Response to comments of Referee #1 Heye Bogena

We thank Heye Bogena for reviewing our manuscript and for the helpful suggestions for improving the study. We answer below to each comment in a point-by-point reply. For clarity, the comments of the referee were copied in black and our response is in blue.

General Comments

Despite the novelty and interesting approach to studying preferential flow, I think this manuscript is not yet ready for publication and would benefit from a more clear description of methods (e.g. using flow charts) and from focusing its content to the most interesting parts.

The number of statistical analyses is rather excessive without providing much additional insights. For instance, the generalized linear regression model analysis is difficult to comprehend (especially for readers who are not familiar with this method) and does not provide clear results.

We have added a flow chart in the method section for a clear description of the analysis. Instead of analyzing small scale spatial patterns, we now focus on the temporal dynamics of soil moisture or rainfall characteristics of large scale spatial units (landscape units). We have removed information and statistical analysis in the text that is not supporting the main findings.

We have removed the generalized linear model (GLM) since it did not provide clear results and showed problems regarding the sample size and pseudo-replicates. As suggested by referee #2 and 3 we tested a generalized linear mixed effect model (GLMM) as an alternative (see response RC3). However, the results of the GLMM provide no new insights and since most variance is explained by the random spatial factors, the fitted GLMM results cannot be used for predictions in other areas. Hence, we did not include the GLMM into the revised manuscript.

Also the discussion section is too excessive should be focused on the most important results found in this study.

The result, discussion and conclusion section was reorganized and shortened to focus on the main findings.

A new aspect of this study is usage of calculated of water flow velocities on basis of 1D steady state flow assumptions to identify preferential flow events. However, although the velocity-based preferential flow assessment of events with a sequential order of sensor response times is appropriate, the derived matrix flow velocities may be prone to large errors. First, the steady state assumption is violated during infiltration events and second, the hydraulic parameters derived from field data which are influenced by preferential flow.

(1) Steady state assumption: During infiltration events a steady state is indeed not what we observe in nature. However, instead of a computationally intensive Richards based numerical 1D solution of all events, which also suffers from the uncertainty of parameters, the boundary conditions or discretization, we decided to use a steady state assumption of unsaturated flow. We tried to account for error that is based on the steady state assumption by using the maximum gradient during the event and are thus overestimating the driving forces. The hydraulic conductivity was previously calculated based on the median water content between the event begin and peak soil moisture. To be on the safe side, we have changed the calculation of the hydraulic conductivity to the maximum (peak) water content of the both sensors during the event. Hence, we overestimate matrix flow velocity rather than underestimating it, leading to a conservative estimate of preferential flow occurrence. Even though the absolute value is overestimated, it provides a maximum matrix flow velocity that can be used for the comparison to the magnitudes of measured flow velocities.

(2) Parameters: The parameters will not be completely unaffected by PF. However, as we wrote in the manuscript the parameters are derived on a daily timestep over many years (including dry phases) and thus do not include soil moisture dynamics on event base (e.g. hours). This prevents optimization of the parameters to be able to account for fast flow in the range of 1000 cm/hour. Therefore, the parameters were seen as a valuable alternative to pedotransfer functions for estimating matrix flow. Additionally, the potential influence of fast flow in the estimated retention parameters of Sprenger et al. (2016) will lead again rather to an overestimate of matrix flow velocities and thus underestimate the frequency of occurrence of preferential flow.

These circumstances may also explain why the measured NSR is lower for Marl grassland sites than predicted by the 1D steady state flow model.

For the hypothesis testing of NSR ($P_{int} > K_{mat}$) in the Marl grassland the hood infiltrometer K_{mat} values were used (not the predicted values by the 1D steady state flow). We apologize for the unclear description and have clarified the methodology in the revised manuscript. Furthermore, we shortened the analysis and moved it to a different section of the results (section 3.1) to improve the structure of the revised manuscript.

Previous sensor based preferential studies (e.g. Wiekenkamp et al., 2016) used infiltrometer measurements to assign a meaningful threshold for the matrix flow velocity. Given that fact that hood infiltrometer measurements are available for the study area I suggest to use this data to define maximum matrix flow velocities for the different landscape units.

We changed the analysis and used both, modelled and measured matrix flow to differentiate between "slow" matrix and "fast" preferential flow.

Specific comments:

P3L5: Change to ". . . PF was more frequent during higher rainfall intensities.

We shortened the section and removed the sentence.

"P4L7: Change to ". . . and that therefore infiltration . . .

We rewrote the research questions and removed the sentence.

"P4L16: Add number of sites.

We added the number of sites to the section.

"To test our research question we analyzed a dataset of 405 soil moisture sensors at 45 sites distributed across a complex landscape (varying geology and land cover) but under similar climatic conditions."

P5L5: Change to ". . . mostly exhibit loamy texture."

We changed the sentence as suggested.

P5L5-6: Sentence reads awkward. Please reformulate and add landuse percentages.

We reformulated the sentence and land use percentage was added.

"The land cover in the Luxembourgian part of the marl region is mainly characterized by agricultural sites (30 %) and grasslands (41 %, mainly pasture) with gentle slopes (~3°)."

P5L6: How was the macroporosity defined/determined?

We specified this in the text.

"The soils show high macroporosity documented by the excavation of horizontal soil profiles and counting of pores > 2 mm Ø."

P5L15: Change to "METER Group Inc., USA"

We changed the sentence as suggested.

P6L8-9: You are actually calculating a "difference" and not a "macropore portion" of saturated hydraulic conductivity.

We agree that this term is misleading. Since this "macropore portion" of saturated hydraulic conductivity was only used for the GLM (which was removed) we removed the sentence.

P7L6: Why 6.7 mm?

The threshold was based on an intensity measurement of 80 mm/h ≈ 6.7 mm/5 min. Was changed to 80 mm h^{-1}.

P7L10-11: This should be reformulated in a less unconditional way, e.g. "The manufacturer gives an accuracy of..."

We changed the sentence as suggested.

P7L20: You should change "diel" into "diurnal" as this term is more common.

We changed the sentence as suggested.

P7L24-25: But later you decide to use 12 hour rainfall breaks, which is somewhat confusing. In order to make this more comprehensive I suggest to present the rainfall event delineation methodology completely in the method section (thus moving P11L5-15 to the method chapter).

Rainfall events were divided by 12-hour breaks, but soil moisture was tracked for additional 48 hours after the end of a rainfall event. However, we do agree that the different time steps for event definitions are confusing and moved the mentioned section (P11 L5-15 and Table 2) to the methods and clarified some parts.

P8L6-8: This is not clear to me (e.g. what is the meaning of "0.4 %"?). Please be more specific.

We clarified the unit (0.4 Vol.%).

P9L08-15: There exists a vast literature on showing that preferential flow cannot be described with classical capillary theory. Why do you still pursue this analysis although this approach is obviously prone to fail?

Good question, however, models based on classical capillary theory are still very common. Anyhow, many people still have the misconception that preferential flow occurs only at saturation or at rainfall intensities exceeding infiltration capacity. We wanted to reiterate that this is not the case while at the same time the motivation was to see the how often classical theory fails, how strong the deviation is and if there are differences between different landscape units (probably some regions could be described by matrix flow).

However, to keep our main focus we have simplified and restructured the comparison of values predicted by capillary theory with measured values (see section 2.2.2 and 3.1).

P9L11: The term "pore water pressure" only applies to subsurface water. Ponded water on the soil surface shows even positive pressures.

We agree that the sentence was unprecise. The section was shortened and the sentence was removed.

P9L13: better: "during a rainfall event infiltration capacity decreases as the soil approaches saturation"

We acknowledge the suggestion for an improved formulation. However, the analysis was simplified and the sentence was removed.

P9L27: Why should the aspect has an effect on the frequency of NSR occurrence?

Some studies found an effect of the slope aspect on the soil water properties (e.g Geroy et al. 2011, doi: 10.1002/hyp.8281). However, to focus on the main findings of our study this section was removed.

P10L4-5: better: ...as the velocity determined from the first responses of two sensors"

We changed the sentence as suggested.

P10L9-11: During infiltration events soil water flow should be governed by non-stationary conditions. Why do you believe that your stationarity assumption can be applied?

Please see our explanation under "General Comments".

P10L19-20: What does "in combination with parameter sets of Sprenger et al. (2016)" exactly means?

The formulation is confusing and was changed. van Genuchten equation was used and parametrized with the parameters from Sprenger et al. (2016).

"For obtaining the matric potential the van Genuchten retention curves (van Genuchten, 1980) were parameterized using the parameter sets of Sprenger et al. (2016) (supplement Table S2)."

P10L23-26: Nevertheless, as the inversely derived Ks-parameter of Sprenger et al.(2016) are derived from field data, they will still be affected by preferential flow and thus will be higher compared to a Ks derived from pure matrix flow.

Please see our explanation under "General Comments".

P11L22: Either use proportion or percentage

We acknowledge the suggestion for an improved formulation. However, we removed the sentence since it did not add important information.

P12L13: Add explanations of the abbreviations

We added an explanation of the abbreviations.

P13L18-26: This section comes somewhat out of the blue as it is not well related to the previous analysis. I suggest separating both sections and adding a short introduction to new one concerning soil water content changes.

We separated both sections and added a short introduction as suggested.

P13L20-21: This is difficult to understand. Please try to rephrase in a more comprehensive way.

We rephrased the sentence.

P15L2-3: This is an interesting finding. Does this correspond with seasonally varying precipitation properties?

The NSR pattern corresponds to the seasonal pattern in maximum precipitation intensity (highest from June – September) and soil moisture (lowest from July – October). We have added a graph to Figure 4 showing this.

P15L5-6: What are the possible reasons?

This result is discussed on P22L21-29. Higher macroporosity, stemflow or hydrophobicity are possible reasons. We restructured the discussion and pointed out possible mechanisms.

P16L6: The formulation "of up to~25 % of events" can be misinterpreted.

We changed the phrasing.

"…(up to ~25 % of events)…"

P16L10-11: Does this finding indicate that the inversely derived Ks-parameter of Sprenger et al. (2016) overestimate pure matrix flow?

Please see the explanation under "General Comments".

P17L1-17: I find this section not very meaningful as it cannot be well reproduced and the results are not very much enlightening. Therefore, for the sake of comprehensibility I suggest removing it.

Please see the explanation under "General Comments".

P18L11: It should "increasing" instead of "decreasing"

We apologized for this unclear phrasing. We meant "velocity is decreasing with decreasing water content." We shortened the section and changed the sentence.

"There is no clear relationship of v_{max} with θ_{ini} or P_{max} and high maximum pore water velocities can be found over the full range of θ_{ini} and P_{max}."

P18L15: I guess it should be again "increasing" instead of "decreasing"

Again we apologize for this phrasing and changed it accordingly.

P19L10: It would be interesting to see how choosing other rain gaps would influence the results (e.g. the proportion of NSR to SR events).

This was included in an earlier version of the manuscript but was removed since it made the results rather complicated and it did not add any additional information. The changes in the proportions (NSR/SR) of the reactions are relatively small (8% for Marl forest, ± 3-5% for all other landscape units), increasing with longer rain gaps for most landscape units (comparing for example 6h, 12h, and 24h rain gaps). However, there is not a clear trend of increasing proportions with longer rain gaps for all landscape units. In general the number of rain events is decreasing with longer rain gaps and events last longer (see Table 2). This leads to a decrease of soil moisture events without a reaction (NR), while SR and NSR are increasing. However, the patterns between the landscape units stay similar.

P21L26: Did you compare pre-response analysis with entire event analysis? This would be interesting with respect to the comparison with the other studies.

Similar patterns are observed using total event rainfall amount or maximum rainfall intensity of the entire event. We added a sentence to give this information for comparison. However, since the response classification is not affected by the rainfall amount or intensity after the first soil moisture sensor response we keep the pre-response in our analysis and figures.

P21L28-29: I cannot follow this argument. Please explain in more detail.

In the sandstone grassland PF seems to be more often initialized at higher initial saturation, simply because infiltration capacity is lower and saturation is achieved faster compared to dry conditions. This is in contrast to the other landscape units with higher clay content, where more NSR is found under dry conditions with soil structure formation or hydrophobicity being the driving mechanism. The section in the discussion was restructured.

P23L7-11: In my view, the results of this study rather suggest that the occurrence of preferential flow is governed by unresolved small-scale structures and processes. The study of Wiekenkamp et al. (2016) used an even denser soil moisture sensor network and still could not find landscape properties to explain their results.

We totally agree. However, these small-scale structures and processes can probably be attributed to landscape properties. Different combinations of the landscape properties could lead to similar flow reactions making it hard to distinguish. We hypothesize that due to the high heterogeneity of soils it would need much more sensors (even more than in Wiekenkamp et al. (2016)) to identify them. Since we removed the analysis of landscape features, such as topography, the section was also removed.

P23L17-18: Why should the lower k_mat values of the Marl site lead to more NSR events and how do you know that the matrix infiltration capacity was underestimated?

See P9L13-15. The saturated matrix hydraulic conductivity (K_{mat}) was estimated using the hood infiltrometer that corresponds to the infiltration capacity at full saturation. We did not measure infiltration capacity at various moisture contents. Since the infiltration capacity is increasing with lower initial soil water content we rather underestimate the infiltration capacity under field conditions using K_{mat} (because soils are rarely saturated in our catchment).

Our capillary-based estimation of NSR is again a conservative approach using this minimum infiltration capacity (K_{mat}). NSR is overestimated, because the infiltration capacity is underestimated (the threshold is more often exceeded then with a higher infiltration capacity).

However, to have a clearer structure of the study (especially results) and focus on the main analysis we will remove the comparison of the observed NSR responses with the estimated preferential flow reaction based on matrix hydraulic conductivity. Instead a short comparison of expected PF occurrence based on P_{max} and K_{mat} was added to section 3.1.

P23L18-19: Why should the overestimation of NSR by capillary theory in the Marl grassland be an indication of more vertical macropore flow?

We estimated more events with infiltration capacities (in our case K_{mat}) lower than maximum rainfall intensities in the Marl grassland and hence we should observe PF. Since we measured NSR less frequently than estimated by this approach, we hypothesized that these events have probably not resulted in PF with a NSR (non-homogenous flow), but rather in fast SR, which is supported by the high wetting front velocities. As correctly stated by the referee it has not to be vertical, but we do not observe a break in the sensor reaction sequence.

We clarified the possible mechanisms in the discussion (section 4.5) and supported the analysis with the seasonal v_{max} patterns showing increased fast flow (high v_{max}) on grasslands during summer.

P24L23-28: These arguments are rather dubious.

We agree that these arguments are rather vague and speculative, hence the section was removed.

P24L23-P25L11: This section is a rather excessive discussion that does not provide much additional insights.

We partly removed this section and some sentences were moved to a different section. In general, the discussion will be restructured and will focus on the main findings.

P24L29: I guess it should be "increase" instead of "decrease".

We apologize again for causing confusion by our repeated erroneous phrasing.

P25L2-4: Remove repetition.

We removed the repetition.

P25L16: ". . . showed . . ."

The conclusion was partly rewritten.

P25L17: ". . . in deeper . . ."

The conclusion was partly rewritten.

P25L20: "showed" instead of "had"

The conclusion was partly rewritten.

P25L21: You did not prove the occurrence of "non-homogeneous wetter fronts". There are other mechanisms that can lead to preferential flow (e.g. by-pass flow).

We used NSR only as a proxy for preferential flow. However, we think that NSR in the first place only proved that there was a non-homogeneous wetting front that could be generated by preferential flow (see P8L22-23). This non-homogeneous wetting front can be generated by various preferential flow process (including by-pass flow). We have clarified that.

P25L23-P26L7: Please focus on presenting the main results in the conclusion section and avoid vague speculations.

We have rewritten the conclusion section and will focus on the main findings.

Figures

Figure 9: Dots are difficult to discern.

The figure was removed.

Response to comments of anonymous Referee #2

We thank the anonymous referee #2 for reviewing our manuscript and the comments concerning mainly statistical issues. We answer below to each comment in a point-by-point reply. For clarity, the comments of the referee were copied in black and our comments are in blue.

General Comments

The results are very difficult to follow and it is not always clear why certain analyses were done and how they link back to the main objectives of the study. It is often not clear how and why soil profiles were grouped for certain analyses. I encourage the authors to provide more clarity on the analyses and highlight how the analyses address the research objectives.

We added a flow chart in the method section for a clear description of the analysis and clarified the grouping of the soil moisture profiles for each analysis step. We have also better connected the different sections to the objectives and therefore improved structure and readability.

a) Statistical issues

Some of the key conclusions made in this study rely on frequentist statistical testing (e.g. p-values), which, as the authors acknowledge (p23,l5-11), can be highly sensitive to sample size issues. There has also been considerable discussion recently about the major limitations to this approach (see Amrhein et al. 2019. Nature 567:305-307 for a very recent example, also Wasserstein and Lazar 2016. The American Statistician 70:129-133). It might be valuable if the authors discuss some of the inferential uncertainties and limitations of their approach.

It is true that different sample sizes can lead to problems in the interpretation of test statistics (as shown in e.g. Amrhein et al. 2019. Nature 567:305-307) and that the p-value should not be used as a rigorous yes/no criterion. However, test statistics can give additional insights, especially while comparing large samples. None of our analysis and interpretations is purely based on p-value statistics and they were just added to give additional information (such as error bars, distributions etc.). Since sample size is a critical issue we added the sample size where it was missing in the manuscript (or supplement) to support interpretation.

1) pseudo-replication: It seems to me that the statistical models should be fit to the 45 sites, not the 135 soil profiles, since the grouping of three profiles within each site cannot be treated as independent. Focusing on the 135 soil profiles could be done within the GLMs if within-site variability were accounted for, but it's not clear to me that this was done.

The linear model (LM) was fitted to the mean NSR percentage of the 45 sites. The generalized linear model (GLM) was fitted to the infiltration events of the 135 profiles since it covers the temporal domain. Indeed pseudo-replications are an issue for the GLM. We tested a generalized linear mixed effect model (GLMM) as an alternative (see response RC3). By using a GLMM for the 45 sites with the individual sites as the random effect of the model we avoided pseudo-replications and treated the individual spatial landscape effects (geology, land-cover, slope, aspect etc.) together as one random landscape effect.

However, the results of the GLMM provide no new insights and since most variance is explained by the random spatial factors, the fitted GLMM results cannot be used for predictions in other areas. Hence, we did not include the GLMM into the manuscript.

2) sample size vs number of predictor variables used in the models: Although there is an impressive amount of data collected for this study, I'm concerned that some of the results (e.g., identification of statistically significant predictors) are simply the product of small sample sizes and noise in the model fits. For example, the GLM for Grassland- Sandstone was fit to 9 soil moisture profiles (so really, just three sites), but 13 predictor variables were used in the model fitting, which will result in an underdetermined solution. If the authors decide to keep the statistical analyses, I would suggest some sort of cross-validation exercise be done to assess the rigor of the models.

The GLM was fitted to all events of the 9 profiles of the Sandstone grassland sites, which are 698 data points. Furthermore, some predictors were removed by stepwise AIC, so that only four predictors were used (not 13). Hence, the model does not result in an underdetermined solution. However, as already mentioned above, the GLM was removed from the analysis.

3) data exclusion. It was suggested in the methods that there is some incompleteness to the time series for each soil profile (due to logger failures and criteria for including data in the analysis). How many sites and profiles were excluded and for what time periods? This is important to know as it relates to the sample size issue outlined above.

We added a diagram to the supplement that shows how many profiles in which landscape units were “active” (met the quality criteria) over the entire time period (~2012-2017).

b) Within-site and temporal variability

Instead of focusing on statistical significance, I think the authors could make an excellent contribution by focusing more on the within-site and temporal variability of their field measurements. My understanding is that the grouping of the sampling approach can be organized as: geology - land cover - site - profile. Most of the analysis focuses at the geological and land cover levels; however, throughout the manuscript I found myself constantly wanting to know more about the within-site variability in terms of both infiltration event characteristics and soil properties. Also, at the profile level, I wanted to know more about the temporal variability. Did profiles that exhibit NSR only exhibit NSR or did they shift between NR, SR and NSR? If so, why? Instead of generalizing the results using p-values, I suggest focusing on graphical approaches to show evidence to support the research objectives.

The within-site/profile variability is indeed an interesting topic. We will add a sentence about the within-site variability to the results. Table 3 already gives some information about the within-profile variability.

“The NSR variability between the single profiles within a landscape unit was found to be high (Table 3). The site-intern variability of NSR (profiles within the same sites) measured as the median standard deviation was highest in marl (forest: 7.5 %, grassland 6.4 %) followed by slate (forest: 4.2 %, grassland 6.1 %) and sandstone (forest: 1.9 %, grassland 3.0 %).”

However, the site or profile-level variability was not the main aim of this study. Other studies have already focused on that topic (see e.g. Wiekenkamp et al. (2016) or Liu and Lin (2015) in the reference list of the manuscript). The aim was to show the effect and variation of larger-scale landscape units with different properties. Furthermore, we wanted to identify potential temporal differences and similarities among their reactions. We clarified the aim of the study in the revised manuscript.

Many results in the manuscript include graphical approaches (see Fig. 3, 4, 6, 7, 8 and new diagrams were added to the revised manuscript). We do not think that adding the test statistics weakens our findings (see response to General Comments).

Specific Comments

p1,l27-28: Consider incorporating the parenthetical into the sentence - as is, this makes for a weak opening.

The parenthetical was removed.

p2,l17: Consider removing this last sentence or expand on it to clarify to the reader what is meant by hotspots and hot moments of PF.

We removed the sentence.

p2,l29-p3,l18: Consider revising these paragraphs. Right now these feel like simply a list of results from other studies. I suggest trying to better synthesize these results and identify key findings and knowledge gaps.

We have revise the paragraph and summarized the studies.

p4,l9-11: I think the research questions could be improved. What is meant by ’underlying controls’? Has this actually been done in this study? It seems like the PF proxies are linked to precipitation, landscape, and soil characteristics through statistical modeling. ’Underlying controls’ suggests to me a more process-based approach (e.g., soil physics modelling), which isn’t done in this study - outside of the predicted matrix flow velocities. What is meant by temporally stable?

Indeed we did not clearly identify processes. The research question will be rephrased. By “underlying controls” we meant spatial and temporal influences or drivers of preferential flow occurrence on a larger scale (e.g. landscape units).

“Temporally stable” refers to the preferential flow occurrence (if it is changing over time or not).

“Therefore, the main aim of this study is to identify and compare the temporal dynamic of PF occurrence by using profiles of soil moisture sensors in different large-scale spatial units that could potentially be used as representative units for catchment modelling. Since it can be expected that rainfall intensity and soil moisture have a strong influence on the initialization of PF (Beven and Germann, 1982) we will mainly focus on the temporal controls of initial soil moisture and rainfall. More specifically, we attempt to answer the following question: Does PF occurrence increase with rainfall intensity since higher intensity leads more frequently to an exceedance of matrix infiltration capacity? Does PF occur more often under wet conditions

since the infiltration capacity is lower? How is the temporal PF dynamic influenced by spatial factors like geology/soil type and land cover?"

p5,l25-26: What is the orifice diameter of the rainfall gauges? How was the placement of the forest gauges determined? Was variability in canopy cover and throughfall a concern?

The orifice diameter of the rain gauges is 16.5 cm (collection area 214 cm^2). The rain gauges were randomly placed on the 29 forest sites. The information was added to the sentence. The experimental design of placing the five throughfall gauges aimed at covering the variability in canopy cover at each site, and variability in measured throughfall between the gauges was expected.

p6,l3: Why weren't infiltrometer measurements available for the grassland/Sandstone sites?

Hood infiltrometer measurements are often time consuming and we were not able to measure all sites during the same field campaigns.

p7,l5: Why would the sensors log these kinds of 'implausible' events? How many events were rejected because of these criteria?

During the reconnecting of the loggers following a logger error (no power etc.), the rain gauges sometimes produced this kind of implausible events. Furthermore, clogging and release of the clogged water could be a reason of the unrealistic rainfall events. The number of rejected events was added (text and flow chart).

"These implausible events were observed to happen during the reconnecting of the loggers following a logger error (no power etc.) or clogging and release of the clogged water."

"By applying the quality criteria for rainfall events using t_e = 12 h, 1392 of 32025 rain events (sum of profile rainfall events) were excluded because of the threshold criteria and 426 because the mean temperature was below 0°C during the event."

p7,l29-31: How many times were data from a profile rejected because of these criteria?

We included the number of rejected soil moisture event and the explanation into the section and the flow chart.

"From the total of 30207 rainfall events, 15645 could be used for the analysis of the soil moisture, since they allowed for a clear separation of soil water flow by more than 24h without a new rainfall input. 7395 of these events did not meet the quality criteria of completeness and consistency of the soil moisture time series, hence 8250 infiltration events (sum of soil moisture

event observations at all 135 profiles) could be used for the analysis. Changing the completeness criterion from 99% usable soil moisture data points during an event to e.g. 95% is only slightly affecting the number of infiltration events (e.g. 8353 events usable in the analysis). This is due to the fact that most exclusions result from long term failure of one sensor of a profile that leads to a complete exclusion of the entire profile.“

Table 1: The first row highlights to me the potential issue of pseudo-replication in this study. It seems more appropriate to report the number of sites, not profiles. Also, for the soil texture and mean clay content, how variable were these values within geological and cover class combinations?

Table 1 is just an overview of the study sites. The different sensor responses (SR, NSR) were calculated for every single soil moisture profile. We think it is appropriate to give the number of profiles, since they determine the number of observations. We added the full textural information and the standard deviation to the supplement materials.

p9,l18-26: This paragraph is unclear. Why were some GLMs fit for individual landscape units and one GLM fit to all profiles? What was the sample size used in each of these models? If I understand this correctly, the GLM model for Sandstone-Grassland was fit to just 3 sites (9 profiles)? This seems like much too small sample size to fit models with up to 13 predictor variables.

Please see our response under General Comments. The GLM was fitted to the individual landscape units to test for differences in the predictors on this scale. Furthermore, we compared it with one GLM for the whole catchment to see the potential for such an approach.

However, as already mentioned above, the GLM was removed from the analysis.

p9,l27: Why restrict to slopes > 10%?

A slope < 10% is relatively flat and the orientation is not strongly pronounced. To focus on the main findings of this study (temporal variability of PF occurrence between landscape units), the analysis of the aspect was removed.

Fig 2a: I’m not sure what conclusions to draw from this graph? The text suggests that it shows no clear difference between landscape units; however, there appear to be considerable differences in cumulative precipitation (e.g., for event numbers ~ 150, we see a range of P[sum] of almost 750 mm). Also, I don’t think the various landscape units share the same event records (i.e., the x-axis is not sequential for each landscape unit), so are they comparable?

It is correct that the events are not identical and necessarily sequential due to the rainfall heterogeneity, quality criteria, and the length of the time series. Therefore, single sites can show high deviation even within the same landscape unit. The motivation was to show that there is no systematic difference between the landscape units. We think that Fig. 2b) provides enough information and we will remove Fig. 2a).

p11,l24: Why only 2014 and 2015?

These were the first two years with all sites installed. Since the calculated proportions of these two years (and also the other years) do not add additional relevant information for interpretation, we removed the section to focus on the main findings.

p15,l1: Would a relationship between NSR and distance to stream be expected? Perhaps a provide a rationale.

Some authors found a relationship on hillslope position (see references P22L32-P23L4). We agree that an explanation should be mentioned earlier in the manuscript and is currently missing. However, the analysis of the small scale spatial patterns will be removed to focus on the main findings (temporal patterns of soil moisture and rainfall).

Fig 4: Where do these data come from? Are these averages across all years in the study? How much did this vary between years? Does this figure account for differing number of events each year or exclusion of profiles due to logger failure or selection criteria?

Fig. 4 is based on the same data as all other diagrams. It shows the mean NSR of all events that were measured in the twelve individual months independent of the landscape unit. Hence, the diagram averages across different years. We have modified this diagram and separate between forest and grassland sites and added additional shaded areas to show the variability among years. The number of events used for this analysis (number of events per month for all years and the min. and max. of individual years) was added to a table in the supplement.

Fig 8: The fit is statistically significant (but see general comment (a) above), but is this relationship practically meaningful? If you were to remove the line of best fit, I'm not sure someone would identify a relationship in these data.

We totally agree, the fit is statistically significant, but explains only little variation (we wrote this on P18L11-12). Furthermore, on P24L28-30 we note: "The θ-v_{max} relationship shows that even though the decrease of v_{max} with [decreasing] θ is significant, it has little explanatory power and fast flow (>1000 cm day^{-1}) can occur at any θ." The fit was included to highlight the strong variation that not simply follows the trend. However, we removed the fit in the new version of the manuscript.

p22,l32: How much range in hillslope position was sampled? Was this the distance to stream metric?

The range of hillslope position was determined by the distance to stream with a range between 4 and 251 m from the different sites to the stream. Please see the table in Appendix A. However, this analysis was removed to focus on the main findings.

p24,l10: Speculations on why this is?

Texture seems not to be the main driver of water flow velocity during infiltration in the classical manner that fine grained texture corresponds to slow flow. Infiltration seems to be strongly controlled by PF phenomena, which are dependent on soil structure (influenced by a high clay content), biotic macropores (roots channels, earthworm borrows) and initiation processes (hydrophobicity, rain intensity). The high heterogeneity of the landscape and its temporal variation leads to PF that is caused by different drivers that are partly independent of texture (e.g. organic carbon content, number and species of soil organisms, vegetation type, rainfall characteristics). We clarified this in the conclusion of the revised manuscript.

Response to comments of anonymous Referee #3

We thank the anonymous referee #3 for reviewing our manuscript and his suggestion for improving the temporal occurrence model of preferential flow (PF). We answer below to each comment in a point-by-point reply. For clarity, the comments of the referee were copied in black and our comments are in blue.

General Comments

Primarily the structure and selection of results should be reconsidered, but also a more defined storyline could assist the reader to extract the main novelties of this study. In general, the manuscript could benefit from reconsidering what information is necessary to broadcast the main message. I recommend to consider a few key figures that conveniently show the reader the approach and main interesting findings, instead of a long sequence of tables and graphs. Lastly, the readability would greatly increase if the authors consider a key phrase in each paragraph that, perhaps almost trivially, highlights what should be learned from the given information.

For the structure of the paper, I would recommend to consider separation of the hypothesis and throughout the paper clearly indicate which sections address information for which hypothesis. I miss this in the paper. The hypothesis could possibly be broken up in two sections. For example: 1) PF is the dominant process during infiltration, and 2) capillary theory does not suffice to explain infiltration. These can be tested for the given explanatory factors, such as land cover, geology etc. Which also gives more structure in the result and discussion section.

In the revised manuscript we have restructured the methods and results and focused on the main findings, the temporal dynamics of PF in different large scale spatial units (landscape units). By removing most of the small-scale spatial analysis we highlighted the main storyline. Additionally, we added introduction phrases for the single sections. A flow chart further helps to follow the analysis that were performed. The comparison with the capillary theory, as one of the aims of the study, was removed.

We think that these changes help to improve the readability and to follow the storyline of the manuscript.

The generalized linear model (GLM) provided insight in the explanatory power of a large set of variables. However, as anonymous referee #2 addressed, there are some limitations to this approach. I will not re-evaluate these points, but I instead would recommend the authors to consider the use of mixed effect models. This approach allows to include random factors that potentially explain variability but are not directly incorporated in the study design. Seen the authors use R, the packages 'lme4', 'lmerTest', and 'nlme' could relatively easily allow to explore the use of mixed effect models.

We thank you for the suggestion and removed the GLM and tested a generalized linear mixed effect model (GLMM) that incorporates the spatial site information as a random effect.

We fitted a binomial GLMM (using the R package lme4) to the response classification of all our 8250 infiltration events with a logit link function due to the binary nature of our data (*NSR* yes/no). The spatial domain was taken as the random effect (random intercept and slope) on the scale of the 45 sites. For evaluating the model, the R^2 (delta method) for GLMMs introduced by of Nakagawa et al. 2017 (http://dx.doi.org/10.1098/rsif.2017.0213) was calculated using its implementation into the "R" package "MuMIn" (https://cran.r-project.org/web/packages/MuMIn/index.html). The R^2 of a GLMM can be divided into a marginal R^2 (R^2_m), which gives the proportion of explained total variance by the fixed effects and a conditional R^2 (R^2_c) that gives the explained variance of both fixed and random effects. We found a R^2_c of 0.17 and a R^2_m of 0.03 showing that most variance is explained by the random effects.

The results of the GLMM provide no new insights and since most variance is explained by the random spatial factors, the fitted GLMM results cannot be used for predictions in other areas. Hence, we did not include the GLMM into the manuscript.

On a final note, I wonder if there is any indication that the contributing area of each site is independent of the occurrence of NSR? A correlation could guide towards rising groundwater tables and associated capillary rise, or horizontal flow. Especially with high antecedent soil moisture groundwater response could be relatively fast when contributing area is large.

We have calculated the upslope contributing area for each site and compared it against NSR occurrence. The Spearman R is 0.1 and hence, influence of groundwater in the upper 0.5 m of soil seems to be small for our sites. This is supported by the fact that % NSR and distance to stream does not show a correlation (P15L1).

Specific Comments

P2L17 Seems out of context to mention hotspots or hot moments, especially as a final statement of the section. The statement needs further elaboration and references.

We agree that the sentence is out of context at the end of this section and removed it.

P2L26 '…scale (~ km2) and' Is this referring to 1 km2 to be considered large scale, or is a number missing?

It means "on a kilometer scale", and is considered to be large scale for PF, since spatial and temporal information on PF occurrence is usually only known on a plot scale (centimeters to meters).

P3L11 This section seems out of place, considering reorganizing with earlier paragraphs covering methods.

The section was reorganized and shortened.

P6L1 Appendix A: consider presenting standard errors of the K measurements

We have added the standard error.

P8L15 How can observations at a single depth be considered sequential?

We changed the classification and combined the 10 cm only reaction together with the NR events (no response) to the new class of "not classifiable" infiltration events (NC).

P11L5 I would start with the most interesting finding of this study, although it could be strictly seen as a result, I could see this information to be more suited in the methods section.

We moved the analysis of the rainfall event separation to the methods.

P24L10 The range of reported flow velocities both in this study and other reported studies generally seems extremely large. If the range is large to begin with, how is it remarkable that they fall in the same range? Perhaps I miss a part of the reasoning.

We have clarified the section.

"In summary, it is remarkable that no clear differences in flow velocities between different soil types could be identified (neither in our study nor across all previous studies). Instead, all soil types showed a similarly large range of velocities (10^0 – 10^5 cm day^{-1}). Furthermore, one can

see orders of magnitude difference in v_{max} between different events but not among the landscape units."

P25L15 Awkward sentence structure.

The conclusion was partly rewritten.

P25L29 Although this seems like an insightful comment, are there any examples how this could be implemented, or is it readily tested on small scale? A reference would be useful here.

The conclusion was partly rewritten and the sentence was changed.

Response to comments of Referee #4 Nicholas Jarvis

We thank Nicholas Jarvis for reviewing our manuscript and his comments on the preferential flow phenomena we have observed. We answer below to each comment in a point-by-point reply. For clarity, the comments of the referee were copied in black and our comments are in blue.

General Comments

As the fourth person to comment, I hesitate to add too much to what the others have already written. However, one thing that surprised me was the data on hydraulic conductivity measured by Hood infiltrometer. Some of the values at matrix saturation are as large as 500 cm/day, which seems excessively large for infiltration rates measured at a tension of 6 cm, ostensibly unaffected by soil macropores. Even some of the total saturated hydraulic conductivities seem extraordinarily large to me, varying up to 1500 to 2000 cm/day. Maybe my surprise is just a consequence of the fact that I am more familiar with arable soils, not forest soils. No details are given of the method. I wonder, for example, how the 3D nature of the flow under the infiltrometer is accounted for? If it isn't accounted for, you could seriously overestimate K, especially in strongly layered soils. Could the authors give more details on the method?

Forest topsoils can have extremely high saturated hydraulic conductivities (see e.g. Greenwood & Buttle 2014, doi: 10.1002/eco.1320; Gonzalez-Sosa et al. 2010, doi: 10.1002/hyp.7640). Our soils were very structured and permeable (sometimes infiltration was too high to fill the hood of the infiltrometer). At some points the values were verified with double ring infiltrometer measurements being in the same range of conductivities. All measurements include tensions close to saturation and hence, the saturated hydraulic conductivity values (tension 0 cm) are more reliable. Matrix saturated hydraulic conductivity (tension 6 cm) was calculated from a Gardner function that was fitted to the measured tensions. Due to the high macroporosity at many forest locations pressure in the hood was difficult to adjust and measurements could only be conducted for maximum tensions of 1-3 cm. Hence, fore some sites matrix saturated hydraulic conductivity is just an extrapolation of the Gardner fit. However, high matrix saturated hydraulic conductivities were mainly measured in the sandy topsoils of the Marl and Luxemburg Sandstone and therefore the values seem to be plausible to us.

The hood infiltrometer is described in greater detail in Schwärzel & Punzel 2007 (doi: 10.2136/sssaj2006.0104). The derivation of matrix saturated hydraulic conductivity from measured infiltration rates (hood infiltrometer) accounts for the 3D nature of flow using the solution of Woodings 1968 (steady state infiltration from a circular source).

We have clarified the hood infiltrometer method in the revised manuscript.

The authors attempt to test the hypothesis that preferential flow in macropores in only generated if the rainfall rate exceeds the matrix infiltration capacity, such that the pore water pressure is close to atmospheric pressure at the soil surface. But their approach is rather indirect and therefore prone to errors and uncertainties. The best (only proper?) way to test this hypothesis would be to install tensiometers to measure soil water pressure potential, as well as the probes for soil moisture content. I think their conclusions on this point may be a little suspect, especially considering the unusually large matrix infiltration rates they measured (see above).

We agree that tensiometers would help to validate our preferential flow observation. At each site we had one profile of the Decagon MPS-2 sensors which measure only water potentials < -90 hPa. Therefore the sensors were not suited to detect preferential flow.

Our method (max. rainfall rate exceeds the matrix infiltration capacity) is indeed an indirect estimation of preferential flow occurrence, as mentioned by the referee. In contrast to a direct method (like tensiometers) the aim of the analysis was not to validate our preferential flow measurements, but rather to compare the observations with an estimation by a capillary approach (based on matrix hydraulic conductivities).

To have a clearer structure of the study (especially results) and focus on the main analysis we have removed this comparison of measured data with a capillary approach ($P_{max} > K_{mat}$) to a large extend.

Connected to this, I think the authors could consider re-phrasing the text at lines 739-743: these non-capillary flow mechanisms certainly contribute to flow close to saturation. However, studies of the physics of these flow processes suggests that they also require pressures quite close to atmospheric pressure for them to generate faster flow velocities than those in the matrix (see discussion and cited papers in Jarvis, 2007, p.528-529). I haven’t seen any later studies that clearly contradict those findings.

It is correct that also alternative flow processes (e.g. film flow) require a relatively low soil water potential (high saturation). On P23L13-15 we wrote: “Higher occurrence of measured

NSR compared to capillary theory prediction could indicate other initiation and flow mechanisms […]”. The sentence is vaguely phrased and we apologize for that. The meaning was, that unknown initiation processes (local depressions, channeling of water by vegetation, hydrophobicity, etc.) can locally lead to higher water contents and alternative flow processes. We have clarified this sentence.

“[…] Furthermore, the mismatch of measured PF occurrence (NSR, fast v_{max}) compared to the prediction based on P_{max} exceeding K_{mat} indicates that initiation processes such as hydrophobicity/water repellency, local microtopographic depressions or channeling of water by vegetation could be the reason of the frequent occurrence of PF (Blume et al., 2008; Doerr et al., 2000; Schwärzel et al., 2012; Weiler and Naef, 2003). Locally, these processes can lead to higher water contents and thereby pressures at the soil surface close to atmospheric pressure which in turn trigger PF.”

The fact that preferential flow is strongest when the soil is dry suggests that the likeliest explanation of your results is the occurrence of water repellency, which is known to be a common feature of forest soils. Water repellency causes water potentials to quickly reach very close to zero, even during quite light rainfall, so that water can flow into surface-vented macropores even when the soil is dry. The authors do briefly mention hydrophobicity as a possible reason for their results (lines 694-697), but then seem to dismiss it, which I think is a pity. Preferential flow through macropores generated by the occurrence of (sub-critical) water repellency has been reported in several studies in recent years (see those cited in the review by Jarvis et al., 2016. Vadose Zone Journal, doi:10.2136/vzj2016). I think this topic should be discussed more fully in the paper and some of these recent studies cited.

We agree. We have restructured and partly rewritten the discussion and have stronger considered hydrophobicity as an initiation mechanism of PF.

I didn’t get a clear idea of whether the hypothesis on Line 145 was accepted or rejected? The first question is what is meant by “dominate”? Is it the frequency of rain events that generate preferential flow or the amount of water recharging through the unsaturated zone (or something else)? Looking at the text on lines 426 and 432-433, it would seem that preferential flow was not a dominant process (which would also tally with the very high matrix saturated hydraulic conductivities). But I got a different impression from the conclusions, at lines 828-832. Could this be clarified?

The word "dominates" might be too strong and we have rephrased the research question and the conclusion. We mainly focus on the frequency of preferential flow occurrence. To draw a conclusion on the amount of water that is transported or that contributes to groundwater recharge it would require a physically based model (out of the scope of this study). Therefore, we only used the observed water content change as an estimate.

To answer the question if preferential flow is "dominant": We found preferential flow in all our landscape units, but being temporally highly variable. We were able to find hotspot landscapes (clayey soils, forests) and hot moments (dry, high rainfall intensity) of preferential flow occurrence. This verifies that preferential flow is a common and important, spatially and temporally variable process, but maybe not a dominating process.

New research question and aim:

"Therefore, the main aim of this study is to identify and compare the temporal dynamic of PF occurrence by using profiles of soil moisture sensors in different large-scale spatial units that could potentially be used as representative units for catchment modelling. Since it can be expected that rainfall intensity and soil moisture have a strong influence on the initialization of PF (Beven and Germann, 1982) we will mainly focus on the temporal controls of initial soil moisture and rainfall. More specifically, we attempt to answer the following question: Does PF occurrence increase with rainfall intensity since higher intensity leads more frequently to an exceedance of matrix infiltration capacity? Does PF occur more often under wet conditions since the infiltration capacity is lower? How is the temporal PF dynamic influenced by spatial factors like geology/soil type and land cover?"

Finally, one general comment on terminology: I think it would good if the authors avoided the use of the term "wetting front" and "wetting front velocity". If you have strong preferential flow, there should not be a well-defined wetting front. Maybe you can write "maximum pore water velocity" instead of "wetting front velocity"?

We agree that the term is not precise. We used this term since it is relatively often used in the literature (see e.g. Hardie et al. 2013, doi: 10.1016/j.jconhyd.2012.10.008; Germann & Hensel 2006, doi: 10.2136/vzj2005.0080). However, the term "maximum pore water velocity" is more appropriate and we have changed it according to your suggestion.

Specific Comments

1.) Line 41: Jarvis (2016) is not in the reference list. I think you mean Jarvis et al. 2016?

We apologize for giving a citation that is not in the reference list. The citation was changed to the intended reference: Larsbo et al. 2014 (doi:10.5194/hess-18-5255-2014).

2.) Lines 64-68: you neglected one very important method and that is the analysis of breakthrough curves for non-reactive solutes (tracers). Perhaps this could be added here with one or two appropriate references?

We have added the analysis of breakthrough curves as a potential method with Koestel et al. 2013 (doi:10.1002/wrcr.20079) as a reference.

3.) Lines 70-72: These are not really direct measurements (see line 69). In this respect, X-ray tomography of flow/transport is the only method that gives direct measurements (see Sammartino, S., et al. 2015. Identifying the functional macropore network related to preferential flow in structured soils. Vadose Zone J., doi:10.2136/vzj2015.05.0070; Koestel, J., Larsbo, M. 2014. Imaging and quantification of preferential solute transport in soil macropores. Water Resources Research, 50, 4357–4378).

We agree that the mentioned methods are no direct measurements. We will change the sentence to: *"Another way to identify the potential for PF are measurements that can be related to the number and volume of macropores or cracks."*

4.) Line 202: robur

We corrected the latin name.

5.) Line 311: "non-uniform flow" is simpler and better than "non-homogeneous wetting front"

We changed it as suggested to the term "non-uniform flow".

6.) Lines 324-328: This is confusing. I think it could be written more clearly and much simpler: "In addition, the hypothesis is tested that preferential flow in macropores is only generated if the rainfall rate exceeds the matrix infiltration capacity, such that the pore water pressure reaches values close to atmospheric pressure at the soil surface"

We thank you for this suggestion of an alternative and simpler phrasing. However, the sentence was removed due to the restructuring of the methods section.

7.) Line 368: "matric" not "matrix"

We corrected the word as suggested.

8.) Line 377: Delete “Mualem”

We removed the word “Mualem”.

~~Relevance~~Spatio-temporal relevance and controls of preferential flow at the landscape scale

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Abstract

The spatial and temporal controls of preferential flow (PF) during infiltration are still not fully understood. ~~Soil~~As soil moisture sensor networks ~~give the possibility~~allow us to ~~measure~~capture infiltration ~~response~~responses in high temporal and spatial resolution~~. Therefore, we used~~ our study is based on a large-scale sensor network with 135 soil moisture profiles distributed across a complex catchment. The experimental design covers three major geological regions (~~Slate, Marl, Sandstone~~slate, marl, sandstone) and two land covers (forest, grassland) in Luxembourg. We analyzed the responses of up to 353 rainfall events for ~~every~~each of the 135 soil moisture profiles. Non-sequential responses (*NSR*) within the soil moisture depth-profiles were taken as ~~an~~one indication of ~~PF~~bypass flow. For sequential responses ~~wetting front~~ maximum pore water velocities (v_{max}) were determined from the observations and compared with ~~predictions by~~ velocity estimates of capillary flow. A measured ~~wetting front velocity~~ v_{max} higher than the capillary prediction was ~~also~~ taken as a ~~proxy for PF.~~further indication for PF. While PF was identified as a common process during infiltration it was also temporally and spatially highly variable. We found a strong dependence of PF on the initial soil water content and the maximum rainfall intensity. Whereas a high rainfall intensity increased PF (*NSR*, v_{max}) as expected, most geologies and land covers showed highest PF under dry initial conditions. Hence, we identified a strong seasonality of both *NSR* and higher v_{mat} dependent on land cover, revealing a lower occurrence of PF during spring and increased occurrence during summer and early autumn, probably due to water repellency. We observed the highest fraction of non-sequential response (*NSR*) in forests on clay-rich soils (~~Slate, Marl). Furthermore, these two landscape units showed an increase of *NSR* with lower initial soil water content and higher maximum rainfall intensity. Wetting fronts~~slate, marl). Maximum pore water velocities ranged from 6 cm day^{-1} to 80640 cm day^{-1} with a median of ~~113~~120 cm day^{-1} across all events and ~~landscape units.~~soil moisture profiles. The soils in the ~~Marl~~marl geology had the highest flow velocities, independent of land cover, especially between 30 and 50 cm depth where the clay content increased. ~~For Marl the median water content change was highest for the deepest soil moisture sensor (50 cm), whereas the other two geologies (Slate, Sandstone) showed a decrease of soil moisture change with depth. This confirms that clay content and vegetation strongly influence infiltration and reinforce preferential flow. Capillary-based soil water flow modelling was unable to predict the~~

observed patterns. This demonstrates the danger of treating especially clay soils in the vadose zone as a low-conductivity layerconductive substrate, as the development of soil structure can dominate over the effectmatrix property of low-conductive the texture alone. This confirms that clay content and land cover strongly influence infiltration and reinforce PF, but also seasonal dynamics and flow initiation have an important impact on PF.

Formatiert: Nicht Hervorheben

1. Introduction

Preferential flow (PF) in soils describes different flow processes with higher flow velocities than soil matrix flow (when soil water content and soil water potential is at equilibrium)and heterogeneous flow patterns (Hendrickx and Flury, 2001). Many studies have shown that PF is ubiquitous (Jarvis, 2007) and that "PF is the norm and not the exception" (Weiler 2017). PF can affect water distribution in soil (Ritsema et al., 1996), groundwater recharge (Ireson and Butler, 2011), root water uptake (Schwärzel et al., 2009) and solute transport (Jarvis 2016).(Larsbo et al., 2014). Since the early work of Beven and Germann (1982), the importance of PF pathways such as macropores (created by roots, earthworms), fissures or cracks is widely recognized. Most studies focusing on different PF processes,Many studies have shown that PF is ubiquitous (Jarvis, 2007) and that "PF is the norm and not the exception" (Weiler 2017). Most of the studies focusing on different PF processes such as fingered flow (Selker et al., 1992), macropore flow (Weiler and Naef, 2003b)(Weiler and Naef, 2003) or funnel flow (Kung, 1990), were carried out at the point or plot scale (spatial scale smaller than a few meters). Since PF increases the range of flow velocities in the vadose zone by orders of magnitudes (Nimmo, 2007), it is essential to include this process when describing and modeling water and solute transport in soil. Given its importance, many models now account for PF processes (see Gerke, 2006; Köhne et al., 2009; Steinbrich et al., 2016). However, these models are difficult to apply without inverse parameter estimation (Christiansen et al., 2004; Köhne et al., 2009) and defining meaningful parameter sets, but defining meaningful parameter sets for these models is challenging (Abbaspour et al., 2004; Arora et al., 2011; Cheng et al., 2017). Furthermore, Reck et al. (2018) showed that macropore networks and related parameters such as macropore distance and diameter are not constant over time. The problem of spatial and temporal variability of PF is also reflected in the updated paper about PF research by Beven and Germann (2013). They stated that some fundamental questions are still not solved. One of the central questions raised by the authors is: "When does water flow through macropores in the soil?".One of the central questions raised by Beven and Germann (2013) is: "When does water flow through macropores in the soil?". We know about the importance of PF, but knowledge about the spatial and temporal properties affecting the distribution of PF across the landscape is still lacking (Lin et al., 2006; Wiekenkamp et al., 2016). This makes it difficult to identify hotspots or hot moments of PF.

Many methods have been developed in the last decades to study and quantify PF in soils (see e.g., Allaire et al., 2009). These methods include using X-ray tomography at the pore to soil core scale (Larsbo et al., 2014; Naveed et al., 2016), the analysis of (dye) tracers and breakthrough curves at the soil core to hillslope scale (Anderson et al., 2008; Flury et al., 1994; Zehe and

Flühler, 2001a) or geophysical methods at the plot or(Anderson et al., 2008; Flury et al., 1994; Koestel et al., 2013; Zehe and Flühler, 2001) or using geophysical methods at the plot to hillslope scale (Angermann et al., 2017; Oberdörster et al., 2010). Another way to identify the potential for PF are direct measurements ofthat can be related to the number and volume of macropores or cracks. Watson and Luxmoore (1986) used a tension infiltrometer to calculate the amount of infiltration that is caused by pores of a specific equivalent pore size, a method that has been frequently used (e.g. Buttle and McDonald, 2000). Stewart et al. (2016) measured soil crack structure and volume and used this information to model soil water infiltration. Nevertheless, most methods lack either spatial or temporal resolution to quantify the amount frequency and properties of PF, to derive flow velocities or water amounts at asimultaneously for larger scale (~areas (~ km²) and the opportunity to relate them to landscape properties (such as topography, soil, land cover). longer timescales (~ years).

An alternative approach to study PF during infiltration are soil moisture measurements at high temporal resolution (~ minutes). While soil moisture sensors only measure at the point or profile scale, they can be deployed widely throughout the landscape (Zehe et al., 2014). Soil moisture sensors can be installed at different depths and are minimally invasive (Hardie et al., 2013). Kim et al. (2007) and Blume et al. (2009) used soil moisture sensors to analyze infiltration responses and small-scale soil moisture patterns. Both studies found a fast soil moisture increase after rainfall events and they concluded that PF occurred in their catchments.So far, soil moisture sensors were used to detect PF by either using the measured response velocities after a rainfall event (Blume et al., 2009; Eguchi and Hasegawa, 2008; Germann and Hensel, 2006; Hardie et al., 2013; Kim et al., 2007) or for analyzing the sequence of their response with depth Lin and Zhou (2008) used soil moisture sensors for detecting PF on the catchment scale in the Shale Hills Critical Zone Observatory (Pennsylvania, USA). They defined out-of-sequence responses of the soil moisture sensors as an indication of PF. Graham and Lin (2011) and Liu and Lin (2015) further expanded the analysis of the soil moisture network to 412 rainfall events using 35 sensor profiles in the Shale Hills Critical Zone Observatory. They observed that PF was higher when rainfall intensities were larger. PF was further sensitive to soil moisture depending on hillslope position, with higher occurrence upslope during dry conditions and downslope during wet conditions (Liu and Lin, 2015). Wiekenkamp et al. (2016) used a similar approach in the Wüstebach catchment in Germany where they studied 367 rainfall events at 101 sensor sites. They considered not only out-of-sequence responses, but also fast flow as proxy for PF. However, while the authors found that rainfall and soil moisture were important drivers, they did not observe a clear pattern with landscape properties (topography, soil). (Graham and Lin, 2011; Lin and Zhou, 2008; Liu and Lin, 2015; Wiekenkamp et al., 2016). Using these methods most studies found a relationship with precipitation characteristics (Liu and Lin, 2015; Wiekenkamp et al., 2016) or initial soil moisture (Blume et al., 2009; Hardie et al., 2013; Liu and Lin, 2015; Wiekenkamp et al., 2016).

Using flow velocity as an indicator of PF was first established by Germann and Hensel (2006) who analyzed 100 sprinkler infiltration experiments at 25 different sites. The authors calculated wetting front velocities as the elapsed time between the first responses of two sensors at different depths along the same profile. They compared the wetting front velocities against

HYDRUS-2D matrix flow simulations and found orders of magnitudes differences. Hardie et al. (2013) also applied this method in combination with the response sequence to classify PF in an agricultural soil for 48 rainfall events in Tasmania (Australia). They found a threshold for PF with initial soil moisture but no relation to rainfall characteristics. Eguchi and Hasegawa (2008) used measured soil moisture together with one-dimensional unsaturated flow and water balance simulations to distinguish between matrix flow and PF in an Andisol.

Even though some of the study sites described above show differences in PF occurrence between soils or landscape properties, most of them do not rigorously compare contrasting landscape units at the larger scale. Zhao et al. (2012) used the methods of Lin and Zhou (2008) for two contrasting land covers and found much higher occurrence of PF in the forest sites compared to a cropland. However, since both sites also had different soils it could not clearly be attributed to land cover. Using multiple linear regression for predicting four target variables of dye tracer flow from artificial sprinkling experiments, van Schaik (2009) found soil texture, land cover and hillslope position as important predictors of PF at a site in Spain. Most field experiments studying the effect of soil texture and land cover on soil water flow measured infiltration characteristics or hydraulic conductivities of soil cores (Bormann and Klaassen, 2008; Gonzalez-Sosa et al., 2010; Jarvis et al., 2013; Zimmermann et al., 2006). In general, higher infiltration rates and hydraulic conductivities were observed at sites with natural vegetation or forests. These higher infiltration rates were often attributed to the presence of macropores, but not connected to the dynamics of PF occurrence under natural field conditions.

Studies linking spatial and temporal distribution of PF and soil water flow velocity with landscape attributes under natural initial and boundary conditions are still scarce. A correct estimation of PF occurrence is important for hydrological predictions (e.g. modeling) and can improve water resource management. Therefore, the main aim of this study is to find patterns of PF at the landscape scale using profiles of soil moisture sensors distributed across contrasting soil textures, topography and land covers in a mesoscale catchment (~288 km²) under almost uniform climatic conditions. We combine soil moisture responses, flow velocities and water content changes to detect PF and to study the relevance of PF in space and time. Furthermore, we test how well the established theory of capillary water flow (e.g. Mualem, 1976; Watson and Luxmoore, 1986) can describe the observed flow patterns. We hypothesize that PF will be the dominant process during infiltration and infiltration cannot be described by capillary theory alone. Besides initial soil moisture and rainfall characteristics, soil texture and land cover are assumed to play a major role in controlling PF. We therefore attempt to answer the following question: how important are PF contributions for different landscape units, how does this vary in time and what are the underlying controls? Is PF temporally stable and how do the identified PF processes affect the water distribution in the vadose zone?

Even though some of the studies described above show differences in PF occurrence between soils or landscape properties, most of them do not rigorously compare contrasting landscape units at the larger scale. Zhao et al. (2012) tested out-of-sequence responses of the soil moisture sensors as an indication of PF for two contrasting land covers and found much higher occurrence of PF in the forest sites compared to a cropland. However, since both sites also had different soils it could not clearly be attributed to land cover. Most field experiments studying the effect of soil texture and land cover on soil water flow measured infiltration characteristics or hydraulic conductivities of soil cores (Bormann and Klaassen, 2008; Gonzalez-Sosa et al., 2010; Jarvis et al., 2013; Zimmermann et al., 2006). In general, higher infiltration rates and hydraulic conductivities were observed at sites with natural vegetation or forests. These higher infiltration rates were often attributed to the presence of macropores, but not connected to the dynamics of PF occurrence under natural field conditions. Studies linking the spatial and temporal PF occurrence in high resolution and comparing contrasting landscapes under natural initial and boundary conditions are still scarce.

A correct estimation of PF occurrence is important for hydrological predictions (e.g. modeling) and can improve water resource management. Therefore, the main aim of this study is to identify and compare the temporal dynamic of PF occurrence by using profiles of soil moisture sensors in different large-scale spatial units that could potentially be used as representative units for catchment modelling. Since it can be expected that rainfall intensity and soil moisture have a strong influence on the initialization of PF (Beven and Germann, 1982) we will mainly focus on the temporal controls of initial soil moisture and rainfall. More specifically, we attempt to answer the following question: Does PF occurrence increase with rainfall intensity since higher intensity leads more frequently to an exceedance of matrix infiltration capacity? Does PF occur more often under wet conditions since the infiltration capacity is lower? How is the temporal PF dynamic influenced by spatial factors like geology/soil type and land cover?

2. Material and Methods

2.1 Study Sites

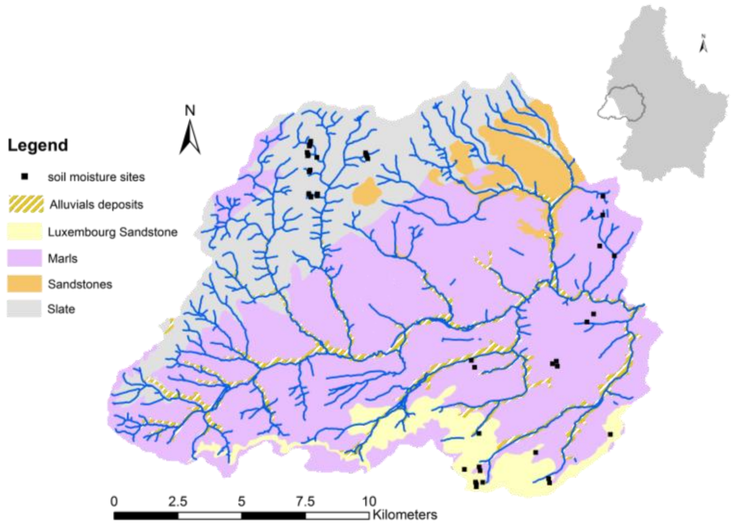
~~We~~To test our research question we analyzed a dataset of 405 soil moisture sensors at 45 sites distributed across a complex landscape ~~to test the hypothesis that PF dominates infiltration.~~(varying geology and land cover) but under similar climatic conditions. The ~~sensor sites are~~monitoring network is located in the Attert catchment in the Grand Duchy of Luxembourg. The climate is temperate semi-oceanic with a mean annual rainfall of 845 mm (Pfister et al., 2006) and mean monthly temperatures between 0°C (January) and 17°C (July) and only very few days per year with snow coverage (Wrede et al., 2015). Elevation ranges between 265 and 480 m a.s.l. and the catchment covers three major geologies (Colbach and Maquil, 2003). The northwestern part of the catchment is located at the southern edge of the Ardennes ~~with~~and the geology here is dominated by Devonian Slate bedrock covered by periglacial slope deposits mixed with eolian loess (Juilleret et al., 2011; Moragues-Quiroga et al., 2017). The southern part of the catchment is dominated by sedimentary rocks of the Paris Basin (Wrede et al., 2015) with Jurassic Luxembourg Sandstone at the southern catchment border and Triassic ~~sandy Marls in the central part of the catchment (Fig.1). The Slate region has agricultural managed plateaus between steep forested slopes (~15-25°). Soil~~

~~types~~Sandy Marls in the central part of the catchment (Fig.1). The slate region has agriculturally used plateaus between steep forested slopes (~15-25°). ~~are Haplic Cambisols (Ruptic, Endosketelic, Siltic) (IUSS Working Group WRB, 2006) with a main texture of silty clay loam (Table 1). Texture was determined by sedimentation analysis following ISO 11277 (2002) from randomly distributed samples taken mostly in the upper 30 cm. The thickness of the Ah horizon is approximately 10 cm for forest sites and up to 30 cm for grasslands. Coarse particle fraction (> 2 mm) is estimated between 10 % and up to 50 % volume fraction in the Bw horizon and increases with depth. Layers of weathered rock (C horizon) are found usually below 50 cm. Slate rocks in the weathered layer are mostly embedded slope parallel due to solifluction of the soil layers during the last ice age (Juilleret et al., 2011) and the bulk density of these soils is low (Wrede et al., 2015). In the Luxembourg Sandstone, Colluvic Arenosols dominate in the valley bottom and Podzols (IUSS Working Group WRB, 2006) with a sandy loam texture on the slopes and plateaus. The depth to the unweathered bedrock is more than 2 m (Sprenger et al., 2015) with banded Bt horizons deeper than 1 m.~~ The sandstone hillslopes are mostly forested with grasslands only present on the footslopes (Juilleret et al., 2012; Martínez-Carreras et al., 2012). The land cover in the Luxembourgian part of the marl region is mainly characterized by agricultural sites (30 %) and grasslands (41 %, mainly pasture) with gentle slopes (~3°).

Soil types in the slate geology are Haplic Cambisols (Ruptic, Endosketelic, Siltic) (IUSS Working Group WRB, 2006) with a main texture of silty clay loam (Table 1). Texture was determined by sedimentation analysis following ISO 11277 (2002) from randomly distributed samples taken mostly in the upper 30 cm. Coarse particle fraction (> 2 mm) was much higher than in the other geologies and is estimated between 10 % and up to 50 % volume fraction in the Bw horizon and increases with depth. Layers of weathered rock (C horizon) are found usually below 50 cm. Weathered slate rocks are mostly embedded slope parallel due to solifluction of the soil layers during the last ice age (Juilleret et al., 2011). In the Luxembourg Sandstone, Colluvic Arenosols dominate in the valley bottom and Podzols (IUSS Working Group WRB, 2006) with a sandy loam texture on the slopes and plateaus. The depth to the unweathered bedrock is more than 2 m (Sprenger et al., 2015) with banded Bt horizons deeper than 1 m. ~~The soils of the Marl~~The soils of the marl geology have a more diverse texture (Wrede et al., 2015) but are often showing a clay rich layer (>50 % clay) starting between 20 and 50 cm depth. Therefore, Stagnosols (IUSS Working Group WRB, 2006) are very common in this region. Sandy horizons ~~are present~~can be found as well, whereas topsoils mostly ~~consist of~~exhibit a loamy texture. ~~Agricultural sites and grasslands are dominant in this region with only gentle slopes (~3°).~~ The soils show high macroporosity ~~due to a high number of biopores and~~documented by the excavation of horizontal soil ~~cracking~~profiles and counting of pores > 2 mm Ø.

~~In this study, the~~The instrumentation at each site includes rainfall measurements and three soil moisture profiles separated by 5-20 meters. A soil moisture profile consists of three soil moisture sensors at 10, 30 and 50 cm depth below the surface. In total 135 soil moisture profiles at 45 different sites were distributed across the catchment (Fig. 1). The time series used in this study start between March 2012 (first installed profiles) and October 2013 (last installed profiles) and end in February 2017 (Table 1). At each of the 45 sites basic meteorological variables (temperature, humidity, radiation, wind), groundwater table elevation, sapflow, volumetric soil water content (θ) and soil matrix potential were measured. The selected sites are distributed along different hillslope transects capturing different hillslope positions, slopes and aspects. The soil moisture sensors (5TE capacitance sensors, ~~Decagon Devices/~~METER ~~Environment,~~Group Inc., USA) measured at 5-minute temporal resolution. These sensors measure with a 70~~-~~ MHz frequency and have a sample volume of around 300-715 ml (Cobos, 2015; Vaz et al., 2013), although other studies found ~~decreasing~~smaller sampling volumes in wetter soils for other sensors of similar type (Blonquist et al., 2005). Due to sensor defects, 43 sensors were replaced with SMT100 (TRUEBNER GmbH, Neustadt, Germany) and 9 sensors with GS3 sensors (Decagon Devices/METER Environment, USA) in 2016. Sensors were installed horizontally with minimum disturbance from a 30 cm diameter hole drilled with ~~an earth drill.~~a power auger. Each sensor was installed slightly shifted in the horizontal direction to the one above, to be unaffected by potential flow path changes by the sensor above. Furthermore, sensor cables were laid downwards in the hole first and led up on the opposite wall to prevent artificial PF along the cables leading to the sensors. In each of the three main geologies, the sensor sites were situated in two different land cover classes, forest and grassland. The selected forest sites were dominated by European beech *(Fagus sylvatica)* with ~~occasional~~ occurrence of oak (*Quercus* ~~*robu*), maple (*Acer pseudoplatanus*~~*robur*, *Quercus petraea*) and ~~spruce (*Picea abies*~~common hornbeam (*Carpinus betulus*). Furthermore, rainfall was measured with one tipping bucket (Davis Instruments, USA, 0.2 mm resolution~~)~~, collection area 214 cm²) at each grassland site and five randomly placed tipping buckets at each forest site to account, to at least some degree, for ~~capturing~~ the spatial ~~pattern~~variability of throughfall~~ at each forest site~~. We defined six different landscape units distinguishing the three main geological formations and the two land covers (forest, grassland) to test our research questions. The number of soil moisture profiles for the different land cover and geological classes are summarized in Table 1. Additional information and specific site properties are shown in Appendix A. ~~We defined six different landscape units distinguishing the three main geological formations and the two land covers (forest, grassland) (Table 1).~~

Hood infiltrometer measurements (Schwärzel and Punzel, 2007) were used to determine matrix infiltration capacity.



Measurements were carried out either in the direct vicinity of our sensor sites or within the same geology and land cover class (Appendix A). Every value of matrix surface hydraulic conductivity (K_{mat}) consists of at least three measurement locations, except for two sites where the infiltration rate was too high and the hood could not be filled. Hood infiltrometer measurements were not available for grassland sites in the Luxemburg Sandstone. In total measurements from 65 locations were used for determining K_{mat} for the different landscape units. For every measurement location infiltration rates with at least three tensions between 0.4 - 5.9 hPa were recorded to be able to fit an exponential function to calculate surface hydraulic conductivity at a tension of 6 hPa (Gardner, 1958). At this tension, pores with a diameter ≥ 0.5 mm are excluded from flow and measured hydraulic conductivities represent matrix infiltration capacities (Jarvis, 2007; Schwärzel and Punzel, 2007). Hood infiltrometer measurements further gave the opportunity to estimate the macropore portion of saturated hydraulic conductivity (K_{MP}). K_{MP} is defined as the difference of K_{mat} to the saturated hydraulic conductivity measured at a tension of 0 hPa (K_s), $K_{MP} = K_s - K_{mat}$.

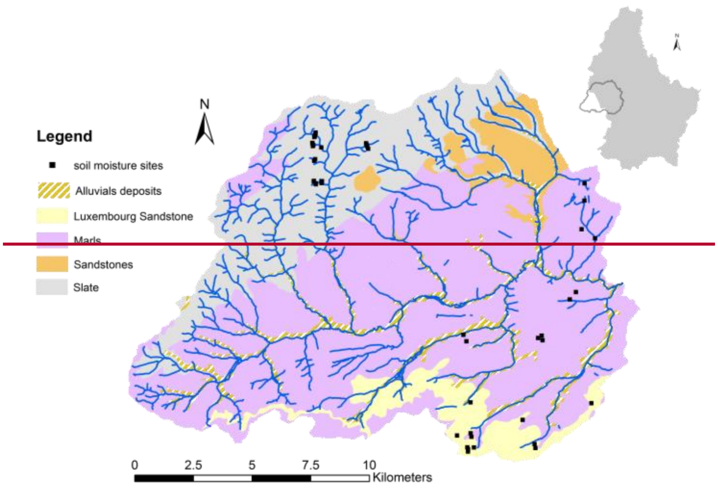


Figure 1: Map of the Attert catchment in Luxembourg with the three main geologies and the locations of the 45 soil moisture monitoring sites.

Table 1: Site information of the six defined landscape units. Additional textural information can be found in the supplement (Table S1). Texture denoted with * was estimated with a field test by feel.

	Slate		Marl		Sandstone	
	Forest	Grassland	Forest	Grassland	Forest	Grassland
# of soil moisture profiles	45	21	15	18	27	9
Dominant soil texture (USDA classification)	silty clay loam	silty clay loam	loam (topsoil) clay* (subsoil)	clay loam (topsoil) clay (subsoil)	sandy loam	sandy loam
Mean clay content [%]	38	40	23 / >50* (</> 30cm)	30 / 48 (</> 30cm)	16	19
Observation period	03/2012-02/2017	04/2012-02/2017	03/2013-02/2017	09/2013-02/2017	03/2013-02/2017	07/2013-02/2017

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2.2~~.~~ Data analysis

2.2.1 Event classification~~ & soil moisture response~~

Rainfall events

A full workflow of the data analysis is depicted in Fig. 2 showing the number of excluded events due to different quality criteria. Rainfall (*P*) events were defined using the rainfall data with 5-minute ~~temporal~~ resolution ~~of the rainfall data~~ individually for each site. For the forest sites the mean of all five tipping buckets for every 5-minute time step was calculated to obtain average throughfall~~.~~ for each site. Forest tipping buckets that measured no rainfall over one hour were excluded (assuming they were clogged), when at least three other buckets observed rainfall during the same timeframe. If the rainfall data contained more than one missing value in a 2-hour period it was excluded from further analysis. Following the approach of Graham and Lin (2011) and Wiekenkamp et al. (2016), a rainfall event was defined as rainfall with a minimum amount of 1 mm. The end was defined as the last monitored response of a rain gauge followed by a specific time period without rain (t_e). ~~The sensitivity of t_e on the number of rainfall events and their characteristics was investigated by testing different values of t_e: 3, 6, 12 and 24 consecutive hours without rain. If an event contained more than one missing value in a 2-hour period it was excluded from further analysis. Events that were not plausible were excluded by using a threshold method for event *P* amount (> 100 mm), average event intensity (> 15 mm h^{-1}) and *P* amount in a 5-minute time step (> 6.7 mm).~~The procedure of determining this time period is described below.

Dividing soil water dynamics into single events based on *P* input is always a trade-off: On the one hand, short rainfall events do not allow for a clear separation of the infiltration signals from different input pulses. On the other hand, long rainfall that is grouped into one event can result in too much information from several consecutive rain input pulses that are merged into one rainfall event. Hence, different rainfall regimes require different threshold values, i.e. hours without rainfall (t_e) for the identification of event endings. The sensitivity of t_e on the number of rainfall events and their characteristics in our case was investigated by testing different values of t_e: 3, 6, 12 and 24 consecutive hours without rain.

For each *P* event total rainfall amount (P_{sum}), the maximum *P* intensity in a 5-min time step (P_{max}) and the event average rainfall intensity of the entire event (P_{int}) was determined. Events that were not plausible were excluded by using a threshold method for event *P* amount (P_{sum} > 100 mm), average event intensity (P_{int} > 15 mm h^{-1}) and maximum *P* intensity in a 5-minute time step (P_{max} > 80 mm h^{-1}). These implausible events were observed to happen during the reconnecting of the loggers following a logger error (no power etc.) or clogging and release of the clogged water. To exclude snowfall or frozen soil conditions, events with a mean air temperature below 0°C during the event were not included in the analysis. By applying the quality criteria for rainfall events using t_e = 12 h, 1392 of 32025 rain events (sum of profile rainfall events) were excluded because of the threshold criteria and 426 because the mean temperature was below 0°C during the event.

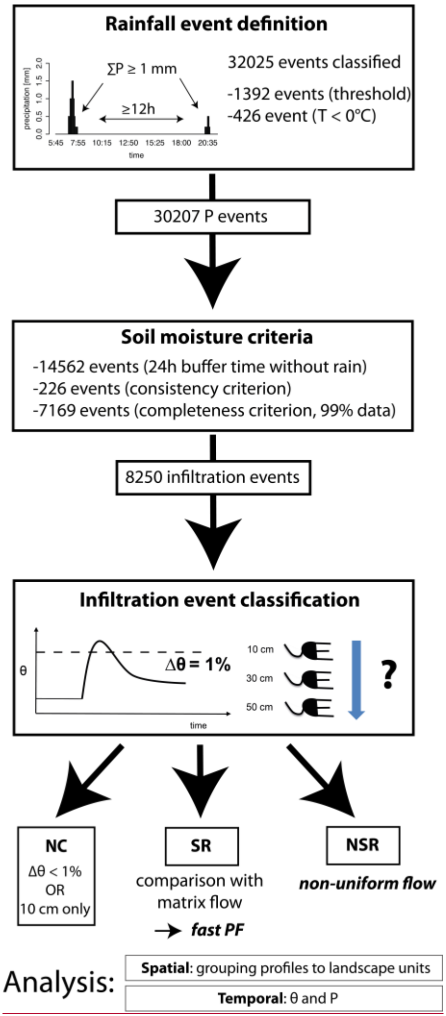

Figure 2: Workflow for the estimation of spatial and temporal PF occurrence from soil moisture data with the number of in- and excluded events. Event numbers refer to the sum of events on a profile base (since this number is the resulting number of data points used for each analysis).

The rainfall event separation method is sensitive to the required number of consecutive hours without rain (t_e) between the events. Table 2 shows t_e values with the resulting number of events, mean event duration, rainfall amount (P_{sum}) and event average rainfall intensity (P_{int}). Shorter t_e results in more events and decreasing mean event duration. Mean P_{int} is gradually decreasing with longer t_e due to longer event durations while mean P_{sum} is increasing. We considered t_e = 12 h to be sufficient to ensure event separation yielding an appropriate event length and to avoid possible superimposition of soil water flow signals from different input pulses. Therefore, the following analyses are performed with the event definition based on t_e = 12 h. This results in total rainfall event numbers between 144 and 353 per profile. 54.2 % of all analyzed rainfall events had sums lower than 5 mm and 77.7 % lower than 10 mm. The distribution of rainfall intensities (P_{int}) shows that 69.2 % of all events had a P_{int} < 0.4 mm h^{-1}. The density distributions show slightly higher P_{max} for grassland sites but no difference among the geologies (Fig. 3).

Table 2: Rainfall event characteristics over all 135 profiles depending on minimum hours without rain (t_e) required between consecutive rainfall events.

	hours without rain (t_e)			
	3	6	12	24
Sum of profile rainfall events	45681	39018	30207	18546
Mean Duration [h]	11.3	18.7	33.8	76.0
Mean P_{sum} [mm]	5.4	6.4	8.1	11.9
Mean P_{int} [mm h^{-1}]	0.88	0.65	0.48	0.33

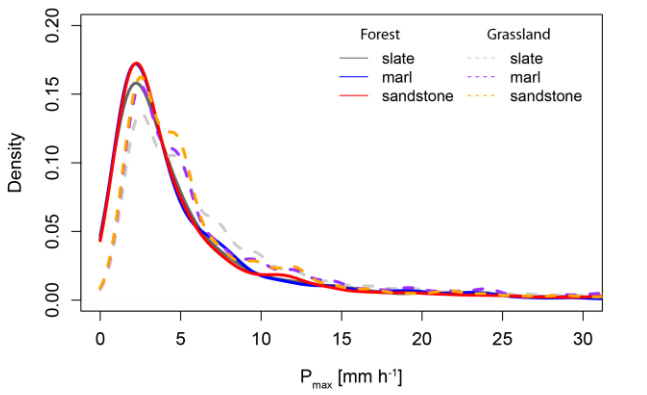

Figure 3: Density distribution of maximum rainfall intensity for the six landscape units.

Soil moisture & infiltration events

Signal spikes (strong increase of soil moisture within a 5 minute time step and a decrease to the initial value) in the measured soil moisture time series were removed by using a threshold method and data was visually checked for plausibility and long-term consistency. In addition, sensor readings were validated against those of the other sensors in the same depth for each site. No site specific calibration of the soil moisture sensors was conducted and soil moisture values were obtained by the sensor

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internal θ-permittivity relationship following Topp et al. (1980). ~~Absolute~~For the 5TE sensors the manufacturer gives an absolute sensor accuracy of volumetric water content ~~is~~of ±3 Vol% (DecagonDevices, 2015). For a relative change of 1 Vol% a maximum sensor-to-sensor difference of ± 0.25 Vol% can be found in the very dry range (θ ~ 10 Vol%) (Rosenbaum et al. 2010). Since Rosenbaum et al. (2011, 2012) showed that temperature effects on the sensors and on soil dielectric properties can cancel each other out, permittivity was not corrected for soil temperature. Furthermore, electrical conductivity effects of soil water on permittivity were neglected as bulk electrical conductivity was low (< 0.1 dS~~-~~ m^{-1}) for most profiles. Although some ~~Marl~~marl profiles show higher bulk electrical conductivities, results of soil water content change should not be affected since these profiles do not reveal fast bulk electrical conductivity fluctuations on the event scale.

For each defined rainfall event the soil moisture time series of all sensors in a profile was checked for their response. Infiltration events were defined as a θ increase of ≥1 Vol% of at least one sensor in the soil profile. This threshold was chosen to avoid ~~diel~~diurnal fluctuation, caused by e.g. soil temperature, being classified as infiltration events (Graham and Lin, 2011; Wiekenkamp et al., 2016). If a soil moisture event was identified, the timing of first response of every sensor was determined. The first response is defined as the point in time when the θ change is higher than the instrument noise (Lin and Zhou, 2008) that was found to be 0.4 Vol% for the 5TE sensors (Rosenbaum et al., 2010; Wiekenkamp et al., 2016). Linear interpolation was used to calculate the time between two 5 min readings to increase the temporal resolution.

The soil moisture response was tracked for up to 48 hours after the end of a rainfall event or until the time a new rainfall event starts. ~~To~~

The chosen rainfall event separation based on t_e = 12 h already avoids superimposition of consecutive rainfall input signals on the soil water content. However, to have clearly separated soil water flow events that are uninfluenced by a new rainfall event for at least 24 hours, both consecutive infiltration events were excluded if ~~a new~~the second rainfall event occurred within 24 hours after the ~~previous~~first rainfall event end. In the case of a response later than 24 hours we assumed that the following infiltration event is likely to be triggered by the new rainfall event (Hardie et al., 2013). Only if more than 99 % of the data points for all profile sensors during an infiltration event were usable, they were considered for further analysis~~. To exclude snowfall or frozen soil conditions, events with a mean air temperature below 0°C during the event were excluded.~~ (termed completeness criterion). Furthermore, infiltration events that showed an increase in soil moisture, but were caused by an oscillating signal (not more than four different θ values during one event) were excluded (termed consistency criterion).

From the total of 30207 rainfall events, 15645 could be used for the analysis of the soil moisture, since they allowed for a clear separation of soil water flow by more than 24h without a new rainfall input. 7395 of these events did not meet the quality criteria of completeness and consistency of the soil moisture time series, hence 8250 infiltration events (sum of soil moisture event observations at all 135 profiles) could be used for the analysis. Changing the completeness criterion from 99% usable soil moisture data points during an event to e.g. 95% is only slightly affecting the number of infiltration events (e.g. 8353 events usable in the analysis). This is due to the fact that most exclusions result from long term failure of one sensor of a profile that leads to a complete exclusion of the entire profile. A diagram showing the portion of active (all quality criteria met) profiles on a daily basis can be found in the supplement (Figure S1).

Various soil moisture and rainfall characteristics were determined for each event. Initial volumetric water content (~~θ_{ini}~~θ_{ini}) was defined as the water content before the rainfall event starts. Furthermore, change of ~~θ_{ini}~~θ_{ini} to the peak water content ($\Delta\theta_{max}$) of every event and sensor response was calculated. We grouped soil moisture into dry and wet initial conditions using θ quartiles of each profile. ~~The total rainfall amount (P_{sum}), the maximum P intensity in a 5-min time step (P_{max}) and the event average rainfall intensity of the entire event (P_{int}) were determined.~~ Additionally, rainfall amounts and intensities were calculated ~~until~~for the time before the first soil moisture sensor response ($\Delta\theta$ = 0.4 Vol%) of any profile (~~pre-response).~~rP_{sum}, rP_{int}, rP_{max}). This was done since ~~soil moisture~~ our infiltration event classification described in the next section is partly based on the first sensor response ~~(θ = 0.4 %)~~ and later rainfall input is not further influencing the classification.

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~~**Table 1: Site information of the six defined landscape units (* estimated by field test)**~~

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	~~Slate~~		~~Marl~~		~~Sandstone~~	
	~~Forest~~	~~Grassland~~	~~Forest~~	~~Grassland~~	~~Forest~~	~~Grassland~~
~~No. soil moisture profiles~~	~~45~~	~~21~~	~~15~~	~~18~~	~~27~~	~~9~~
~~Dominant soil texture (USDA classification)~~	~~silty clay loam~~	~~silty clay loam~~	~~loam (topsoil) clay* (subsoil)~~	~~clay loam (topsoil) clay (subsoil)~~	~~sandy loam~~	~~sandy loam~~
~~Mean clay content [%]~~	~~38~~	~~40~~	~~23 / >50* (</> 30cm)~~	~~30 / 48 (</> 30cm)~~	~~17~~	~~19~~
~~Dataset period~~	~~03/2012-02/2017~~	~~04/2012-02/2017~~	~~03/2013-02/2017~~	~~09/2013-02/2017~~	~~03/2013-02/2017~~	~~07/2013-02/2017~~

2.2.2 ~~Sensor~~Soil moisture sensor response ~~sequence and flow velocity~~by infiltration events

For all soil moisture profiles and rainfall events which met the described quality criteria, the sequence of the first sensor response was classified similar to Liu and Lin (2015) into:

~~(i)~~ ~~no response (***NR***~~not classifiable (***NC***): none of the sensors in the profile showed a response (≥1 Vol%)

~~(ii)~~(i) ~~sequential response (***SR***): the sensors in the profile showed a response in sequence from the uppermost sensor downwards (e.g., 10 cm to 30 cm to 50 cm or 10 cm to 30 cm). Events with~~ or only a 10 cm sensor response ~~were also included in this group~~was observed

~~(iii)~~(ii) non-sequential response (***NSR***): events where the first response did not progress in a sequence starting from the surface (e.g., the 30 cm sensor showed a response before the 10 cm sensor) sequential response (***SR***): the sensors in the profile showed a response in sequence from the uppermost sensor downwards (e.g., 10 cm to 30 cm to 50 cm or 10 cm to 30 cm

(iii))

The potential for using these different infiltration responses (*SR*, *NSR*) and related parameters as a proxy for PF are described in the following sections. All statistical analysis were performed using Dunn's rank sum test (Dinno, 2017).

Additionally, we estimated how often PF should have be observed based on the classical assumption that rainfall intensity exceeded matrix infiltration capacity (Beven and Germann, 1982). We used matrix saturated hydraulic conductivity (K_{mat}) as the minimum infiltration capacity and tested how often maximum 5-min rainfall intensity exceeded this threshold ($P_{max} > K_{mat}$; for the measurements of K_{mat} see section 2.2.2.2). Furthermore, comparison of maximum water content change during an event ($\Delta\theta_{max}$) between the infiltration response types can give information on PF processes by showing differing water content depth distributions and can help to estimate the relevance of the different flow processes in terms of transported water quantity.

2.2.2.1 Non-sequential response (*NSR*)

The *NSR* classification indicates ~~a non-homogenous wetting front or bypassing of the upper soil moisture sensors,~~non-uniform flow that can be a result of various PF processes (e.g. bypass flow), hence it is taken as a proxy for PF. *NSR* could also be a result of subsurface lateral flow or groundwater rise before the vertically downward progressing wetting front reaches that depth (Lin and Zhou, 2008). But even in these cases, such responses describe water flow that shows either ~~a~~ non-~~homogeneous wetting front~~uniform flow or surroundings that infiltrate water faster than the profile. Both can be seen as an indication of PF. None of the profiles showed a permanent water table ~~in~~smaller than 50 cm below ground level, nevertheless some profiles are influenced by groundwater fluctuations and are temporary ~~waterlogging~~waterlogged in 50 cm especially during winter. The length of the time series is adequate for detecting patterns of *NSR* as Liu and Lin (2015) showed in their analysis that overall sensor response patterns show stable results using >3 years of soil moisture data. The occurrence frequency of *NSR* was analyzed with respect to initial soil moisture and rainfall characteristics for the landscape units. All *NSR* analyses were done with pre-response rainfall characteristics (rP_{sum}, rP_{int}, rP_{max}). Calculated portions of *NSR* for the landscape units, geologies or land covers for different rP_{max}, θ_{ini} or month are always calculated as the sum of *NSR* responses of the indicated class divided by total number of infiltration events in the same class.

~~The occurrence frequency of *NSR* was analyzed with respect to initial soil moisture, rainfall characteristics and landscape properties. All *NSR* analyses were done with pre-response rainfall characteristics. In addition, the *NSR* occurrence is compared against a theoretical capillary occurrence of PF to test the hypothesis that PF can be described by capillarity. Classical capillary theory assumes that macropores only contribute to flow if rainfall rate exceeds the matrix infiltration capacity leading to a pore~~

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Formatiert: Schriftart: Nicht Kursiv water pressure close to atmospheric pressure at the soil surface (Beven and Germann, 1982; Jarvis, 2007; Weiler, 2005). We calculated the frequency with the maximum 5-minute rainfall intensity exceeding the matrix infiltration capacity of the profile. Since matrix infiltration capacity increases under drier conditions, taking K_{mat} as the matrix infiltration capacity rather underestimates this value and thus overestimates the occurrence of PF in this capillarity-based estimation, unless soils are close to saturation.

Statistical Analysis of NSR

We applied a range of statistical methods to predict *NSR* occurrence and identify explanatory parameters. To describe the probability of an event to produce *NSR*, generalized linear regression models (*GLMs*) with a logistic link function were applied (temporal *NSR* occurrence model). This was done separately for the six individual landscape units (3 geologies with 2 land covers each) and across all profiles without differentiating into landscape units. A backward stepwise model selection (stepwise AIC; software "R", package MASS) was used to reduce predictors that are either not significant or are correlated. All tested predictors can be found in Appendix A. To predict the probability of *NSR* occurrence (%) for each profile a linear model (*LM*) was fitted across all 135 profiles (spatial *NSR* occurrence model). The predictors of the *LM* were the same as for the *GLM*, but instead of using θ and *P* characteristics of each single event, median values across all events per profile were used.

To determine the effect of aspect on the frequency of *NSR* occurrence, only profiles at sites with slopes > 10 % were used for analysis. We distinguished between north- (270°–90°) and south-facing (90°–270°) aspects. The two-sided Wilcoxon rank sum test was used for testing of significant differences. For all other statistical comparisons in this study, a two-sided Dunn test with Benjamini-Hochberg correction was used.

Sequential response (SR)

Even if an event was classified as *SR*, it cannot be excluded that PF (macropore flow, finger flow) has occurred. By comparing matrix (capillary) flow velocities to measured flow velocities, the influence of PF can be estimated. We

2.2.2.2 Sequential response (*SR*)

A sequential response of the sensors in the profile does not necessarily mean that no PF occurred. To get an estimate for the frequency of *SR* events showing PF, one method is comparing soil matrix (capillary) flow velocities to measured in-situ flow velocities (Germann and Hensel, 2006; Wiekenkamp et al., 2016). A measured flow velocity that is faster than the soil matrix flow velocity can be expected to be influenced by PF. Matrix flow velocity can either be obtained by modeling or with measurements. To determine the in-situ flow velocities we used the approach of Germann and Hensel (2006) where the maximum pore water velocity of the wetting front (v_{max}) is defined as the velocity betweendetermined from the first responses of two sensors. (often called wetting front velocity). The upper sensor allows for the definition of a clear starting time of the water flow. Hence, vertical wetting frontmaximum pore water velocities were calculated from the *SR* for two distinct flow depths: 10 to 30 cm and 30 to 50 cm. It is important to note that v_{max} represents only the fastest flow components in the sphere of influence around the soil moisture sensor (Hardie et al., 2011).

To calculatemodel matrix flow velocity (v_{mat}), the 1D steady state flow equation according to Darcy's law for unsaturated conditions was used (Hillel, 1998):

$$q = -K(\psi_m)\ \partial H/\partial z \qquad (1) \qquad (1)$$

With q being the vertical volume flux [cm day^{-1}], K the hydraulic conductivity [cm day^{-1}], ψ_m the matrixmatric potential [cm], H [-] the hydraulic potential including matrix potential and gravitation[-] and z the depth [cm]. For the vertical 1D case, wetting frontmatrix flow velocity (or piston flow velocity) can be calculated by dividing the volume flux by the volumetric water content θ [-] (Gerke, 2006):

$$v_{mat} = q/\theta \qquad (2) \qquad (2)$$

The hydraulic gradient was calculated between two sensors using the site-specific soil water retention curvesmatric and the gravitation potential ($H = \psi_m + \psi_g$). The maximum gradient between the θ peak of the upper sensor and θ_{ini} of the lower sensor is calculated to obtain maximum v_{mat}. This assumesis a more conservative approach since steady state assumptions are used to calculate flow velocity. Retention curves were parameterized usingFor obtaining the matric potential the van Genuchten-Mualem equation retention curves (van Genuchten, 1980) in combination withwere parameterized using the parameter sets of Sprenger et al. (2016). (supplement Table S2). The van Genuchten-Mualem parameters of Sprenger et al. (2016) do not need further corrections for matching θ with absolute values of e.g., soil core data since these parameters were calibrated for a shorter period of the same dataset. For those ten sensor sites where no parameters were determined by Sprenger et al. (2016), we simply used the mean fit for the respective geology. Although these retention parameters were inversely fitted and should therefore account for fast flow components, they rathermore closely represent matrix flow due to the single domain Richards equation and the unimodal nature of the van Genuchten-Mualem retention function that was used (Durner et al. 1994). In addition, the fit on a daily basis does not allow for fast processes other than matrix flow. A geometric mean hydraulic conductivity was calculated between two sensors located in different depths (Zhu 2008) to obtain the effective unsaturated hydraulic conductivity of the vertical layered soil profile. The To again provide a conservative estimation of PF and rather overestimate v_{mat} the moisture content used to determinecalculate this unsaturated hydraulic conductivity was the medianmaximum event water content (θ_{event}), calculated from first response to the peak water content at, determined for both sensor depths. individually. The mean of these two maximum event water contents was also used to calculate the matrix flow velocity (v_{mat}) from the volume flux (q). Events that showed an upward hydraulic gradient based on this calculation were excluded from further comparisons. Event water content was also used to calculate the matrix flow velocity (v_{mat}) from the volume flux (q).

For directly measuring matrix flow velocity we assumed that saturated matrix hydraulic conductivity at the surface is an appropriate threshold

3. Results

for dividing flow into matrix flow and PF (Wiekenkamp et al., 2016). Tension infiltrometer measurements were used to obtain saturated matrix hydraulic conductivity in the field. The tension infiltrometer used in this study is a special type called "hood infiltrometer". The advantage of the hood infiltrometer is that it can be placed directly on the soil surface without need of any contact material (Schwärzel and Punzel, 2007). The derivation of matrix saturated hydraulic conductivity (K_{mat}) from measured infiltration rates accounts for the three-dimensional nature of flow using the solution of Wooding (1968) (steady state infiltration from a circular source). Measurements were carried out either in the direct vicinity of our sensor sites or within the same geology and land cover class (Appendix A). All values of matrix surface hydraulic conductivity consists of at least three measurement locations (median), except for two sites where the infiltration rate was too high and the hood could not be filled. Hood infiltrometer measurements were not available for grassland sites in the sandstone and hence observed flow velocities of this landscape unit were not compared with measured matrix flow velocities. In total measurements from 66 locations were used to determine K_{mat} for the different landscape units. For every measurement location infiltration rates with at least three tensions between 0.4 - 5.9 hPa were recorded to be able to fit an exponential function to calculate surface hydraulic conductivity at a tension of 6 hPa (Gardner, 1958). At this tension, pores with a diameter > 0.5 mm are excluded from flow and measured hydraulic conductivities represent matrix infiltration capacities (Jarvis, 2007; Schwärzel and Punzel, 2007). 3.1. Rainfall and soil moisture events

The event separation method is sensitive to the required number of consecutive hours without rain (t_e) between the events. Table 2 shows t_e values with the resulting number of events, mean event duration, rainfall amount (P_{sum}) and event average rainfall intensity (P_{int}). Shorter t_e results in more events and decreasing mean event duration. Mean P_{int} is gradually decreasing with longer t_e due to longer event durations while mean P_{sum} is increasing. We considered t_e = 12 h to be sufficient to ensure event separation yielding an appropriate event length and to avoid possible superimposition of soil water flow signals from different input pulses. Therefore, the following analyses are performed with the event definition based on t_e = 12 h. This results in total rainfall event numbers between 144 and 353 per profile.

Table 2: rainfall event characteristics over all 135 profiles depending on minimum hours without rain required between consecutive rainfall events.

	hours without rain (t_e)

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	3	6	12	24
Sum of profile rainfall events	45681	39018	30207	18546
Mean Duration [h]	11.3	18.7	33.8	76.0
Mean P_{sum} [mm]	5.4	6.4	8.1	11.9
Mean P_{int} [mm h^{-1}]	0.88	0.65	0.48	0.33

Cumulative event rainfall amounts for every site are shown in Fig. 2a. The cumulative P_{sum} is mainly influenced by the length of the time series and the increase with increasing number of events shows no clear difference among the six landscape units. 54.2 % of all analyzed rainfall events had sums lower than 5 mm and 77.7 % lower than 10 mm. The distribution of rainfall intensities (P_{int}) shows that 42.0 % of all events had a mean P_{int} < 0.2 mm h^{-1} and 69.2 % a P_{int} < 0.4 mm h^{-1}. The density distributions show slightly higher P_{max} for grassland sites but no difference among the geologies (Fig. 2b). The annual proportion of throughfall (mean annual forest P / mean annual grassland P) varied between 62 % and 86 % for the three different geologies in the years 2014 and 2015.

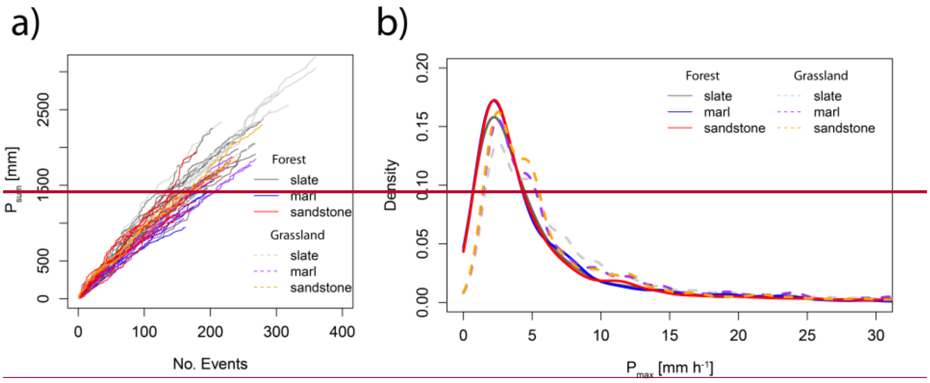

Figure 2: Consecutive number of events vs. cumulative rainfall for each site (a) and density distribution of maximum rainfall intensity (b).

The infiltration event responseDue to the high macroporosity at many forest locations pressure in the hood was difficult to adjust and measurements could only be conducted for maximum tensions of 1-3 hPa. Hence, for some sites matrix saturated hydraulic conductivity is just an extrapolation of the Gardner fit to a tension of 6 hPa.

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~~3.~~ Results

3.1 Infiltration events

The number and proportions of classified infiltration event responses (*NC*, *SR*, *NSR*) of the six defined landscape units are shown in Table 3. The absolute number of events in a certain landscape unit and response class, which were included in the different analysis, can be found in the supplement (Table S3). Between ~~36~~63.2 % and ~~56.3~~79.5 % of the ~~rainfall~~infiltration events ~~show no~~per landscape units were not classifiable (*NC*) in their infiltration response ~~(*NR*) in soil moisture~~, with the ~~Marl~~marl grassland sites having the lowest amount of ~~*NR*. 64~~*NC*. 49.6 % of all ~~*NR*~~*NC* events resulted from events with a P_{sum} of 3 mm or less. Approximately a third of all infiltration events showed a change in soil moisture deeper than 10 cm. Most ~~detected~~classifiable infiltration events were of type *SR*. Under ~~Sandstone~~sandstone forest sites they accounted for ~~55.7~~ 24.6 %, whereas under ~~Marl~~marl grassland sites they accounted for only ~~36.8~~13.6 % of all events. Within the group of *SR*, ~~54.6~~47.4 % were observed ~~only~~ at a depth of ~~10~~30 cm, whereas sequential flow to ~~deeper~~ sensors at 50 cm depth was found for 52.6 % of the *SR*. *NSR* events occurred ~~less frequent (21.5 % reaching 30 cm and 23.9 % 50 cm). *NSR* events were found to occur~~ in 5.3 % to 16.1 % of all events depending on the landscape unit. The ~~Slate~~slate and ~~Marl~~marl forest regions showed the highest proportion (13.3 % and 16.1 %, respectively). In total ~~67.1~~48.7 % of the *NSR* events showed a response in 30 cm first and ~~32.9 % in 50 cm.~~ 23.9 % in 50 cm. 27.4 % of the *NSR* events reacted in 10 cm first and then in 50 cm without a 30 cm reaction in-between. The *NSR* variability between the single profiles within a landscape unit was found to be high (Table 3). The site-intern variability of *NSR* (profiles within the same sites) measured as the median standard deviation was highest in marl (forest: 7.5 %, grassland 6.4 %) followed by slate (forest: 4.2 %, grassland 6.1 %) and sandstone (forest: 1.9 %, grassland 3.0 %).

~~**Table 3: Infiltration responses of the six landscape units.**~~

	Slate		Marl		Sandstone		All
	Forest	Grassland	Forest	Grassland	Forest	Grassland	
Sum of profile rainfall events	9774	6372	2823	4137	4830	2271	30207
Sum of infiltration events	2975	1121	733	852	1872	698	8251
NR [%]	43.2	47.2	36.2	56.3	39.0	51.9	
SR [%]	43.5	46.1	47.7	36.8	55.7	42.8	
NSR [%]	13.3	6.7	16.1	6.9	5.3	5.3	
Min.-Max. profile *NSR* [%]	0 - 46.2	0 - 22.7	0 - 37.6	0 - 17.4	0 - 31.8	0 - 15.6	
NSR standard deviation [%]	9.4	7.5	11.8	5.4	8.7	4.8	

~~The effect of~~To estimate how often PF should have be observed based on the classical assumption that rainfall intensity exceeded matrix infiltration capacity in the different landscape units we calculated the portion of rainfall events with a P_{max} exceeding K_{mat}. With the exception of marl grassland (13.8 % $P_{max} > K_{mat}$), all other landscape units only showed an exceedance rate lower than 2 % (Table 3).

Table 3: Number of events, infiltration responses and standard diviation (*sd*) of the six landscape units, showing a not classifiable response (*NC*), sequential response (*SR*) and non-sequential response (*NSR*).

	Slate		Marl		Sandstone	
	Forest	Grassland	Forest	Grassland	Forest	Grassland
# of infiltration events	2975	1121	733	852	1871	698
NC [%]	65.0	75.0	63.2	79.5	70.1	72.8
SR [%]	21.7	18.3	20.7	13.6	24.6	21.9
NSR [%]	13.3	6.7	16.1	6.9	5.3	5.3
Min.-Max. *NSR of* single profiles [%]	0 - 46.2	0 - 22.7	0 - 37.6	0 - 17.4	0- 31.8	0 - 15.6
sd NSR (variability between single profiles) [%]	9.4	7.5	11.8	5.4	8.6	4.8
P_{max} > K_{mat} [%]	0.9	1.8	0.0	13.8	0.2	no K_{mat} measurement

To test how much *P* characteristics and θ_{ini} on the infiltration types were examined by calculatinginfluence the different response behaviors, we calculated the median of each parameter for all infiltration events of a certain response type and their corresponding depth (Table 4). We included pre-response *P* characteristics (*rP*) to show their differences between *NSR* and *SR* events. To analyze the effect of rainfall amount on infiltration depth, *SR* was also compared with the total event rainfall. *P* characteristics High P_{sum} mainly affect the depth of the sequentially progressing soil moisture front. Response at 50 cm depth shows a median event P_{sum} that is much higher than at 10 cm depth (Table 4). during *SR*. In addition, the P_{max} is also increasing with depth of response, which could partly be due to a correlation of P_{max} and P_{sum} (Spearman R = 0.54). The *SR* events show similar median θ_{ini} is similarvalues for all *SR*both infiltration depths, which suggests no effect of θ_{ini} on the flow depth. ComparedThe rP_{sum} is similar for *SR* and *NSR* 30 and 50 cm events, while rP_{max} is higher for *NSR* events. *NSR*10-50, with a response in 10 cm first followed by a 50 cm reaction, shows a different pattern than the other *NSR* reactions with the lowest *rP* intensities, but the highest θ_{ini} and rP_{sum}. In contrast to the *SR* events, the median θ_{ini} of the *NSR* events is lower and also decreases with increasing depth of first response. The pre-response P_{sum} is similar for *SR* and *NSR* events, while P_{max} is higher for *NSR* events. (30, 50 cm), which indicates that these infiltration response type is sensitive to dry soil moisture conditions.

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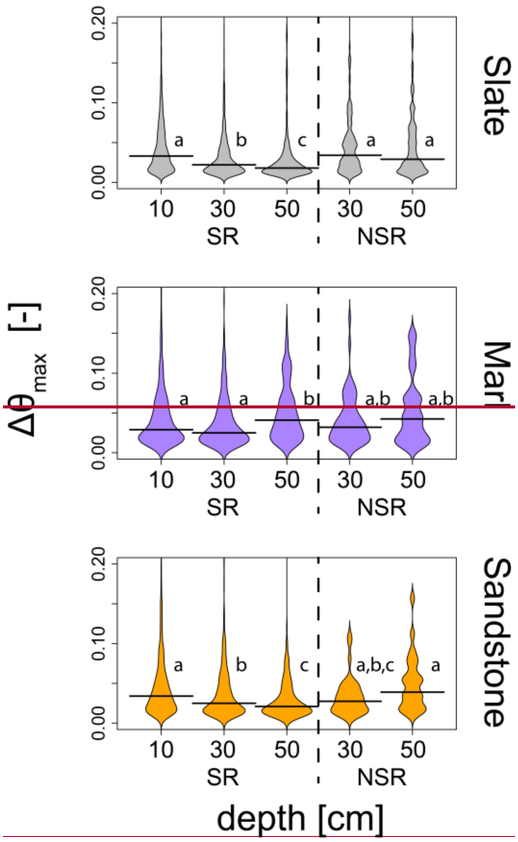
Table 4: Rainfall characteristics of the different infiltration types and their corresponding depths (median values of all profiles and events). Sequential response (*SR*) with maximum response depth (cm) and non-sequential response (*NSR*) with depth (cm) of first out-of-sequence response. Each variable was (cm). Rainfall variables were calculated for the entire event (total*P*) and also for the time prior the first (out-of-sequence) sensor response (pre-response*rP*).

Response type	*NC*	*SR10SR*		*SR30*	*SR50NSR*	*NSR30* *NSR50*
Depth (cm)		30	50	10-50	30	50
Total P_{sum} [mm]	P_{sum} [mm]3.1	5.39.4	9.418.0	18.0-	-	-
P_{int} [mm h^{-1}]	0.23P_{int} [mm h^{-1}]	0.2427	0.2730	0.30-	-	-
P_{max} [mm h^{-1}]	P_{max} [mm h^{-1}]3.4	34.8	4.86.6	6.6-	-	-
Pre-response*rP*$_{sum}$ [mm]	P_{sum} [mm]-	2.65	2.56	3.2.6	2.4	2.8
rP_{int} [mm h^{-1}]	P_{int} [mm h^{-1}]-	0.4139	0.39	0.3932	0.49	0.55
rP_{max} [mm h^{-1}]	P_{max} [mm h^{-1}]-	2.4	2.4	2.49	4.8	4.8
-θ_{ini} [-]	θ_{ini} [-]0.212	0.218	0.218221	0.221224	0.207	0.177

Water content change

To estimate the relevance of the different response types in terms of the transported water quantity through the soil, the maximum change in water content for every event ($\Delta\theta_{max}$) has been taken as a proxy which can further indicate differences in response properties. The patterns of maximum water content changes ($\Delta\theta_{max}$) in each geology were compared with respect toamong response type and depth. $\Delta\theta_{max}$ is taken as a proxy for the amount of water transported and can indicate differing response properties between the geologies. Figure 3 4 shows $\Delta\theta_{max}$ violin plots with $\Delta\theta_{max}$ in the *SR* at 10 and 30 cmtwo individual depth also including the water content changesduring *SR*. For *SR* the plots include all events that show a response in the respective depth from flow events that ended at deeper sensors., independent of the maximum response depth. For *NSR* 30 and 50 cm events only $\Delta\theta_{max}$ of the first response depth was considered. Median in the respective depth. For *NSR*10-50 only the water content change in 50 cm (first out-of-sequence reaction) was taken into account. Observed median $\Delta\theta_{max}$ values range between 1.8 and 4.3 Vol%. For the *SR* events, a significant decrease of $\Delta\theta_{max}$ with depth was observed for Slateslate and Sandstonesandstone sites. Marl sites did not show this damping of the water content signal with depth and exhibited a significant increase of $\Delta\theta_{max}$ at 50 cm depth (*SR*). For the *NSR* events no damping of $\Delta\theta_{max}$ with depth was observed. In contrary, Sandstone*NSR* in sandstone and Marlsmarls both havehad higher $\Delta\theta_{max}$ at 50 cm depth compared to 30 cm. Furthermore, for all geologies $\Delta\theta_{max}$ at *NSR* 50 cm (*NSR*) was similar or highereven stronger than the least dampened response at for *NC/SR* 10 cm foror *SR* events30 cm responses.



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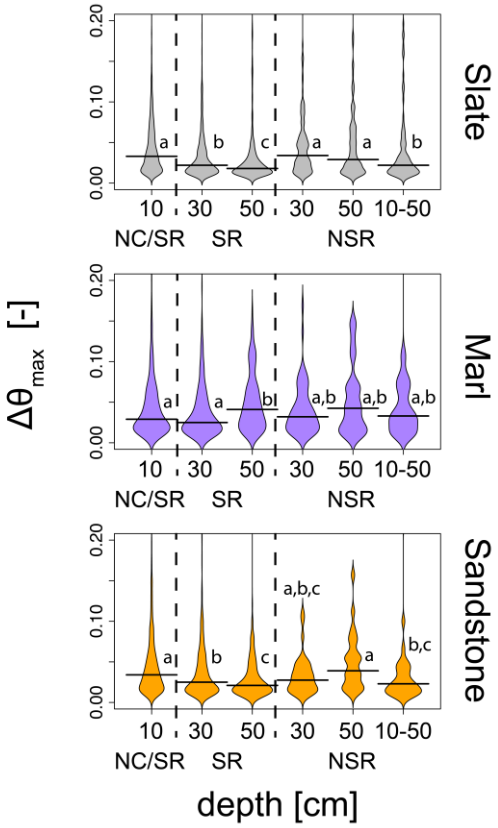

Figure ~~3~~4: Violin plots of maximum volumetric soil moisture change ($\Delta\theta_{max}$) ~~of *SR* and *NSR* events~~per depth for the three geologies and differentiated by infiltration response ~~depths.~~. $\Delta\theta_{max}$ at 10 cm could result from a *NC* response (10 cm only) or a *SR* that ends at a deeper sensor (30 or 50 cm). Horizontal lines in the plot indicate the median $\Delta\theta_{max}$. Same letters symbolize no significant difference between the response classes of the same geology (~~$p < 0.05$~~Dunn test, two sided, Benjamini-Hochberg correction, $p > 0.025$).

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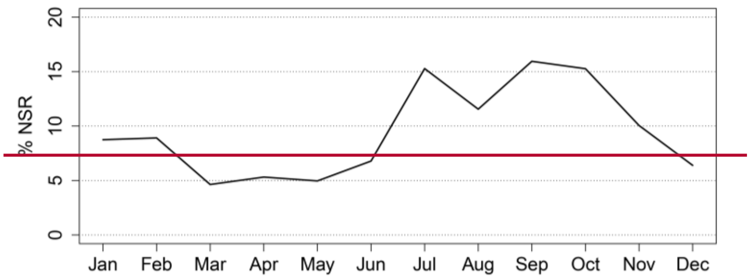
3.2~~.~~ Non-sequential response (*NSR*)

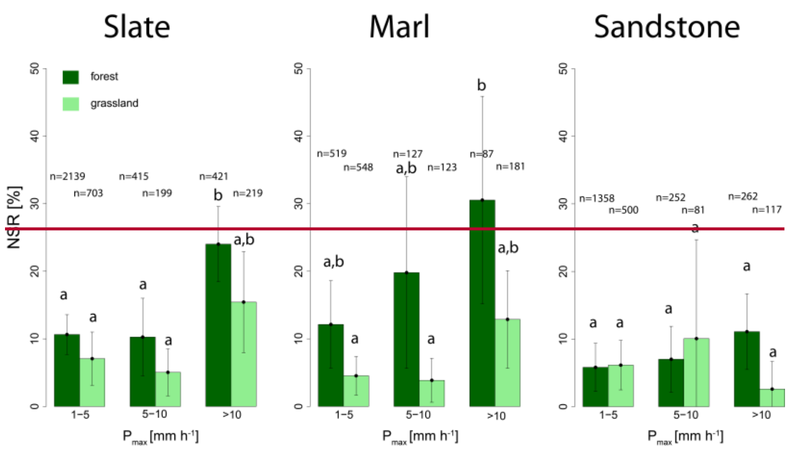
~~*Spatial and seasonal patterns*~~

The fraction of *NSR* events in dependence of θ_{ini} and *P* characteristics was analyzed to reveal the spatial and temporal patterns and possible controls of PF. ~~The single soil moisture profiles reveal a high variability with 0 to 46.2 % of the events showing *NSR* (Table 3). The effect of site-specific variables on the frequency of *NSR* such as aspect, distance to the next tree and distance to stream were tested. We found no significant (p=0.819) differences between north- and south-facing aspects on the frequency of *NSR*. Furthermore, no correlation between *NSR* and distance to surrounding trees was found (Spearman R =~~

~~0.014). None of the six individual landscape units showed a significant linear trend between *NSR* and distance to stream. The monthly means of *NSR* across all sites show distinct seasonal dynamics (Fig. 4): From March to June *NSR* shows a constant value of around 5 % which increases to 11.6-15.9 % from July until October and decreases again towards winter.~~P_{max} and θ_{ini} of each profile are only weakly correlated (median profile Spearman R: -0.19). An increase of *NSR* with increasing ~~P_{max}~~rP_{max} was observed (Fig. 5). Especially forested sites in the ~~Slate~~slate and ~~Marl~~marl region showed a ~~high and significant~~strong increase of *NSR* above a threshold of ~~P_{max}~~rP_{max} = 10 mm h^{-1}. ~~No comparable~~This pattern was ~~found~~only weakly pronounced for the grassland sites. More *NSR* with higher rP_{max} in the forests was also found when using maximum rainfall intensity for the whole event (*P*) instead of the pre-response characteristics (*rP*).



~~**Figure 4: Mean monthly fraction of *NSR* events over all 135 profiles.**~~



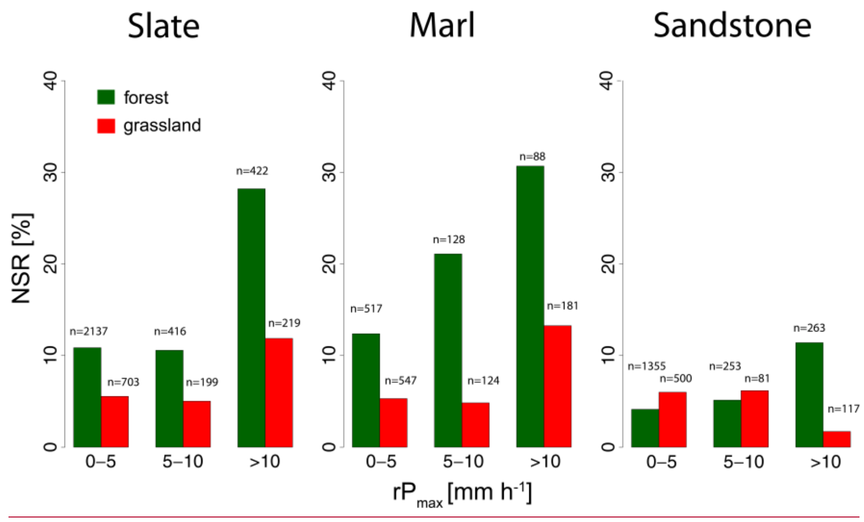


Figure 5: *NSR* vs ~~P_{max} (pre-response). Bars indicate the mean occurrence of *NSR* and error bars show the standard deviation.~~ rP_{max}. The numbers above the bars (*n*) indicate the ~~total~~ number of events~~. Same letters indicate no significant differences of *NSR* between P_{max} and land cover for each geology (p > 0.05).~~ per class.

~~*Comparison of NSR observations with preferential flow from capillary prediction*~~

~~To make additional use of this unique data set, we also tested the ability of capillary theory to predict the observed *NSR* occurrence. We hypothesize that *NSR* will occur as soon as the maximum matrix infiltration capacity is reached. Thus, we compared the occurrence of *NSR* against capillary flow prediction, both in dependence of θ_{ini}~~ Figure 6 shows the portion of *NSR* response for the six different landscape ~~units (Fig. 6).~~ depending on individual θ_{ini} quartiles for every profile to account for the differences in absolute θ_{ini} values among landscape units. We observed that the drier the forested sites were, the higher the measured *NSR* occurrence was. Especially ~~Slate~~slate and ~~Marl~~marl sites showed a strong increase in *NSR* occurrence (~~of~~ up to ~25 % of events) for the driest θ_{ini} quartile. At ~~Slate~~slate grassland sites observed *NSR* occurrence was not ~~related~~responding to drier conditions in the same way as for the forested sites. The fraction of *NSR* events at the ~~Marl~~marl grassland sites did not change with initial conditions and at ~~Sandstone~~sandstone grassland sites *NSR* occurrence increased only under wetter conditions. ~~The predicted occurrence of *NSR* based on capillary theory was much lower than the observed proportion of *NSR* events, except for the Marl grassland sites where measured *NSR* is lower than predicted. For some of the landscape units predicted proportion of *NSR* events was close to zero while *NSR* was actually quite frequently observed (e.g. in 24.6 % of the driest 769 soil moisture events for Slate forest). Predicted *NSR* fraction by capillary theory increases slightly under dry conditions compared to wet conditions for all landscape units due to the higher P_{max} during dry summer months~~

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~~(P_{max} = 4.8 mm h^{-1} for the driest quartile and 3.36 mm h^{-1} for the wettest quartile, respectively). P_{max} and θ_{ini} of each profile are only weakly correlated (median profile Spearman R: -0.19).~~

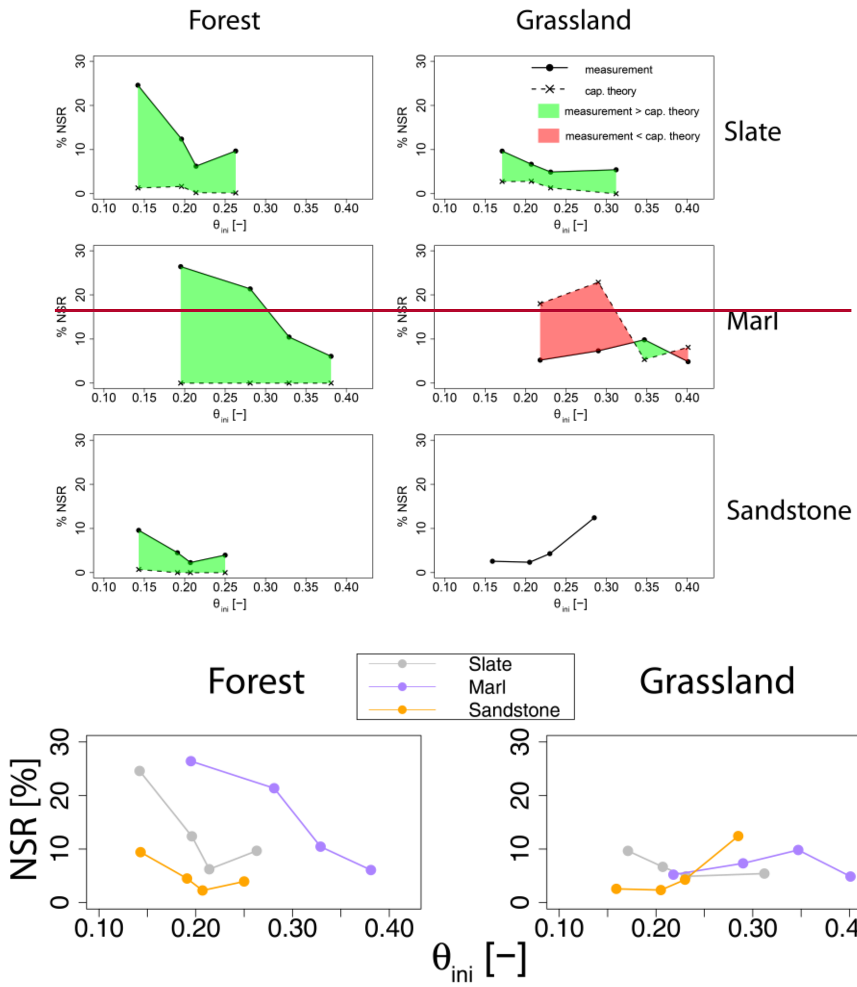

Figure 6: Relationship of *NSR* with θ_{ini} for ~~measured values and calculated theoretical capillary *NSR* occurrence for each geology/land cover group. Each~~each landscape unit. Every point represents % *NSR* for all events which fall in the four different quartiles of initial soil moisture (the ~~plotted~~plotting position of θ_{ini} value represents a quartile median). Number of events observed in the different classes can be found in the supplement (Table S4).

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~~*Statistical exploration: predicting preferential flow occurrence*~~

In a next step we used *GLM*s to predict the occurrence of *NSR* based on event and landscape characteristics (temporal occurrence). Individual models were fitted for the six landscape units (Appendix B). The stepwise model selection function was only partly able to appropriately reduce the predictors. With our statistical modeling approach, we could again verify that the Marl and Slate forested soils are mostly influenced by initial soil moisture and *P* characteristics. Many predictors such as the hydraulic conductivities (K_{MP}, K_{mat}), distance to stream, rooting depth, θ_{ini}, P_{sum} and aspect were significant at the forested Sandstone sites, which exhibited the highest Pseudo-R^2 of all *GLM*s. Grassland sites seemed to be influenced by *P* characteristics and other landscape properties such as slope, distance to stream or elevation. All forested sites revealed a negative relationship between θ_{ini} and probability of *NSR* events, while the grassland sites showed a positive relationship (Appendix B). One overall *GLM* was fitted without differentiating between the landscape units. Only the Sandstone grassland was excluded for the joint *GLM*, because no hood infiltrometer data was available for that group. This model produced a poor fit (McFadden Pseudo R^2 = 0.08) with K_{MP} being the most significant predictor. Again, the other important predictors are rainfall event characteristics, θ_{ini}, distance to stream, rooting depth and elevation. A linear model (spatial *NSR* occurrence) was used to predict the proportion of *NSR* events per soil moisture profile. One model was fitted for all soil moisture profiles, excluding the Sandstone grassland sites (R^2=0.40). Important predictors (P_{sum}, P_{ini}, θ_{ini}, K_{MP}) are similar to those of the joint temporal model (*GLM*) used for all profiles (five landscape units).

To test for a seasonal effect on the *NSR* occurrence we also analyzed the frequency of *NSR* on a monthly basis. Since land cover seems to play an important role for *NSR* occurrence (Fig. 5 and 6) the *NSR* portion for all infiltration events of the two land covers was calculated separately. Forests show a distinct seasonal dynamics (Fig. 7): From March to June *NSR* showed a constant value slightly higher than 5 % which increases to 13-20 % from July until October and decreases again towards winter. In the same time period θ_{ini} dropped to its lowest annual values and also rP_{max} had its maximum in the summer month. For grasslands this dynamic was less pronounced with the highest value in September.

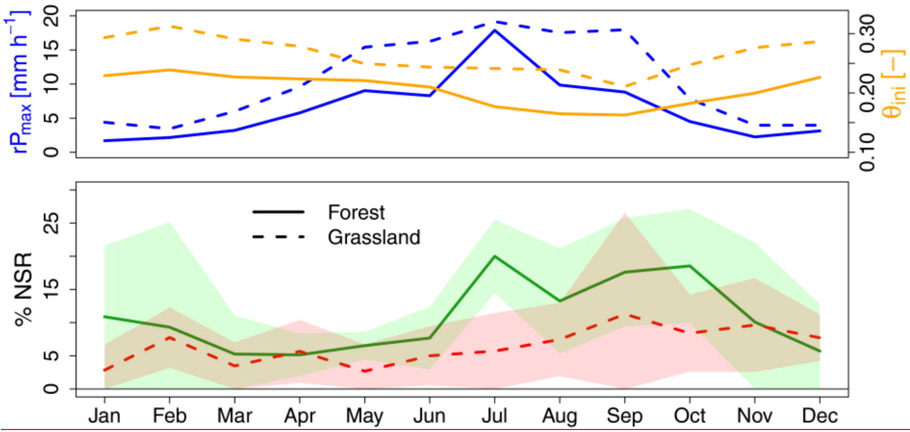

Figure 7: Monthly mean *rP_{max}* and *θ_{ini}* (upper diagram) and fraction of *NSR* events for the two land covers (lower diagram). The solid lines represent the forest and the dotted lines the grassland response. The shaded areas in the lower diagram show the standard deviation between the single years for each month. For number of events observed in the individual month over the total time period and for individual years see the supplement (Table S5).

3.3 Sequential responses (*SR*) and flow velocities

~~*Observations*~~

~~Not only *NSR* events but also *SR* events can point towards~~ *Estimating PF* ~~if the wetting front~~*by comparison with modeled and measured matrix flow*

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To identify PF from *SR* we further compared measured maximum pore water velocities ~~are higher than expected for capillary~~(v_{max}) against measured (hood infiltrometer, K_{mat}) and modeled matrix flow ~~in the soil matrix.~~velocities (v_{mat}). Table 5 indicates the percentage of observed v_{max} that exceed either the measured infiltrometer or modeled values. Both comparisons indicate that observed water flow is in most of the cases faster than water that is flowing in the soil matrix only. Between 72.9 and 89.0 % of the observed *SR* responses are faster than the modeled matrix flow velocities. The median difference in flow velocity for the events with $v_{max} > v_{mat}$ is 114 cm day^{-1}. The model matches with the exceedance obtained by the hood infiltrometer, except for marl and sandstone forest sites with an exceedance rate of the infiltrometer being only 48.7 and 44.0 %, respectively. This is due to the high surface K_{mat} values that were measured with the hood infiltrometer for these two landscape units. The high conductive parameters of these two landscape units were not distinct higher in the set of hydraulic parameters used for modeling.

Table 5: Percentage of event with measured v_{max} exceeding the infiltrometer (K_{mat}) or modeled matrix flow velocities (v_{mat}).

-	-	Infiltrometer	Modeled
Forest	Slate	80.0	78.0
	Marl	48.7	88.1
	Sandstone	44.0	77.2
Grassland	Slate	74.1	72.9
	Marl	79.2	87.7
	Sandstone	-	89.0

Observed maximum pore water velocities

Since the v_{max} observed from soil moisture responses (*SR*) exceeded the modeled or measured matrix values most of the time we examined v_{max} in more detail. The measured v_{max} ranged from 6 to 80640 cm day^{-1} with a median of ~~113~~120 cm day^{-1}. Only a weak correlation was found between v_{max} of the shallow versus the ~~larger~~deeper depths (10-30 cm to 30-50 cm; Spearman-R: 0.~~22~~36). Median observed v_{max} values per group ranged between ~~71~~72 cm day^{-1} for forested ~~Sandstone~~sandstone sites (for the shallow depth 10-30 cm) and ~~297~~274 cm day^{-1} for forested ~~Marl~~marl sites (for the depth 30-50 cm) (Fig. ~~7~~8). Comparing v_{max} for all landscape units the ~~Marl~~marl soils showed more variable flow velocities and higher median values, especially between 30 and 50 cm soil depth. Slate soils do not show a significant difference between the two depths ~~and~~or the land covers. Sandstone exhibited highest flow velocities under grassland sites. Forested ~~Sandstone~~sandstone soils had a significant lower *SR* flow velocity than all other soils. ~~Further analysis revealed no correlation between %-*NSR* and median flow velocities for each profile (Spearman R= 0.37) and P_{max} and v_{max} were also not significantly correlated (Spearman R = 0.22).~~

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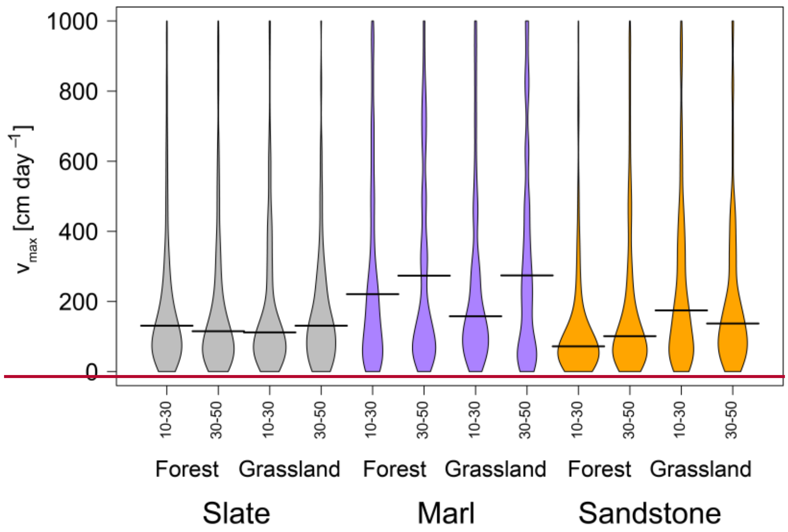

	S_F 10-30	S_F 30-50	S_G 10-30	S_G 30-50	M_F 10-30	M_F 30-50	M_G 10-30	M_G 30-50	Sa_F 10_30	Sa_F 30-50	Sa_G 10-30
S_F 30-50	0.06										
S_G 10-30	0.13	0.45									
S_G 30-50	0.14	0.45	0.42								
M_F 10-30	**0.01**	**0.00**	**0.00**	**0.01**							
M_F 30-50	**0.01**	**0.00**	**0.00**	**0.00**	0.34						
M_G 10-30	0.05	**0.01**	**0.01**	**0.02**	0.40	0.24					
M_G 30-50	0.05	**0.01**	**0.02**	**0.02**	0.45	0.41	0.40				
Sa_F 10_30	**0.00**	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**			
Sa_F 30-50	**0.00**	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	0.50		
Sa_G 10-30	0.18	**0.02**	0.05	0.05	0.16	0.08	0.29	0.20	**0.00**	**0.00**	
~~Sa_G 30-50~~	~~0.29~~	~~0.43~~	~~0.46~~	~~0.40~~	**0.02**	**0.01**	~~0.05~~	~~0.04~~	**0.00**	**0.00**	~~0.12~~

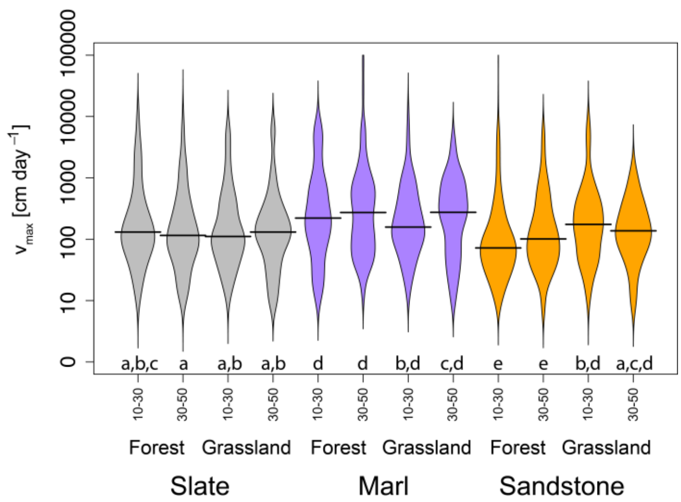

Figure ~~7~~8: Violin plot of observed v_{max} for the six landscape units (colors) and two depths (10-30, 30-50 cm). ~~The table~~Same letters below ~~shows~~ the ~~*p*-values of the test statistics (~~plots symbolize no significant difference (*p* < 0.025, Dunn test, two sided, Benjamini-Hochberg correction).~~ Values above 1000 cm day^{-1} are not shown. Significant~~

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differences (p < 0.05) are marked bold and highlighted in grey. S: Slate; M: Marl; Sa: Sandstone; F: Forest, G: Grassland and 10-30 and 30-50 are the depths between the two points where flow was measured.

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To test for a dependence of v_{max} on soil water content the relationship of all observed events was shown as 2D kernel density estimations (KDE) (Venables and Ripley, 2002) with higher KDE values indicating more events (Fig. 8). The logarithmic v-θ relationship ($v_{max} = 10^{a\theta+b}$) was approximated by a linear regression on a semi log scale (y-axis). The correlation is significant (p < 0.001) and v_{max} is decreasing with water content. However, the relationship only explains a small fraction of the variance (R^2=0.06). v_{max} showed a very high variability with fast flow velocities observed over all water contents. Furthermore, only weak v_{max}–θ relationships of the form $v_{max} = 10^{a\theta+b}$ were found for the individual landscape units with the highest explained variance in the Sandstone grassland between 10 and 30 cm (R^2 = 0.17). All landscape units showed a decrease of wetting front velocity with water content, although not all were significant.

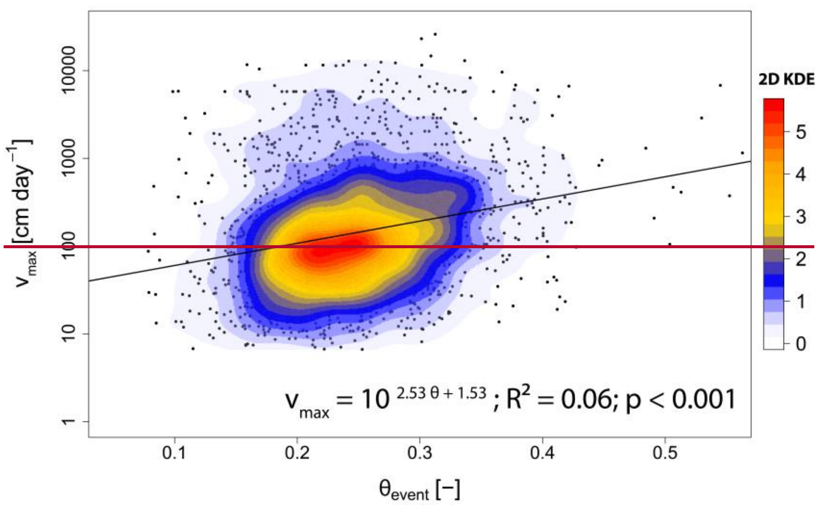

Figure 8 To further evaluate the variability of v_{max} in respect to θ_{ini} and P_{max} for all observed events, 2D kernel density estimations (KDE) (Venables and Ripley, 2002) are shown in Figure 9 with higher KDE values indicating more events. There is no clear relationship of v_{max} with θ_{ini} or P_{max} and high maximum pore water velocities can be found over the full range of θ_{ini} and P_{max}.

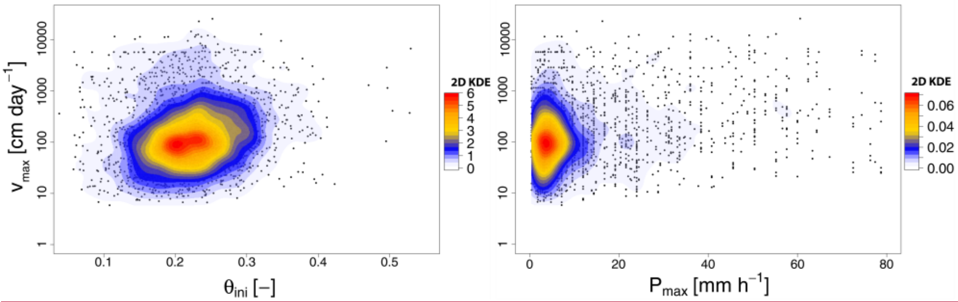

Figure 9: Measured wetting front SR maximum pore water velocities (v_{max}) in relation to θ_{event}. The event water content is the median water content of the two flow depths (10-30, 30-50 cm) between first response and peak soil moisture θ_{ini} and P_{max}. Color contours indicate 2D kernel density estimation (2D KDE). The points show single event values. The line shows the semi-log linear fit.

Comparison with capillary prediction

To identify PF from *SR* we further compared measured v_{max} against calculated matrix wetting front velocities (v_{mat}). The relationship of measured to calculated matrix flow velocities shows a strong underestimation of v_{max} by capillary matrix flow (v_{mat}) (Fig. 9). Wetting front velocities from capillary calculation are in part orders of magnitudes lower than the observations. Across landscape units between 84 and 96 % of the v_{max} in 10-30 cm yield higher values than v_{mat}. Slate grassland showed with 84 % the lowest proportion of v_{max} underestimated by v_{mat}, whereas Marl grassland shows with 96 % the highest. In 30-50 cm between 78 % (Sandstone forest) and 92 % (Marl forest) of the values have higher observed wetting front velocities than we have calculated by matrix flow.

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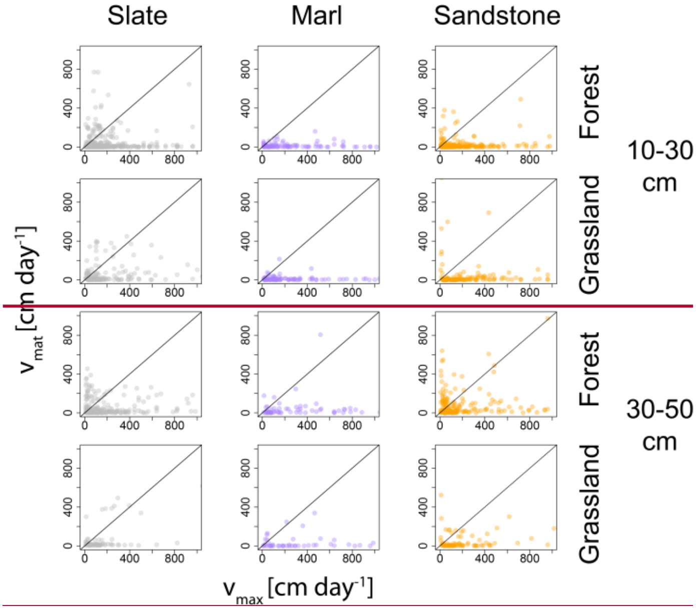

Analyzing the median response of v_{max} to θ_{ini} and P_{max} for the different landscape units we can see an increase of median v_{max} for high P_{max} for most landscape units (Fig. 10). Furthermore, the median v_{max} is increasing under dry conditions for marl independent of land cover and for slate grassland (Fig. 11). The other landscape units do not show a clear pattern between v_{max} and θ_{ini}.

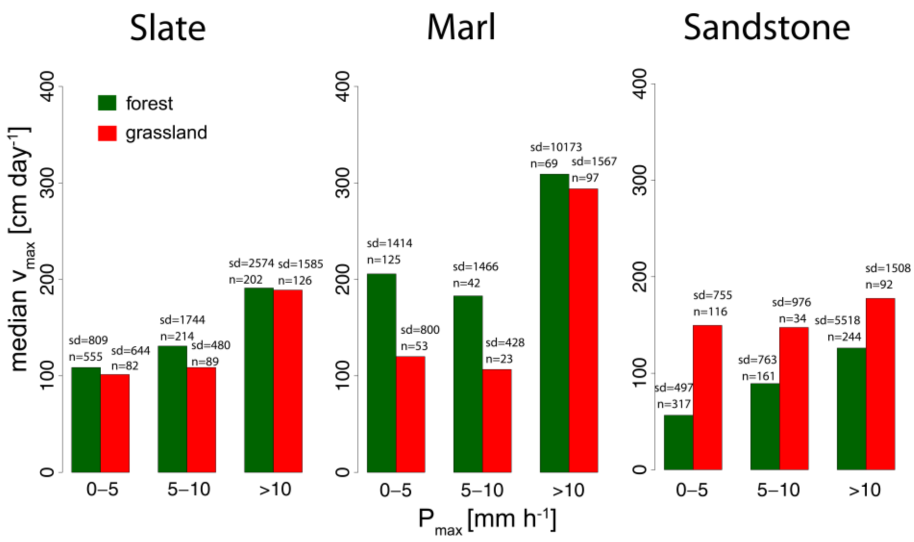

Figure ~~9: Scatterplots of measured wetting front velocity (~~10: Median v_{max}~~) against~~ vs P_{max}. The numbers above the bars indicate the number of events included into the ~~capillary predicted flow velocity (v_{mat}). The line~~analysis (n) and the standard deviation (sd).

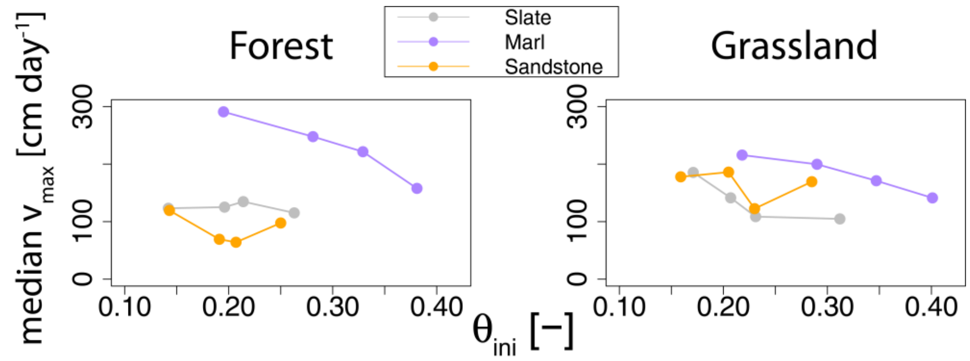

Figure 11: Relationship of median v_{max} with θ_{ini} for each landscape unit. Each point represents ~~the 1:1 relationship. Events~~median v_{max} for all events which fall in the four different quartiles of initial soil moisture (the plotting position of θ_{ini} value represents a quartile median). Number of events observed in the different classes can be found in the supplement (Table S6).

Although, the relationship of v_{max} with P_{max} and θ_{ini} is not as clear as with *NSR*, the seasonal dynamics of median v_{max} shows an increase during the summer months with ~~v_{max} higher than 1000~~the highest flow velocities during times with low θ_{ini} and high P_{max}. In contrast to *NSR* grasslands showed a stronger increase than forests with a maximum between June and August and a median v_{max} between 225-325 cm day^{-1} ~~are not shown~~. For forests a weaker increase in the time between July and August and a stable median v_{max} of around 200 cm day^{-1} was seen. The number of observed events furthermore indicates that most *SR* events are not observed during the times of high v_{max} but rather during the wet winter month.

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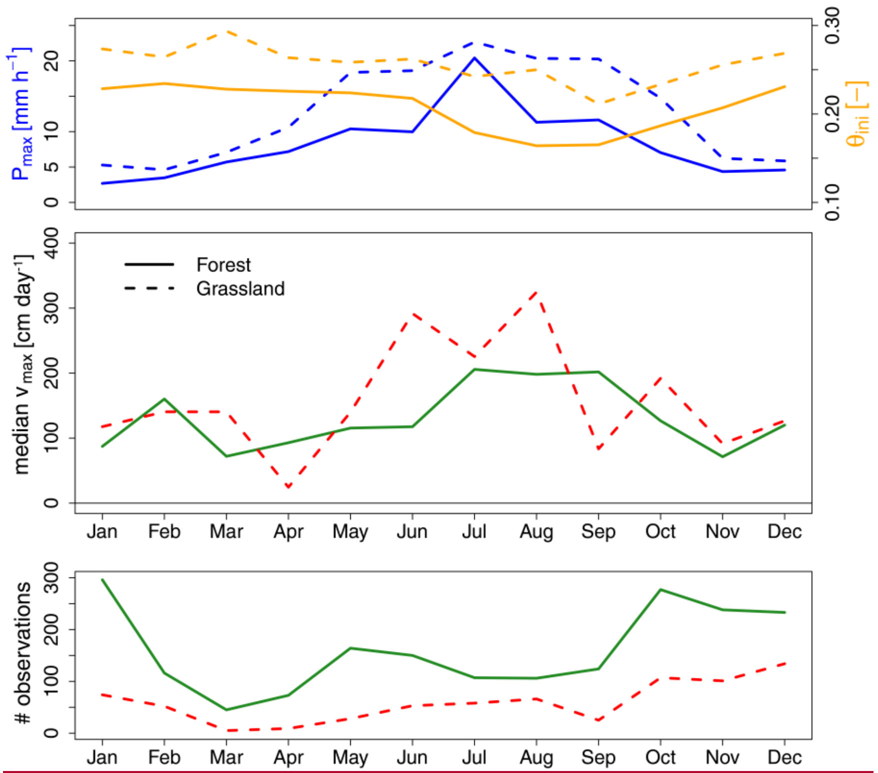

Figure 12: Monthly mean P_{max} and θ_{ini} (upper diagram), monthly median v_{max} for the two land covers (middle diagram) and number of observed v_{max} values (*SR* that reached either 30 or 50 cm) for each land cover and month (lower diagram). The solid lines represent the forest and the dotted lines the grassland response.

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4. Discussion

4.1 ~~Event classification~~General relevance of PF

PF as either non-uniform flow (*NSR*) or as fast sequential flow was observed in all landscape units and ~~sensor~~under all event conditions (P_{max}, θ_{ini}). The importance of PF during infiltration was highlighted by the fact that observed *SR* flow velocity (v_{max}) was most of the time faster than pure soil matrix flow and depended on the landscape unit *NSR* accounted for 18-44 % of the responses deeper than 10 cm. The variability of response types within the landscape units and even within some sites was high, which highlights soil heterogeneity on such larger scales and shows the importance of small scale soil properties and soil water flow. However, we found a strong variability in PF occurrence that was dependent on spatial and temporal factors which are discussed in section *4.4* and *4.5*.

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Dividing soil water dynamics into single events based on P input is always a trade-off: On the one hand, short rainfall events do not allow for a clear separation of the infiltration signals from different input pulses. On the other hand, long rainfall that is grouped into one event can result in too much information from several consecutive rain input pulses that are merged into one rainfall event. Different rainfall regimes require different threshold values, i.e. hours without rainfall (t_e) for the identification of event endings. While at the Shale Hills critical zone observatory a threshold value of 24 hours without rain was chosen (Liu and Lin, 2015), 12 hours seemed more appropriate in our study. However, different event definitions lead to difficulties in comparing actual numbers. This problem was already mentioned by Haas et al. (2018) in the event definition of erosion events. For an oceanic climate, with longer phases of rainfall, event-based analysis of soil water dynamics is more challenging compared to e.g. semi-arid climates with more clearly differentiable events.

Occurrence of preferential flow

PF is not only important in terms of its occurrence frequency, but also relevant for the quantity of transported water as indicated by the observed water content changes ($\Delta\theta_{max}$). Especially during *NSR* the $\Delta\theta_{max}$ is higher than $\Delta\theta_{max}$ for *SR* at the same depth, which implies fast flow of large amounts of water into deeper zones. Furthermore, the marl sites with their high velocities in 50 cm depth also showed the strongest $\Delta\theta_{max}$ increase in this depth, unlike the other geologies. Similar observations were made by Hardie et al. (2013), who found higher $\Delta\theta_{max}$ in greater depth during *NSR* or events with high v_{max}, and Eguchi & Hasegawa (2008) calculated that high amounts (16 to 27 %) of the total annual drainage was produced by PF.

4.2 Observed non-uniform flow (*NSR*)

In our study, occurrence of *NSR* for single soil moisture profiles was in the same magnitude (0-46.2 %) as those ofwas similar to other studies. Liu and Lin (2015) found profile *NSR* occurrence varying between <1 and 72.4 % for single years, Graham and Lin (2011) found 18 to 54 % for a three-year period and Wiekenkamp et al. (2016) found 7-51 % also using a three-year time series. However, we found a lower average *NSR* occurrence (mean of the profiles within one landscape unit) of 5.9-14.6 % for the landscape units in our study (data not shown) compared to 26% in the Shale Hills catchment of Graham and Lin (2011) (26 %).. Until now, most studies on *NSR* events from soil moisture time series focused on a relatively similar substrate (shale), land cover (forest) and a temperate climate (Graham and Lin, 2011; Lin and Zhou, 2008; Liu and Lin, 2015; Wiekenkamp et al., 2016). The Slateslate forest of our study is the landscape unit most comparable to the studies cited above. It shows a comparable range of *NSR* occurrence (max. 0-46.2 % for a single profile). However, we found large differences between the As our experimental design targeted not one but 6 different landscape units, we were able to compare responses observed in our study.the shale forest to other environments. Sandstone grassland showed a maximum *NSR* at a single profile of only 15.6- % of the events at a single profile. Forested. Soil profiles under forest on clayey soils (Slate & Marlslate & marl) had a higher occurrence of *NSR* (based on the landscape units) and a higher maximum *NSR* occurrence for single profiles within these landscape units compared to Sandstonesandstone or grassland sites. Zhao et al. (2012) also found difference in land cover (forest vs. cropland) and soil characteristics to affect *NSR* occurrence. They found lower values with 5.8 - 32.4 % *NSR* in the croplands compared to the nearby Shale Hills forest, but also having contrasting geologies. Our study highlights the effect of land cover and geology on the occurrence of a non-homogenous wetting front by a systematical comparison. The landscape units exhibit clear patterns in *NSR*, although the variability within the landscape units is highas geology differs between the sites the lower *NSR* cannot be unequivocally attributed to land cover.

4.2 Influences on non-sequential response (*NSR*)

We found two main properties affecting the *NSR* occurrence, the initial soil moisture (θ_{ini}) and the3 Observed maximum rainfall intensity (P_{max}) (Fig. 5 and 6). These finding are supported by the results of the *GLM* showing that θ_{ini} and *P* characteristics were important temporal *NSR* predictors for most landscape units. However, examining the effect of θ_{ini} and P_{max} in detail, results were not consistent throughout all landscape units in our study. Both effects (θ_{ini}, P_{max}) were most strongly pronounced in the clay-rich Slate and Marl forest profiles. A higher probability of *NSR* under dryer conditions and with higher *P* intensities were also found by Wiekenkamp et al. (2016), Hardie et al. (2013) and Liu and Lin (2015) although they used rainfall event characteristics for the entire event instead of pre-response *P* characteristics.pore water velocities

Evaluating both main factors affecting *NSR* occurrence separately, we found *NSR* decreasing with higher θ_{ini} except for Sandstone grassland. The increase of *NSR* with increasing θ_{ini} in Sandstone grassland could be an indication for macropore dominated PF with lower infiltration capacities due to higher saturation. For the other landscape units, the increase of *NSR* with lower θ differs among the landscape units, being stronger in the Marl and Slate forest. Many studies showed that clay content increases macroporosity under dry conditions through shrinkage and the subsequent cracking of the soil (e.g. Li and Zhang, 2011; Novák, 1999; Stewart et al., 2016a). This can lead to preferential flow as observed by dye tracers and soil moisture measurements (Hardie et al., 2011; Sander and Gerke, 2007; Zhang et al., 2014)Maximum pore water. Liu and Lin (2015) found clay content to be an important predictor of *NSR* in the Shale Hills catchment. Das Gupta et al. (2006) measured high infiltration capacity for the macropore domain of clay soils using a tension infiltrometer. The relationship between *NSR* and θ_{ini} could also explain the observed seasonality of *NSR*, with the drier months in late summer and autumn showing the highest *NSR*. However, the question arises why the effect of clay content is much stronger in forests compared to grassland. One reason might be the higher connected macroporosity caused by roots in addition to soil cracks. Lange et al. (2009) found roots to be a key factor for preferential flow and Alaoui et al. (2011) and Gonzalez-Sosa et al. (2010) measured higher

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macroporosity in forest soils than for other land covers. More laterally directed PF pathways created by roots could also enhance *NSR* (Bachmair et al., 2009). Furthermore, higher soil organic carbon content in forest can enhance aggregate stability in clayey soil and thereby be an explanation for higher *NSR* due to the resulting interaggregate porosity (Lado et al., 2004; Six et al., 2002). Carminati et al. (2009) observed root shrinkage for lupin in dry sandy soil, which might also affect the tree roots in our study sites and enhance PF in forests. Furthermore, forest are more likely to develop hydrophobic layers which can trigger PF at the soil surface (Bachmair et al., 2009; Blume et al., 2009), but this was mostly observed as finger flow on sandy soils (Blume et al., 2009; Clothier et al., 2000; Wessolek et al., 2008). Another explanation for more *NSR* in clayey forest sites could be that forest soils become drier than grassland soils (e.g. observed by Hayati et al., 2018) due to more water uptake by trees and thus potentially more pronounced cracks (Fig. 6). While we do measure drier conditions in forests, the lack of sensor-specific calibration causes uncertainty when comparing absolute values of soil moisture.

The second factor systematically increasing the occurrence of *NSR* was higher P_{max}. A general effect of *P* intensity on *NSR* can be explained by the initialization of PF: with higher *P* intensities the water pressure at the surface gets closer to zero and PF is triggered (Gjettermann et al., 1997; Jarvis, 2007; Weiler and Naef, 2003b). In our case, forest sites again showed a stronger increase in *NSR* with P_{max} (in this case of throughfall). Besides the higher macroporosity that previous studies have observed in forests (see discussion above), different input fluxes could become active with higher *P* intensity. Funneling of rainfall by stemflow (not measured in this study) could be a possible mechanism enhancing PF occurrence (Schwärzel et al., 2012). Distance to tree or rooting depth, as potential predictors of the influence of vegetation on infiltration, did not show strong correlations with *NSR* in the *GLMs* in our study. However, vegetation has numerous impacts on soil water balance and the main driver cannot clearly be determined from this analysis. The higher stone content in the Slate and the higher earthworm abundance found in the Marl, two possible drivers for PF (Bogner et al., 2008; Reck et al., 2018), were found in both land covers and thus cannot explain the higher *NSR* fraction observed in forests.

In our study, topographic properties did not seem to have a clear impact. This was also observed by Wiekenkamp et al. (2016). We neither found a difference in PF depending on aspect as observed (non-significant) by Liu and Lin (2015) nor did we find a dependence on hillslope position. Van Schaik (2009) and Zehe and Flühler (2001b) identified effects of hillslope position on Brilliant Blue FCF infiltration patterns. However, while Zehe and Flühler (2001b) found most PF near the footslope, van Schaik (2009) found most PF dye patterns near the hilltop plateau. Liu and Lin (2015) found a temporally variable dependence on hillslope position depending on water content. This indicates that the nature of topographic controls on PF are not universal, but strongly site dependent.

That no topographic or soil properties other than clay content were found to influence infiltration processes in this and other studies can also be attributed to the heterogeneity in larger scale catchments (> km²) where two soil profiles rarely show the same overall conditions. Therefore, comparing for one effect always involves a lot of variability of other factors and singling out individual controls is difficult. For large-scale sensor networks even more soil moisture profiles than used in this study would be necessary to have enough statistical power to identify clear patterns. Consequently, in addition to soil moisture sensor networks, it needs clear comparative studies of single properties and their interaction on soil water flow minimizing the number of other variables with experiments specifically designed for that purpose.

Comparing capillary flow theory with the measured *NSR* reveals that the occurrence of PF is underestimated by the theory most of the time. Higher occurrence of measured *NSR* compared to capillary theory prediction could indicate other initiation and flow mechanisms than pure capillary flow, such as film flow in macropores, along crack walls or in roots channels (Germann et al., 2007; Nimmo, 2010). In addition, microtopography can be important for PF initialization and has been often ignored (Weiler and Naef, 2003b). Only in the Marl grassland much lower *NSR* is observed under dry conditions than predicted from capillarity. This is due to the low K_{mat} value that has been measured in the Marl grassland and the underestimation of matrix infiltration capacity under dry conditions. However, the overestimation of *NSR* by capillary theory in the Marl grassland could also be an indication of more vertical macropore flow. The high wetting front velocities from the *SR* reactions in this landscape unit would support the idea.

4.3 Flow velocities and water content

Wetting front velocities (v_{max}) in this study (6-80640 cm day^{-1}) are in the same range as observed in other studies, however we measured slightly lower median v_{max} (113120 cm day^{-1}) than other studies (e.g. Germann and Hensel, 2006; Hardie et al., 2013; Nimmo, 2007). In addition, studies that measured v_{max} in single sprinkling experiments in the Slate forest region of the Attert catchment observed higher velocities than the median v_{max} found in our study: Angermann et al. (2017) measuredIn addition, studies that measured v_{max} in single sprinkling experiments in the slate forest region of the Attert catchment observed a v_{max} of 864-19000 cm day^{-1} using GPR and TDR during a hillslope irrigation experiment with an intensity of 30.8 mm h^{-1}. (Angermann et al. 2017). Jackisch et al. (2017) observed vertical transport velocities of bromide in the range of 2732 cm day^{-1} with sprinkling intensities of 30 and 50 mm h^{-1}. However, theThe highest wetting frontmaximum pore water velocity of the Slateslate forest landscape unit measured in our study was with 14662 cm day^{-1} in a similar range.

Most of the studies mentioned above are sprinkling experiments which apply high *P* intensities (>10 mm h^{-1}) and high P_{sum} and thus do not provide information on the response to low intensity events that make up a large portion of the annual rainfall events (see Fig. 23). In his review, Jarvis (2007) found that solute transport studies were either carried out at (near-) saturated conditions or with high irrigation rates (> 10 mm h^{-1}). Langhans et al. (2011) found an increase of infiltration capacity with higher rainfall intensity, probably due to the initiation of more macropore flow. This could be an explanation for the higher velocities found by high intensity sprinkling experiments. Therefore, a reason of partly lower v_{max} observed in this study might be that we are also accounting for low *P* intensity events. due to our focus on natural rainfall events. This assumption is supported by the fact that Hardie et al. (2013) measured a v_{max} of 24 – 960 cm day^{-1} under natural rainfall conditions which is more in the range of most velocities observed in our study. In summary, it is remarkable that no clear differences in flow velocities between different soil types could be identified (neither in our study nor across all previous studies). Instead, all soil types showed a similarly large range of velocities (10^0 – 10^5 cm day^{-1}). Furthermore, one can see orders of magnitude difference in v_{max} between different events but not among the landscape units. A clear reduction of maximum pore water velocity with decreasing θ (dry soils) as predicted by conventional unsaturated hydraulic conductivity relationships (e.g. van Genuchten, 1980) was not observed the results of our study. In general, it is remarkable that the high diversity of soils reported in the literature as well as in our study produce flow velocities in a similar range independent of texture.under field conditions. In contrast, higher flow velocities during driest conditions were observed for most profiles in our study.

Comparing the variability and median of v_{max} for the six landscape units, Marl profiles were most distinct to the other landscape units but did not have a significant land cover effect. Highest values were observed in 30-50 cm where most profiles show clay contents >50 %. This is in accordance to

4.4 Temporal controls of PF

We found that both, a low initial soil moisture (θ_{ini}) and a high maximum rainfall intensity (P_{max}) affect the occurrence of PF. This results in a higher occurrence of PF during summer time. Increased PF (*NSR*, v_{max}) during low θ_{ini} is in contrast to the classical assumption of PF, which should be initiated more often under wet initial conditions with a lower infiltrability. Furthermore, the mismatch of measured PF occurrence (*NSR*, fast v_{max}) compared to the prediction based on P_{max} exceeding K_{mat} indicates that initiation processes such as hydrophobicity/water repellency, local microtopographic depressions or channeling of water by vegetation could be the reason of the frequent occurrence of PF (Blume et al., 2008; Doerr et al., 2000; Schwärzel et al., 2012; Weiler and Naef, 2003). Locally, these processes can lead to higher water contents and thereby pressures at the soil surface close to atmospheric pressure which in turn trigger PF. The higher probability of *NSR* under dryer conditions and with higher *P* intensities was also found by Wiekenkamp et al. (2016), Hardie et al. (2013) and Liu and Lin (2015). Also Hardie et al. (2011) found faster flow velocities under dry conditions, which they concluded, was due to hydrophobicity and resulting finger flow and Blume et al. (2009) found response time of soil moisture and thereby flow velocity to be much faster during summer time. However, Buttle and Turcotte (1999) did not find a relationship of PF and initial soil water content, but on throughfall intensity.

Due to the strong seasonal variation with a maximum in summer and early autumn (Fig. 7 and 12), the most probable explanation is the influence of water repellency that has frequently been observed on natural surfaces in summer (Doerr et al., 2006; Täumer et al., 2006). Water repellency hinders infiltration and ensures a pressure buildup at the soil surface until pressure reaches a positive water entry potential (Bauters et al., 2000). Gimbel et al. (2016) observed that their clayey and loamy plots developed strong water repellency during a simulated drought field experiment with a 40-year return period and that infiltration patterns changed from homogeneous to preferential flow. Also sandy soils were found to be strongly affected by water repellency (e.g. Ritsema et al., 1997). Wessolek et al. (2008) found from a one year TDR measurements on a pine stand that PF is minor from February to April since the soil was not water repellent. They found a maximum of PF from May to September which matches in general with our observations, just that our observed maximum starts and ends approximately one month later. Furthermore, Täumer et al. (2006) observed a similar seasonal pattern over a 3-year period with a maximum of PF in summer and early autumn and also Rye and Smettem (2015) observed a similar seasonality in Australia. That during these dry and water repellent conditions the *P* intensity is highest further supports the initialization of PF. In general higher *P* intensities can lead to water pressures at the soil surface close to the water entry potential (Gjettermann et al., 1997; Jarvis, 2007; Weiler and Naef, 2003).

4.5 Spatial controls of PF

Clay content

Examining the temporal effects of θ_{ini} and P_{max} between the landscape units in detail, PF dynamics were not the same throughout all landscape units in our study. Especially clayey soils seems to be strongly influenced by low θ_{in} and clay content enhance *NSR* occurrence and v_{max}. Many studies showed that the clay content increases macroporosity under dry conditions through shrinkage and the subsequent cracking of the soil (e.g. Li and Zhang, 2011; Novák, 1999; Stewart et al., 2016a). Das Gupta et al. (2006) measured high infiltration capacity for the macropore domain of clay soils using a tension infiltrometer. The higher macroporosity of the clay soil can then further enhance the occurrence of PF, initialized by higher P_{max} and hydrophobic condition in summer as observed by (dye) tracers, infiltration and soil moisture measurements (Dekker and Ritsema, 1996; Hardie et al., 2011; Jarvis et al., 2008). Liu and Lin (2015) found clay content to be an important predictor of *NSR* in the Shale Hills catchment and we also measured higher *NSR* in clayey landscape units (slate, marl). Furthermore, we found high maximum pore water velocities in the clay rich subsoil of the marl sites. High v_{max} in the marl topsoil (lower clay content) is probably more attributed to the high abundance of biopores observed in the topsoil of this region. The high flow velocities in the subsoil are in accordance to other studies that showed fastest velocities due to structure development in unsaturated clay soils (Baram et al., 2012; Hardie et al., 2011; Tiktak et al., 2012). Probably ponding of water on top of the clay layer and subsurface initiation of macropore flow could be a reason of higher flow velocities in the subsoil (Weiler and Naef, 2003). Such a process was observed in the field by Hardie et al. (2011). This demonstrates that in the unsaturated zone close to the surface, clay should not be treated as a low conductivity but rather as a high conductivity material.

Land cover

The question arises why *NSR* is much more often observed in forests during summer compared to grassland and why v_{max} is higher in grassland. In general, forests tend to have highly connected macroporosity caused by roots (Alaoui et al., 2011;

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Gonzalez-Sosa et al., 2010; Lange et al., 2009). Furthermore, higher soil organic carbon content in forest can enhance aggregate stability and hence interaggregate porosity in clayey soil (Lado et al., 2004; Six et al., 2002). However, the sole presence of a higher macroporosity in forests does not explain the higher *NSR* occurrence. That higher macroporosity results in more *NSR* could also be caused by more laterally directed pathways in forests created by roots as observed by Bachmair et al. (2009). Funneling of rainfall by stemflow (not measured in this study) may support this mechanism (Schwärzel et al., 2012). However, in the Marl also the clay-poorer depth of 10-30 cm shows higher v_{max} than the clay-rich Slate region. One reason could be the higher density of biopores that was observed in the Marl topsoilsIn contrast, the stronger increase of v_{max} in grasslands during summer could be an indication of a seasonally changing macroporosity due to high temporal variation of biopores created by the soil fauna (e.g. earthworms), as observed in our study region (Schneider et al., 2016). Since the amount of biopores was found to decrease with depthBiopores such as earthworm burrows were frequently found to enhance vertical PF (Reck et al., 2018), but the velocity is increasing, clay cracks were seen as the primary influence. However, probably ponding of water on top of the clay layer and subsurface initiation of macropore flow could be a reason of higher flow velocities in the subsoil (Weiler and Naef, 2003b). Such a process was observed in the field by Hardie et al., (2011). This leads to the question how soil structure development in clay and flow initiation is influenced by the interaction with other factors, such as layers of contrasting texture, bulk density, stones or macropores created by flora and fauna. (Reck et al., 2018; Weiler and Flühler, 2004; Zehe and Flühler, 2001).

In contrast to *NSR*, *SR* occurrence was more influenced by P_{sum} than θ or $P_{int/max}$. Hardie et al. (2013) evaluated the rainfall characteristics for the different response types and found higher P_{sum} for *SR*, although not significant in all cases. Higher P_{sum} lowers the capillary forces due to higher saturation of the soil and thereby could be an explanation for the wetting front reaching deeper sensors. This could point towards more capillary flow with *SR*. However, also macropore flow could reach deeper sensors with higher P_{sum} due to less water abstraction by the matrix with a more saturated soil (Weiler and Naef, 2003a). This is the more likely explanation, since the minor effect of texture driven matrix flow during infiltration is indicated by v_{max} values that are magnitudes higher than calculated capillary flow (v_{mat}). The θ-v_{max} relationship shows that even though the decrease of v_{max} with θ is significant, it has little explanatory power and fast flow (>1000 cm day^{-1}) can occur at any θ. Furthermore, one can see orders of magnitude difference in v_{max} between different events but not between the landscape units having diverse soils and land cover. A clear decline with decreasing θ comparable to unsaturated hydraulic conductivities (e.g. van Genuchten, 1980) was not observed for flow velocities under field observations. Hence, infiltration was not primarily driven by saturation deficit. Similar results were obtained by Buttle and Turcotte (1999) who did not find a relationship of PF and initial soil water content. Other studies (Blume et al., 2009; Hardie et al., 2011) demonstrated higher flow velocities under dry conditions, however, this was not clear in this study. Hardie et al. (2011) found faster flow velocities under dry conditions, which they concluded, was due to hydrophobicity and resulting finger flow. Blume et al. (2009) measured response lags of θ in a Chilean volcanic ash soil catchment until 40 cm depth. They found response time and thereby flow velocity to be much faster during summer time.

The different pattern of $\Delta\theta_{max}$ with depth in the Marl region (compared to Slate and Sandstone) supports the finding of enhanced PF in the Marl. Also Hardie et al. (2013) found higher $\Delta\theta_{max}$ in greater depth during *NSR* or events with high v_{max}. In combination with the higher $\Delta\theta_{max}$ during *NSR* responses this highlights the importance of PF again not only to be fast, but also to transport significant amounts of water. This is relevant for e.g. pesticide transport, because water bypasses the upper soil layers without much interaction.

5. Conclusions

Our study quantified preferential flow (PF), flow velocities and related water content changes in a heterogeneous catchment (focusing on 3 geologies and 2 land covers). PF was found to be highly variable, but a dominant process during infiltration that cannot be ignored. Up to 46 % of the events for single soil moisture profiles show a non-homogeneous wetting front that often resulted in high water content changes at deeper soil zones. Furthermore, wetting front velocities of 78-96 % of the events are underestimated by capillary flow. Our analysis revealed that high flow velocities could occur across the entire range of soil moisture, texture and for both land covers. However, clay-rich layers showed highest median wetting front velocities and largest water content changes. Soils with a high clay content and forest land cover had increased occurrence of a non-homogeneous wetting front. These soils also showed a stronger dependency on initial soil moisture content (*NSR* occurred more often under dry conditions) and maximum rainfall intensity.

Clay-rich soils in the vadose zone should not be treated as a low-conductivity layer only due to their low hydraulic conductivity of the soil matrix. Our study highlights the importance of soil structure in clayey soil and vegetation for non-homogenous and fast unsaturated vertical transport of water during infiltration. To account for the effect of clay and roots in physical water flow descriptions, information on the dynamics of the soil structure in clay soils is needed as well as on root architecture and structural interactions with the soil matrix under variable θ. Further research is needed to explain the initiation and partitioning of water into the matrix and macropore domain. We suggest to include landscape hydraulic properties such as macropore properties rather than soil core hydraulic conductivities in large-scale physically based hydrological models since soil cores can only partly capture the variability of complex landscapes.Our results demonstrate that infiltration is strongly controlled by PF phenomena. As expected a higher maximum rainfall intensity increases the occurrence of PF, but different from common theory a higher soil moisture decreases the PF occurrence. However, the here studied landscape units show a high spatial heterogeneity and high temporal variation with different PF processes involved, such as more fast PF in grasslands and more non-uniform flow (*NSR*) in forest. Clay-rich soils showed to increase both, non-uniform PF (*NSR*) and fast PF (high v_{max}). By systematically comparing the dynamics of different landscape units we were able to identify that beside the amount of connected macropores such as cracks (influenced by a high clay content and low soil moisture) or biotic macropores (roots channels, earthworm borrows), PF strongly depends on initiation processes (water repellency, rain intensity). This leads to a strong seasonal dynamics with more non-uniform flow and highest flow velocities in summer and early autumn due to dry soils, high rainfall intensities and hydrophobic soil surfaces. Furthermore, the amounts of transported water are higher during non-uniform flow. This can have a potential impact solute transport during summer months and should be considered in water management.

We could show that soil texture is not the main driver of water flow velocity during infiltration in the vadose zone as we typically assume. We suggest to include dynamic flow, dynamic initialization processes and varying macroporosity into physically based hydrological models rather than static hydraulic conductivities derived from soil cores or soil maps. Therefore it needs ~~More effort is necessary to find or adapt already existing approaches of measuring and monitoring PF in diverse landscapes. That includes~~ easily transferable relationships or pedotransfer functions, which can help to find structure-related PF parameters similar to retention parameters. More effort is necessary to find or adapt already existing approaches of measuring and monitoring PF in diverse landscapes. We further suggest implementing large-scale sensor networks under different climatic settings, substrates, topographies, and land covers worldwide and to create standardized approaches for analyzing soil moisture datasets. ~~Patterns identified by large-scale sensor networks need to be complemented by comparative studies on single small-scale effects on soil water flow paths (e.g. vegetation covers or stone content).~~ Our approach can be expanded by combining it with groundwater response time series and stable isotope methods to identify and understand flow patterns in the vadose zone at the landscape scale.

Author contribution

DD prepared the data, developed and performed the analysis strategy and planned and conducted the fieldwork. MW and TB designed the sensor cluster setup, were involved in their installation and contributed to the data analysis strategy. DD prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Appendix A: Site characteristics

S: Slate; M: Marl; Sa: Sandstone

*** indicates Grassland sites** sd = standard deviation

~~Rooting depth was taken from Sprenger et al. (2016)~~

Site ID	Elevation [m asl]	Slope [°]	Aspect [°]	~~Distance to stream [m]~~	~~Distance to tree profile 1 [m]~~	~~Distance to tree profile 2 [m]~~	~~Distance to tree profile 3 [m]~~	~~Rooting Depth [cm]~~	K_{mat} [cm day^{-1}]	~~K_{MP} [~~ *sd* K_{mat} [cm day^{-1}]	median *θ* profile 1 [-]	median *θ* profile 2 [-]	median *θ* profile 3 [-]
M_A	358.2	4.3	26	~~6.0~~	~~3.2~~	~~2.4~~	~~4.4~~	~~82~~	174	~~185~~346	0.269	0.232	0.28
M_B	361.6	4.3	208	~~15.0~~	~~1.6~~	~~1.6~~	~~1.9~~	~~82~~	371	~~1218~~203	0.36	0.336	0.354
M_C*	326.0	3.0	61	~~192.0~~				~~34~~	30	~~491~~287	0.28	0.241	0.226
M_D*	295.0	2.4	260	~~10.1~~					30	~~30~~287 ~~491~~	0.331	0.37	0.303
M_E*	277.9	1.9	182	~~369.9~~				~~37~~	11	~~51~~138	0.344	0.292	0.398
M_F*	265.2	3.3	176	~~39.2~~				~~63~~	11	~~51~~138	0.303	0.359	0.336
M_G*	285.1	4.5	7	~~374.0~~				~~25~~	262	~~709~~89	0.364	0.377	0.337
M_H*	271.3	3.4	3	~~77.0~~				~~39~~	23	~~27~~29	0.284	0.29	0.268
M_I	291.6	1.3	265	~~30.0~~	~~2.1~~	~~2.4~~	~~2.5~~	~~87~~	462	~~1184~~230	0.308	0.291	0.266
M_J	282.6	4.6	244	~~6.0~~	~~2.1~~	~~2.7~~	~~3.6~~	~~99~~	499	~~733~~only 1 meas.	0.355	0.381	0.275
M_K	282.2	2.9	173	~~10.0~~	~~1.3~~	~~4.6~~	~~2.8~~	~~99~~	462	~~1184~~230	0.31	0.291	0.338
S_A	451.0	14.7	131	~~78.0~~	~~1~~	~~2.65~~	~~3~~	~~69~~	50	~~99~~110	0.234	0.254	0.183
S_B	462.4	20.0	132	~~105.1~~	~~1.3~~	~~1.4~~	~~2.2~~	~~63~~	50	~~99~~110	0.234	0.179	0.225
S_C	464.8	22.4	24	~~100.3~~	~~1~~	~~1.5~~	~~1.25~~	~~78~~	50	~~99~~110	0.21	0.229	0.125
S_D	452.8	14.5	34	~~67.5~~	~~1.85~~	~~1.9~~	~~1.2~~	~~69~~	50	~~99~~110	0.226	0.218	0.271
S_E	442.9	19.1	26	~~26.4~~	~~1.3~~	~~0.7~~	~~1.65~~	~~86~~	50	~~99~~110	0.211	0.234	0.207

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S_F	434.7	7.6	172	~~4.0~~	~~2.9~~	~~2.95~~	~~1.8~~	~~49~~	50	~~99~~110	0.17	0.154	0.275
S_G	458.5	26.2	178	~~72.7~~	~~1.75~~	~~2.5~~	~~4.2~~	~~46~~	50	~~99~~110	0.191	0.199	0.193
S_H	478.0	10.2	180	~~131.8~~	~~1.8~~	~~2.5~~	~~2.6~~	~~42~~	50	~~99~~110	0.202	0.167	0.193
S_I*	479.2	6.9	126	~~163.3~~				~~35~~	57	~~80~~79	0.218	0.21	0.189
S_J*	412.7	5.0	240	~~4.0~~				~~39~~	57	~~80~~79	0.378	0.514	0.229
S_K*	448.3	18.2	212	~~75.7~~				~~35~~	57	~~80~~79	0.208	0.228	0.194
S_L*	428.0	7.5	186	~~3.2~~				~~43~~	57	~~80~~79	0.229	0.349	0.333
S_M	470.6	25.8	166	~~70.0~~	~~2.15~~	~~2~~	~~4.12~~	~~81~~	50	~~99~~110	0.208	0.18	0.199
S_O	464.6	17.4	338	~~65.5~~	~~0.8~~	~~4.6~~	~~2.4~~	~~107~~	50	~~99~~110	0.201	0.241	0.208
S_P*	481.0	4.6	326	~~150.3~~				~~34~~	57	~~80~~79	0.203	0.168	0.203
S_Q*	453.0	16.8	183	~~35.6~~				~~46~~	57	~~80~~79	0.196	0.2	0.24
S_R*	446.4	13.5	166	~~7.7~~				~~54~~	57	~~80~~79	0.174	0.21	0.229
S_S	433.3	25.6	181	~~92.5~~	~~1.9~~	~~1.1~~	~~3.3~~	~~80~~	50	~~99~~110	0.2	0.167	0.213
S_T	409.2	28.4	188	~~41.8~~	~~1.1~~	~~0.92~~	~~1.5~~	~~74~~	50	~~99~~110	0.18	0.163	0.162
S_U	393.6	33.1	185	~~6.0~~	~~2.5~~	~~4.9~~	~~5~~	~~76~~	50	~~99~~110	0.208	0.177	0.154
S_V	429.0	17.4	3	~~6.8~~	~~0.7~~	~~1.6~~	~~2.4~~	~~89~~	50	~~99~~110	0.203	0.157	0.192
S_W	443.3	23.6	0	~~40.4~~	~~1.9~~	~~3.1~~	~~2.6~~	~~84~~	50	~~99~~110	0.19	0.165	0.178
Sa_A	374.1	9.5	142	~~269.8~~	~~3.6~~	~~2.4~~	~~5.8~~	~~104~~	77	~~250~~8	0.151	0.155	0.142
Sa_B	314.2	8.9	325	~~32.8~~	~~4.3~~	~~2.1~~	~~4.3~~	~~97~~	510	~~976~~227	0.28	0.247	0.239
Sa_C	363.8	11.3	333	~~121.3~~	~~1~~	~~1.8~~	~~4.1~~	~~115~~	77	~~250~~8	0.198	0.171	0.194
Sa_D	353.6	19.5	149	~~429.8~~	~~1.5~~	~~4.2~~	~~5~~	~~81~~	77	~~250~~8	0.177	0.165	0.198
Sa_E	347.0	12.5			13				~~411.3~~31 ~~2.8~~ ~~2.6~~ ~~3.5~~ ~~106~~	31 ~~282~~	0.201	0.227	0.258
Sa_F	367.5	10.3	4	~~450.6~~	~~4.2~~	~~2.4~~	~~5~~	~~63~~	77	~~250~~8	0.174	0.165	0.213
Sa_G	323.1	6.8	54	~~150.8~~	~~2.3~~	~~3.7~~	~~1.7~~	~~107~~	510	~~976~~227	0.244	0.228	0.201
Sa_H	338.5	13.9	106	~~309.8~~	~~1.35~~	~~2.4~~	~~3.8~~	~~93~~	77	~~250~~8	0.197	0.185	0.191
Sa_I	326.2	20.5	329	~~142.4~~	~~4.3~~	~~1.3~~	~~2.6~~	~~120~~	77	~~250~~8	0.182	0.179	0.184
Sa_J*	297.4	3.7			323				~~104.2~~-	- ~~33~~	0.224	0.258	0.257
Sa_K*	304.9	10.0			100				~~255.4~~-	- ~~10~~ ~~1~~	0.198	0.233	0.214
Sa_L*	297.7	6.8			300				~~256.5~~-	- ~~29~~	0.202	0.201	0.194

Appendix B: Generalized linear regression models and linear model

Full equations for the generalized linear model (*GLM*) for estimating temporal occurrence for a *NSR* and the linear model to predict the spatial occurrence of *NSR*.

GLM - Probability of event NSR		Intercept	P_{sum} [mm]	P_{max} [mm h^{-1}]	P_{int} [mm h^{-1}]	$θ_{ini}$ [-]	elevation [m a.s.l.]	aspect [°]	slope [°]	distance to stream [m]	distance to tree [m]	rooting depth [cm]	Avg. Monthly air temprature [°C]	K_{mat} [cm day^{-1}]	K_{MP} [cm day^{-1}]	McFadden Pseudo-R^2
5 groups		-2.452*	0.023*	0.025*	-	-3.851*	0.003*	-0.001	-	-0.003*	X	-0.007*	-	-	0.001*	0.08
Forest	Slate	-2.784	0.02*	0.036*	-	-10.97*	0.008	-	-0.027	-	-	-0.005	-	-	-	0.09
Forest	Marl	-0.538	0.059*	0.042*	-	-7.172*	-	-	-	-0.062*	0.253	-	-	-	-	0.18
Forest	Sandstone	4.386	0.035*	-	-	-14.983*	-	0.015*	-	-0.016*	-	-0.11*	-	-0.102*	0.062*	0.21
Grassland	Slate	-47.859*	0.034*	0.03*	-	3.079	0.118*	-	-0.211*	-0.056*	X	-0.099	-	-	-	0.16
Grassland	Marl	-3.351*	-	0.051*	-0.253	9.078*	-	-0.012*	-0.538	-	X	-	-	-	-	0.10
Grassland	Sandstone	25.056	0.042*	-	-	-	-0.092	-	-	-	X	-	-0.136*	X	X	0.09

Linear model - % NSR on profile scale	Intercept	Median profile P_{sum} [mm]	Median profile P_{max} [mm h^{-1}]	Median profile P_{int} [mm h^{-1}]	Median $θ_{ini}$ [-]	elevation [m a.s.l.]	aspect [°]	slope [°]	distance to stream [m]	X	rooting depth [cm]	Avg. Monthly air temprature [°C]	K_{mat} [cm day^{-1}]	K_{MP} [cm day^{-1}]	R^2
5 groups	-0.2996	0.0737*	-	-0.5063*	0.5081*	0.0004	-	-	-0.0001	X	-0.0009	-	-0.0002	0.0001*	0.40

- : Not required predictor (stepwise AIC) * $p < 0.01$

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