

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 will explain, why we think that horizontal subsurface flow did not affect the calibration of FluSM for the PPs of the case study.

For the layers of a PP (pavement, bedding, base and subbase layer), a high hydraulic conductivity is required. Therefore, vertical flow should dominate within those layers. If the conductivity of underlying soil layers is low, there are two possible cases. Either horizontal subsurface flow occurs at the bottom of those layers, or the soil storage gets filled gradually until there is saturation overland flow. Since we applied FluSM only for PPs with a “free drainage behavior” (see R3C2), the second case is not relevant for our study.

Within FluSM, the observed soil moisture recession is used to calibrate a simple drainage model. For this calibration, 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 PPs showing a “restricted drainage behavior”, which were therefore excluded from our 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. We will clarify this by adding the following description to the revised manuscript:

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 will clarify this 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. 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 et al., 2014a; 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).

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.

We will clarify this in the revised manuscript, accordingly

R3C6: Any recommended next steps for FluSM and potential improvements

Thank you for this comment. We will discuss next steps and possible improvements in more detail in the revised manuscript.

Potential improvements include adaptations for the application on sites with vegetation cover and the consideration of horizontal subsurface flow. For a detailed discussion on those improvements we refer to our answers on R1C1 and R3C7. Concerning recommendations for next steps, we refer to the 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. In the following, we will point out a parsimonious concept which allows extending FluSM to account also for horizontal subsurface flow on PPs.

For PPs, the occurrence of horizontal subsurface flow is mainly limited to the border subbase layer – underlying soil, since this border might be associated with a strong decrease in soil hydraulic conductivities. Describing horizontal subsurface flow at this border requires knowledge on the soil hydraulic parameters of both layers. 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. Thereby, the saturated hydraulic conductivity needs to be determined e.g. during the construction of PPs.

We think that such an extension is beyond the scope of this paper, since we applied FluSM only for PPs showing a free drainage behavior. However, in the revised manuscript, we will discuss the aforementioned possibility for an extension.

R3C8: Recommendations to implement the model in practice

Thank you for this remark. We will include the following recommendations in the discussion.

The main advantage of FluSM is the possibility to derive continuous water fluxes from soil moisture and meteorological measurements in a relative easy and cheap way. Therefore, FluSM allows to study the water balance of fields with limited knowledge (e.g. missing soil hydrologic parameters or lack of knowledge on the correct representation of processes). Regarding the ever-increasing availability of soil moisture data on different spatial scales, the demand of such parsimonious approaches should increase.

So far, long-term, high resolution hydrological fluxes of PPs under field conditions were obtained only by lysimeter studies. Since such measurements are costly, the availability of data for validating generalized modelling approaches is limited. In the future, data-driven derivations of soil hydrological fluxes might serve as a simulation benchmark for the application of process based urban hydrological models.

Comments on presentation

P2, L23: change to “enable the calculation”

Acknowledged

P2, L18: change to “lead to an improved”

Acknowledged

P14, L4: change “fist” to “first”

Acknowledged

Literature

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