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Studying the hydrological balance of (partially) sealed surfaces using high precision weighable lysimeters

Anne Timm[1*] und Gerd Wessolek[1]

Zusammenfassung

Urbanisierung und Versiegelung verändern Transportwege von Niederschlagwasser. Der städtische Wasserhaushalt wird großflächig zumeist mit einfachen Ansätzen simuliert, weil nur wenige Informationen zu den Flächeneigenschaften und tatsächlich ablaufenden Prozessen vorliegen. Feldstudien zeigen, dass Verdunstung und Versickerung eine größere Rolle spielen können als bislang angenommen. In Berlin werden Prozessstudien an Lysimetern mit unterschiedlichen Oberflächenbelägen durchgeführt. Neben dem Lysimetergewicht werden Oberflächenabfluss, Klimadaten, Wassergehalte und Temperaturen im Boden gemessen. Dies ermöglicht eine zeitlich hochaufgelöste Wasserbilanz. Die jährliche Versickerung unter teilversiegelten Flächen kann ähnlich hoch ausfallen wie unter Vegetation. Jährliche Verdunstung und Versickerung können sogar höher ausfallen als der Oberflächenabfluss. Verdunstung erfolgt größtenteils direkt nach Regenereignissen, wenn die Wasserverfügbarkeit hoch ist. In den Zeiten danach findet eine Umverteilung durch kapillaren Aufstieg statt, was zu niedrigen Verdunstungsraten an Tagen ohne Niederschlag führen kann.

Schlagwörter: urbane Verdunstung, TDR, Bodenfeuchte, Bodentemperatur

Summary

With increased urbanisation, soil sealing and its drastic effects on hydrological processes have received a lot of attention. Since little information about surface properties and altered processes is available, many models use rather simple approaches to simulate the urban water balance. Studies challenge the idea that all rainfall will generate runoff and evaporation and infiltration from (partially) sealed surfaces can be neglected. In Berlin, two partially sealed lysimeters are used for process studies of the hydrological balance, as well as water and heat transport processes of these surfaces. Measurements include lysimeter weight, runoff, climate, and soil temperature and water content. It can be shown that evaporation and infiltration play a significant role in the hydrological balance and can exceed the amount of runoff. For the most part, evaporation occurs directly after precipitation events but may also occur on days without precipitation. Combined with soil moisture profile observations, this indicates that both surfaces may allow for upward water transport and evaporation from the upper underlying soil layers.

Keywords: urban evaporation, TDR, soil moisture, soil temperature

Introduction

With increased urbanisation, soil sealing and its drastic effects on hydrological processes have received a lot of attention (e.g. Hibbs & Sharp 2012). Based on safety concerns, there has been a clear focus on urban drainage and prevention of urban floods caused by storm water events. For this reason, any kind of sealing is often seen as impermeable runoff generator that prevents infiltration and evaporation (e.g. Jacobson 2011). While many hydrological models, especially storm water models, have been developed, there are only a handful of empirical studies actually measuring the hydrological balance of (partially) sealed surfaces (Flöter 2006, Ragab et al. 2003, Ramier et al. 2004, Rim 2011, Wessolek 2001). They challenge the general assumption of negligible infiltration and evaporation and show that these processes take place even for severe sealing such as asphalt. *Figure 1* shows the water balance of different land uses in Berlin, including three types of sealing materials ranging from severe (asphalt) to very low (lawn bars – Rasengittersteine). As can be seen, annual seepage from partially sealed areas can be as high for vegetated ones and in summer much more water will infiltrate into deeper soil layers of (partially) sealed ones. This is caused both by increased runoff and decreased evaporation from sealing. Furthermore, there is a distinct variation between the three sealing types, which illustrates how different the behaviour of these surfaces can be. Another example of this is the generation of runoff, which is often estimated using a fixed runoff coefficient (RC). Approaches range from using one RC for all sealing types to different RC for various materials, and can use annual, seasonal or monthly variations. More recent event based studies based on higher temporal resolution show that the RC does not only vary depending on the material but also on rainfall intensity and duration. For partially sealed surfaces the RC can range from 0 to almost 0.7, depending on the precipitation intensity (Rim 2011). These examples show that more detailed knowledge is needed to improve our understanding and models. For this reason, two partially sealed weighable lysimeters were equipped with multiple temperature and soil moisture sensors in order to study the hydrological balance, as well as water and heat transport

[1] Technische Universität Berlin, Institut für Ökologie, Standortkunde und Bodenschutz, Ernst-Reuter Platz 1, D-10587 BERLIN
[*] Ansprechpartner: Anne Timm, anne.timm@uwi.tu-berlin.de

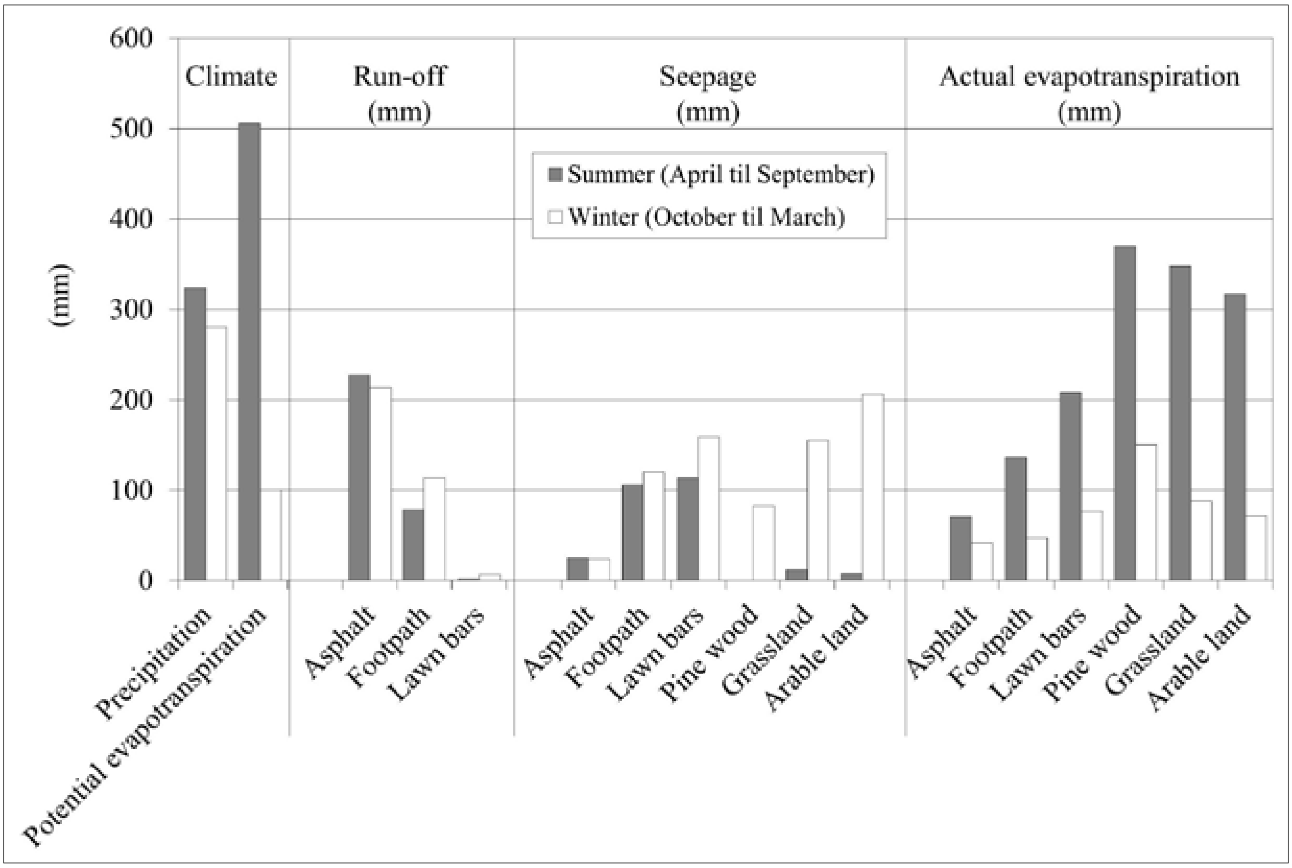

Figure 1: **Water balance components of various land uses and sealing materials (average from three-year lysimeter measurements of the Berliner Wasserbetriebe and water balance investigations).**

Figure 2: **Partially sealed lysimeters with cobblestones (left) and concrete slabs (right).**

processes, of these surfaces. To our best knowledge, this is the first time weighable lysimeters and soil moisture measurements are combined for pavement surfaces. This yields new insights into the water transport processes, which are assessed at hourly intervals.

Material and Methods

The two partially sealed lysimeters are incorporated into a lysimeter station at the southern border of Berlin which is the joint project of the Technical University Berlin and the Federal Environment Agency (Umweltbundesamt). As can be seen in *figure 2*, two different sealing types are used: cobblestones and concrete slabs. Both sealing types are very commonly used for Berlin pavements. The immediate surrounding area is paved with the concrete slabs used in one of the lysimeters. The wider surrounding area includes grass patches, sealed areas and small buildings. A climate station recording relevant climate data at 10-minute intervals is installed directly next to the lysimeters. The lysimeters have a surface area of 1 m² and a depth of 50 cm. A shorter depth was chosen to decrease the overall weight of the system and thereby increase the measurement accuracy, as smaller changes can be registered. At the bottom, a layered gravel and sand layer (increasing coarseness towards the bottom) of a total thickness of 10 cm ensures the drainage from the system. On top of the drainage layer, construction sand (sand with 12.4 % coarse sand and 1.6 % silt) is used to fill the lysimeter. At the very top, the sealing material (thickness of 4-8 cm for cobblestones and 4 cm for concrete slabs) is installed at a slight slope to ensure runoff and prevent the formation of puddles. The share of seams is 20 percent for the cobblestones and 6 percent for the concrete slabs. The seams are filled with seam material (sand with 6 % coarse sand and 2.4 % silt). *Figure 3* illustrates the overall setup of the lysimeters. Each of the lysimeters rest on three weighing cells which record the weight at 1-minute intervals. Infiltrated water is collected in plastic containers resting on scales and recorded together with the lysimeter weight at 1-minute intervals. When the containers fill up to a certain height, magnetic valves open and water is automatically drained, reducing manual maintenance effort. Water forming surface runoff is drained and flows into a tipping bucket. In order to be able to register even smaller events and achieve a higher time resolution, the weight of the tipping bucket is registered at 1-second intervals. The general idea

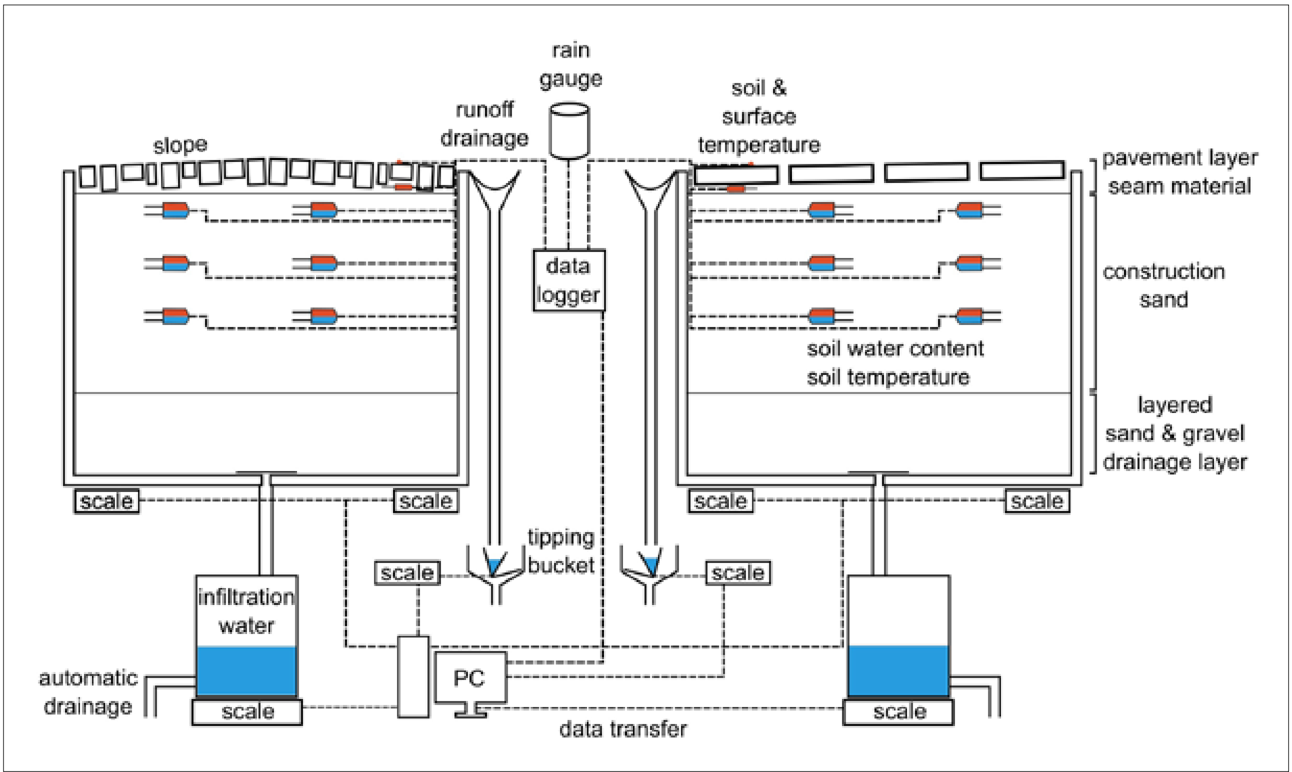

Figure 3: **Schematic setup of the lysimeters.**

of the weighable tipping bucket and the setup of an earlier version are described in Nehls et al. (2011). The changes in lysimeter weight are filtered using improved Adaptive Window Adaptive threshold (AWAT) routine (Peters et al. 2014, 2016) in order to clear the data from wind and other noise sources. This yields hourly values of precipitation, evaporation and infiltration. As described before, runoff is measured independently and also aggregated to hourly values. Since the AWAT routine does not consider runoff, the aggregated runoff values are added to the precipitation values calculated by AWAT. Additionally, sensors are installed to measure soil moisture and soil temperature. Temperature is measured at the surface, directly below the paving material and in the construction sand at 5, 15 and 25 cm depth starting from the underside of the paving (beginning at 13 cm depth for cobblestones and 9 cm for concrete slabs). The soil temperature in the construction sand is measured with two sensors at each depth, which also measure the volumetric water content using time domain reflectometry (TDR). All sensors measure at 15-minute intervals and send their information to one central data logger. At the end, the dataset consists of hourly values of precipitation, evaporation, infiltration and runoff, as well as 15-minute values of soil moisture, surface temperature and soil temperature. Data has been collected since June 2016 but older data with a different bottom boundary condition and without temperature and moisture sensors is available.

Results and Discussion

Given the dataset obtained, different time scales and responses can be evaluated. For a longer time period, the hydrological balance can provide information about general behaviour of the surfaces. As can be seen in *figure 3*, this can differ significantly depending on the paving material. Depicted is the hydrological balance over 156 measurement days between June and December 2016 for cobblestones and concrete slabs. The measured runoff is significantly smaller than normally assumed, with very low runoff for cobblestones which have wide seams through which water can easily infiltrate. Despite much more water leaving the area paved with concrete slabs, infiltration is the same for both areas and accounts for over half of the precipitation. This can be attributed to higher evaporation from the cobblestone paving. For concrete slabs, most evaporation will occur from water adhering to the surface and water stored in the pores of the concrete and the seam material. It can be assumed that very little water from underlying soil layers contributes to evaporation rates. Contrary to that, the cobblestones themselves have very low porosity and most water is redirected towards the seams and infiltrates. Hence, evaporation occurs mainly from the seam material. Because of the larger width of the seams, water from underlying soil may rise upwards and evaporate. On a smaller timescale, the response of the surfaces to certain climatological conditions can be assessed. *Figure 5* illustrates hourly hydrological processes over four days in June 2016 with numerous rainfall events and warm temperatures. Multiple rainfall events took place on June 15th and June 17th, with daily precipitation sums of 9 mm and 18.5 mm, respectively. As can be seen, precipitation duration and intensity play a significant role for evaporation processes. Contrary to vegetated or bare soils, very little water stored in the underlying soil layers can be transported upwards to evaporate through the seam or paving material. However, some upward transport does take place, as becomes evident on June 16th, where a small amount of water evaporates (daily sum of 0.5 mm for concrete slabs and 0.8 mm for cobblesto-

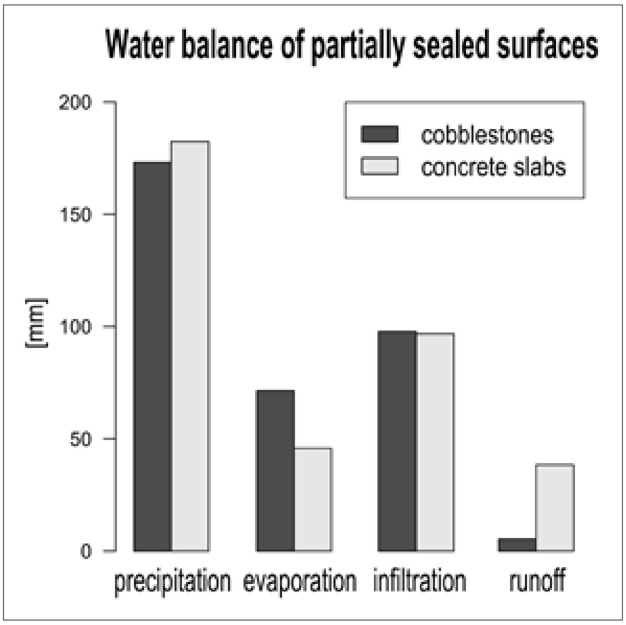

Figure 4: **Water balance of partially sealed surfaces over 156 measurement days between June and December 2016.**

nes) despite no precipitation taking place. The higher value for cobblestones further indicates that the low porosity of the concrete pavers, as well as the narrow seams which can cause chimney effects, limit evaporation from underlying soil layers. While cobblestones generally have higher evaporation (sum over the four day period 9.5 mm for cobblestones and 5.3 mm for concrete slabs), concrete slabs can have higher evaporation rates for smaller rainfall intensities. The distinction is clearer for runoff, where concrete slabs have significantly higher rates of runoff. On June 15th, the total runoff amount was 0 mm for cobblestones and 1.41 mm for concrete slabs and on June 17th, the sums were 0.9 and 5.6 mm, respectively. For concrete slabs, all precipitation events lead to runoff, but only the high intensity event on June 17th forms runoff for the cobblestone surface. Finally, runoff and evaporation processes determine how much water will infiltrate into deeper soil layers. During the illustrated period, more water infiltrated through the cobblestone surface (17.4 mm compared to 13.1 mm for concrete slabs), which in this case can be attributed to runoff processes. *Figure 6* illustrates water transport processes within the soil column using water content measurements at 5, 15 and 25 cm depth below the paving material. In general, the water content is higher below cobblestone paving which allows increased infiltration through a larger share of seams. For both lysimeters the water content increases with depth and in all three depths there is a clear reaction to precipitation events. However, not all changes are linked to precipitation, such as the increase in water content at 5 cm depth on the 16th of June where there was no precipitation event. This increase can be linked to the evaporation rates shown in *figure 5* during the same time period, which further indicates that some water stored in the soil reaches the pavement layer through capillary rise and is able to evaporate.

Conclusion

The combination of hourly water balance, soil moisture and temperature data affirmed previous observations and offered new insights into altered hydrological processes of partially sealed surfaces. It could be confirmed that partially sealed surfaces do not transform all precipitation into runoff. Even for a relatively high sealing degree of concrete slabs with narrow seams, evaporation and infiltration exceeded runoff. For cobblestones, runoff was very small and only precipitation events of high duration or high intensities generated runoff. It could be shown, that due to lack of plant roots, the hydrological balance is mostly governed by precipitation events and evaporation occurs mostly directly after rainfall. However, both surfaces may allow for upward water transport and evaporation from the underlying soil layers. The extent of this upward movement, as well as the maximum depth from which water reaches the surface have to be further studied. The behaviour of these surfaces can be very diverse. It becomes apparent that numerous factors such as share and width of seams, porosity and thickness of the paver, climate conditions like precipitation intensity and duration, and others determine hydrological processes of partially sealed surfaces. The presented method is able to improve our understanding of the processes. Combined with the detailed measurement data of the hydrological balance, this enables the development of improved, application-oriented models for estimating the hydrological balance of partially sealed surfaces. In a next step, this information will be used to develop an improved evaporation formula for partially sealed surfaces.

Acknowledgements

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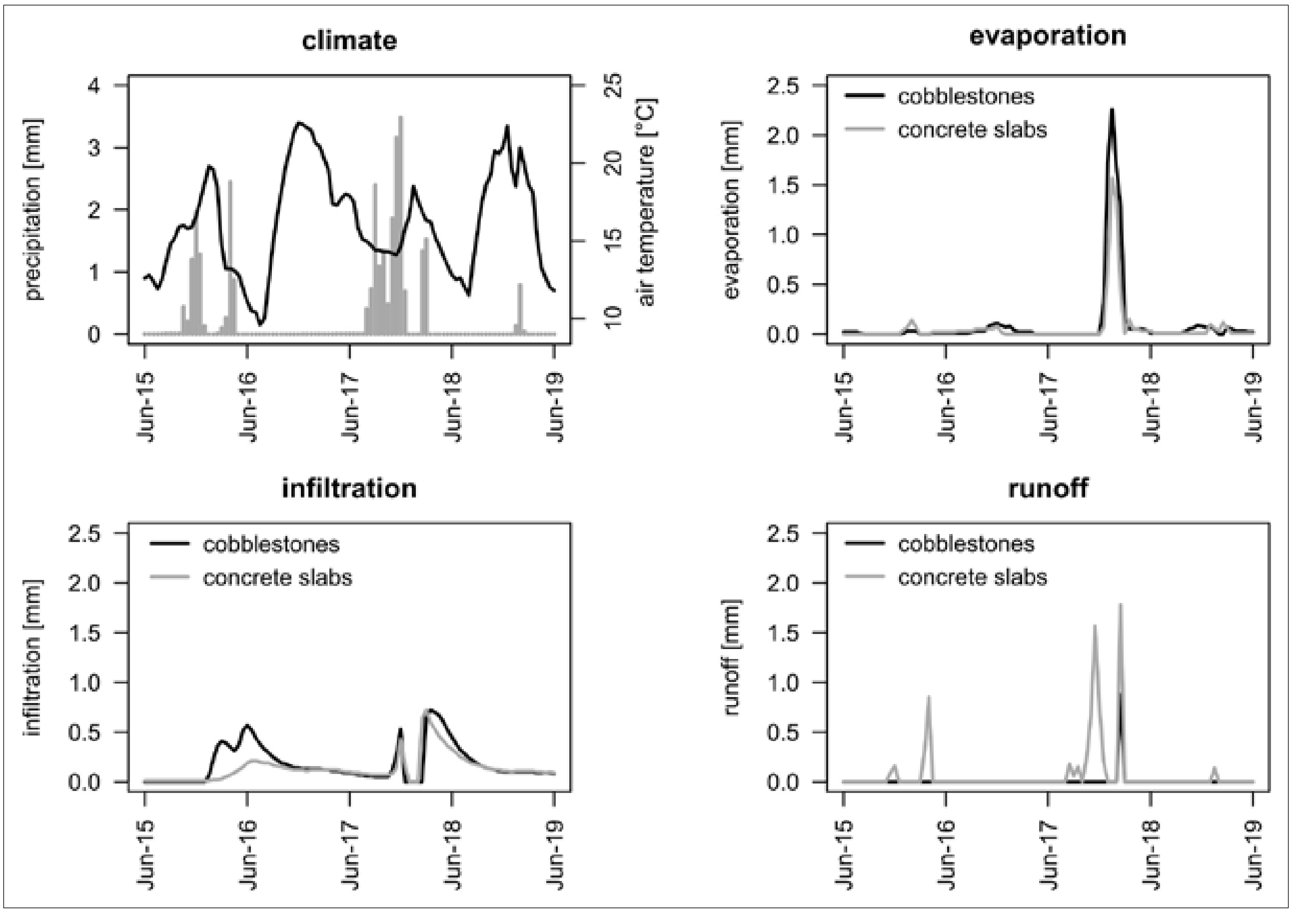

Figure 5: **Detailed hourly water balance and climate conditions for two partially sealed surfaces.**

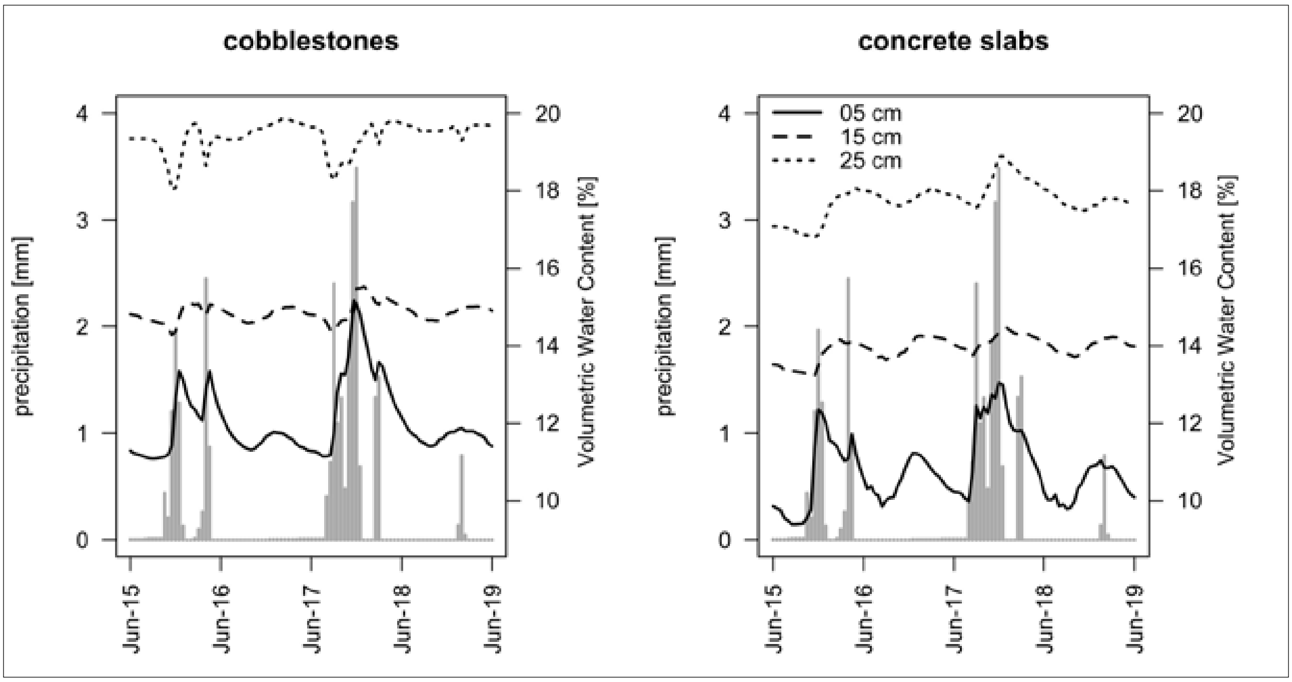

Figure 6: **Soil water regime of two partially sealed soils; hourly precipitation and volumetric water content measured at 5, 15 and 25 cm below the paving material.**