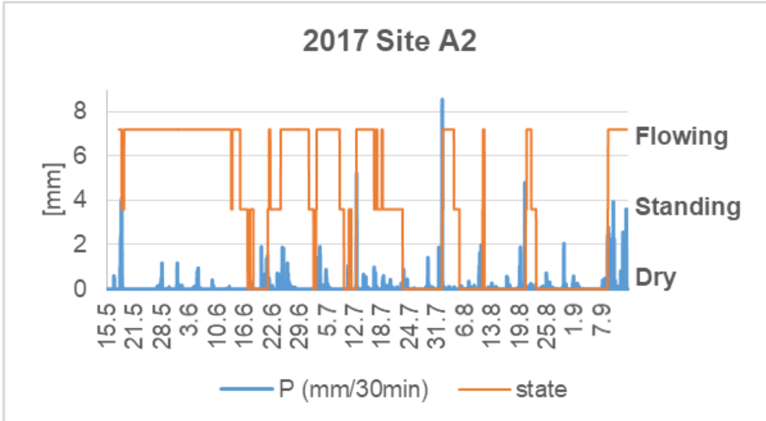


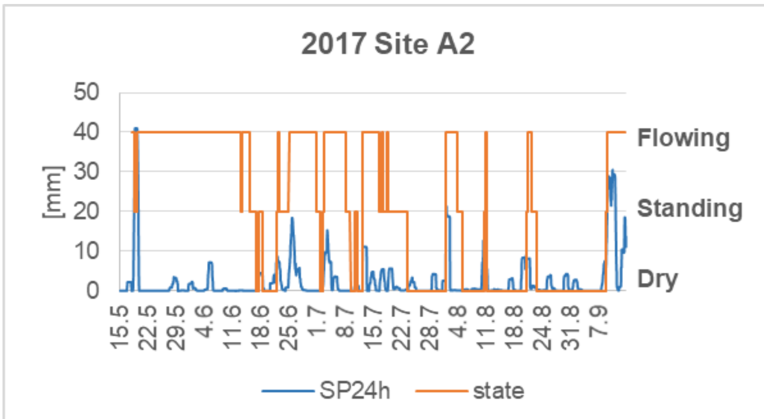


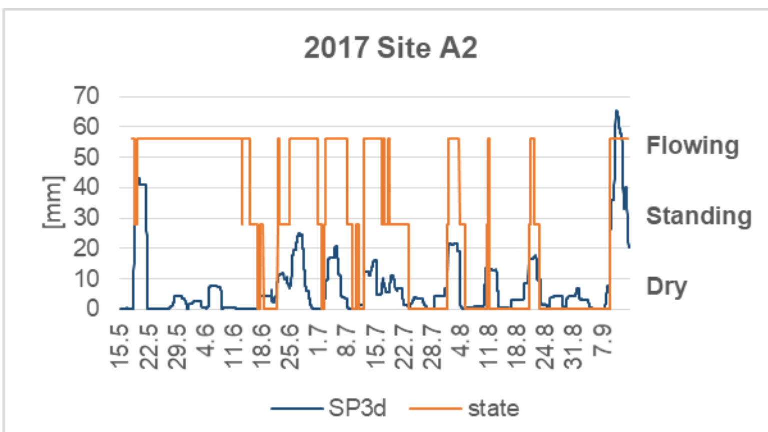


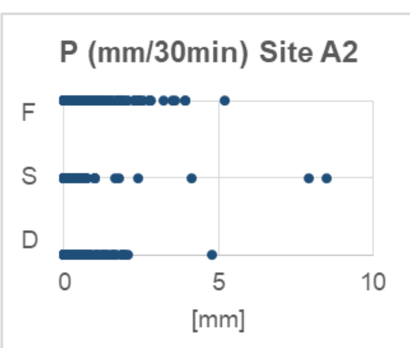


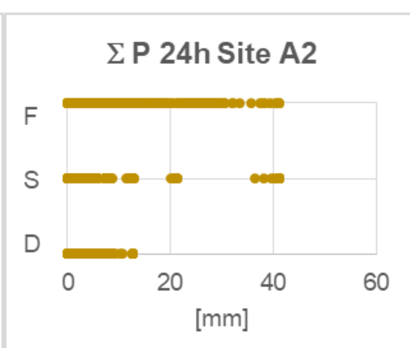



2017 Site A2
[mm]
0
2
4
6
8
Flowing
Standing
Dry
15.5 21.5 28.5 3.6 10.6 16.6 22.6 29.6 5.7 12.7 18.7 24.7 31.7 6.8 13.8 19.8 25.8 1.9 7.9
P (mm/30min)
state


2017 Site A2
[mm]
0
10
20
30
40
50
Flowing
Standing
Dry
15.5 22.5 29.5 4.6 11.6 18.6 25.6 1.7 8.7 15.7 22.7 28.7 4.8 11.8 18.8 24.8 31.8 7.9
SP24h
state


2017 Site A2
[mm]
0
10
20
30
40
50
60
70
Flowing
Standing
Dry
15.5 22.5 29.5 4.6 11.6 18.6 25.6 1.7 8.7 15.7 22.7 28.7 4.8 11.8 18.8 24.8 31.8 7.9
SP3d
state


P (mm/30min) Site A2
F
S
D
0
5
10
[mm]


Σ P 24h Site A2
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S
D
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20
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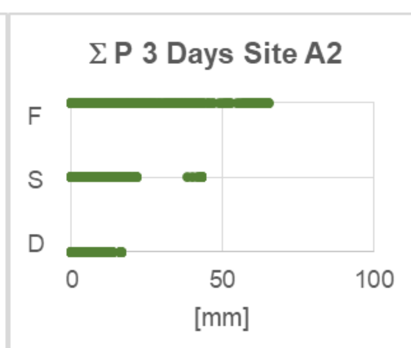
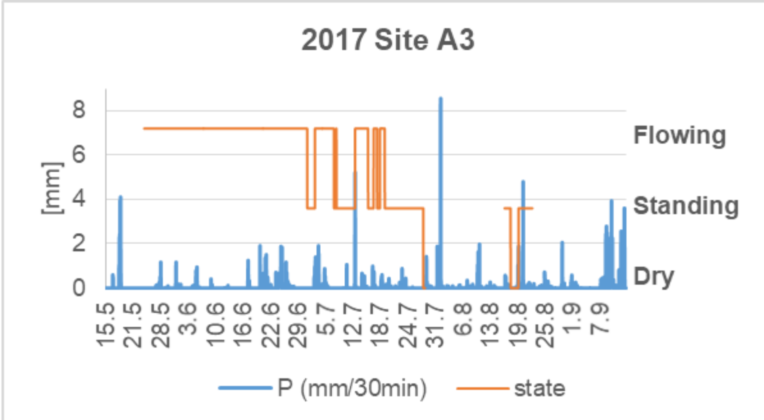
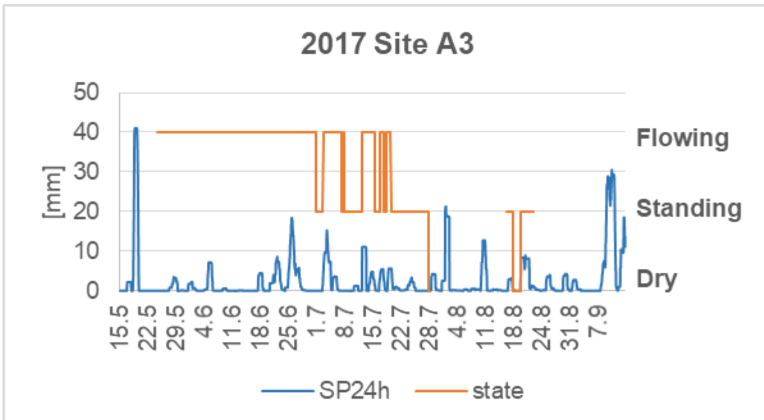
60
[mm]


Σ P 3 Days Site A2
F
S
D
0
50
100
[mm]


2017 Site A3
[mm]
8
6
4
2
0
Flowing
Standing
Dry
15.5
21.5
28.5
3.6
10.6
16.6
22.6
29.6
5.7
12.7
18.7
24.7
31.7
6.8
13.8
19.8
25.8
1.9
7.9
P (mm/30min)
state


2017 Site A3
[mm]
50
40
30
20
10
0
Flowing
Standing
Dry
15.5
22.5
29.5
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11.6
18.6
25.6
1.7
8.7
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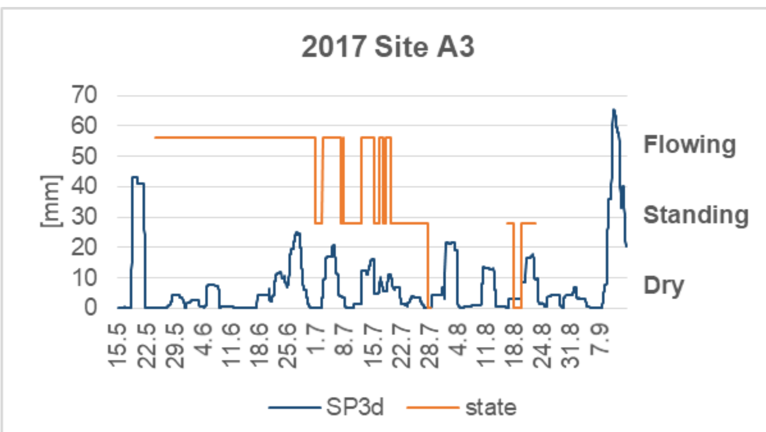
28.7
4.8
11.8
18.8
24.8
31.8
7.9
SP24h
state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[mm]
70
60
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40
30
20
10
0
Flowing
Standing
Dry
15.5
22.5
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4.6
11.6
18.6
25.6
1.7
8.7
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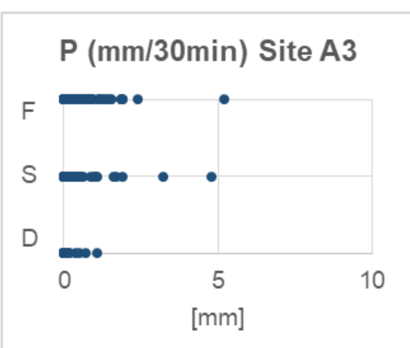
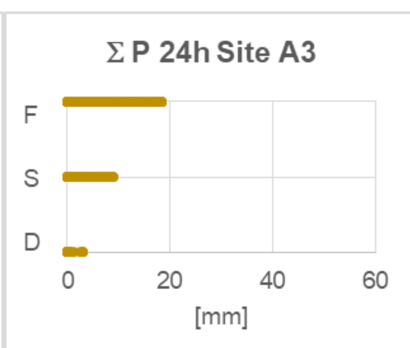
22.7
28.7
4.8
11.8
18.8
24.8
31.8
7.9
SP3d
state


P (mm/30min) Site A3
F
S
D
0
5
10
[mm]


Σ P 24h Site A3
F
S
D
0
20
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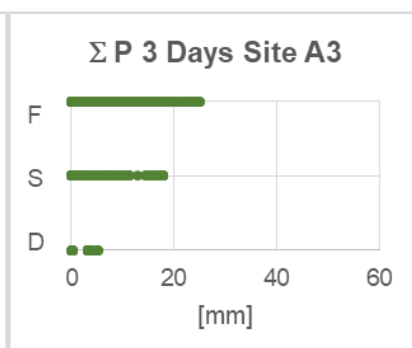
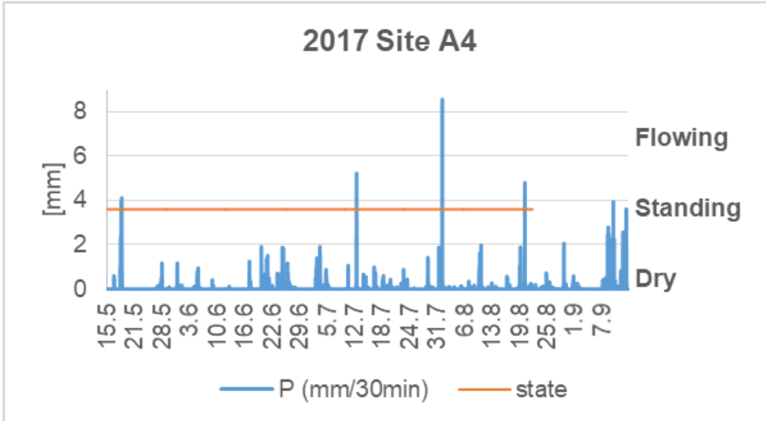
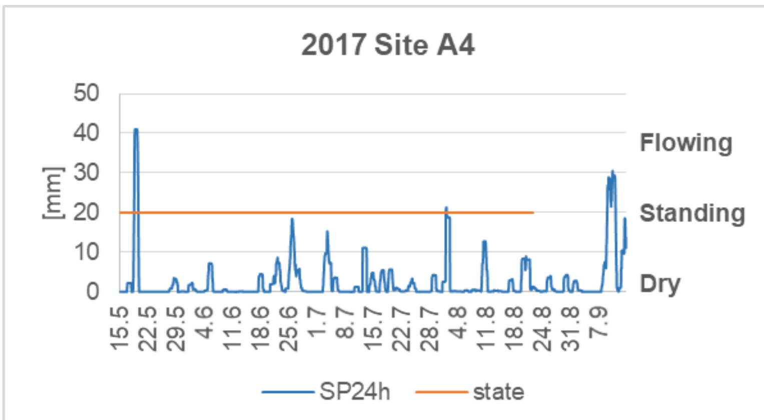
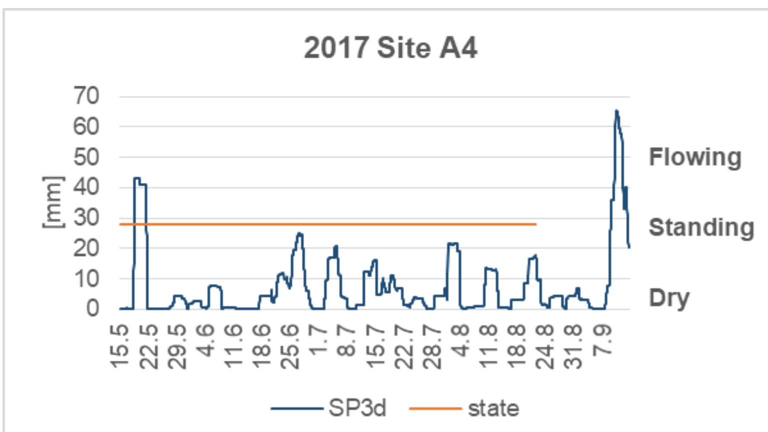
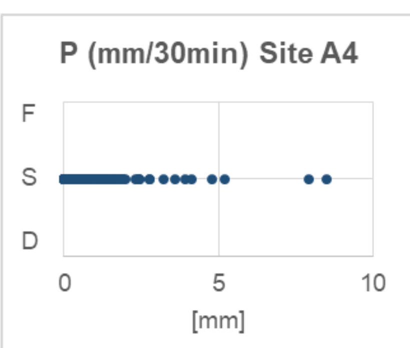
60
[mm]

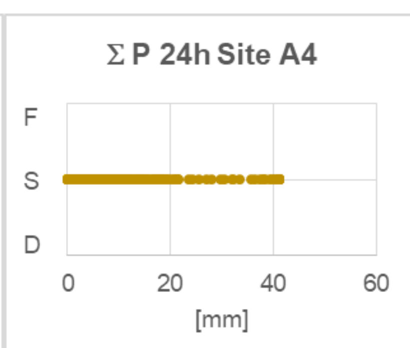

Σ P 3 Days Site A3
F
S
D
0
20
40
60
[mm]

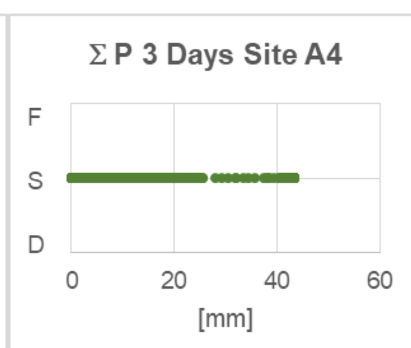

2017 Site A4
[mm]
0
2
4
6
8
Flowing
Standing
Dry
15.5 21.5 28.5 3.6 10.6 16.6 22.6 29.6 5.7 12.7 18.7 24.7 31.7 6.8 13.8 19.8 25.8 1.9 7.9
P (mm/30min)
state

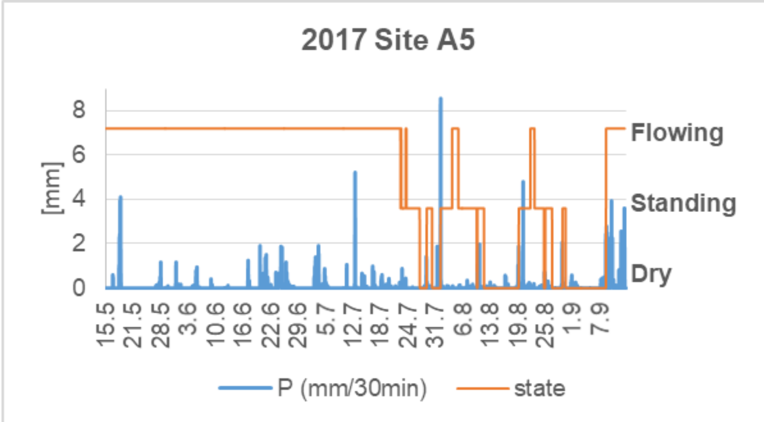

2017 Site A4
[mm]
0
10
20
30
40
50
Flowing
Standing
Dry
15.5 22.5 29.5 4.6 11.6 18.6 25.6 1.7 8.7 15.7 22.7 28.7 4.8 11.8 18.8 24.8 31.8 7.9
SP24h
state

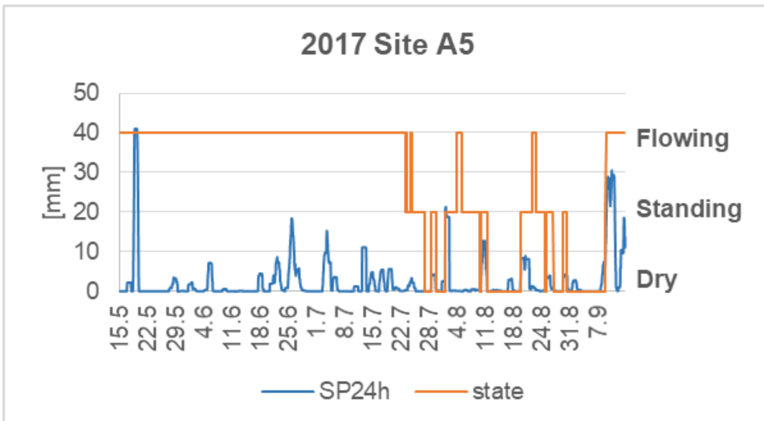

2017 Site A4
[mm]
0
10
20
30
40
50
60
70
Flowing
Standing
Dry
15.5 22.5 29.5 4.6 11.6 18.6 25.6 1.7 8.7 15.7 22.7 28.7 4.8 11.8 18.8 24.8 31.8 7.9
SP3d
state


P (mm/30min) Site A4
F
S
D
0
5
10
[mm]


Σ P 24h Site A4
F
S
D
0
20
40
60
[mm]


Σ P 3 Days Site A4
F
S
D
0
20
40
60
[mm]


2017 Site A5
[mm]
8
6
4
2
0
Flowing
Standing
Dry
15.5
21.5
28.5
3.6
10.6
16.6
22.6
29.6
5.7
12.7
18.7
24.7
31.7
6.8
13.8
19.8
25.8
1.9
7.9
P (mm/30min)
state


2017 Site A5
[mm]
50
40
30
20
10
0
Flowing
Standing
Dry
15.5
22.5
29.5
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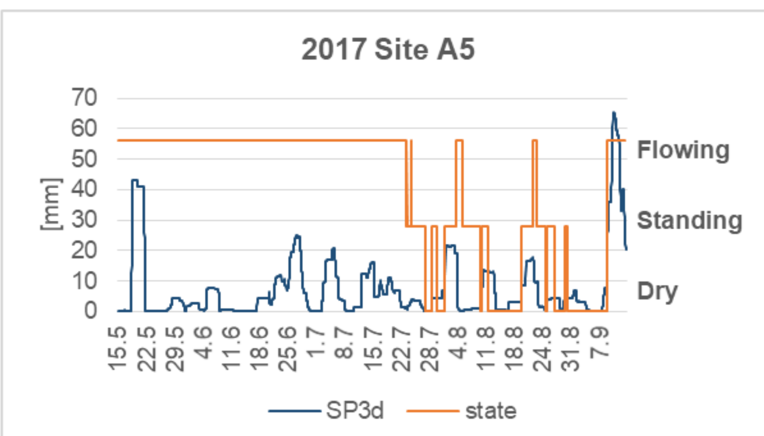
11.6
18.6
25.6
1.7
8.7
15.7
22.7
28.7
4.8
11.8
18.8
24.8
31.8
7.9
SP24h
state


2017 Site A5
[mm]
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60
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30
20
10
0
Flowing
Standing
Dry
15.5
22.5
29.5
4.6
11.6
18.6
25.6
1.7
8.7
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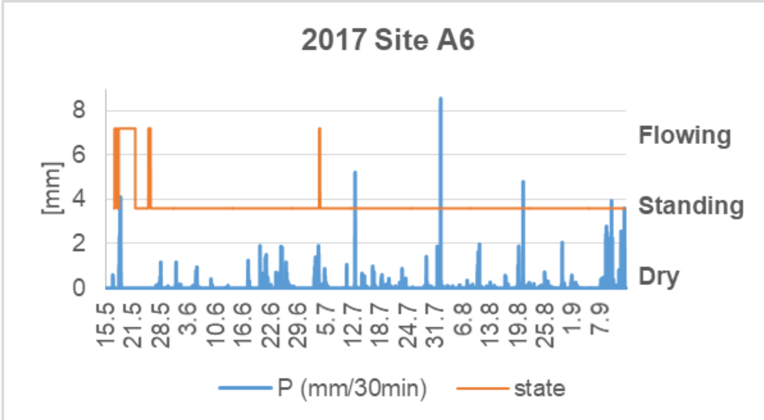
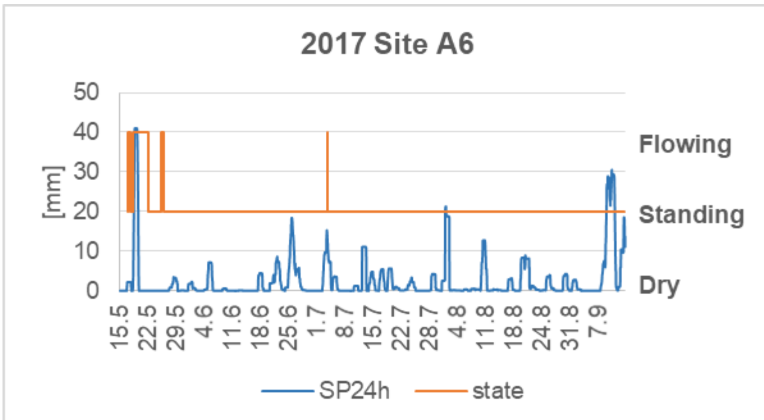
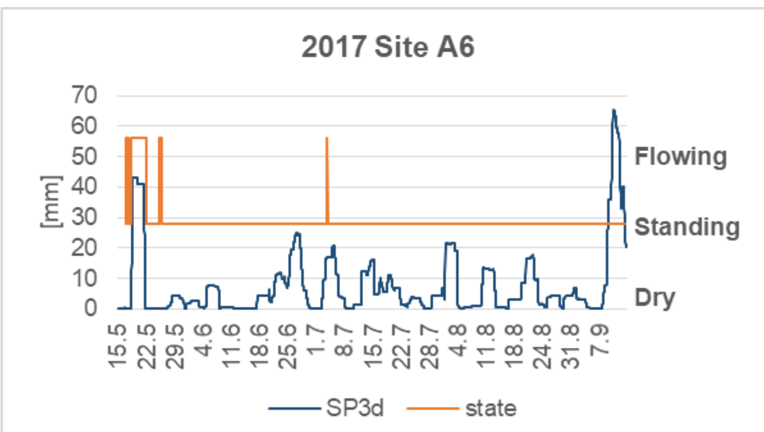
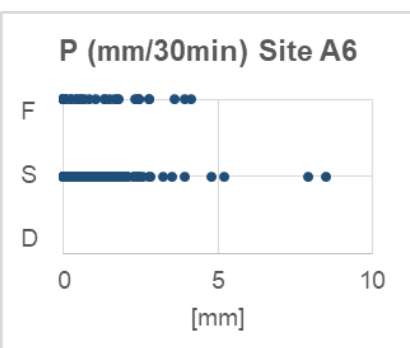
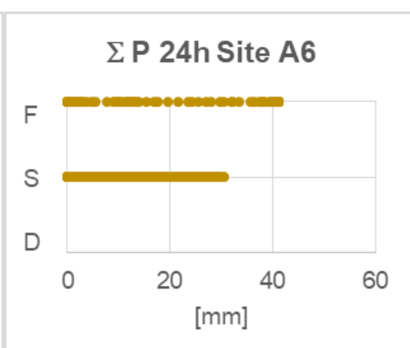
22.7
28.7
4.8
11.8
18.8
24.8
31.8
7.9
SP3d
state

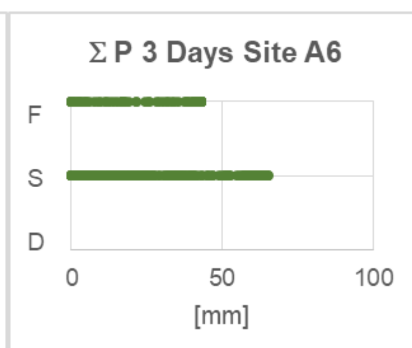

2017 Site A6
[mm]
8
6
4
2
0
Flowing
Standing
Dry
15.5
21.5
28.5
3.6
10.6
16.6
22.6
29.6
5.7
12.7
18.7
24.7
31.7
6.8
13.8
19.8
25.8
1.9
7.9
P (mm/30min)
state

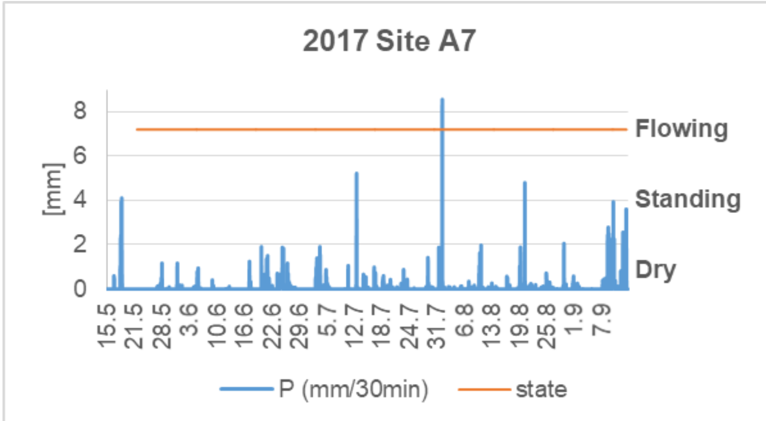

2017 Site A6
[mm]
50
40
30
20
10
0
Flowing
Standing
Dry
15.5
22.5
29.5
4.6
11.6
18.6
25.6
1.7
8.7
15.7
22.7
28.7
4.8
11.8
18.8
24.8
31.8
7.9
SP24h
state

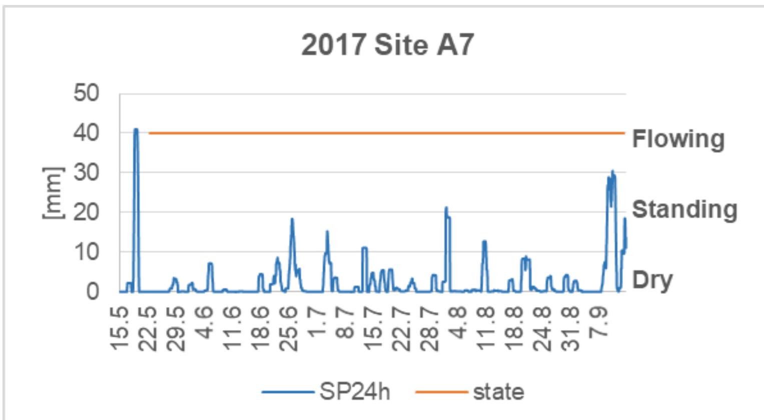

2017 Site A6
[mm]
70
60
50
40
30
20
10
0
Flowing
Standing
Dry
15.5
22.5
29.5
4.6
11.6
18.6
25.6
1.7
8.7
15.7
22.7
28.7
4.8
11.8
18.8
24.8
31.8
7.9
SP3d
state

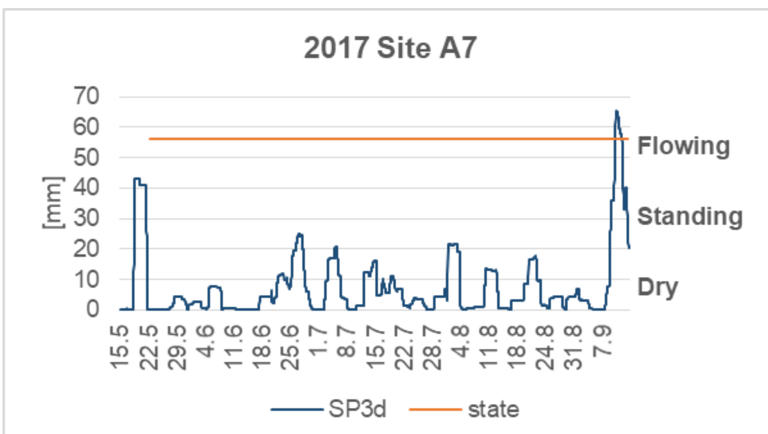

P (mm/30min) Site A6
F
S
D
0
5
10
[mm]

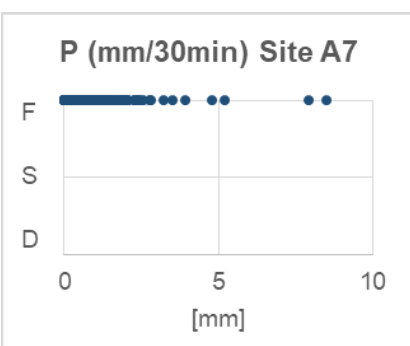

Σ P 24h Site A6
F
S
D
0
20
40
60
[mm]

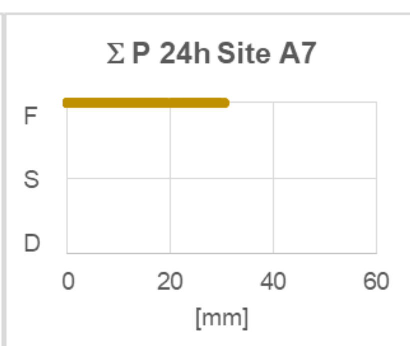

Σ P 3 Days Site A6
F
S
D
0
50
100
[mm]

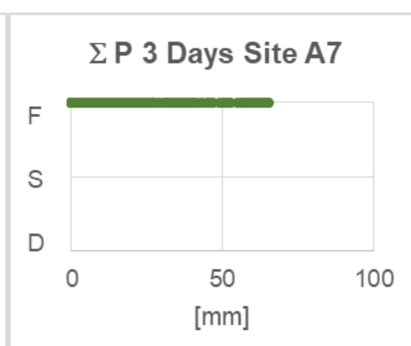

2017 Site A7
[mm]
Flowing
Standing
Dry
P (mm/30min)
state

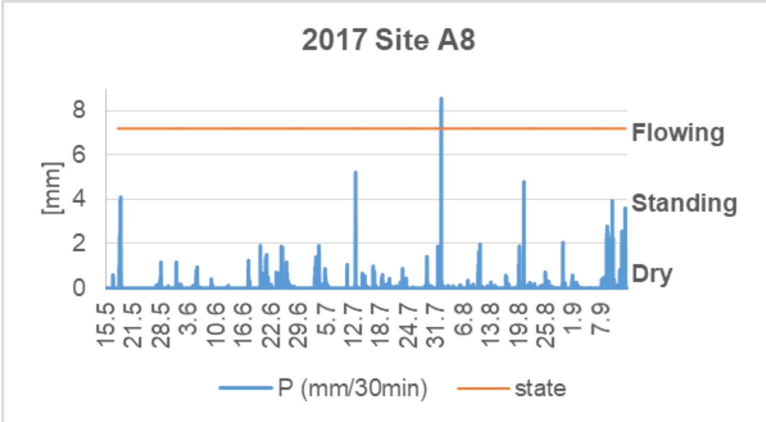

2017 Site A7
[mm]
Flowing
Standing
Dry
SP24h
state

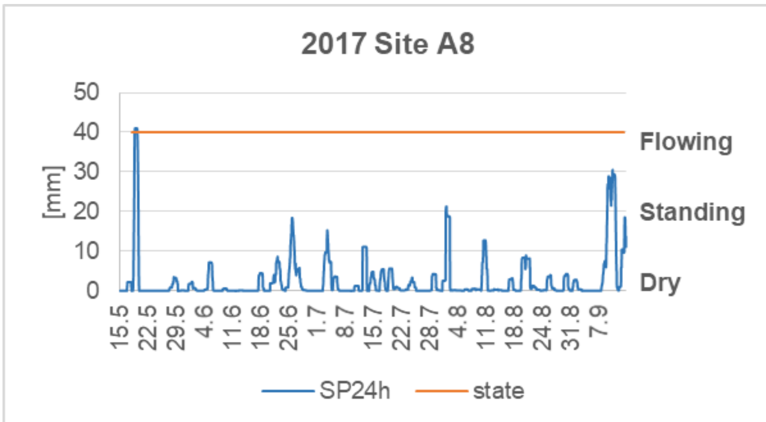

2017 Site A7
[mm]
Flowing
Standing
Dry
SP3d
state

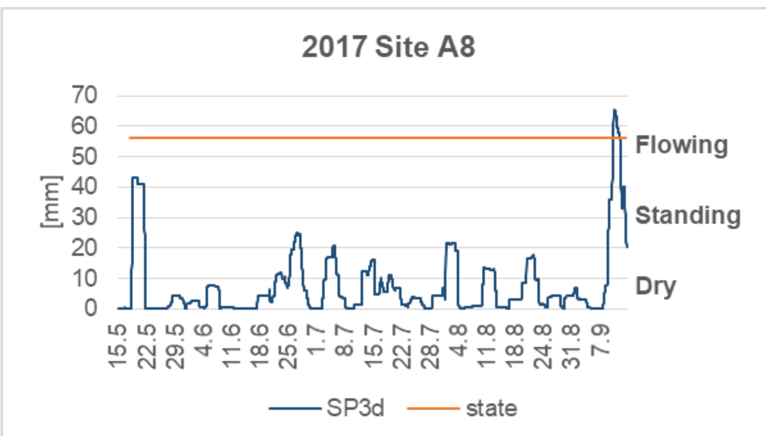

P (mm/30min) Site A7
F
S
D
[mm]

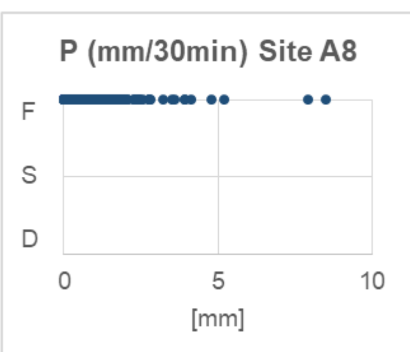

Σ P 24h Site A7
F
S
D
[mm]

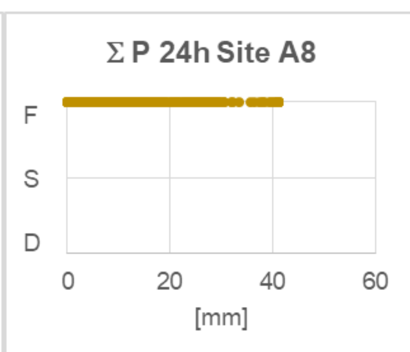

Σ P 3 Days Site A7
F
S
D
[mm]

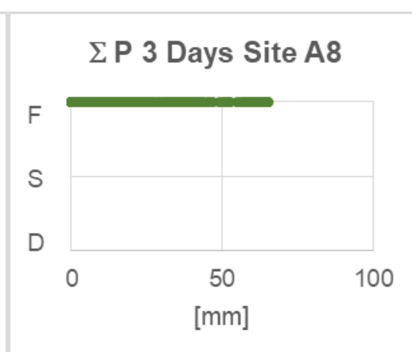

2017 Site A8
[mm]
8
6
4
2
0
Flowing
Standing
Dry
15.5 21.5 28.5 3.6 10.6 16.6 22.6 29.6 5.7 12.7 18.7 24.7 31.7 6.8 13.8 19.8 25.8 1.9 7.9
P (mm/30min)
state

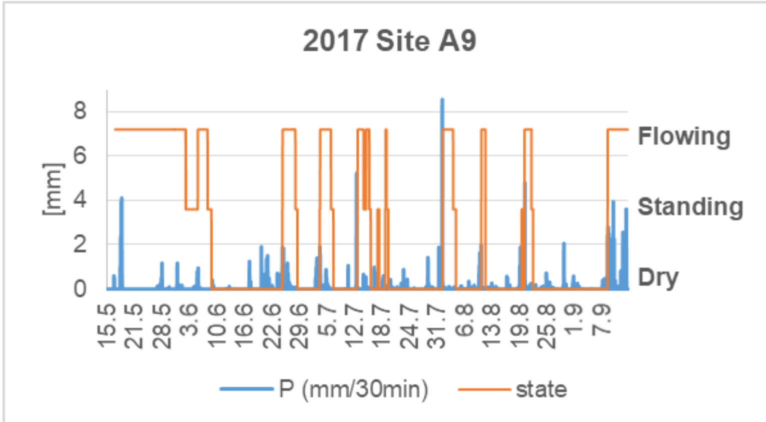

2017 Site A8
[mm]
50
40
30
20
10
0
Flowing
Standing
Dry
15.5 22.5 29.5 4.6 11.6 18.6 25.6 1.7 8.7 15.7 22.7 28.7 4.8 11.8 18.8 24.8 31.8 7.9
SP24h
state

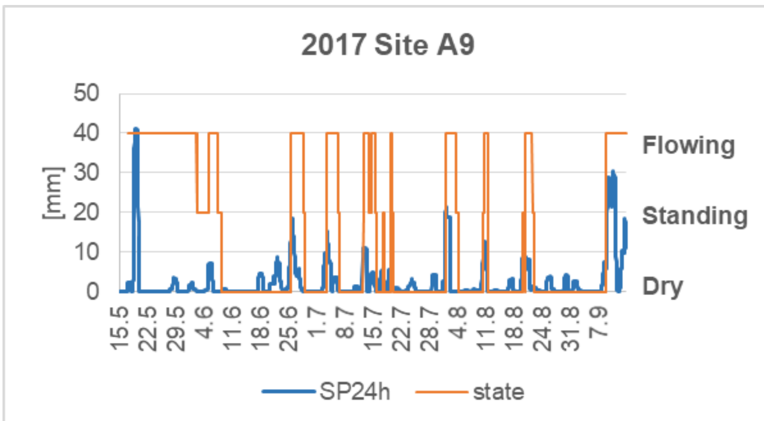

2017 Site A8
[mm]
70
60
50
40
30
20
10
0
Flowing
Standing
Dry
15.5 22.5 29.5 4.6 11.6 18.6 25.6 1.7 8.7 15.7 22.7 28.7 4.8 11.8 18.8 24.8 31.8 7.9
SP3d
state

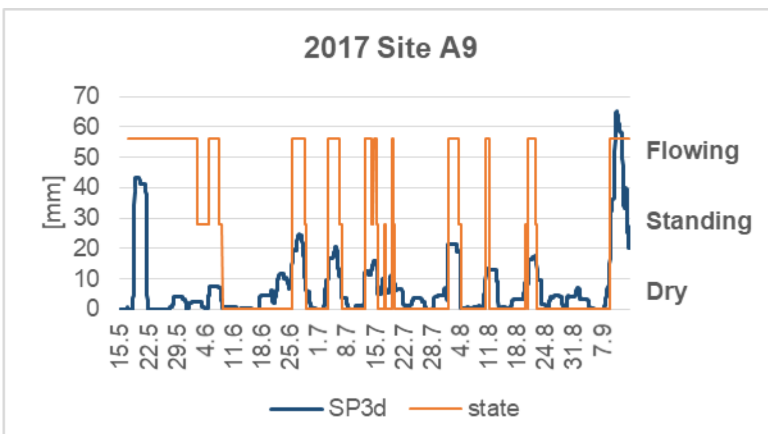

P (mm/30min) Site A8
F
S
D
0
5
10
[mm]

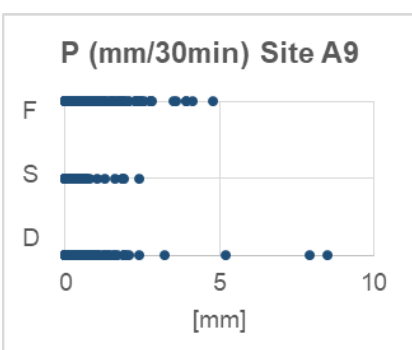

Σ P 24h Site A8
F
S
D
0
20
40
60
[mm]

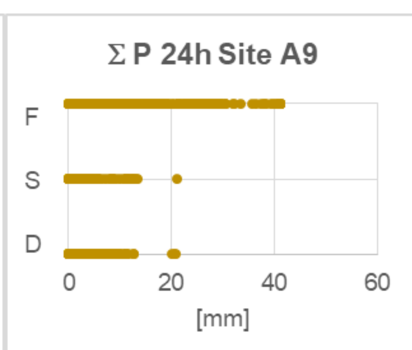

Σ P 3 Days Site A8
F
S
D
0
50
100
[mm]

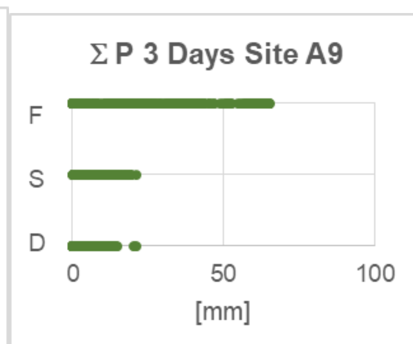

2017 Site A9
[mm]
8
6
4
2
0
Flowing
Standing
Dry
15.5
21.5
28.5
3.6
10.6
16.6
22.6
29.6
5.7
12.7
18.7
24.7
31.7
6.8
13.8
19.8
25.8
1.9
7.9
P (mm/30min)
state

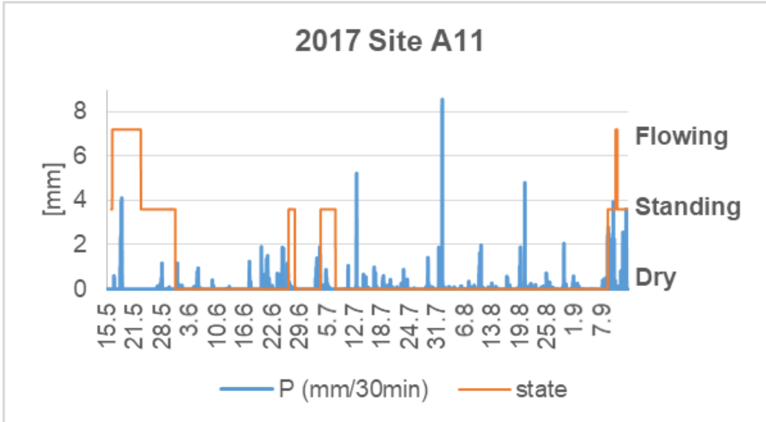

2017 Site A9
[mm]
50
40
30
20
10
0
Flowing
Standing
Dry
15.5
22.5
29.5
4.6
11.6
18.6
25.6
1.7
8.7
15.7
22.7
28.7
4.8
11.8
18.8
24.8
31.8
7.9
SP24h
state

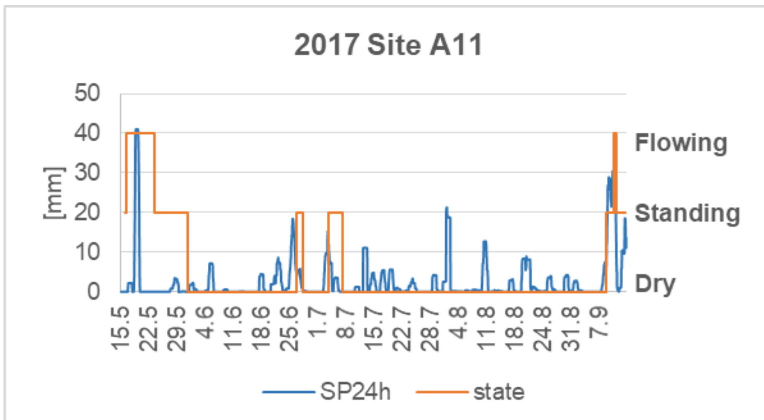

2017 Site A9
[mm]
70
60
50
40
30
20
10
0
Flowing
Standing
Dry
15.5
22.5
29.5
4.6
11.6
18.6
25.6
1.7
8.7
15.7
22.7
28.7
4.8
11.8
18.8
24.8
31.8
7.9
SP3d
state

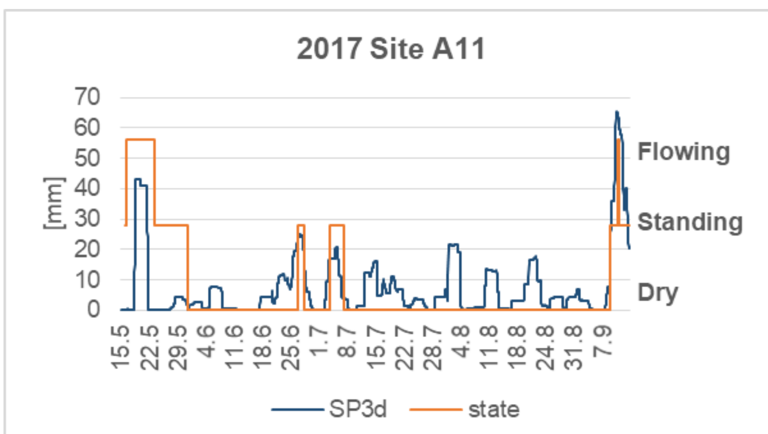

P (mm/30min) Site A9
F
S
D
0
5
10
[mm]

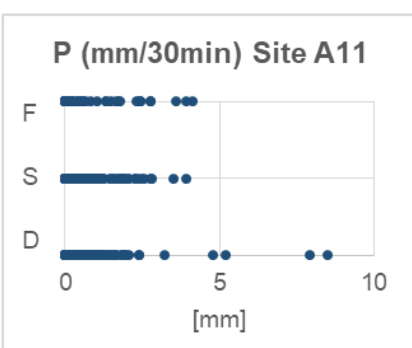

Σ P 24h Site A9
F
S
D
0
20
40
60
[mm]

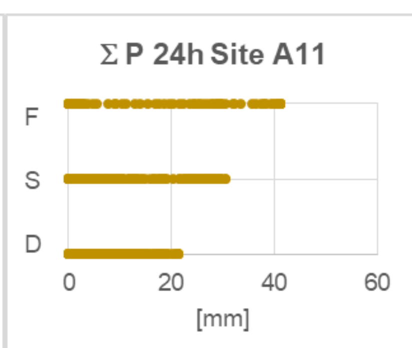

Σ P 3 Days Site A9
F
S
D
0
50
100
[mm]

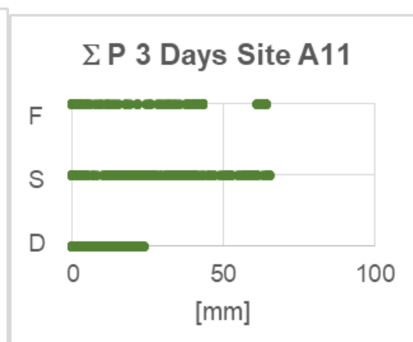

2017 Site A11
[mm]
8
6
4
2
0
Flowing
Standing
Dry
15.5 21.5 28.5 3.6 10.6 16.6 22.6 29.6 5.7 12.7 18.7 24.7 31.7 6.8 13.8 19.8 25.8 1.9 7.9
P (mm/30min)
state

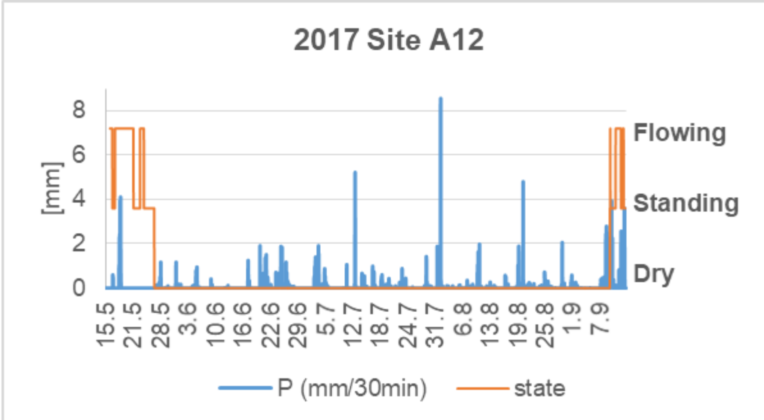

2017 Site A11
[mm]
50
40
30
20
10
0
Flowing
Standing
Dry
15.5 22.5 29.5 4.6 11.6 18.6 25.6 1.7 8.7 15.7 22.7 28.7 4.8 11.8 18.8 24.8 31.8 7.9
SP24h
state

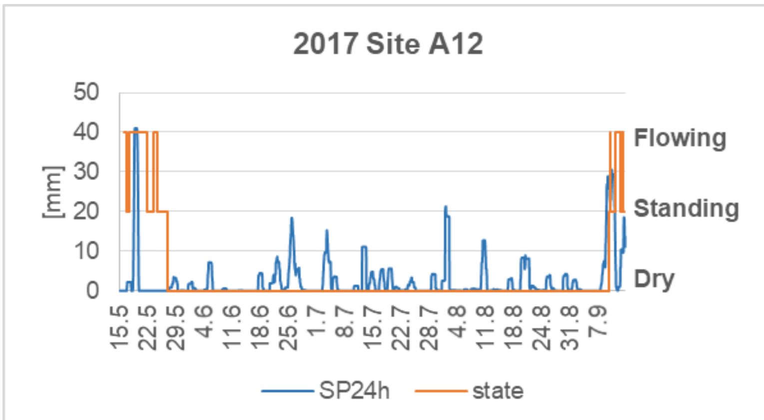

2017 Site A11
[mm]
70
60
50
40
30
20
10
0
Flowing
Standing
Dry
15.5 22.5 29.5 4.6 11.6 18.6 25.6 1.7 8.7 15.7 22.7 28.7 4.8 11.8 18.8 24.8 31.8 7.9
SP3d
state

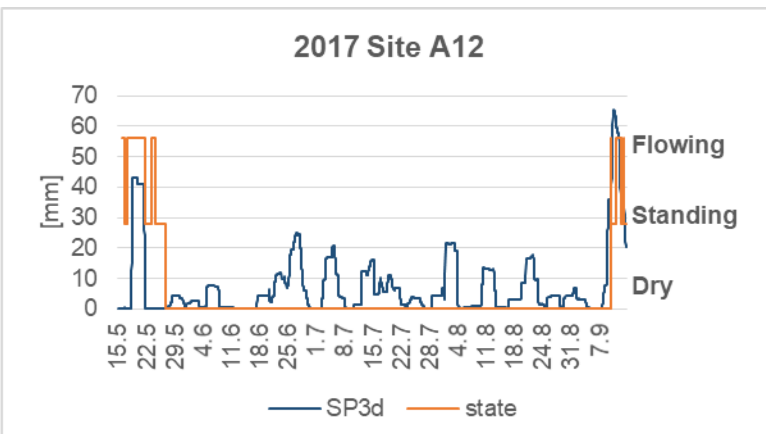

P (mm/30min) Site A11
F
S
D
0
5
10
[mm]

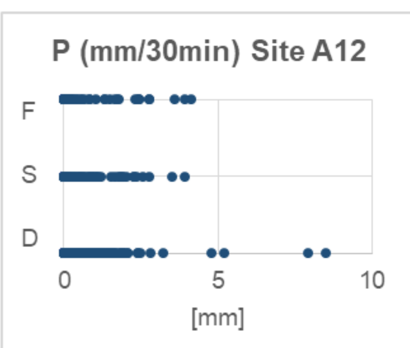

Σ P 24h Site A11
F
S
D
0
20
40
60
[mm]

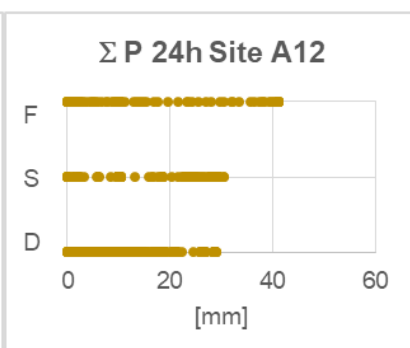

Σ P 3 Days Site A11
F
S
D
0
50
100
[mm]

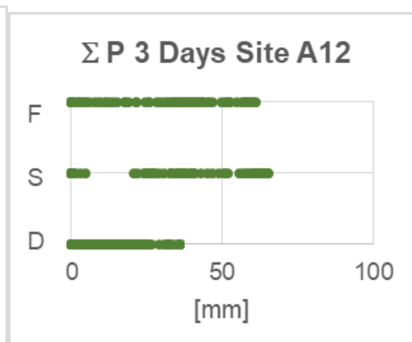

2017 Site A12
[mm]
Flowing
Standing
Dry
P (mm/30min)
state


2017 Site A12
[mm]
Flowing
Standing
Dry
SP24h
state

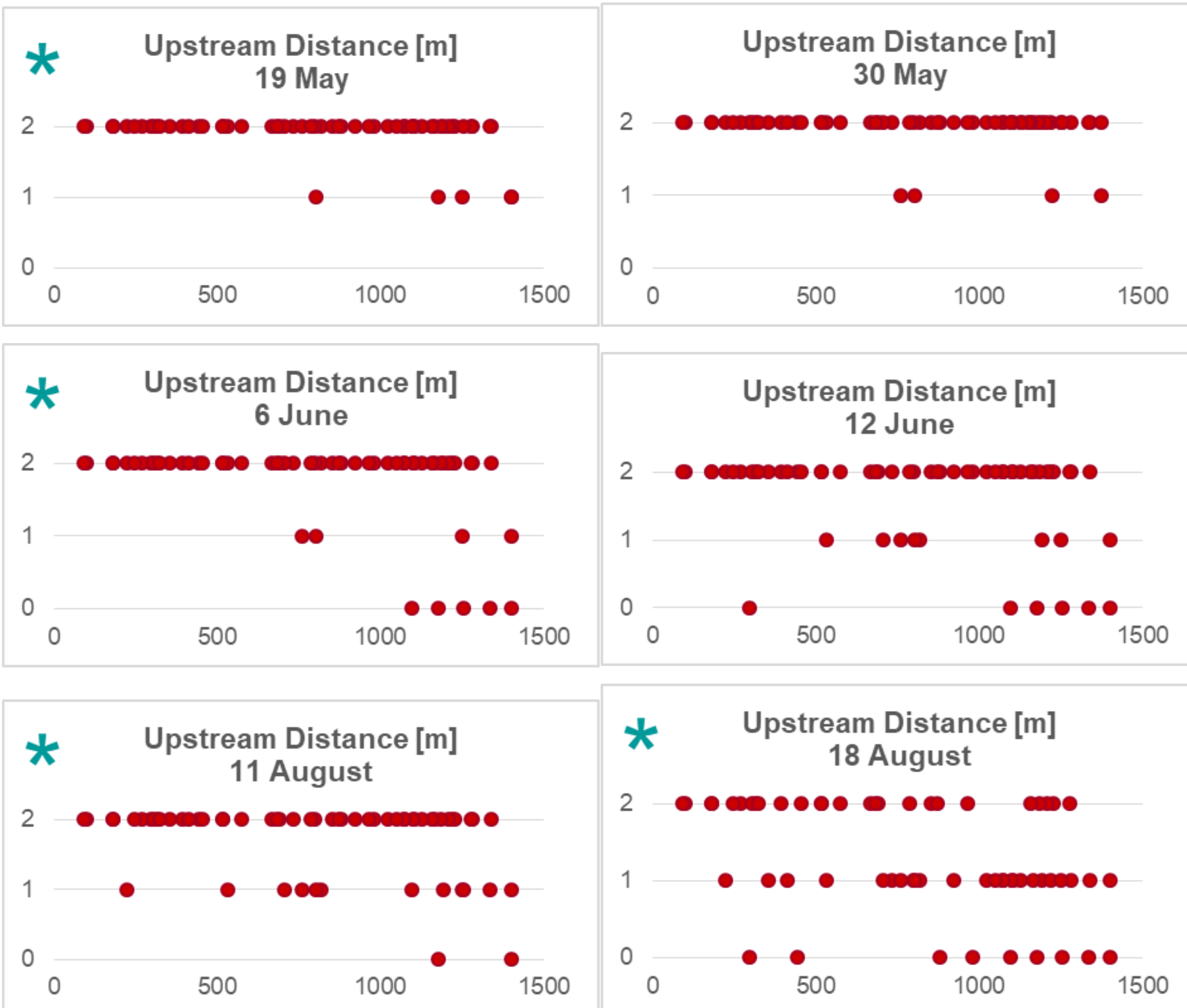

2017 Site A12
[mm]
Flowing
Standing
Dry
SP3d
state


P (mm/30min) Site A12
F
S
D
[mm]

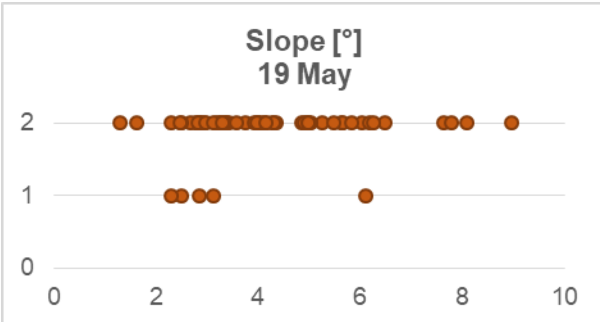

Σ P 24h Site A12
F
S
D
[mm]

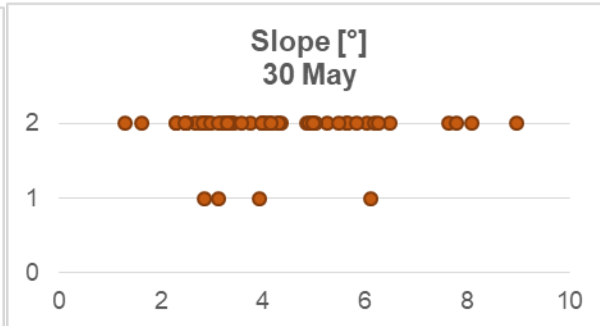

Σ P 3 Days Site A12
F
S
D
[mm]

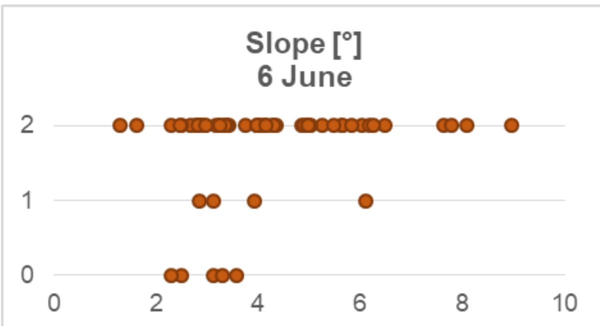
9.6. Upstream distance

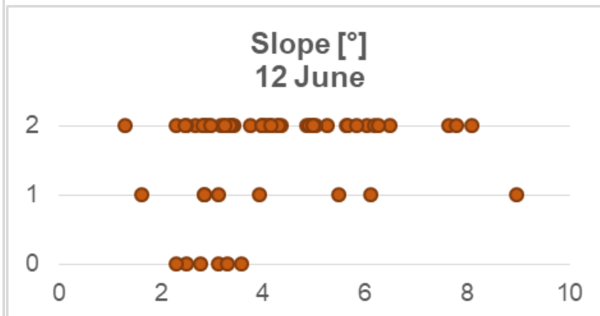


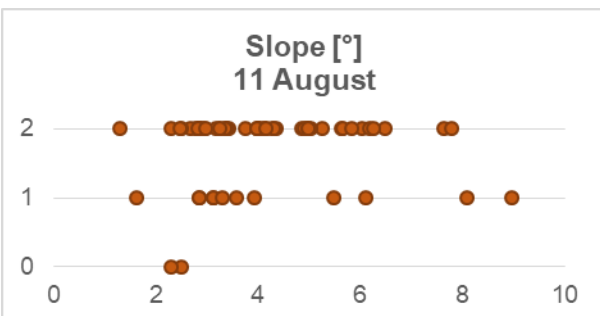
9.7. Slope

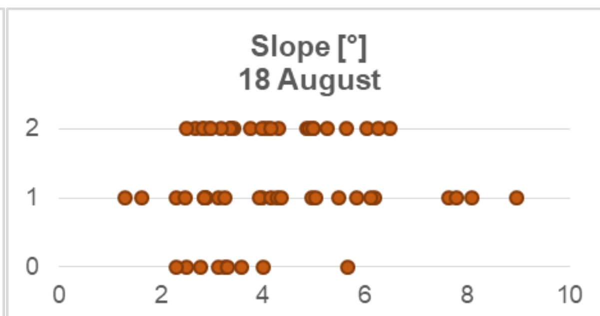

Slope [°]
19 May
2
1
0
0
2
4
6
8
10


Slope [°]
30 May
2
1
0
0
2
4
6
8
10

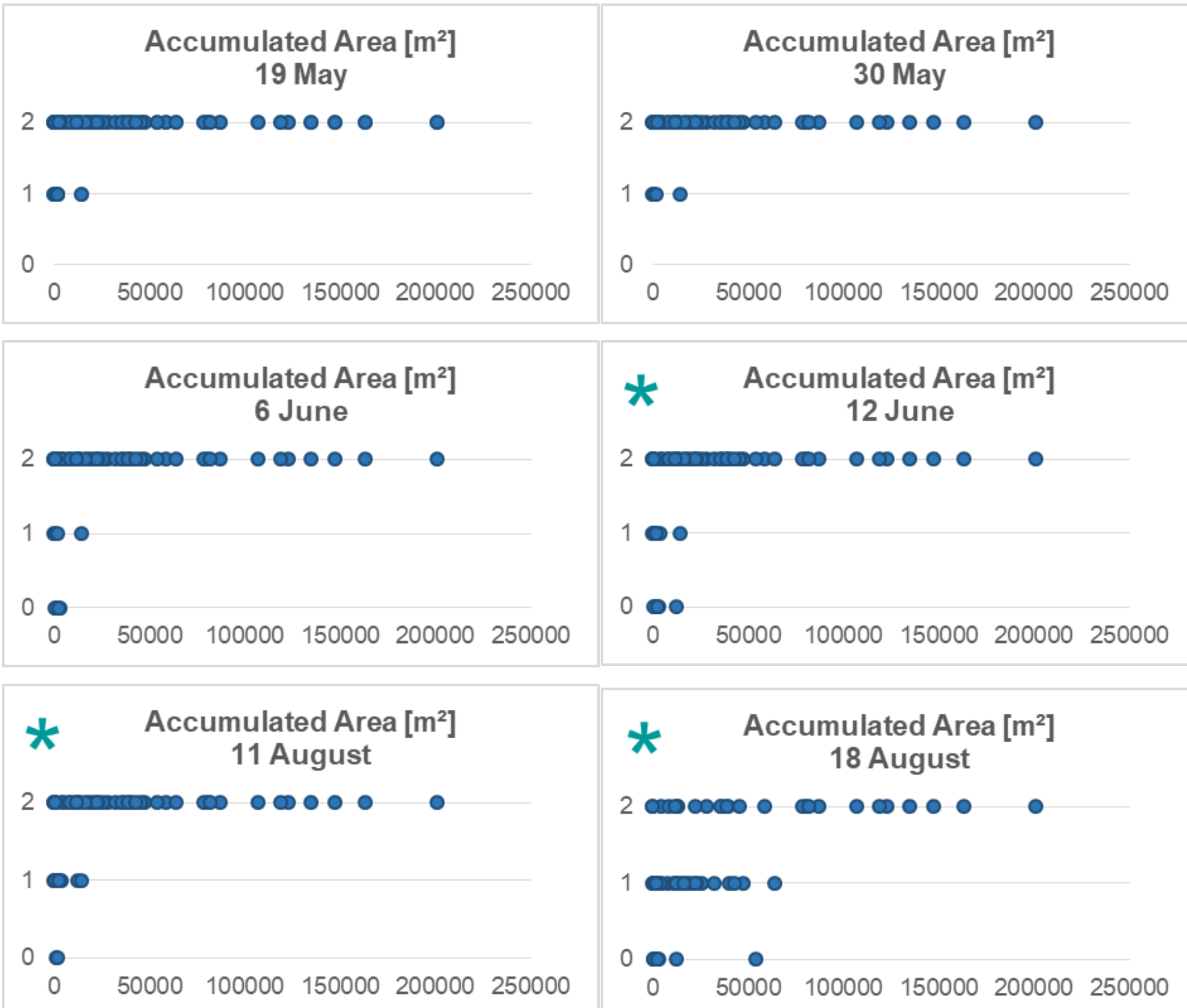

Slope [°]
6 June
2
1
0
0
2
4
6
8
10


Slope [°]
12 June
2
1
0
0
2
4
6
8
10

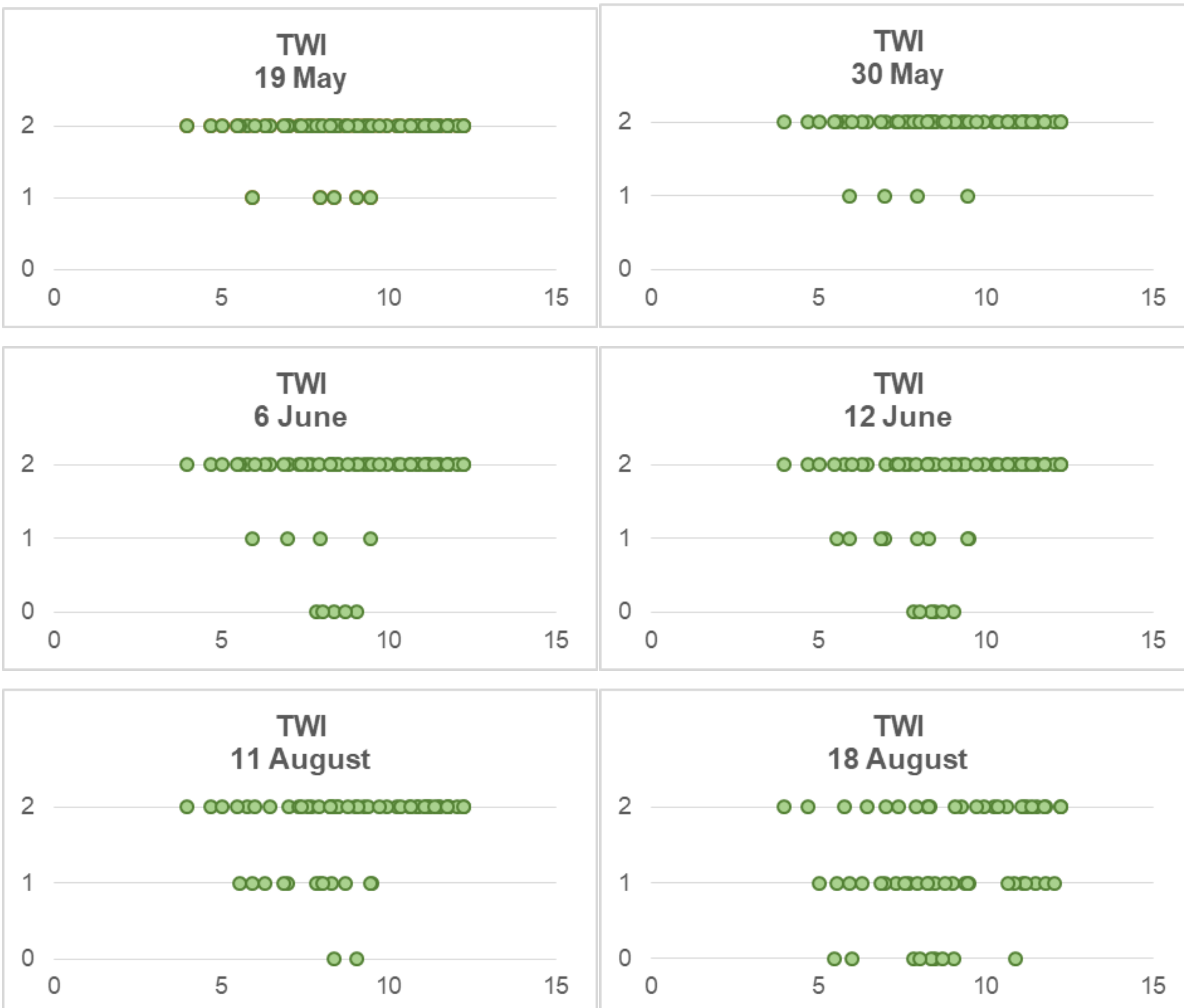

Slope [°]
11 August
2
1
0
0
2
4
6
8
10


Slope [°]
18 August
2
1
0
0
2
4
6
8
10

9.8. Accumulated area



9.9. Topographic wetness index



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.

Zürich, 26.01.2018