Dear editor,

Thank you for editing our manuscript. The first part of this document includes the point-by-point response to the reviews (R1, R2, R3). Comments of the referees are marked as e.g. << R1C1: “referees’ comment”>> followed by the answer from the authors, which includes a description of the changes made in the manuscript to fulfill the referees’ suggestions.

Best regards,
Schaffitel et al.

Response to the comments of Anonymous Referee #1 on the manuscript „Fluxes from Soil Moisture Measurements (FluSM v1.0). A Data-driven Water Balance Framework for Permeable Pavements

We thank Anonymous Referee #1 for reviewing our manuscript, for his positive overall evaluation and for his helpful suggestions for improving the manuscript. In the following, we answer the comments in a point-by-point reply.

R1C1: It is not clear if the proposed model is applicable only to permeable pavements or if its structure can be generalized and used in different areas.

Thank you for this point, which we clarified in the manuscript. As pointed out in the manuscript, FluSM was designed for fields where the application of Richards based models is critical. Although we applied FluSM only for PPs, FluSM can also be used for different land-use and surface types specified in the following.

For an application of FluSM, soils must fulfill two requirements which are: Drainage must be driven primarily by gravity (due to the used unit gradient approach) and the infiltration capacity must be high (see our answers to R1C3 and R2C7 for an explanation of this requirement).

Besides the application on PPs, FluSM is also applicable for bare soils. Furthermore, we think that FluSM is applicable for sites with vegetation cover, since soil moisture measurements should capture the soil hydrological effect of transpiration. However, for sites with vegetation cover, the location of soil moisture sensors within the profile should be adapted. For our study, we use only shallow measurements since the effect of soil evaporation should be captured best in shallow depths. In contrast, at sites with vegetation cover, root water uptake may act also on deeper depths. Therefore, the installation of multiple sensors covering the entire rooting depth should be considered.

An adaption of the FluSM routine may be necessary e.g. for fields with seasonal varying canopy coverage (e.g. deciduous forests) and sites with seasonal variable vegetation cover (e.g. agricultural fields). Such seasonal changes affect the capacity of the surface storage, which so far is assumed to be constant over time. For a further discussion of the surface storage and possible adaptions see our answer to R1C2 and R2C5.

We included these details in the discussion of the revised manuscript to clearly define the applicability of the approach.

R1C2: It should be clarified whether the surface layer is only related to the application of FluSM to permeable pavements. Model structure and parametrization should be discussed more in detail.

In the revised manuscript this point is acknowledged by the following discussion:

Currently, the implementation assumes that the surface storage capacity remains constant over time. This is a reasonable assumption for PPs and should also be valid for e.g. for bare soil and grassland sites. However, for sites with seasonal varying vegetation/canopy cover the concept of a constant surface storage capacity might be problematic due to the seasonally variable canopy coverage (Link et al., 2004). Under such conditions, an adaption of the routine should be considered. We think that a seasonal variable surface storage capacity might be determined directly from soil moisture and precipitation data by adapting the determination (FluSM step 1) to work on a monthly basis. This would require measurements over multiple years. Further alternatives to account for a seasonal variable surface storage capacity include using throughfall measurements or augmenting FluSM by a canopy interception model.

Another characteristic of the surface layer is that the partitioning between infiltration and surface runoff is controlled by the parameter infiltration rate, which remains constant with time. This parameter is discussed in R1C3.

R1C3: The parameter I_{cap} should be discussed more in detail in terms of model sensitivity, parameter uncertainty and details on the estimation of I_{cap}. Additional information on I_{cap} should be provided and a further discussion is expected inter alia in terms of the effect of I_{cap} on uncertainties of the results.

Indeed, estimating the infiltration rate (I_{cap}) is crucial, especially for large areas. For PPs, values for I_{cap} in dependence of PP type are provided by Illgen (2009). Since the range of possible I_{cap}-values for a given PP-type is high, we recommend using infiltration experiments to derive this parameter site-specifically. Since FluSM is a data-driven approach which requires plot-specific soil moisture measurements, infiltration experiments could be performed together with the installation of soil moisture sensors. In our study, we used plot-specific I_{cap}-values, which were derived from infiltration experiments by Schaffitel et al. (2019). Indeed, those I_{cap}-values are quite high (only 5 plots have an I_{cap} < 20 mm/h). However, this is not surprising since constructional requirements call for a high I_{cap} of PPs (FGSV, 2012).

For the reason of parsimony, we use a constant I_{cap} to describe the infiltration process. However, for most soils I_{cap} decreases during the infiltration course, which is mainly due to declining matrix suction gradients during the proceeding of the infiltration front (Hillel, 1998). This is also evident in the data of the infiltration experiments. Thereby, the variability of I_{cap} is documented in a plot-specific infiltration rate derived at the beginning and at the end of the experiment (I_{start} & I_{end}) (see Schaffitel et al., 2019).

The results of our uncertainty analysis show that the water balances calculated for PPs with an I_{cap} > 70 mm/h are not sensitive to this parameter. In contrast water balances calculated for 3 PPs with an I_{cap} < 3 mm/h showed a high sensitivity. For a further discussion of I_{cap}, we refer to the answer R2C7.

We clarified these points in the revised manuscript

R1C4: Additional studies, which have used soil moisture measurements to infer water fluxes, should be discussed in the introduction

We added the following paragraph to the introduction which points out a common way of using soil moisture measurements for soil hydrologic modelling.

One possibility for using soil moisture measurements for vadose zone modelling is by using them to determine soil hydrologic properties inversely (e.g. Ries et al., 2015; Ritter et al., 2003; Wollschläger et al., 2009). Nevertheless, estimating soil hydrological parameters from soil moisture data only leads to equifinality of parameter sets. Hence, additional information should be incorporated into the inverse estimation procedure to further constrain the obtained parameters (Vereecken et al., 2010).

<u>**Specific comments**</u>

P7, L14: "no influx into the soil layer" Which soil layer? Please clarify.

There is only one single soil layer implemented in FluSM, shown in Fig. 1. To remain consistent with the naming, we changed "soil layer" into "soil storage"

P23, L7-10: For very high infiltration rate, surface runoff is not playing a role. In these conditions, all rainfall infiltrates into the soil and fluxes estimation is easier. Please consider this aspect in the discussion.

Indeed, for plots with a high I_{cap}, the uncertainty of this parameter has no effect on the water fluxes. We considered this aspect by adding the following point to our discussion: *"…*This highlights the requirement of a high plot-specific infiltration rate for the reliability of the FluSM approach*…".*

P24, L9-27: This part is not relevant for the purpose of this paper, particularly L9-15. I would remove this subsection 4.2.

We removed subsection 4.2 from the manuscript

Table 4: The bucket depth shows large variability, e.g., for sites CP2 and GP1 from 96 to 185 mm. How is that possible? Please clarify.

Within FluSM, we use a regression approach to derive the bucket depth from the observed soil moisture reaction and from the infiltration calculated by the surface water balance. Since surface runoff is negligible on plots CP2 and GP1 (both plots have a very high infiltration rate), the amount of total infiltration should be comparable (although not identical e.g. due to different surface storage capacities). Hence, the deviations between the derived bucket depths originate from differences in the amplitude of the soil moisture reaction to infiltration. Such may be caused by differences in the 3-dimensional propagation of the wetting front underneath the joints (e.g. caused by spatial distribution of impermeable paving stones and joints or by differences in soil properties), soil-specific parameters (e.g. the amount of skeleton) and by the connection of soil moisture sensors to surrounding soils. Due to the derivation of the bucket depth by a regression approach, all site-specific characteristics are lumped in this parameter which hampers a physical interpretation.

We clarified this point in the revised manuscript accordingly.

Response to the comments of Referee #2 (James Ball) on the manuscript „Fluxes from Soil Moisture Measurements (FluSM v1.0). A Data-driven Water Balance Framework for Permeable Pavements”

We thank James Ball for his general remarks, his comments on urban hydrology and the points concerning the structure of FluSM. In the revision, we will consider those points which will help us improving the quality of the manuscript. We are deeply grateful for that.

R2C1: The response time for most urban surface water systems is significantly shorter than 10 min. Using a 10-minute computation step results in a lack of information and data in the surface flow hydrograph

> Thank you for this comment, which we considered in the revised manuscript by discussing the following points:
>
> A key characteristic of urban areas is the fast concentration, collection and conveyance of surface runoff (Shuster et al., 2005). This causes a high flashiness in surface flow hydrographs and modelling calls for a high temporal resolution of rainfall data. Besides the temporal resolution, also the spatial resolution of rainfall is decisive, since urban hydrological processes are characterized by a high variability not only in time, but also in space (Cristiano et al., 2017). Since high resolution rainfall data is rarely available, precipitation is often seen as a main source of uncertainty in urban hydrology (Cristiano et al., 2017; Niemczynowicz, 1999). This might also be the case for our study, for which we used rainfall data with a 10-min temporal resolution originating from one single urban climate station. Due to the location of our study sites within the public urban space, it was not possible to set-up site-specific rainfall gauges. We are aware that both factors (the spatial location of precipitation measurements and the temporal resolution) lead to an uncertainty of the precipitation input used for our study. However, we accounted for this uncertainty within our uncertainty analysis.
>
> Within the uncertainty analysis, we accounted for the spatial heterogeneity of rainfall by using time series of different climate stations as ensembles. In order to account for small-scale rainfall variability, we additionally multiplied the time series by a factor ranging between 0.8 and 1.2. By doing so, we considered a large uncertainty range for precipitation (550-1150 mm/year), which we think should also account for the uncertainty caused by the 10-min temporal resolution. The results of the uncertainty analysis reveal that the effect on surface runoff is small for most plots. Only the results for 3 plots (GP15, CP14 and CP13), show large uncertainties in surface runoff, which we attribute to the low infiltration rate of those plots. However, the uncertainty of the results obtained for those plots, is also caused by the input uncertainty of precipitation.

R2C2: Errors in the surface flow hydrographs will be balanced by equal but opposite errors in the infiltration component of the water balance (extension of R2C1)

Indeed, errors in the calculated infiltration lead to opposite errors which are equal in absolute value in surface runoff. Uncertainties in precipitation and in the infiltration rate may cause such an error in infiltration and surface runoff. Its possible magnitude is reflected in the uncertainty ranges obtained for surface runoff (Fig. 11). The results show that this error is negligible for plots with an infiltration rate above 70 mm/h while it is high for plots with an infiltration rate below 3 mm/h (CP15, CP14 and CP13).

We clarified this point in the revised manuscript.

R2C3: The distribution between surface runoff and infiltration needs to be provided if the 10-minute computation step is to be validated

We updated the code of FluSM on the Gitlab repository (https://gitlab.com/ASchaffitel/flusm). Now, the surface water balance is returned also with a temporal resolution of 10 min.

R2C4: Surface runoff measurements are not provided for validation

We agree that such measurements would be desirable for validation. Most valuable would be measurements at the plot scale, since runoff measurements integrating large areas (e.g. measurements in sewer drains) would be difficult to interpret for the plot scale. Unfortunately, our plots are located in the public urban space (e.g. on residential roads, bicycle tracks, parking lots and pedestrian roads) and we are not aware of any practicable and affordable measurement set-up, suited for continuously measuring plot-scale surface runoff within the public urban space. Due to this, such measurements do not exist. However, there is data for plot-specific infiltration experiments provided in Schaffitel et al. (2019).

R2C5: C_{surf} is defined as the surface storage capacity, which is normally defined as the volume of water in temporary transit to the catchment outlet. It is therefore suggested that C_{surf} refers to the initial loss storage (sometimes also referred to as depression storage)

To our knowledge, in urban hydrology, the initial loss is often determined by a linear regression of runoff against rainfall (intersect with the x-axis; e.g. Rodriguez et al., 2000). For sake of clarity, we decided to use the term surface storage instead of initial loss. Furthermore, we decided to clearly distinguish between the state of this storage (S_{surf}) and its capacity (C_{surf}).

To clarify this point, we included the following description to the manuscript: In FluSM, the surface storage is the water storage exiting at the atmosphere-soil/pavement boundary. Following Mansell & Rollet (2009) the surface storage consists of a depression storage (storage due to the micro relief of the surface) and the wetting capacity of the surface (amount of water required for wetting the surface).

R2C6: A comparison of the obtained C_{surf} values with initial loss obtained by previous studies would be interesting

Indeed, we think that such a comparison is valuable for the manuscript and we therefore added the following paragraph to our discussion:

Regarding the surface storage capacity of PPs, we obtained values between 1 mm and 4.5 mm, which is in accordance with the range specified by previous studies (e.g. Brown and Borst, 2015; Flöter, 2006; Illgen, 2009; Starke et al., 2010; Wessolek et al., 2008; Wessolek and Facklam, 1997; Wiles and Sharp, 2008).

R2C7: The parameter I_{cap} may vary with time and not be a constant as assumed by the authors. Temporal distribution of storm and inter-storm periods determines the variability of I_{cap} and therefore additional information about precipitation events and mechanisms should be provided. In case of consistent precipitation mechanisms and self-compensating errors, the results could be reliable. Consideration of the rainfall mechanisms and attempting to include a variety of mechanisms would increase confidence in the authors' approach to parameter estimation.

This is a very interesting point. As pointed out in R1C3 and R2C2, we added an additional discussion of the parameter I_{cap} to the manuscript. However, we think that an additional analysis of precipitation events and mechanisms will not lead to further insights, which we will explain in the following.

We agree that the infiltration rate may vary with time, which is caused by a change of soil moisture during the infiltration course (which in turn controls the matrix potential and the hydraulic conductivity). However, describing infiltration only by matrix flux might be insufficient for PPs, since infiltration might be controlled also by other processes (e.g. preferential flow and hydrophobicity). For our plots, the variability of the infiltration rate over time is documented by plot-specific infiltration experiments under ponded conditions (see Schaffitel et al., 2019). Those experiments were used to derive a plot-specific infiltration rate for the beginning and for the end of the infiltration course (I_{start} & I_{end}). Thereby, I_{start} represents the infiltration rate when soils are dry, while I_{end} represents infiltration under steady-state conditions (constant soil moisture, matrix potential and hydraulic conductivity). Hence, the documented I_{start} and I_{end} should capture the possible variability of the infiltration rate caused by the temporal distribution of storm and inter-storm periods. We considered this variability in our uncertainty analysis and discussed its effect on the water balance. Thereby, the results show that the uncertainty of the parameter I_{cap} (and hence also the effect of the temporal storm and inter-storm distribution on this parameter) is relevant only for 3 plots with a very low I_{cap}, while it is negligible for the majority of the plots. Due to this, the results of FluSM for plots with a low I_{cap} should be regarded with care, while results are reliable for plots with an I_{cap} of at least 9 mm/h.

In the revised manuscript, we put a stronger emphasize on the requirement of high I_{cap}-values for the reliability of FluSM.

Response to the comments of Anonymous Referee #3 on the manuscript „Fluxes from Soil Moisture Measurements (FluSM v1.0). A Data-driven Water Balance Framework for Permeable Pavements

We thank Anonymous Referee #3 for the positive feedback and for the constructive comments, which we will consider to improve the manuscript. In the following, we answer the comments in a point-by-point reply.

R3C1: Horizontal permeability can be greater than vertical, and flows can be considerable, especially for PP, because of natural soil deposition which is sheets often which creates horizontal planes of soil fabric with greater permeability, and the inevitable compaction of the subgrade (bottom of the bucket) from construction which reduces vertical infiltration relative to horizontal. Some more discussion about how this might have affected the calibrations. Also, can you give a better idea of horizontal surface area on the bottom of the bucket vs vertical surface area on the sides of the sections used to calibrate to provide an indication how much leaving out the horizontal flow might have affected the calibration results.

> Indeed, horizontal subsurface flow may account for a large share of the water balance for PPs, especially since the hydraulic conductivity of underlying soil layers may be low due to the compaction of the subgrade. In the following we explain why horizontal subsurface flow should not affect the calibration of the drainage model. We clarified this accordingly in the revised manuscript.
>
> Within a PP system (pavement, bedding, base and subbase layer), horizontal subsurface flow should play an only minor role, since a high hydraulic conductivity is required for all layers. This is also reflected in the free drainage behavior observed for the PPs of our case study. However, horizontal subsurface flow may occur at the bottom of the PP system (e.g. border between subbase layer and underlying soil). Such horizontal subsurface flow would not affect the calibration of the drainage model, since it is not it is not relevant whether the soil moisture recession is due to vertical drainage or if it is due to horizontal subsurface flow. Both fluxes are summarized in the calculated drainage flux. The calibration of FluSM would be problematic only for plots showing a restricted drainage behavior, which we therefore excluded from our case study
>
> Regarding a possible separation between vertical and horizontal subsurface flow, we refer to our answer on R3C7.

R3C2: What was the definition of free draining versus restricted in “Schaffitel et al. (2019) classified the PPs into free-draining PPs”? Please give a one sentence definition

Thank you for pointing out the missing definition. In the revised manuscript, we clarified this point by adding the following:

The classification applied in Schaffitel et al. (2019), is based on a combination of statistical analysis and visual inspection. Plots were classified as “restricted drainage” when soil moisture reached saturation frequently during rain events and remained saturated even after the end of rainfall. In contrast, plots which showed a fast recession of soil moisture were classified as “free drainage”. Thereby, the fast soil moisture recession indicates a high hydraulic conductivity of underlying soil layers.

R3C3: Do the case study pavements have a porous reservoir layer?

According to the local construction authority, the PPs of the case study should not have a porous reservoir layer. Except two plots, this is in accordance with the observations made during field works. Only at two plots (CP12 and CP2) we encountered coarse gravel underneath the pavement layer which could serve as kind of porous reservoir layer. Those two plots are located on a private parking lot.

We clarified this point in the revised manuscript.

R3C4: Were there soil hydraulic conductivity measurements for the case study section done prior to installation of the reservoir layer as a check?

This is an interesting question which we clarified in the revised manuscript. Unfortunately, information is neither available for construction works, nor for preceding measurements. We therefore planned to extract undisturbed soil samples for determining the hydraulic conductivity function from multistep-outflow experiments in the laboratory. Due to the high fraction of soil skeleton and due to the high soil compaction it was impossible to extract undisturbed soil samples. However, for the PPs of our study the soil hydraulic conductivity of underlying soil layers should be high since all PPs were classified as “free drainage” (see R3C”).

R3C5: Pg 24 line 25, Surface permeability is highly variable across a permeable pavement surface at a scale larger than most surface permeability measuring devices. Generally, not a problem until whole surface clogs because on the same pavement the areas of high permeability areas can handle the flow from low permeability areas nearby. Example:
https://www.sciencedirect.com/science/article/pii/S0301479711003525?via%3Dihub
Was that also seen in the cited references?

> Indeed, there are various studies showing the variability of surface clogging across a permeable pavement surface (e.g. Razzaghmanesh and Beecham, 2018; Sañudo-Fontaneda et al., 2014). Factors controlling the surface clogging of PPs include age, traffic load, maintenance measures, surrounding land use, joint proportion and filling material of joints (Boogaard, Lucke, & Beecham, 2014; Winston et al., 2016). Previous studies showed, that surface clogging occurs mainly in the first years after the construction (e.g. Boogaard et al., 2014b; Borgwardt, 2006; Lucke and Beecham, 2011). The effect of run-on from surrounding surfaces on PP clogging was investigated e.g. by Razzaghmanesh and Borst (2018).
>
> Following the specific comment of reviewer#1, we removed subsection 4.2 from the manuscript. However, to clarify this point, we added the following paragraph to subsection 2.2 of our manuscript.
>
> At the plots of our study, infiltration experiments were performed only once at the beginning of the study period. Due to the lack of successive infiltration experiments, a direct quantification of the clogging progress over the study period is not possible. However, soil moisture time series should allow for an indirect assessment, since surface clogging affects the infiltration capacity which in turn affects soil moisture dynamics. In this way, Razzaghmanesh and Borst (2018), used soil moisture measurements to study clogging dynamics of a PP surface.
>
> For the PPs of our study, we analyzed the measured soil moisture dynamics over the study period. Since we did not observe a change in dynamics over time, we expect that the state of surface clogging remained more or less constant over the study period. One possible explanation therefore might be that none of the PPs was newly build and therefore all plots were already clogged at the beginning of the study period.

R3C6: Any recommended next steps for FluSM and potential improvements

> Thank you for this comment. Potential improvements include adaptions for the application on sites with vegetation cover and the consideration of horizontal subsurface flow.
>
> We included these points in the revised manuscript according to our answers on R1C1 and R3C7. Concerning recommendations for next steps, we refer to our answer on R3C8.

R3C7: Possibility to extend FluSM to account also for horizontal flow, which might be important for estimating possible effects on surrounding infrastructure

Indeed, this is a very interesting point, which we took into account by adding the following paragraph to the manuscript (in conjunction with R3C1):

In case horizontal subsurface flow at the bottom of the PP system is of interest, an extension of FluSM is possible. In a parsimonious approach, the saturated hydraulic conductivity of the underlying soil layer could be used as single parameter to describe the partitioning between deep percolation and horizontal subsurface flow at this border.

R3C8: Recommendations to implement the model in practice

Thank you for this remark, which in the revised manuscript is considered by the following paragraph:

The FluSM approach allows deriving continuous water fluxes from soil moisture and meteorological measurements. Compared to direct measurements of soil hydrological fluxes, this poses a relative easy and cheap way for water balance studies and is especially valuable for fields with limited soil hydrologic knowledge (e.g. missing soil hydrologic parameters or lack of knowledge on the correct representation of processes). In this way, we successfully applied FluSM to derive long-term, high resolution hydrological fluxes for 15 different PPs under field conditions. So far, such data were obtained only by costly lysimeter studies. Besides the application for water balance studies, FluSM may also be beneficial for studying soil hydrological processes and contribute to an increased data availability for model validation purposes. In the future, data-driven derivations of soil hydrological fluxes might serve as a simulation benchmark for the application of process based hydrological models. Regarding the ever-increasing availability of soil moisture data on different spatial scales, the demand of such parsimonious approaches should increase.

Comments on presentation

P2, L23: change to “enable the calculation”

Acknowledged

P3, L18: change to “lead to an improved”

Acknowledged

P14, L4: change “fist” to “first”

Acknowledged

Literature

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