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 will clarify 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 which we will specify 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 fields 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 answer to R1C2 and R2C5.

We will include these details in 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.

We acknowledge this comment. In the revised manuscript, we will discuss the model structure and parametrization more in detail.

The current implementation of the surface layer assumes that the capacity of the surface storage 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. For sites with seasonal varying vegetation/canopy cover, an adaption should be considered to account for the annual variation of the surface storage capacity. As discussed in the manuscript, we think that a seasonal variable surface storage capacity might be determined directly from soil moisture and precipitation data by adapting the method currently implement in FluSM to work on a monthly basis. Therefore, 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 the following point.

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 specific. 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.

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

We agree, that including further studies which use soil moisture measurements to infer water fluxes will improve the manuscript and will be included in a revised manuscript

Specific comments

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 will change "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 will point out this aspect in our discussion

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

Recognized. We will consider removing subsection 4.2

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.

Literature

FGSV: Richtlinien für die Standardisierung des Oberbaus., 2012.

Hillel, D.: Environmental Soil Physics, Acad. Press, San Diego, Calif., 1998.

Illgen, M.: Das Versickerungsverhalten durchlässig befestigter Siedlungsflächen und seine urbanhydrologische Quantifizierung., 2009.

Schaffitel, A., Schuetz, T. and Weiler, M.: A distributed soil moisture, temperature and infiltrometer dataset for permeable pavements and green spaces, Earth Syst. Sci. Data Discuss., 1–27, doi:10.5194/essd-2019-97, 2019.