Event controls on intermittent streamflow in a temperate climate

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Abstract. Intermittent streams represent a substantial part of the worldwide stream network and their occurrence is expected to increase due to climate change. Thus, it is of high relevance to provide detailed information of the temporal and spatial controls of streamflow intermittency to support management decisions. This study presents an event-based analysis of streamflow responses in intermittent streams in a meso-scale catchment with temperate climate. According to the streamflow responses, events were classified into flow or no-flow classes. Response controls like precipitation, soil moisture, and temperature were used as predictors in a random forest model to identify temporal controls of streamflow intermittency at the event-scale. Soil moisture was revealed as the most important predictor in the catchment. However, different patterns of predictor importance were found among the three dominant geologies in the catchment. Streamflow responses in the slate geology were controlled by soil moisture in the shallow and deep soil layers, while streamflow in the marl geology was primarily controlled by the soil moisture in the upper soil layer. Streamflow responses in catchments covering both marls and sandstone were dependent on soil moisture whereas streamflow in the only catchment with pure sandstone geology depended on precipitation characteristics. In both the slate and marl geology, streamflow intermittency also showed a relationship with seasonal fluctuations of soil temperature, probably as a proxy-variable of seasonal changes in evapotranspiration as well as an indicator of freezing conditions.

1. Introduction

The scientific literature contains a variety of terms and definitions to define different degrees of streamflow intermittency including temporary, ~~ephemeral~~, seasonal and episodic streams, and intermittent rivers, which are all characterised by ceasing flow during certain periods of the year (Uys and O’Keeffe, 1997; Costigan et al., 2016; Datry et al., 2017; Fritz et al., 2020). The stream network changes its spatial extent with the wetting and drying of these intermittent reaches. Perennial reaches are expected to shift to intermittent streamflow as a result of climate change (Reynolds et al., 2015). Management of these transforming perennial reaches and current intermittent streams can adapt if controls of streamflow intermittency are better understood. In numerous studies, climate, geology, soil, topography, and land use were identified as major spatial controls of streamflow intermittency (Olson and Brouillette, 2006; Reynolds et al., 2015; Trancoso et al., 2016; Costigan et al., 2016; Jaeger et al., 2019; Kaplan et al., 2020a). The temporal dynamics of runoff were shown to result from fluctuating contributions of base flow and storm flow depending on the antecedent wetness state of the catchment (e.g. Zehe et al., 2007, Zimmermann et al., 2014; Jaeger et al., 2019). Since Horton (1933) first described the infiltration-excess overland flow, later followed by the description of shallow subsurface stormflow (Hewlett, 1961; Tsukamoto, 1961; Weyman 1973) and saturation-excess overland flow (Dunne and Black, 1970; Dunne et al., 1975), these three dominant processes were identified to control storm flow generation. At the hillslope and catchment scale, antecedent moisture conditions and storm size were identified as key controls of streamflow response (James and Roulet, 2009). Storm flow is frequently mentioned as the predominant source of runoff in ephemeral reaches (e.g. Boulton et al., 2017; Zimmer and McGlynn, 2017), whereas runoff in intermittent streams is predominantly driven by the seasonal fluctuations of the near-surface groundwater table (e.g. Uys and O'keeffe, 1997; Sophocleous. 2002; Goodrich et al., 2018; Fritz et al., 2020).

Although extensive research on storm flow generation at the hillslope and reach scale as well as baseflow contributions to perennial streams has been conducted, there are still few studies on the temporal controls of the ephemeral and intermittent reaches (James and Roulet, 2009; Zimmer and McGlynn, 2017). In recent years, an increasing pool of low-cost sensor technology has been developed to monitor the presence and duration of streamflow at multiple sites (Blasch et al., 2002; Goulsbra et al., 2009; Bhamjee and Lindsay, 2011; Bhamjee et al., 2016; Jensen et al., 2019; Kaplan et al., 2019). From the new opportunities provided by these sensors, a growing number of studies emerged which focused on investigating the controls of streamflow intermittency (e.g. Jaeger and Olden, 2012; Zimmermann et al., 2014, Jensen et al., 2019; Prancevic et al., 2019; Kaplan et al., 2020a). These studies on controls of intermittency can be roughly categorised into four types: (1) continental scale studies based on datasets from environmental agencies, which are usually not specifically dedicated to intermittent streams (Reynolds et al., 2015; Eng et al., 2016; Trancoso et al., 2016; Jaeger et al., 2019), (2) (nested) catchment scale studies which often rely on a limited number of stream mapping campaigns (Godsey and Kirchner, 2014; Sando and Blasch, 2015; Shaw, 2016; Goodrich et al., 2018; Jensen et al. 2017, 2018), (3) single sites or the hillslope scale studies based on conventional discharge measurements (Sidle et al., 1995, Ries et al., 2017, Moreno-de-las-Heras et al., 2020), and (4) the recently emerging studies that are based on continuous observations at multiple locations which are specifically aimed at monitoring the intermittent stream network (Jaeger and Olden 2012; Zimmermann et al. 2014; Zimmer and McGlynn, 2017; Jensen et al. 2019, Kaplan et al., 2020a).

The first type of intermittency studies commonly uses statistical models to predict intermittency at the large scale and tries to incorporate the dynamic climatic controls at coarse temporal resolution such as mean or total annual precipitation (Reynolds et al., 2015; Trancoso et al., 2016; Jaeger et al., 2019), annual evapotranspiration (Trancoso et al., 2016), snowpack persistence or share of total precipitation in form of snow (Reynolds et al., 2015; Sando and Blasch, 2015; Jaeger et al., 2019), as well as measures like average number of days of measurable precipitation (Reynolds et al., 2015), dryness or seasonality index (Trancoso et al., 2016), or zero flow days (Eng et al., 2016). These rather static climatic predictors are used to identify the likelihood of the stream network being spatially intermittent (Reynolds et al., 2015; Trancoso et al., 2016; Jaeger et al., 2019) or to identify long-term changes of streamflow intermittency under a changing climate (Eng et al., 2016). The second type of studies uses the data from mapping campaigns to predict the channel network dynamics at the catchment scale based on observed discharge (Godsey and Kirchner, 2014; Jensen et al., 2017)~~,~~ the recession rate at the catchment outlet as predictors (Shaw, 2016), or by modelling the dynamic stream network with groundwater recharge data (Goodrich et al., 2018). In studies of the third type streamflow is usually measured continuously with streamflow gauges at a single site or in nested sub-catchments and hillslopes, where intermittent streamflow is detected by zero flow observations. The streamflow dynamics are typically analysed in combination with high-resolution soil moisture data (Penna et al., 201[illegible] [illegible]ies et a., 2017; Zimmer and McGlynn, 2017), local groundwater measurements (Zimmer and McGlynn, 2017; Sidle et al., 1995), and trench subsurface flow observations (Sidle et al., 1995) as well as with high-resolution local precipitation data to distinguish between streamflow contributions from Hortonian overland flow (HOF), saturation excess overland flow (SEOF) or subsurface storm flow (SSF) at the event scale. The fourth type of studies is based on streamflow duration data captured by newly developed sensor technology, such as [illegible]nd flow-sensors, ~~monitoring multiple sites~~ along the stream network. These studies evolved from research which was initially strongly focused on the validation of the capability of these new sensor technologies through a comparison of the obtained streamflow data and network dynamics with precipitation data ([illegible]ger and Olden, 2012, Bhamjee et al., 2016). Recent studies have broadened these approaches with event-based analyses and the inclusion of additional measures to capture the antecedent wetness state of the catchment (Zimmermann et al., 2014; Jensen et al., 2019). Jensen et al. (2019) investigate the link between peak runoff at the catchment outlet and the maximum wetted fraction of the stream network during [illegible]event with principal component analysis. They ~~find~~ 60% of the variance was explained by the antecedent wetness proxy of 7 to 30 days antecedent precipitation prior to the [illegible]ts and ~~an additional~~ 16% by the ~~event~~ precipitation. Zimmermann et al. (2014) ~~model~~ the connectivity of the drainage network at the event scale using ~~a predictor set comprising~~ precipitation characteristics ~~such as event~~ [illegible]tion, maximum precipitation intensity, and total rainfall as well as the antecedent precipitation index (API) as surrogate for the antecedent wetness of the system. Zimmermann et al. (2014) identified total rainfall and maximum precipitation intensity as the major controls and the long-term antecedent wetness (API including 128 days prior to the event) as a minor control of the connectivity.

Although controls of intermittency at the continental, headwater catchment and hillslope-scale are well represented by the different types of studies described above, studies of intermittency in meso-scale catchments and for temperate climates remain scarce.

With this study we aim to close this research gap and benefit from a large dataset of binary streamflow monitoring (Kaplan et al., 2019), high-resolution precipitation (Neuper and Ehret, 2019), ~~and~~ soil moisture and temperature data (Zehe et al., 2014; Demand et al., 2019; Mälicke et al., 2020) in the meso-scale Attert catchment. ~~The~~ three distinct main geologies in the catchment were identified as major ~~static~~ spatial controls of streamflow intermittency (Kaplan et al., 2020a). Thus, in this study, the influence of geological parent material on the temporal controls of streamflow intermittency is evaluated. Following the approaches of Zimmermann et al. (2014) and Jensen et al. (2019), we present an event-based analysis of precipitation and ~~the corresponding reactions of~~ streamflow. Similar to their approaches, antecedent and event precipitation measures are considered but, additionally, soil moisture and temperature are utilised in a random forest modelling approach. We aim to answer the following questions: (1) which types of rainfall events trigger ~~runoff reactions~~ in intermittent streams and which do not, (2) what are the main dynamic controls of streamflow ~~reactions~~ in intermittent streams, and (3) are the controls of intermittent streamflow dependent on the geological setting of the catchment?

2. Research area

The Attert catchment is located in the mid-~~western part~~ of Luxembourg, with a minor area located in Belgium, and has a catchment area of 247 km² at the outlet at Useldange (Hellebrand et al., 2008). The geological setting comprises of three dominant geologies. Devonian slate is the dominant bedrock in the northern part of the catchment in the Luxembourg Ardennes, the central part consists of Keuper marls, and the southern part of the Jurassic Luxembourg Sandstone formation (Fig. 1, Martínez-Carreras et al., 2012). The topographical layout of the catchment shows the highest altitudes in the Ardennes and Luxembourg sandstone formation at 549 m a.s.l. and 440 m a.s.l., respectively, while the catchment outlet in Useldange has an altitude of 245 m a.s.l. (Martínez-Carreras et al., 2012; Pfister et al., 2018). The Luxembourg Ardennes are characterised by steep inclined valleys with forested hillslopes and plateaus with agricultural land use. The central part of the catchment consists of gentle hills that are mainly used for agriculture, grassland, and forest. The Sandstone areas are characterised by steep hillslopes which are dominantly forested and in the lower part used as grassland and for agriculture (Kaplan et al., 2020a). Soils in the Attert catchment are linked to lithology, land cover and land use (Cammeraat et al., 2018). Soils in the slate geology are dominated by stony silty soils, while the soils in Keuper Marls comprise silty clayey texture and the Luxembourg Sandstone region is largely covered by sandy and silty soils (Müller et al., 2016).

The climate is classified as pluvial oceanic (Wrede et al., 2014). Annual precipitation amounts vary ~~in space~~ from the Ardennes in the north-west with 1000 mm to roughly 800 mm in the Luxembourg Sandstone in the south-east (Pfister et al., 2017). The mean seasonal variability ranges between 70 mm in August and September, to 100 mm from December until February (Wrede et al., 2014). ~~However,~~ evapotranspiration fluctuates significantly with the seasonal changes of temperature and is ~~lowest in~~ winter with monthly evapotranspiration rates of 13 mm in December (average temperature 0°C) and highest in July with monthly evapotranspiration of 82 mm (average temperature 17°C; Wrede et al., 2014). These seasonal fluctuations in evapotranspiration control the runoff regime, resulting in high flows during the winter season, while low flows occur in the summer months (Wrede et al., 2014). Spatial differences in the seasonal variance between summer and winter runoff ~~were~~ shown to be strongly dependent on the bedrock permeability which controls the storage mixing and release of water in the Attert catchment (Pfister et al., 2017). Kaplan et al. (2020) ~~have~~ demonstrated the importance of bedrock permeability and soil hydraulic conductivity as drivers of streamflow intermittency in the Attert catchment. They also highlighted the potential of streamflow alteration through either artificial surface and subsurface drainage, dams and trenches in the agricultural areas as reported by Schaich et al. (2011) or the return ~~of waste water~~ from ~~water~~ wastewater treatment plants on the plateaus of the Ardennes.

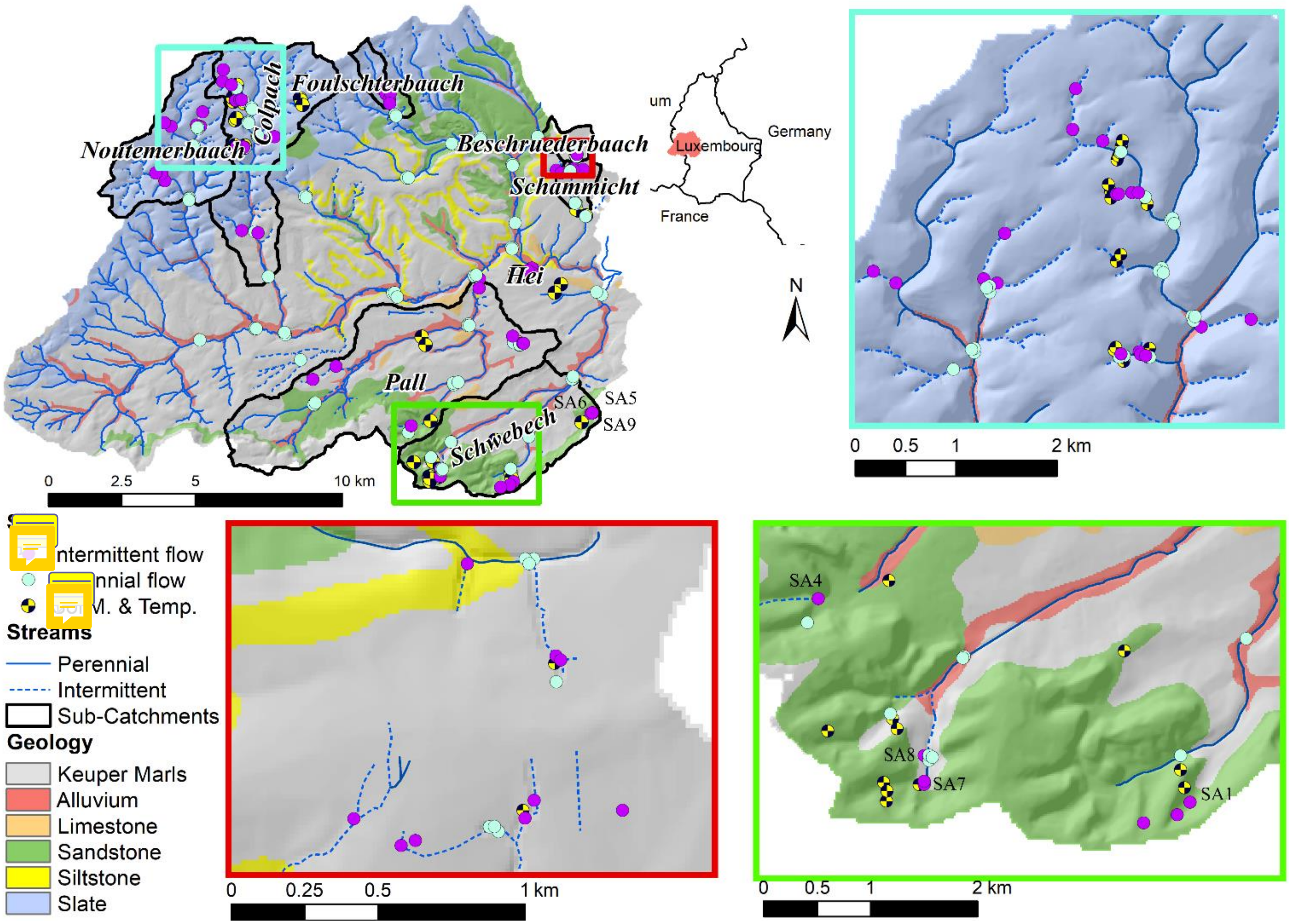

Figure 1: Geology and stream network of the Attert catchment and for streamflow monitoring as well as soil moisture and temperature measurements. Sites with intermittent flow were used for analyses in this study, while the sites with perennial flow have been used as pour point sites to delineate the catchment boundaries for the eight sub-catchments “Noumtemerbaach”, “Colpach”, “Foulschterbaach”, “Beschruederbaach”, “Schammicht”, “Hei”, “Pall” and “Schwebech”. The map sections show the more intensively instrumented areas in each predominant geology slate (blue frame), marls (red frame) and sandstone (green frame). Selected sites in the sandstone geology are labled with their ID (e.g. SA1) as reference in the discussion. The geological map from 1947 was provided by the Geological Service of Luxembourg (adapted from Kaplan et al., 2019).

3. Methods

3.1 Data acquisition

We used areal precipitation estimations derived from weather radar data combined with data from six disdrometers, two micro rain radars, re[illegible] rain gauges, and weather radar reflectivity using an information theory approach. The precipitation data has a temporal resolution of one hour and was extracted from a gridded dataset with 100m resolution at the locations of the gauging sites (data from Neuper and Ehret (2019)). The precipitation data at [illegible] sites was thereafter used to calculate precipitation averages for eight sub-catchments for a catchment scale analysis of precipitation events.

Soil moisture and soil temperature were measured at 45 sites distributed across the catchment ~~with a total of 135 soil profiles~~ (Figure 1). ~~Three combined~~ soil moisture and temperature sensors were installed ~~in each soil profile~~ at depths of 10, 30 and 50cm below the surface and ~~measured~~ with a temporal resolution of five minutes. First measurements started in March 2012 to October 2013 and ended in February 2018. In this study, a subset of the data for the period from 01.04.2016 until 17.07.2017 was used, which has the largest overlap between the other data sources used in this study. The initially installed sensors were 5TE capacitance sensors (Decagon Devices/METER Environment, USA). Due to sensor malfunction, 43 sensors were replaced with SMT100 (TRUEBNER GmbH, Neustadt, Germany) and nine sensors with GS3 sensors (Decagon Devices/METER Environment, USA) in 2016. The data was visually checked and offsets between soil moisture measurements after sensor replacement were detected in four timeseries. Additionally, seven timeseries with ~~strong artifacts~~ and/or extensive plateaus of constant soil moisture values were identified and removed from the dataset. Measured absolute values of soil moisture were normalised to the minimum and maximum of the time series for each sensor to be independent from possible bias among sensors. Soil moisture dynamics of each geology is represented by the mean of the normalised time series for all sites located in the corresponding geology. The soil moisture data was aggregated to hourly means.

The measurement [illegible] were located in each of the three main geologies in the catchment with land cover of either forest or grassland. Combined, these two land cover classes represent the predominant land cover in the catchment (Kaplan et al. 2019). However, in the marls and slate regions, agricultural land use has a substantial share of [illegible] and 42%. Sites were mainly arranged along different hillslope transects, covering different positions on the hillslope, different slopes and aspects. Eleven sites were located in the Marl region, 22 sites were in the Slate region and 12 sites in the Sandstone with a total of 33, 66 and 36 ~~profiles per~~ geology, respectively. Although some land cover classes are not covered by the distribution of the sites, the assumption was made that the sites represent the general soil moisture dynamics in the three geologies.

We used the intermittency dataset described in Kaplan et al. (2019), which is a binary data set of streamflow presence ~~and~~ absence. ~~This~~ [illegible] ~~was~~ monitored at 182 sites in the Attert catchment using various sensors, including time-lapse imagery, electric conductivity sensors, and conventional gauges. Due to the temporal resolution of the precipitation data, the streamflow data was aggregated from the original temporal resolution of 15 min to one-hour intervals by calculating the mean of the binary values and rounding the resulting value to one digit, i.e. back to binary values (0/1). A subset of gauges was selected from the sites which were monitored by time-lapse camera (C) and conventional gauges (CG) and showed intermittent streamflow, here defined as sites showing at least [illegible] period of no flow. The subset was split into further subsets according to the dominant geology ([illegible]l, Sandstone, Slate) of the upslope contributing area. For the different geological regions, 22 [illegible] were identified in slate, 23 in marl and nine in sandstone (See Figure 1 and Figure 3). The contributing area of all sites is shown in figure S6 in the supplement.

3.2 Definition of precipitation events and runoff response

Precipitation (P) event analysis was carried out for the time period from 01.04.2016 to 17.07.2017, which covers the maximum temporal overlap of the available data. In accordance with Wiekenkamp et al. (2016) and Demand et al. (2019), a precipitation event was defined as having a minimum precipitation sum of 1 mm. The required time period to separate two successive events was defined as three hours (3h) after testing a set of four different values (3, 6, 12 and 24 hours without rain, Penna et al. 2011; Penna et al. 2015; Demand et al., 2019). The maximum time between the start of a precipitation event and the start of the runoff response was limited to 48 hours after testing, with 24 and 48 hours as thresholds (Figure 2). In the case of multiple precipitation events within 48 hours before the runoff response, the latest precipitation event before the runoff response was chosen as the initialising precipitation event. The following characteristics were calculated for each event: Cumulative Antecedent Precipitation (CAP) within 24h before the precipitation event and the seven and 14 day antecedent precipitation index (API) defined as:

$$API = \sum_{t=-1}^{-i} P_t k^{-t} \qquad (1)$$

with P_t as the precipitation during time step t, i the number of antecedent time steps (7 or 14 days) and k as a decay constant (Kohler and Linsley, 1951). Values for the decay constant usually range between 0.80 and 0.98 (Heggen, 2001). A lower range of [illegible] was used in this study.

Additional ~~measures~~ included the maximum precipitation intensity (P_{max}), mean precipitation intensity (P_{mean}), total sum of precipitation (P_{sum}), duration of the precipitation event (P_D), and the normalised soil moisture ~~in~~ 10 cm (θ_{10}, Fig. S1), 30 cm (θ_{30}) and 50 cm (θ_{50}) depth at the first and last time step of the precipitation event as well as the minimum, mean, and maximum soil moisture and the minimal soil temperature during the precipitation event (T_{min}, Fig. S2) as a proxy of seasonal changes in temperature and the corresponding fluctuations in evapotranspiration (Wrede et al., 2014) as well as a potential identifier of freezing conditions.

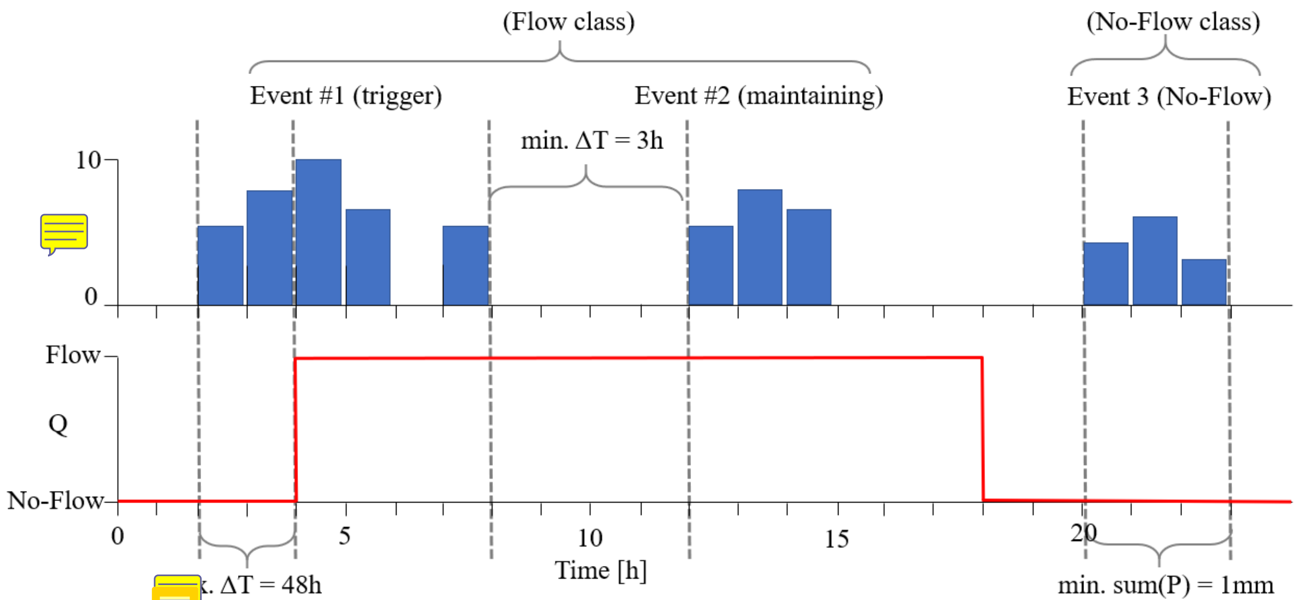

Figure 2: Events are defined with a minimum precipitation sum of 1mm and a minimum of three hours between separate precipitation events. Flow events are assigned to the last precipitation event within 48 hours before the flow initialisation. Precipitation events are classified as either triggering or maintaining events for the corresponding runoff events and summarised in the "flow class" or classified as "no-flow" in cases without flow response within 48 hours after the precipitation event.

Events were classified according to the presence or absence of flow at the stream gauges. Precipitation events which triggered the initialisation of a runoff response within 48h after the event – according to the definition above – were classified as "flow initialising". Precipitation events which have no flow responses are classified as "no-flow". Those precipitation events that are classified neither as flow initialising nor as no-flow response and happen during flow events, are classified as "flow maintaining". For the purpose of modelling runoff responses, the two classes flow-initialising and flow-maintaining were merged into one response class named "flow" (Figure 2), because we assume from the event data that preconditions for flow initiation and maintenance are highly similar. The event definition and runoff classification were carried out both for rainfall measured locally in the grid cell at the stream flow monitoring sites as well as catchment averaged rainfall for each of the eight sub-catchments "Pall", "Beschruederbaach", "Hei", "Schammicht" (marl geology), "Schwebich" (sandstone geology), "Noutemerbaach", "Colpach" and "Foulschterbaach" (slate geology, Figure 1).

3.3 Random forest model for intermittency

In general, a random forest (RF) model contains an ensemble of regression trees. Predictions of a RF model are based on the averaged predictions of all trees in the forest (Breiman, 2001). A RF model is created by bootstrapping several random samples from the original data and fitting a single classification tree to a bootstrap sample (Out Of Bag samples (OBB)). Validation of the OBB classification is performed with the data remaining outside of the bootstrap sample (OBB). This data is used for independent predictions for each OBB based tree. From these predictions the OBB error rate is calculated over all trees to provide a measure of the predictive performance of the model (Breiman, 2001).

Multiple RF models were used to model the classes of runoff responses (flow or no-flow) as a function of the predictor variables (Table 1). Table 1 includes the selected predictor variables. Only maximum soil moisture θ_{10} and θ_{50} were selected due to high correlations (Kendall's $\tau > 0.8$) among the other soil moisture predictors (θ_{10}, θ_{30}, θ_{50} as initial, end, minimum, mean, see Fig. S3). For each site an individual random forest model with the site-specific dataset containing the classification of runoff responses and the corresponding predictor variables was set up. This is necessary as the number of events varies considerably among the sites (40 to 119 events, see Fig. 3 and Tab. S3, S4, S5) and hence a common dataset is not feasible. However, despite the varying number of precipitation events, the temporal controls of streamflow reactions to the events can still be analysed for each site. The dataset was split into a training dataset (70% of the data) for model fitting and a test dataset (30% of the data) for model validation. Several training datasets showed highly unequal numbers between the classes flow or no-flow, which would lead to an overfitting by the model to the class with a higher number of events. Thus, the two methods of data resampling from the R-package ROSE (Random Over-Sampling Examples, Lunardon et al., 2014) were used to avoid the overrepresentation of one class. In this way three different datasets were tested as training data: a) the original training dataset, b) a resampled training dataset using the oversampling function of ROSE and c) a resampled training dataset using the over-/under-sampling (called “both”) function of ROSE. The oversampling function from the ROSE package performs simple oversampling with replacement from the minority class until the specified sample size N is reached. With the option *both* of the ROSE package the minority class is oversampled with replacement and the majority class is undersampled without replacement until the sample size N is reached. The resampling is carried out with the probability for the minority class given by the value p (in this study 0.5; Lunardon et al., 2014). Oversampling was set up to generate a dataset holding twice the number of observations of the overrepresented class, whereas the over-/under-sampling was aiming for the 1.5-fold number of all events contained in the original dataset. In a first run, the three different datasets for each site were used to fit three random forest models which were validated with the corresponding test dataset. The random forest models were run with the R-package “randomForest” (Liaw and Wiener 2002) with a seed set to 123, the number of trees set to 2500 and [illegible] variables tried at each split. The confusionMatrix function from the R-package “caret” (Kuhn et al., 2015) was used for validation. Only models with averaged sensitivity (correct flow predictions / total flow observations) and specificity (correct no-flow predictions / total no-flow observations) of > 0.5 were considered for further analysis. The dataset with the highest averaged sensitivity/specificity at one site was chosen for further analysis for this site. In cases where multiple datasets for one site had the same values of sensitivity/ specificity, the original data was chosen over the resampled datasets. The model accuracy (total correctly classified events / total number of modelled events) was used as an additional indicator for the assessment of the model quality but was not used during the evaluation process. With the selected datasets, one model was run for each site and the mean decrease Gini (MDG) calculated for each model using the importance function from the R-package “randomForest”. The MDG is calculated for each predictor variable X in the random forest model. For each decision tree in the model, the summed-up decrease of the node impurity measure (the Gini index) is weighted by the proportion of data points reaching the nodes that are split by the specific predictor variable. These decreases in Gini index for single trees are averaged over all trees in the forest to the mean decrease Gini (Louppe et al., 2013). A higher mean decrease in Gini indicates higher variable importance. The MDG is recognised as a robust measure to rank the importance of the predictor variables of the random forest models (Calle and Urrea, 2010).

Table 1: Predictor variables used in the random forest model selection.

Predictor	Abbreviation
Mean event precipitation intensity [mm/h]	P_{mean}
Event precipitation sum [mm]	P_{sum}
Maximum Event precipitation intensity [mm/h]	P_{max}
Cumulative antecedent precipitation (24h) [mm]	CAP
Antecedent precipitation index (7 days) [mm]	API_7
Antecedent precipitation index (14 days) [mm]	API_14
Maximum normalized soil moisture in 10 cm depth [-] during the event	θ_{10}
Maximum normalized soil moisture in 50 cm depth [-] during the event	θ_{50}
Duration of the precipitation event [h]	P_D
Minimum soil temperature during an event [°C]	T_{min}

4. Results

4.1 Event analysis

4.1.1 Event analysis based on local rainfall characteristics

For the 22 sites in the slate geology, between 64 and 119 events were identified (Figure 3, Tab. S1). The differences in detected precipitation events are caused by the natural spatial variability of precipitation ~~events~~ but also by missing data in the runoff response dataset. For 17 sites the precipitation events lead predominantly to flow responses, while no-flow responses ~~are~~ only dominant for five sites (Figure 3). The share of no-flow responses at the sites ranges from 0 to 89%. This means that for one site – although showing intermittent flow – no precipitation event was observed which caused a flow event. For the 23 sites located in the marl geology, between 51 and 114 events were identified. Twelve of these sites show a higher number of flow responses to precipitation, while eleven sites have more no-flow responses (Tab. S2, Figure 3). The proportion of no-flow responses compared to the total number of events ranges between 0 and 93%. This is due to one site without any detected no-flow response. The total number of precipitation events for the nine sites in the sandstone geology varies between 40 and 110

(Tab. S3, Figure 3). These sites show nearly an equal split of sites with predominance in flow (5 sites) and no-flow (4 sites) responses. The proportion of no-flow responses to the total number of precipitation events ranges from 3 to 82 %. Generally, the number of flow reactions to precipitation events are lower in the sandstone geology (Figure 3).

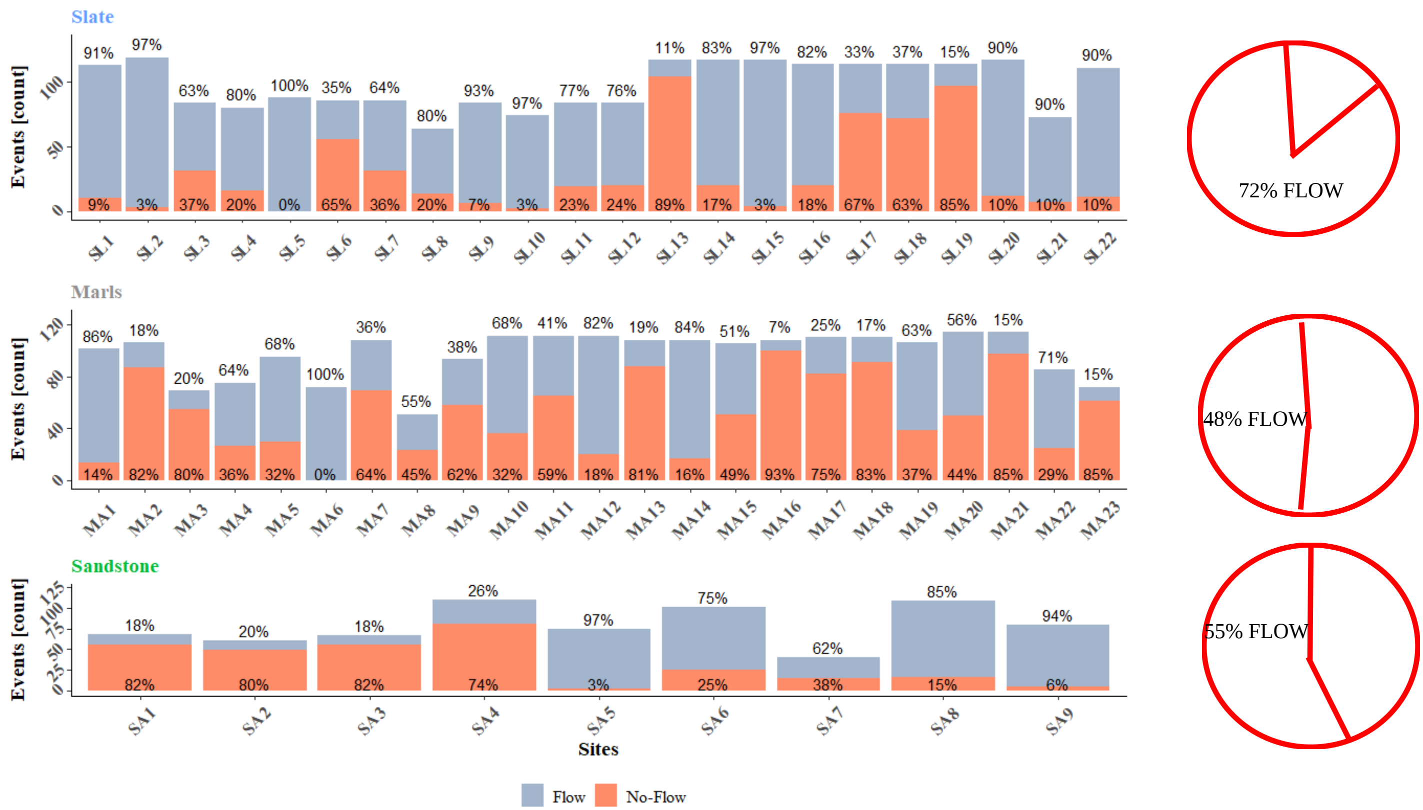

Figure 3: Number of precipitation events having either flow or no-flow reactions in the geologies slate, marls, and sandstone.

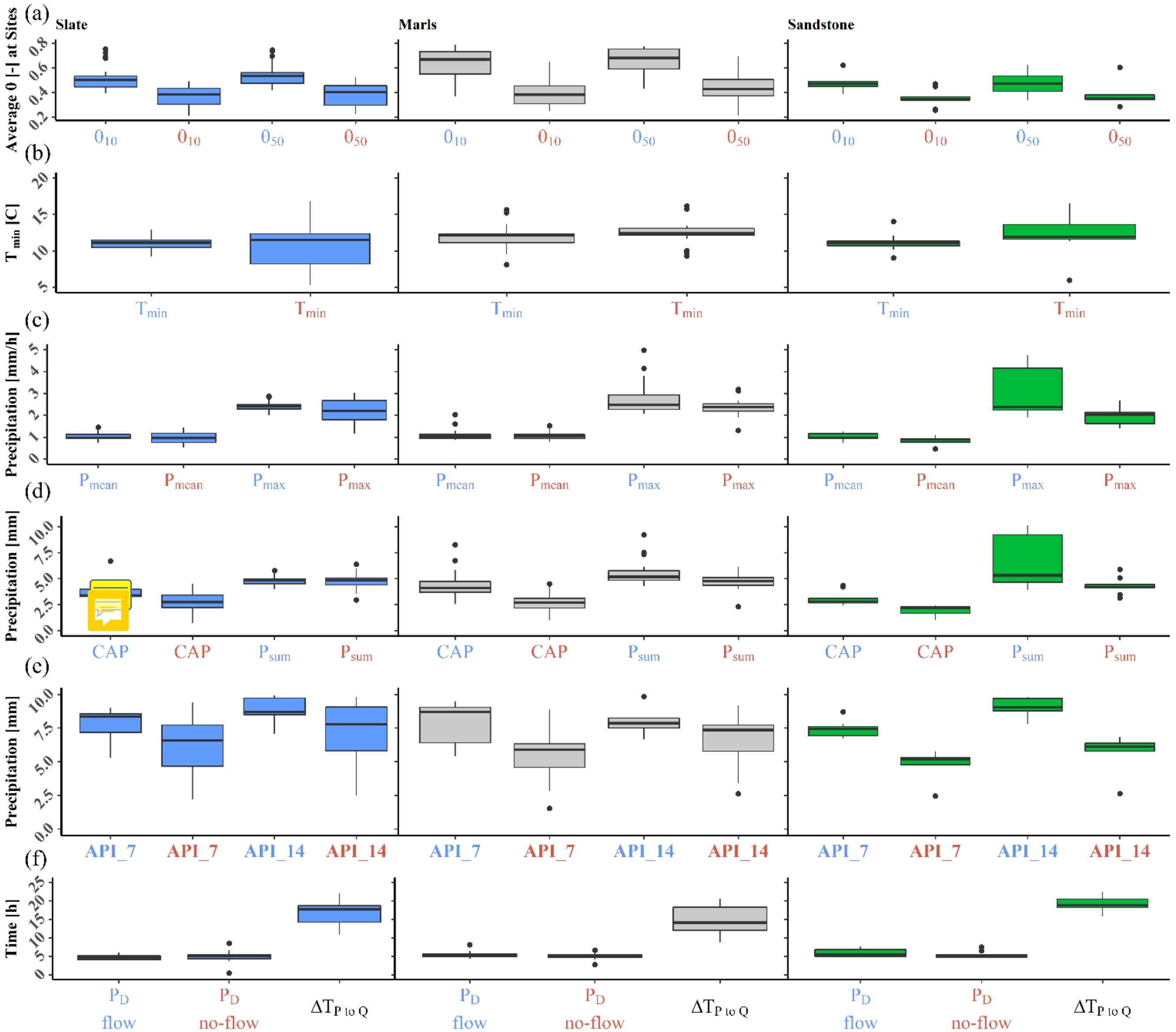

Figure 4: Flow (blue x-axis labels) and no-flow (red labels) responses in the three geologies (slate, marls, sandstone) are shown with their (a) averaged maximum soil moisture in 10 cm and 50 cm depth during precipitation events, (b) the averaged minimum soil temperature in 10 cm depth durign the precipitation event, (c) the precipitation measures P_{mean} and P_{max}, (d) the cumulative antecedent precipitation (CAP) and the cumulative event precipitation (P_{sum}), (e) the 7 and 14-day antecedent precipitation index (API_7 / API_14) and (f) the duration of precipitation events (P_D) as well as the time between initial precipitation and flow initiation ($\Delta T_{P\ to\ Q}$). One outlier of P_{mean} (6.5 mm/h) in slate is not shown to enhance the readability of the plot by reducing the scale maximum.

The results of a t-test show on average significantly ($p < 0.05$) higher soil moisture during flow events compared to the no-flow events at all sites (Figure 4a). The largest differences of soil moisture in both depths between flow and no-flow responses are observed in the marl geology, with a mean θ_{10} of 0.63 [-] and θ_{50} of 0.66 [-] during flow conditions averaged over all sites and events compared to 0.38 (θ_{10}) and 0.44 (θ_{50}) during no-flow conditions (Figure 4). The difference of soil moisture values in the sandstone are the lowest with θ_{10} of 0.48 and θ_{50} of 0.47 during flow and 0.35/0.36 respectively during no-flow conditions. Soil moisture of sites in the slate ~~was~~ slightly higher than in the sandstone with θ_{10} of 0.52 and θ_{50} of 0.55 during flow events and 0.37 in both depths ($\theta_{10/50}$) during no-flow events. In contrast to soil moisture, the averages for minimum soil temperature show no significant differences between flow and no-flow events (Figure 4). Also, the precipitation measures P_{mean}, P_{sum} and P_{max} are very similar when comparing flow and no-flow responses at sites in slate and marls (Figure 4c). However, the t-test showed significantly higher values for P_{sum} and P_{max} for flow responses (P_{sum} = 6.4 mm, P_{max} = 3 mm/h) compared to no-flow responses (P_{sum} = 4.3 mm, P_{max} = 2 mm/h) are found in the sandstone as well as a significantly higher P_{sum} during flow responses (P_{sum} = 5.5 mm) to no-flow responses (P_{sum} = 4.6 mm) in the marl. The pre-event precipitation measures show contrasting results: while the API_7 and API_14 varies significantly between flow and no-flow responses across all geologies, the 24 hours cumulative antecedent precipitation is significantly higher for flow responses in marl (CAP_{flow} = 4.7 mm, $CAP_{no\text{-}flow}$ = 2.7 mm) and sandstone (CAP_{flow} = 3.1 mm, $CAP_{no\text{-}flow}$ = 1.9 mm) (Figure 4d, e) compared to no-flow responses, whereas the differences in the slate were not significant. The duration of a precipitation event shows no significant difference between flow or no-flow responses as they are very similar in most geologies despite a small increase of precipitation duration for flow responses in the sandstone (Figure 4f). However, noteworthy differences between geologies result in the lag between initiation of the precipitation events and the begin of the runoff response (Figure 4f). The sites in Marl have the shortest, slate sites intermediate and sandstone sites the longest response times.

4.1.2 Event analysis based on sub-catchment averaged rainfall characteristics

At the sub-catchment scale all precipitation events for a sub-catchment are based on the same spatially averaged catchment precipitation data and thus the precipitation events for each sub-catchment are identical for all sites within a sub-catchment. The spatial aggregation of precipitation data is possible due to the very high correlation between the precipitation measured at the single sites in the sub-catchments (fig. S4). Thus, for each site responses to the precipitation event can be “flow”, “no-flow” or “NA” (No Data) in cases of larger data gaps in the flow data (Figure 5). The response data is shown in Figure 5 for the catchments “Pall”, “Beschruederbaach”, “Hei”, “Schammicht” (Marls), “Schwebich” (Sandstone), “Noutemerbaach”, “Colpach” and “Foulschterbaach” (Slate). The mapped data revealed large differences in flow responses even between catchments which are located close to each other. The two small sub-catchments ~~of the~~ Hei catchment are prominent examples of two catchments with gauging sites that are less than 500m apart but which show very different shares of flow and no-flow responses (Figure 5).

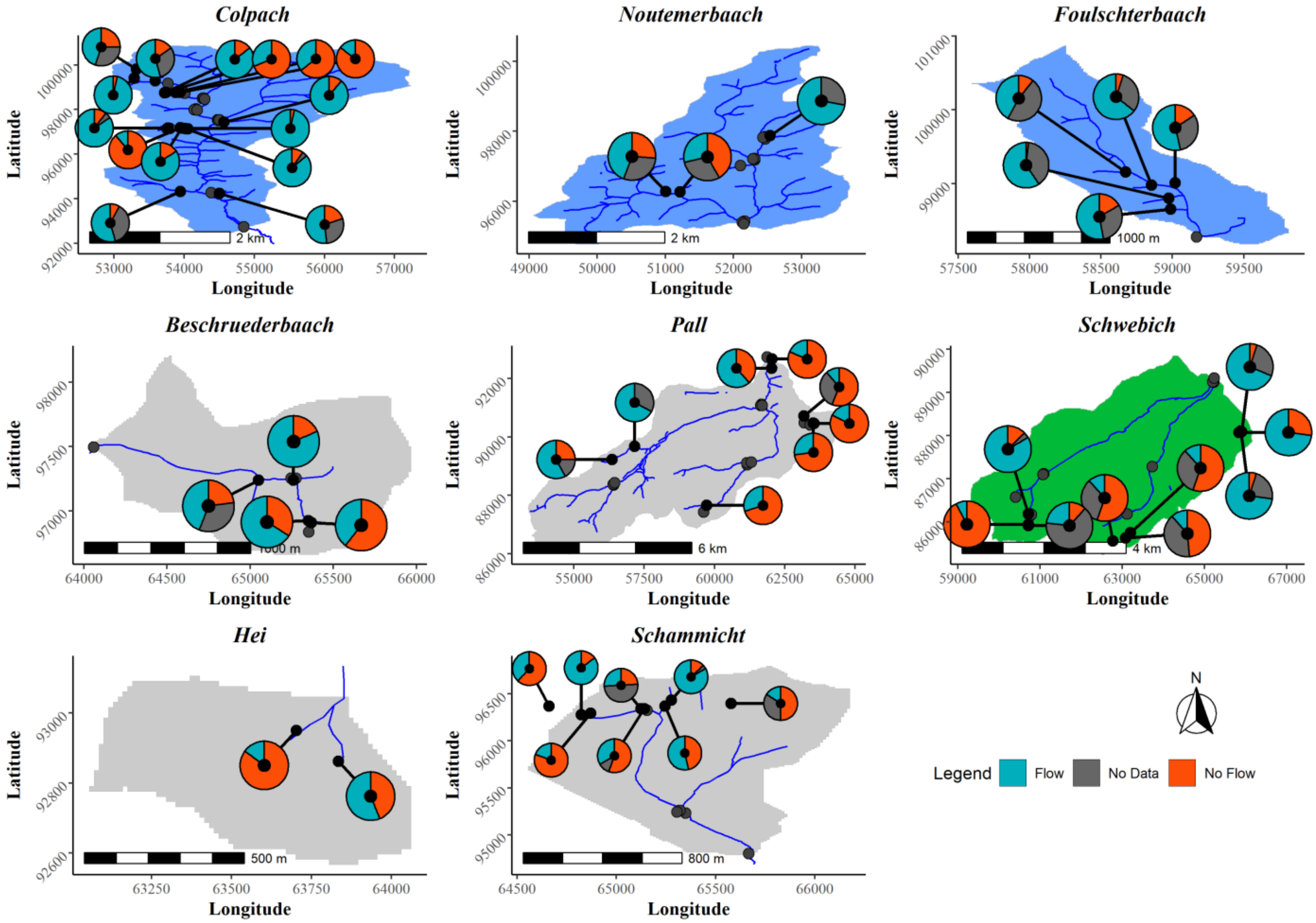

Figure 5: Spatial distribution of the sites and their corresponding proportional flow responses to event precipitation. The prevalent geology at the majority of the sites in each catchment is indicated by the colour of the catchment shape: blue = slate, grey = marls and green = sandstone. The dominant geology at the site does not always reflect the dominant geology of the entire catchment.

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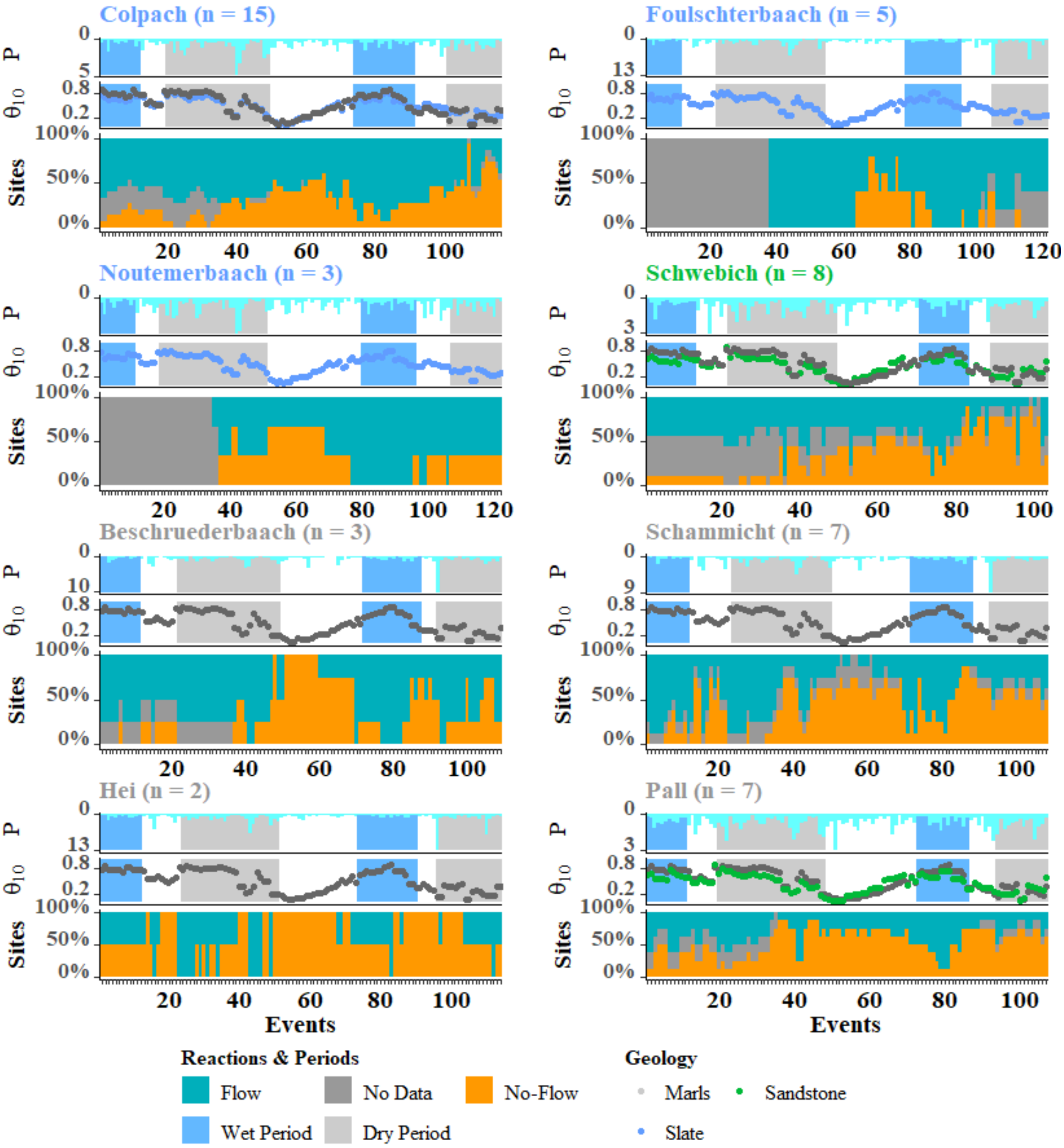

Figure 6: Event dynamics for each catchment ordered by their temporal succession. Catchment geology is colour coded in the header of the sub-plot (blue = slate, gray = marls, green = sandstone). The header also includes the number (n) of sites in the catchment. Each sub-plot consists of the mean event precipitation (top), soil moisture in 10 cm depth (mid) and the proportional share of sites in the catchment with the response categories "flow", "no data" or "no-flow". In cases of sub-catchments having sites in two different geologies, the soil moisture dynamics in each of the geologies are included in the corresponding plot. In addition, the events in the months February, March and April are highlighted with a blue background representing a period with a high number of sites in the Attert catchment showing flow, whereas the months June, July and August highlighted with a gray background indicate a dry period. Beware that the event numbers on the x-axis differ between the plots, i.e. Event #40 does not refer the same event across all sites.

The temporal succession of the events responses in the catchments, the precipitation as well as the soil moisture dynamics are shown in Figure 6: The Colpach catchment has more sites with no-flow reactions during precipitation events with low soil moisture compared to those precipitation events with higher soil moisture. However, for few events with very high mean precipitation, all sites of the Colpach catchment have flow conditions, mostly with a little delay. In the Foulschterbaach catchment all sites maintain flow for a first sequence of events, even with low soil moisture, while some of the sites fall dry during events with lower precipitation and intermediate soil moisture. Flow is regained at all sites when the normalised soil moisture reaches a threshold of around 0.65. The Noumtemerbaach shows a gradual decline of flowing sites with a corresponding decline in soil moisture. Also, in this catchment, a precipitation event of high mean precipitation intensity leads to an activation of flow for all sites in the catchment (Figure 6: , Event# 80). This behaviour can be repeatedly found for a few more events during the period of lower normalised soil moisture (<0.50). Subsequent events with soil moisture above that threshold are connected with the initiation of flow at all sites in the Noutemerbaach catchment. The Schammicht catchment is located in marl geology and monitored sites represent many smaller sub-catchments. Five series of precipitation events with high corresponding proportions of flowing streams can be identified (Figure 6:). Two of these sequences with the most subsequent events show relatively high soil moisture values of higher than 0.72 (Event# 1-16), while a third period is associated with some missing values and a very dynamic soil moisture, but successive events of larger mean precipitation (Event# 23-35). Further, two short series of precipitation events (Events# 18 - 20 and 42 - 44) of flow correspond to successive events of larger mean precipitation. It is worth noting that a single event of very high mean precipitation (60mm/h) does not lead to flowing conditions in the complete catchment in times of low soil moisture (Event# 94). The flow dynamics for the Beschruederbaach are generally closely related to those observed at the Schammicht catchment, as both catchments are very close to each other and have a similar geological and land use setting (Figure 1). The Hei catchment has rarely flowing conditions at both monitored sites. These flow responses mostly correspond to either comparably high mean event precipitation and/or high soil moisture (> 0.8, Figure 6:). The Pall catchment has one site located in the sandstone region while all others are situated in the marls (Figure 1). The share of sites without flow reactions to precipitation events is notably higher during times of lower soil moisture (Events# 37-70, 85-110). However, in these dry periods, rapid flow activation introduced by larger event precipitation is possible (e.g. Events# 40-43 and #97). Other periods with a higher number of sites having active flow are linked to higher soil moisture values (higher than 0.73). In the Schwebich catchment, the majority of the sites are located in the sandstone geology. Unfortunately, the share of “No-Data” observations are quite significant during the first third of the events (Figure 6:). Nevertheless, the relation between higher soil moisture and a high proportion of sites with flow seems to apply to the sites in the sandstone but with less clear indication. Notable runoff responses from the majority of the streams in the catchment occur at comparably low soil moisture but a higher mean precipitation intensity during events #36, #53 and # 96.

4.2 Random forest model results

4.2.1 Site selection

Not all models for all sites were able to meet the evaluation criteria for a good model. Thus, those sites were rejected to avoid the inclusion of results of bad performing models in the further analysis. The site selection is based on a combination of the evaluation criteria (specificity and sensitivity) during validation. A site was selected for further analysis if the specificity and sensitivity was higher than 0.5 and the sum of both measures was higher than one. In the marl region models, 20 out of 23 sites met the evaluation criteria and had a mean model accuracy of 0.84 (Figure 7, Tab. S5-7). The approved sites were selected with datasets from all types of resampling methods (no resampling, over-sampling, over- and under-sampling). The three sites which did not match the evaluation criteria were among the sites with the lowest number of observed precipitation events and had a notably unequal distribution of flow to no-flow responses (in case of site MA6 even only flow responses). These sites are located in the Schammicht and Pall sub-catchments (Figure 8). For the sandstone models, four of nine sites did not meet the evaluation criteria, with either very high sensitivity and very low specificity, or vice versa (Figure 7). This also corresponds to an unequal distribution of the flow responses (Figure 3). All of the sites in the sandstone geology are located at very small reaches or steep logging tracks on the hillslopes (Figure 8). The mean model accuracy over all sites that matched the evaluation criteria was 0.79. All sites in the sandstone geology that qualified showed the best results with the over- and under-sampling approach. Eight out of 22 sites in the slate geology were rejected from further analysis based on the model evaluation criteria (Figure 7). After rejection of the unsuccessful models, the mean accuracy over all sites in the slate reaches 0.90. The rejected sites in the slate geology are distributed over all sub-catchments (Figure 8). However, the Foulschterbaach catchment had a ~~remarkably~~ high share of sites (3 out of 5) that did not meet the evaluation criteria. All of the rejected sites in the slate geology have a comparably low number of no-flow responses (Figure 3). In the case of SL5 and SL10, the splitting of the dataset into training and test data was leading to zero samples of the no-flow class. For SL2 the ratio of 116:3 of flow to no-flow responses could not be compensated through the resampling of the data. Roughly two-thirds of the sites in the slate geology selected for further analysis showed better results with the resampled data.

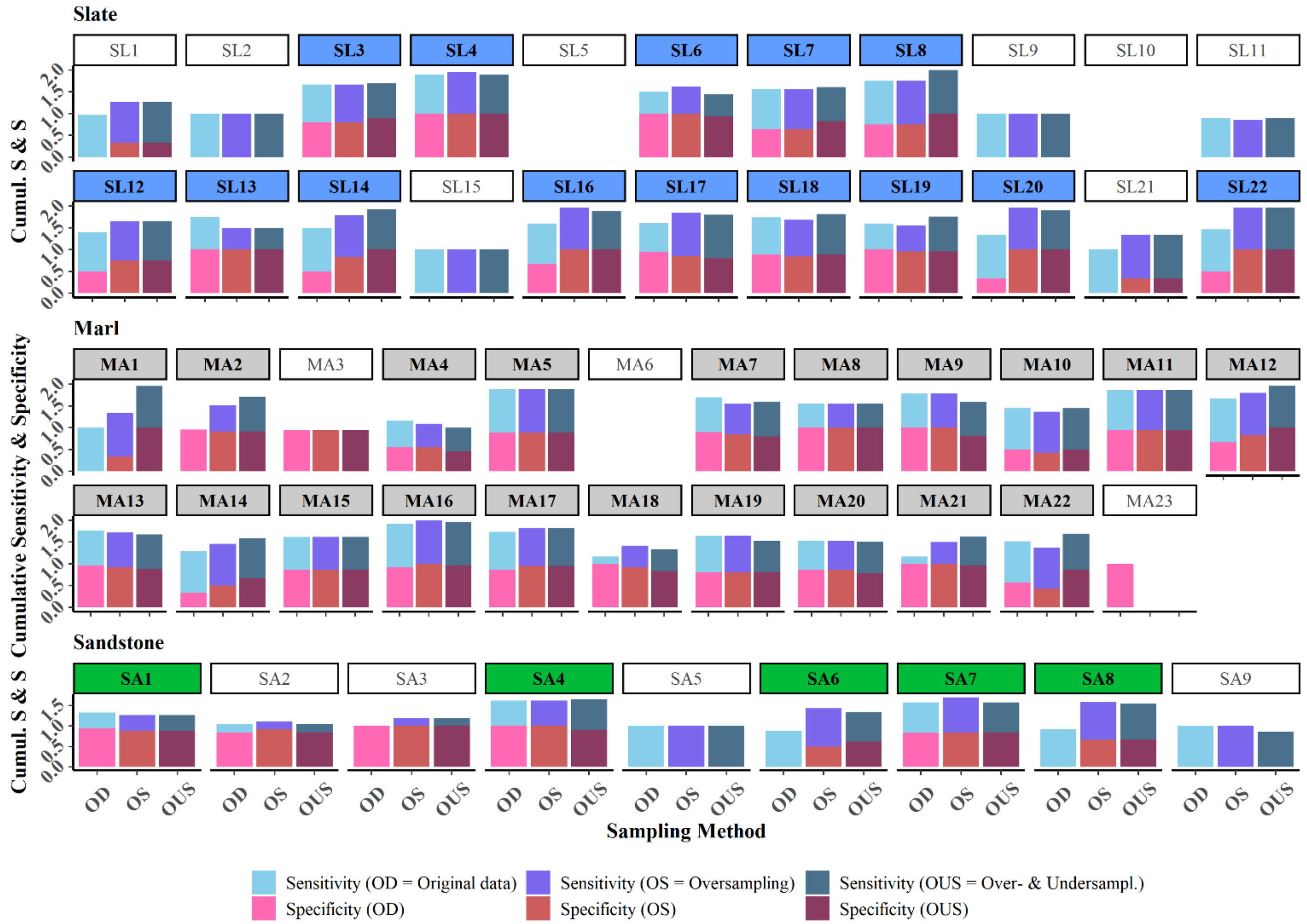

Figure 7: Cumulative sensitivity and specificity of the random forest models at the different sites using the three data samples original data (OD), oversampling dataset (OS), and over- and undersampling dataset (OUS). Sites that meet the selection criteria for a good model fit are indicated with coloured boxes corresponding to the dominant geology in the catchment (blue = slate, gray = marls, green = sandstone).

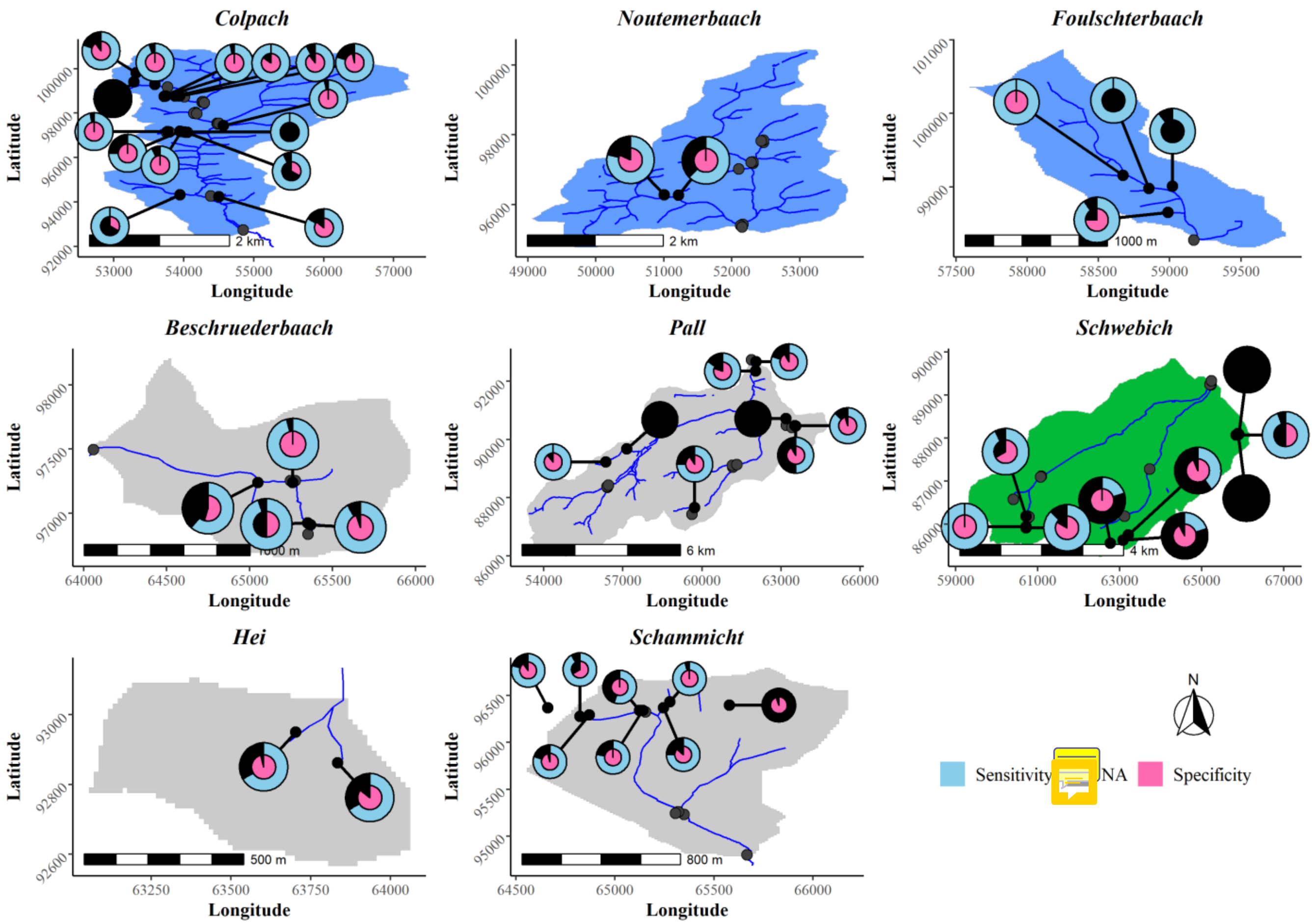

Figure 8: Sensitivity and specificity of the random forest models at the different sites in the sub-catchments (including the sites that did not fulfil the evaluation criteria). Both measures range from 0 to 1, thus the larger the proportion of the circle that is filled with colour, the better the model quality.

4.2.2 Predictor importance

The predictor importance at each site is defined by the ranked mean decrease Gini measure of the predictors in the site-specific model. The rank of a model predictor shows the relative importance in relation to the other predictors in the model (Figure 9). For the sites located in marl the soil moisture at 10 cm depth is by far the key predictor – being among the top three most important predictors for nearly all sites (Figure 9). The soil moisture at 50 cm depth is ranked ~~as slightly less important~~, ~~but is among the most important predictors for nearly all sites.~~ The API measures complete the highly important predictors with the long-term API_14 measure having a slightly higher importance than the API_7 measure. The ~~highly~~ ranked predictors include soil moisture and API and hence represent either directly or indirectly the soil moisture during the precipitation event. While the precipitation measures (P_{mean}, P_{sum}, P_{max}) play only a minor role at three-quarters of the marl sites, the cumulative antecedent precipitation was ranked as important for two-thirds of the sites. The ~~comparably~~ high ranks for the minimum soil temperature in the marl geology is remarkable as is the low importance of the duration of a precipitation event. Sites in slate have similar patterns of predictor importance to sites in marl (Figure 9). In contrast to the marl sites, in the slate geology the soil moisture at 50 cm depth has a higher ranking than that at 10 cm depth. On average both predictors are among the first two most important predictors for the majority of slate sites. Minimum soil temperature is the third key predictor in the slate region with many sites having it between the third and first most important predictor. Short and long-term API had an intermediate ranking in the slate geology. Precipitation measures were among the second to fourth most important predictors only for one-third of the slate sites, while the duration of a precipitation event was not important for any sites in slate. The sites in the sandstone geology show more diverse patterns of predictor importance (Figure 9). Soil moisture at 10 cm and 50 cm is also among the most important predictors for most of the sites in sandstone with ranks of nine and 10. In contrast to the other geologies the precipitation sum is very important for one site in the sandstone geology but still notably more important for the other sites compared to the other geologies, representing the third most important predictor in the sandstone geology. Furthermore, mean event precipitation ranks high for two sites in the sandstone geology. Compared to the API_14 which was the only important antecedent precipitation measure at two sandstone sites, the API_7 and CAP have lower rankings. The minimum temperature has a much lower importance in the sandstone compared to the other geologies. One of the two sites with higher importance of precipitation duration also shows a higher importance of other event precipitation measures (P_{mean}, P_{sum}, P_{max}) while these measures are not important for the other site. For all other sites in the sandstone geology, the duration of the precipitation event plays a minor role.

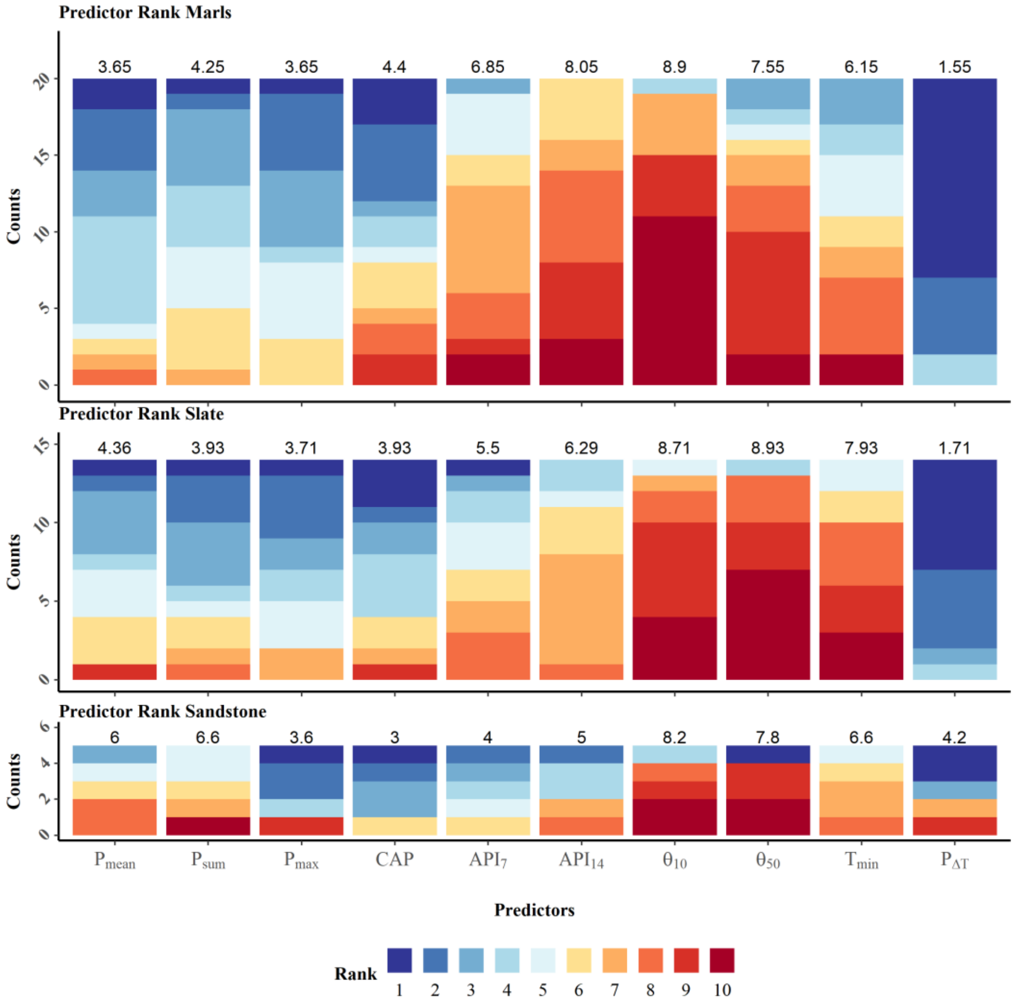

Figure 9: Rank of the parameter importance of each model predictor at the different sites in each geology. The rank is colour-coded, with the highest rank in red representing the most important predictor and the lowest rank in blue representing the least important predictor.

5. Discussion

5.1 Controls of streamflow intermittency

Hydrological researchers identified three major controlling mechanisms of event runoff generation: infiltration (Hortonian) overland flow, saturation excess overland flow and subsurface stormflow (Sidle et al., 1995; Zimmermann et al., 2014). The drivers that are involved in these processes are always inputs of water to the system either in the form of precipitation or melt water (e.g. Horton, 1933; Weyman, 1973; Dunne and Black, 1970; Sando and Blasch, 2015; Tolonen et al., 2019). The ability of the system to buffer the incoming precipitation is limited by the infiltration capacity, the ability to channel subsurface storm flow, and the antecedent soil moisture (e.g. Tromp-van Meerveld and McDonnell, 2006; Bachmair and Weiler, 2014; Stewart et al., 2019).

The event analysis of this study reveals that the average soil moisture at the sites in all geologies shows significant differences between precipitation events with flow, and precipitation events without flow responses (Figure 4). Additionally, the antecedent precipitation (7 day and 14 day API) showed notable importance in the marl and slate geology. The high potential to distinguish the two classes of flow responses by soil moisture is confirmed by the results of the random forest models (Figure 9). The importance of soil moisture in the system is in line with the findings of Kaplan et al. (2020) who identified catchment area and curvature, which are ~~a surrogate~~ of the topographic wetness index, as the two crucial predictors in the spatial model of streamflow intermittency. The event analysis in this study indicates a certain timing (Figure 6) and thresholds (Figure 4) of soil moisture at which streamflow is initiated. Times of low or high soil moisture and respective responses of no-flow or flow roughly follow the seasonal fluctuations. Thus, in the winter months with higher soil moisture, a succession of multiple precipitation events with flow reactions are more common than in the summer months with lower soil moisture (Figure 6). Annual variations of runoff in temperate regions are usually explained by the seasonal fluctuations of evapotranspiration which affects the soil moisture conditions of the catchment (e.g. La Torre Torres et al., 2011; Penna et al., 2011, 2015; Trancoso et al., 2016; Zimmer and McGlynn, 2017). The seasonal variations of soil moisture are visible in all geologies of the catchment. Besides the seasonal fluctuating soil moisture, due to temperature/evapotranspiration, dynamics soil moisture can increase rapidly in reaction to precipitation events. These fast soil moisture reactions support the initation of flow predominantly in the marl geology but also in weaker form in the other geologies (Figure 6). The importance of soil moisture in both soil depths in the marl geology is reflected by the results of the random forest model which ranks those predictors and the API the highest (Figure 9). The importance of the event precipitation measures (P_{max}, P_{mean}, P_{sum},) that can play a major role for the establishment of hydrological connectivity (e.g. Bracken and Croke, 2007) was surprisingly low. This may result from the small share of precipitation events exceeding the infiltration capacity in all geologies of the catchment as found by Demand et al. (2019) and thus limiting the probability for Hortonian overland flow. Kaplan et al. (2020) identified bedrock geology and saturated soil conductivity as one of the major spatial controls of streamflow intermittency in the Attert catchment. This influence of geology and soil on the appearance of intermittency and on the dominant runoff processes was confirmed by other studies (e.g., Tanaka et al., 2005; Jencso and McGlynn, 2011; Sando and Blasch, 2015; Gutiérrez-Jurado et al, 2019; Pate et al., 2020). Thus, the temporal controls of streamflow intermittency are separately discussed for each of the dominant geologies in the following sections.

5.1.1 Intermittency controls in marl

The soils in the marl geology were reported to have the highest flow velocities of the geological regions in the Attert catchment (Demand et al., 2019). However, the underlying marl geology is characterised by a low permeability (Wrede et al., 2014).

Beiter et al. (2020) showed strong transmissivity feedback after only a few precipitation events through shallow groundwater to the stream response in the sub-catchments Beschruederbaach and Schammicht, which are located in the marl geology (Figure 1). Under lower antecedent moisture conditions, they found a change towards higher incidences of overland flow and runoff contributions through preferential flow paths during precipitation events. Also, Wrede et al. (2014) linked the fast responses of event water in the Wollefsbach catchment – a sub-catchment in the marl region of the Attert catchment – to lateral subsurface flow of pre-event water and contributions of event water through preferential pathways. This process is accompanied by saturation excess overland flow during periods of higher saturation (Wrede et al., 2014). The findings of Demand et al. (2019) and Beiter et al. (2020), combined with the strong dependency of streamflow initiation by increased soil moisture as indicated by the random forest model, suggest that saturation excess overland flow and shallow subsurface stormflow are among the dominant processes controlling the streamflow responses in the marl geology. This finding is supported by the importance of the 14-day API, which indicates an increased probability of streamflow initiation and continuation following larger antecedent precipitation. Demand et al. (2019) also analysed precipitation events of a time period overlapping with the one in this study and found no events exceeding the infiltration capacity of the soil matrix at sites located in forests. This finding is in accordance with the low importance of all precipitation measures in the models for sites located in the marl region, which were predominantly forested . Soil temperature showed high importance in the random forest model for the majority of sites in the marl geology (Figure 9). This underlines the dependency of flow initiation on the seasonal changes of temperature and evapotranspiration in the Attert catchment, which were also found in other temperate catchments (Wrede et al., 2014; Zimmer and McGlynn, 2017). Overall, the models showed a good ability to separate flow and no-flow responses with the random forest models dominated by soil moisture and temperature data, indicating shallow sub-surface storm flow and saturation excess overland flow in the marl geology.

5.1.2 Intermittency controls in slate

The most important model predictors in the slate are soil moisture in the upper and the lower soil layer followed by temperature, while precipitation related predictors play a minor role (Figure 9). The soil moisture at 50 cm depth is slightly more important than the soil moisture at 10 cm depth at several of the sites. This can be caused by the high fraction of preferential flow paths in the clay-rich soils as frequently found in the forested regions in the slate geology of the Attert catchment (Demand et al., 2019). This would allow event water to travel quickly into deeper soil layers and to trigger sub-surface storm flow. Additionally, slate bedrock is relatively impermeable. Runoff responses in the Weierbach catchment – a sub-catchment of the Colpach catchment (Figure 1) – support a "fill and spill" mechanism of subsurface stormflow (e.g., Wrede et al., 2014; Martínez-Carreras, 2016; Beiter et al., 2020). Tromp-van Meerveld and McDonnell (2006) explain this mechanism appears when depressions at the bedrock surface have to be filled until water spills over the bedrock relief. They present a distinct precipitation threshold that has to be reached to trigger strongly enhanced subsurface stormflow in their study area. For the Weierbach catchment, this mechanism was identified as inducing double peak runoff when the catchment storage state reaches a certain threshold during the dormant season or after intense precipitation events in the dry season (Martínenz-Carreras, 2016). Single peak runoff was observed below the threshold, which resulted from direct precipitation into the stream channel and saturation excess overland flow in the riparian areas (Martínenz-Carreras, 2016), but also partly by subsurface stormflow through macropores and fractures on the hillslopes which are connected to the saturated riparian areas (Angermann et al., 2017; Jackisch et al., 2017). Double peak hydrographs showed a first peak of younger water fractions followed by a second, delayed peak with higher fractions of old water from activated catchment storages which appeared as subsurface stormflow and shallow groundwater reactions (Martínenz-Carreras, 2016; Schwab et al., 2017; Beiter et al., 2020).

As the only site in slate, site SL12 shows deviations in the composition of predictor importance in the models with very low importance of soil moisture (Figure 9). This site is located in the Foulschterbaach catchment (Figure 1), where the majority of the sites did not match the evaluation criteria for the model selection (Figure 8). The low model performance might be due to the spatial distance between the measurement sites of soil moisture and temperature which were mainly obtained in the Colpach catchment and the streamflow observations from the Foulschterbaach catchment. Thus, the soil moisture of the Colpach catchment might not be representative for the Foulschterbaach catchment (Figure 1). This assumption is supported by CAP and API_14 being the second and third most important predictors at this site after temperature. The different behaviour between those two catchments in the slate geology is also recognisable in the succession of events and soil moisture dynamics plotted in Figure 4. The water ceased to flow for the period 28.10.2016 until 23.02.2017, with only one single flow response with a duration of three hours on 16.02.2017. This long dry period in the winter months was notable at several sites in the slate geology (Figure 6). However, the first streamflow response after this dry period lags nine events behind in the Foulschterbaach catchment compared to the other catchments in the slate. One reason for this might be due to the differences of the precipitation input. The Foulschterbaach catchment has an overall higher precipitation than the Colpach catchment (Kaplan et al., 2020ab), but for these events the precipitiation events are very similar. Due to the different precipititation sums, differences in the soil moisture dynamics need to be expected, something that is also underlined by the importance of API as an alternative soil moisture measure at the sites of the Foulschterbaach catchment (Figure 6).

5.1.3 Intermittency controls in sandstone

Sandstone layers are generally characterised by a high permeability which provides a large aquifer storage that feeds permanent springs (Colbach, 2005). The high permeability also supports a high infiltration capacity and limits surface runoff during precipitation events (Wrede et al., 2014). In fact, identifying monitoring sites which show a regular intermittency of streamflow was challenging for the site selection (Kaplan et al., 2019). As intermittent streamflow in the sandstone is less common and the relatively low number of initial sites in this geology had to be reduced after the model evaluation (Figure 7), a general pattern of typical controls of intermittent streamflow in this geology could not be identified. Thus, the predictor importance and the potential controls of streamflow intermittency are discussed at the site scale rather than at the scale of the entire geology.

The sites SA5 and SA9 were quasi-perennial and the number of events showing no-flow was therefore too small for a balanced class representation in the random forest model. However, the site SA6 (fig. 1), which was located downstream of the two springs feeding the reaches at SA5 and SA9, could often be observed to cease flow 10 to 15 m downstream during field visits. This site shows a strong dependence on soil moisture, the duration of precipitation events and the antecedent precipitation. This indicates that either a specific soil moisture threshold or a long period of precipitation is required to produce streamflow and to compensate the transmission losses. This type of flow cessation through transmission losses was reported for small catchments with low or moderate channel gradients and coarse sediments (e.g. Constantz et al., 2002; Costa et al., 2013). Sites SA7 and SA8 are located in the marly zones at the foot of sandstone hillslopes (fig. 1). Both sites may acquire a certain share of streamflow from nearby groundwater springs which are also used as wells for drinking water. The two sites also share the same important model predictors soil moisture in both depths and temperature. At these sites, the controls of flow cessation during dry periods can either relate to natural controls caused by seasonal fluctuations of soil moisture and transmission losses in the marl layer, or can be amplified by higher rates of water withdrawal in the wells during summer seasons. This kind of anthropogenically induced alteration of streamflow intermittency has been reported for many rivers worldwide (Chiu et al., 2017). The most important predictors for site SA4 were soil moisture in the two depths followed by maximum precipitation intensity and precipitation sum. The geological setting characterised by marls in the upstream part and sandstone in the lower part of the catchment may influence the streamflow at this site. In contrast to the other sites, which show a high importance of soil moisture, the streamflow response of SA4 is always flashy with longer events during periods of high soil moisture saturation. The predictor ranks of maximum and cumulative event precipitation are also comparably high at this site (Rank 7 and 8). This might indicate that large precipitation events are needed to compensate for the transmission losses through the sandy streambed. This assumption is supported by the regularly ceasing streamflow 100 to 150m downstream of the gauging point (Fig. 1) which is also indicated in the topographic map of the region (Le Gouvernement du Grand-Duché de Luxembourg, 2009). The stream channel at the site SA1 is characterised by a steeply inclined logging track. The most important predictors at this site are precipitation sum and maximum precipitation intensity, while mean precipitation intensity and cumulative antecedent precipitation show a minor and soil moisture the lowest importance. This is a clear indication for infiltration excess overland flow being the main process at this site. This contradicts the findings of Wrede et al. (2014) who did not notice infiltration excess overland flow as relevant process in the sandstone sub-catchment of the Attert, Huewelerbaach. The differing result at SA1 might result from the specific constitution of the site's surrounding, where a logging track had been eroded down to the bedrock. Infiltration excess overland flow in a sandstone catchments was also observed in other catchments (Scherrer and Naef, 2003; Tanaka et al., 2005).

5.2 Uncertainties of event analysis and random forest model

This study relied on the availability of data for runoff controls, such as precipitation, soil temperature and soil moisture data. The event classification was based on two assumptions: a) snow can be neglected and b) every flow response was induced by a rainfall event. Based on those assumptions, three potential scenarios can lead to a misclassification of the events: (1) precipitation occurs as snowfall delaying the flow response (e.g. Floyd and Weiler, 2008), (2) water in the channel ceases to flow during a period of temperatures below zero (Tolonen et al., 2019) then the flow response is not captured as a direct response to a precipitation event and thus ignored by the event analysis or (3) inaccuracies or gaps in the streamflow observations exist, as described by Kaplan et al., 2019. However, scenarios (1) and (2) occur only for short timespans in the studied period and the streamflow data observed through time-lapse photography was carefully quality checked. The occurrence of snowfall and freezing water in the channel was validated by the time-lapse images from which the binary streamflow information was obtained (Kaplan et al., 2019). Freezing and thawing of water in the channel was only the main control of flow cessation and reactivation at the sites MA6, SL21 and potentially influenced the flow responses of SL2 and SL5 (Figure 3), and these sites were rejected by the model evaluation procedure.

In cases where the random forest models are not capable to represent flow responses correctly, this is usually caused either by a small test dataset (Ließ et al., 2012) or by an imbalance of the modelled classes (Lunardon et al., 2014) but also in one watershed by the differences between the locations of the observational sites where the predictor data (soil moisture and temperature) and the locations of the gauging sites where the response variables (streamflow) were collected. The comparison between the mapped event responses (Figure 5) and the model specificity and sensitivity (Figure 8) reveals that the number of events has a major effect on the accuracy of the model in all geologies. Sites with low numbers of events where this is likely to have an impact are the sites MA3, MA23, SA2 and SA3 (Figure 3). Additionally, all sites in the Foulschterbaach have a lower total number of events due to a delayed installation (Figure 5), but the reason for poor model results may also result from non-representative soil moisture data which was obtained in a different sub-catchment (See also Section 5.1.2). Mälicke et al. (2020) identified rainfall and the seasonal dynamics of evapotranspiration as the two major controls of soil moisture in the Colpach catchment. While the seasonal component is expected to be similar in the Colpach and the Foulschterbaach catchment, soil moisture responses to rainfall differ (Figure 6). The flow at the sites SL9-SL11 may also be influenced anthropogenically. Surge tanks are indicated on the plateaus of the eastern and western hillslopes of the Foulschterbaach catchment in the topographic map of the region (Le Gouvernement du Grand-Duché de Luxembourg, 2009). The flow responses classes at the sites SL1 and SL15 (both in the Colpach sub-catchment) were highly imbalanced with significantly more flow (> 100) than no-flow responses (4 - 10). This reduced the likelihood to select a representative dataset for the training datasets for these sites.

If, during the process of splitting data into training and test datasets only few events of the no-flow classification remain in the training dataset for the resampling, this leads to a non-adequate representation of the class with fewer events in the model. Based on the findings of this study, we recommend a longer monitoring period to capture a higher number of events.

Additionally, it has to be underlined that a good representation of the temporal soil moisture dynamics for all analysed catchments is important as the soil moisture was identified as the most crucial predictor for streamflow intermittency. Uncertainty may also arise from the final step of the analysis in which the importance of model predictors at each site are used in a comparison to the other sites which are located in the same geology, due to the variation of the catchment sizes. According to the findings of Kaplan et al. (2020), catchment size is among the strongest spatial predictors of intermittent streamflow occurrence in space, thus superimposing the effect of geology. The catchments included in this study have a notable range in catchment size in each geology ranging between 450m² and 734.223m² (Figure S6). However, no significant correlation between catchment size and parameter importance or mean decrease Gini was found (Figures S7, S8, S9).

6. Summary and conclusions

This study provides insight into the characteristics of rainfall events that either do or do not trigger runoff reactions in intermittent streams in watersheds of temperate climate. The results underline that controls of intermittent streamflow are dependent on the geological setting of the catchment. The main findings are summarised as follows:

(1) The classification of precipitation events into “flow” and “no-flow” responses provided an appropriate basis for further analysis in a random forest model. The number of detected events varied significantly among the different sites due to data gaps in streamflow data as a result of technical problems and delayed installation at some of the sites.

(2) A random forest model was applied for each site to model flow response classes based on the predictors of precipitation characteristics (P_{mean}, P_{max}, P_{sums} and P_D), antecedent precipitation indices (7 and 14-day API), maximum soil moisture in two soil depths (θ_{10} and θ_{50}) and minimum soil temperature. For the majority of the random forest models, maximum soil moisture during the precipitation event was identified as the main temporal control of streamflow responses.

(3) Differences between the controls of streamflow responses to precipitation events were revealed for the three geological regions. Overall, soil moisture was ~~also~~ the most prominent predictor for intermittency in the random forest models for the sites in the sandstone region in this study. However, a detailed evaluation of site location in the sandstone regions revealed either parts of marl geology in the contributing area or the presence of permanent springs, which are likely to be located at the marl-sandstone boundary. In both cases streamflow intermittency is likely caused by transmission losses. Only one site, which might be the most representative site for stream flow intermittency in sandstone, showed ephemeral streamflow controlled solely by precipitation and infiltration excess overland flow. Due to the limited number of sites with intermittent streamflow in the sandstone geology, no overarching pattern of streamflow controls could be identified. In regions characterised by marl geology the predominant controls were soil moisture in the top soil layer, antecedent precipitation, and air temperature, suggesting saturation excess overland flow are the most important processes for runoff generation, which are governed by the overlaying seasonal fluctuations of temperature. For the slate regions, soil moisture in the lower soil layer constitutes a slightly stronger predictor than soil moisture in the upper layer. This finding corresponds with results from earlier studies that

hypothesised subsurface flow with a fill and spill mechanism as the dominant control of streamflow generation in an Attert sub-catchment located in the slate region.

The combined dataset of intermittent streamflow observations, precipitation, soil moisture, and soil temperature and the methodology of using classified events in a random forest modelling allowed us to identify characteristic controls of streamflow intermittency in the marl and slate geologies. The control of soil moisture on flow responses seems to be threshold driven, while a threshold control of soil temperature was less clear and requires future research to disentangle the temperature effect as an intermittency control in temperate climates. A combined investigation of seasonal changes in evapotranspiration, snow accumulation and melt, temporary freezing of the water bodies as well as seasonal variations in the interception capacity and their effect on intermittent streamflow may have larger potential for future studies. Overall, the results of this study highlight the importance of soil moisture and temperature as controls of intermittency in a temperate climate and the different controls in the three geological settings. Future studies may increase the understanding of the spatio-temporal controls of streamflow intermittency by analysing it at geological boundary zones in the headwater catchments of the temperate climates.

Author contributions

NHK installed the monitoring network of time-lapse cameras, prepared the data, designed the analysis and carried it out. TB and MW designed the overall study and the sensor cluster monitoring network. NHK prepared the manuscript with contributions from the co-authors TB and MW.

Competing interests

The authors declare that they have no conflict of interest. Markus Weiler and Theresa Blume are editors of the journal.

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