Technical Notes

Core Ideas

- The monitoring system synchronizes soil water extraction with real drainage periods.
- It is remote controllable and has SMS notification in case of automated sampling initiation.
- It is easy to duplicate using commonly available measuring equipment.
- The system can monitor field soil solute fluxes, such as contaminant migration.

Technische Univ. Berlin, Ecohydrology and Landscape Evaluation, Ernst-Reuter-Platz 1, 10587 Berlin, Germany. *Corresponding author (a.reck@tu-berlin.de).

Advanced In Situ Soil Water Sampling System for Monitoring Solute Fluxes in the Vadose Zone

Arne Reck,* Eva Paton, and Björn Kluge

To estimate potential risks of groundwater contamination, national and international environmental legislation stipulates standard values referred to pollutant contents in the soil and more rarely referred to loads in the soil leachate. Although in situ soil leachate analysis yields more realistic drainage water quality estimates than soil contamination level–derived estimates, there is no existing standard for how to explicitly sample soil leachate for the required contaminant migration detection. The objective of this study was to overcome current limitations of soil seepage sampling for detecting a contaminant migration in the unsaturated zone by introducing a technical solution that automatically restricts soil water extraction to drainage periods using active devices such as suction cups. Sampling is triggered by a moisture threshold parameterized according to the respective soil water retention properties defining the onset of a drainage period. We tested our sampling approach on two different bioretention systems in Germany for stormwater drainage quality analysis out of the upper soil layer. We present the monitoring results of the 4-mo testing phase containing 19 individual storm events illustrating the fundamental functioning of the in situ soil leachate sampling system under different climatic conditions. The results clearly demonstrate the feasibility of restricting soil water extraction to drainage periods by means of actual soil moisture measures and indicate a general transferability of our approach. Our approach is easily duplicable, based on the included technical description, for further studies requiring explicit soil leachate sampling and is likely to help improve the reliability of field-monitored pollutant migration from contaminated sites.

Abbreviations: GSM, Global System for Mobile Communication; SMS, Short Message Service; TOC, total organic carbon.

Soils can be contaminated with diverse pollutants from various human activities (Bradl, 2004; Cheng, 2003; Science Communication Unit, 2013; Wilcke, 2000; Wong et al., 2006). The contaminants vary in their tendency of being evaporated into the air, biodegraded, bound to the soil, or leached out of the soil matrix by infiltration water (Pitt et al., 1999). The latter may lead to high pollutant concentrations in the soil solution, which in turn could result in contamination of receiving water bodies (Holt, 2000; Lapworth et al., 2012; Nielsen et al., 1986; Pitt et al., 1999), with all its harmful effects for the environment and human beings (Carlon, 2007; Science Communication Unit, 2013).

To assess the leaching potential for the soil–groundwater transfer pathways, many guidelines and regulations stipulate screening values only referred to pollutant contents in soils (Carlon, 2007) and more rarely referred to pollutant concentrations in the soil leachate when entering the capillary fringe, such as the Federal Soil Protection and Contaminated Sites Ordinance of Germany (Bundes-Bodenschutz- und Altlastenverordnung, 1999). However, sampling soil leachate for monitoring purposes directly from the capillary fringe is often limited because the groundwater table might be situated too deep or might vary temporally or because the monitoring is time consuming and expensive. Therefore, soil water sampling from the capillary fringe is usually substituted by diverse laboratory test methods (e.g., extraction protocols) for assessing the potential risk of a groundwater contamination (Carlon, 2007; Fang et al., 2017; Kumpiene et al., 2017). In addition, the

application of exposure modeling is often used to predict a potential pollutant transport through the soil into the groundwater (Nimmer et al., 2010; USEPA, 1996; Zhang et al., 2016; Zia et al., 2018; Zimmermann et al., 2005). Drawbacks of both methods are that laboratory tests often do not represent field conditions adequately and that laboratory data, instead of field data, are used for model parameterization, which makes modeling results ambiguous. In situ soil leachate sampling from the upper vadose zone (i.e., the upper two meters of the pedon) over a representative period might be a compromise for this conflict regarding the risk assessment of groundwater degradation from a contaminated site. Compared with screening values, capillary fringe sampling, laboratory tests, and exposure modeling, this approach provides a method of practicable and representative data collection to reliably detect contaminant migration in the unsaturated zone.

In situ soil water sampling from the vadose zone can be grouped into active or passive sampling systems (Singh et al., 2017; Weihermüller et al., 2007). Passive sample systems, such as pan or zero-tension lysimeters, have the drawback that zero-tension lower boundary conditions cause a small saturated zone above the lower boundary and hence influence soil water fluxes and solute concentrations (Flury et al., 1999). Active soil sampling devices, such as suction cups, suction plates, a rhizon sampler, or a wick lysimeter need a hanging water column or a vacuum to extract soil water (Singh et al., 2017; Weihermüller et al., 2007). All vacuum-controlled methods could operate in continuous/discontinuous or variable pressure modes possibly regulated by soil water tension. If vacuum-controlled methods are operated continuously, soil water is sampled generically, meaning different soil water origins are not considered. Hence, the received samples represent soil water assemblages of capillary water from primary pores and or gravitational water from secondary pores with a differing chemistry due to differing resident times in the soil, also known as the "two water worlds hypothesis" or "ecohydrological separation" (Berry et al., 2017; Brooks et al., 2009; McDonnell, 2014). Such soil water assemblages enable conclusions regarding the presence of dissolved contaminants, but their leaching risk into receiving water bodies cannot be derived directly from such samples. A possibility to ensure soil water sampling of defined pore origin would be a continuous pressure application of a fixed vacuum to restrict sampling to the desired matrix potential. However, drawbacks of this operation mode are the risk to receive composite samples of more than one infiltration event if the samples cannot be collected in short time and the fact that continuous pressure application might initiate preferential flow paths in the surrounding substrate (Singh et al., 2017; Weihermüller et al., 2007). Moreover, Weihermüller et al. (2007) concluded that it seems difficult or maybe even impossible to derive soil water samples unbiased by the sampling procedure and stated that each sample only temporally represents the sample location. In short, a robust leaching risk assessment for contaminants based on soil water samples requires the strict consideration of initial and boundary conditions. Especially the knowledge of meteorological and soil hydrological conditions is an imperative to ensure (i) qualitative water analysis based on soil water of a defined (pore) origin, (ii) capturing concentration variations due to weather conditions, and (iii) to assess the representativeness of determined pollutant concentrations. To our best knowledge, no national or international standard protocol or guideline exists regulating in situ soil water monitoring for assessing the transfer potential for the soil leaching pathway. However, a promising approach was tested by McGuire and Lowery (1994) by coupling soil water extraction with soil moisture monitoring to coordinate sampling with drainage periods in column experiments.

The objective of this study was to overcome current limitations of soil seepage sampling for detecting contaminant migration in situ by introducing an advanced field soil water sampling system that uses active devices such as suction cups in a discontinuous operation modus. In this method, sampling is triggered by a soil moisture threshold (θ_{ST}) to synchronize water extraction with drainage periods and to separately analyze soil leachate qualitatively as a function of the initial soil hydrological and meteorological boundary conditions (i.e., precipitation patterns and antecedent soil moisture). We tested our advanced in situ soil water sampling system on two stormwater infiltration sites with bioretention in Germany. We provide the technical construction, describe the main components used for construction, and present the sampling results for the first 19 individual stormwater events within a 4-mo test phase. Our advanced in situ soil water sampling system can be technically duplicated and is considered helpful for further studies dealing with the contamination potential along the soil–groundwater migration pathway.

Materials and Methods
The Advanced In Situ Soil Water Sampling System

The designed measurement system is comprised of four main components: (i) suction cups with vacuum controller system for soil pore water sampling, (ii) a soil moisture sensor for actual soil water state determination, (iii) a Global System for Mobile Communication (GSM) module for building a monitoring automation system, (iv) a data logger to save the monitored data, and (v) a 12 V battery for powering components (i), (ii), and (iii). The measurement components and their specifications are presented in Table 1. Figure 1a shows a technical drawing of the soil water sampling system and the set-up of the field-installed system (Fig. 1b and 1c) at Site BS1 (located in Berlin in the northeastern part of Germany, urban setting) (Table 2). A description of the set-up and functioning of the developed monitoring system follows.

A key component is the soil moisture sensor monitoring the soil water status of the pedon at the same depth the suction cups are installed (Fig. 1a, Point 1), in our case at a depth of 25 to 30 cm. The moisture signal is measured constantly, and the sensor is connected to the Analog Digital Converter input channel of the GSM module (Fig. 1a, Point 2). The GSM module is configured with an individual millivolt threshold for the soil moisture (θ_{ST}) of the respective bioretention soil, which was determined

Table 1. Description of the components used for constructing the in situ soil water sampling system.

Components	Company	Model no.	Description	Specification
Suction cups	METER Group	SPE20	suction cup with low sorption for sampling metals, herbicides and pesticides	cup consists of an inner nylon membrane and an outer protective polyethylene membrane; porosity of 0.2 μm; bubble point -80 kPa
Vacuum controller system	METER Group	VS-twin	vacuum unit with two vacuum circuits, for constant or tension controlled vacuum regulation	vacuum regulation range: 0 to -85 kPa; accuracy: ±0.05 kPa
Soil moisture sensor	Delta-T Devices	Theta Probe ML2x	volumetric soil moisture content determination using frequency domain reflectometry	measurement: range 0–1 $m^3\ m^{-3}$, accuracy ±0.05 $m^3\ m^{-3}$
GSM† module	Conrad Electronic SE	GX110	monitoring automation system with nine inputs (one analog) and 14 outputs; each input can send a SMS‡ regarding a previously defined input signal; each output is assigned a specific function or input signal; four outputs are controllable via SMS and incoming calls; remote request of status of all inputs and outputs	quad GSM band; operating voltage 5–30 V DC; power consumption at standby of max. 30 mA; analog input of 0–14 V and accuracy of ±14 mV; relay output: rated voltage of relay core/switching current voltage max. 10 A/5 V
Battery	Panasonic	LC-P1228AP	valve-regulated lead-acid battery	12 V/28 Ah
Datalogger	Delta-T Devices	DL2e	programmable field datalogger for analog signal; logs DC or AC voltage, resistance, pulse, or frequency	nominal analog range of each input channel ±4 mV to ±2 V; resolution of 0.5 mV; accuracy: $\pm0.1\%$ reading; powered internal by six AA alkaline cells

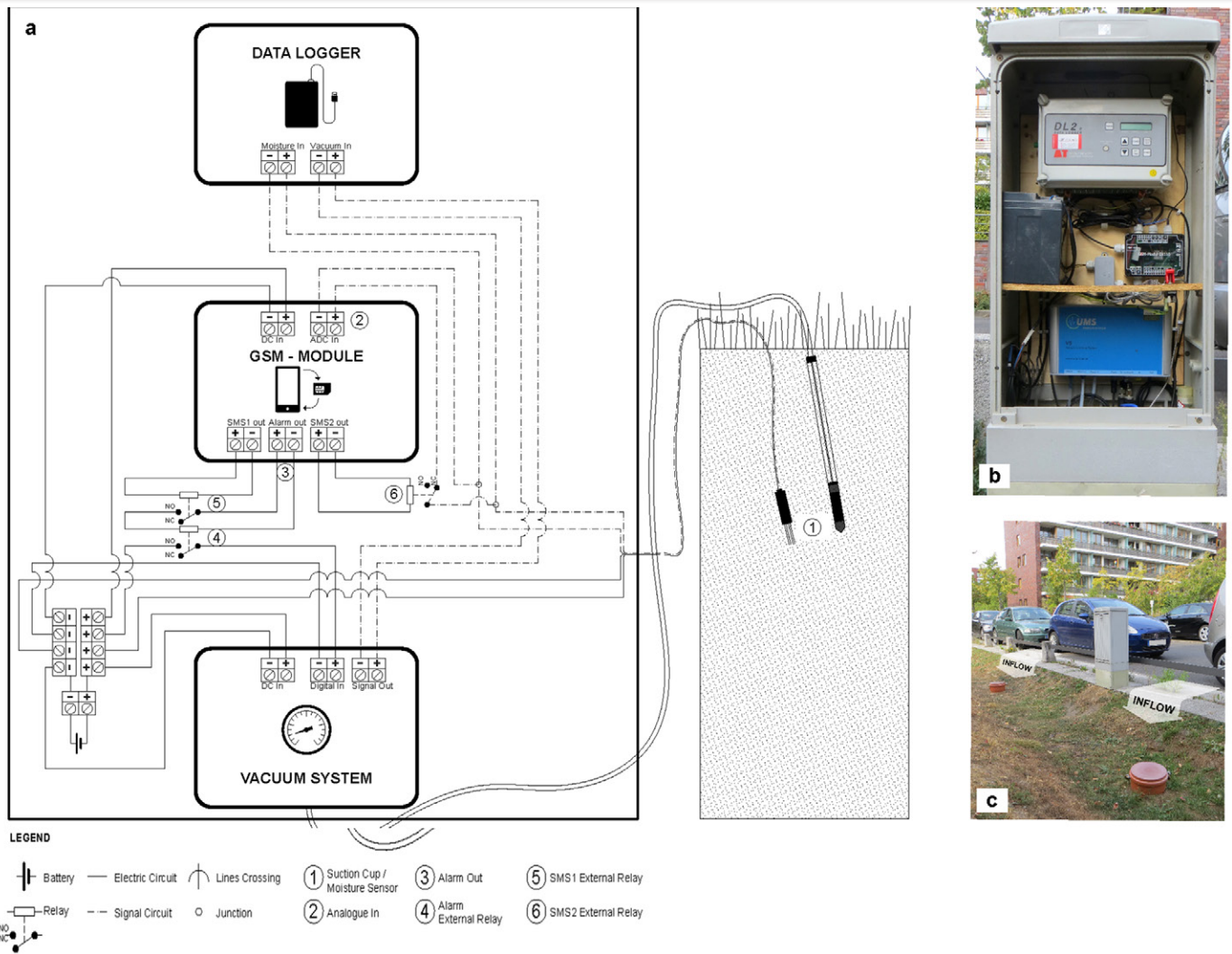† Global System for Mobile Communication.
‡ Short Message Service.

Fig. 1. (a) Technical drawing of the designed in situ soil water sampling system (the circled numbers highlight the key components and points of the designed approach), (b) field-installed measurement infrastructure with distribution box housing, and (c) example bioretention swale with areal inflow at Site BS1 (located in Berlin in the northeastern part of Germany, urban setting).

Table 2. Basic information on the two bioretention systems with installed measurement stations. Soil textural classes and total organic C (TOC) were determined using composite samples of the upper 20 cm of soil. Soil water retention properties and bulk densities were determined using undisturbed core samples from depths of 25 to 30 cm and are presented as mean values with SD. Saturated hydraulic conductivity (K_{sat}) represents in situ values determined in a previous investigation (Kluge et al., 2016) by double-ring infiltrometers.

Parameter	Bioretention system†	
	Site BS1	Site BS2
Drainage area type	residential road, sidewalks	roofs, parking lots, truck maneuvering area
Total drainage area, m^2	649.00‡	2540.00‡
Connected drainage area, m^2	42.00‡	140.00‡
Clay, %	2.94	3.59
Silt, %	6.18	14.41
Sand, %	90.89	82.00
Soil textural class, after FAO (2006)	sand	loamy sand
TOC, % w/w	1.3	7.56§
Dry bulk density, g cm^{-3}	1.60 ± 0.11	1.14 ± 0.09
Field capacity,¶ m^3 m^{-3}	0.20 ± 0.03	0.25 ± 0.01
Saturated water content, m^3 m^{-3}	0.43 ± 0.01	0.55 ± 0.03
Approximate K_{sat}, m s^{-1}	6.7×10^{-5}	7.0×10^{-5}
θ_{ST},# m^3 m^{-3}	0.23	0.33

† BS1 is located in the northeastern part of Germany (urban setting); BS2 is located in the central-western part of Germany (suburban setting).
‡ According to the planning documents.
§ After 25 yr operation time.
¶ Volumetric soil water content at a matric potential of -6.3 kPa (laboratory standard after the German soil classification [Eckelmann et al., 2006]).
# Soil moisture threshold for sampling initiation.

via retention data (see below and Table 2). We set θ_{ST} according to the laboratory-derived moisture value at field capacity (soil tension of -6.3 kPa) plus an individual offset to incorporate the measurement errors of the frequency domain reflectometry sensor, the GSM module, and the laboratory tests as well as site-specific conditions. If θ_{ST} is exceeded, a Short Message Service (SMS) text message alarm is sent to all given contacts. Simultaneously, the alarm output channel is activated (Fig. 1a, Point 3), which drives an external relay that closes the controlling circuit connected to the digital input of the vacuum controller system (Fig. 1a, Point 4). This digital input can be configured to externally activate and deactivate the vacuum circuits with a voltage signal. By default, the vacuum circuits are deactivated below an input voltage of 1 V. Only if the input voltage exceeds 4.5 V, as in the present case of a moisture alarm, the vacuum circuits are activated, and the system starts regulating the pressure. As long as the alarm output is activated, the vacuum station regulates the set vacuum value, and the suction cups will collect soil water. We configured the alarm output to remain switched on for 4 h after threshold exceedance

and set the vacuum controller system to evacuate around -35 kPa for meeting the analytical requirements (i.e., water volume) of the targeted analytes.

The outputs SMS1 and SMS2 of the GSM module are used for safety measures. Both outputs can be activated or deactivated externally via a SMS command and are connected to a relay. The SMS1 output is connected as an upstream switch (Fig. 1a, Point 5) controlling the alarm circuit that activates the vacuum system. Thus, a moisture alarm can only activate the vacuum controlling unit if the SMS1 output is activated. We use this output channel as emergency stop in case of a false moisture alarm or a system malfunction or simply if soil water sampling is not desired. The SMS2 output is connected as a moisture switch upstream of the moisture Analog Digital Converter input channel (Fig. 1a, Point 6). This output channel is used for decoupling the moisture circuit after a moisture alarm to avoid alarm SMS duplications in case of soil moisture fluctuations around the set threshold (e.g., in case of intermitting precipitation). This external moisture signal is switched off automatically by an auto-reply app sending the respective SMS command in case of an alarm SMS receiving the addressed mobile phone.

The complete part of Fig. 1a is hosted in a distribution box (1120 by 1000 by 330 mm, length by height by width) to ensure a weatherproof, rugged, and theft-proof housing of the GSM module, vacuum controlling unit, and battery and to allow easy maintenance of the measurement infrastructure (Fig. 1b). From the distribution box, the vacuum tube and moisture sensor cable are laid underground at a frost-resistant depth of 10 cm until the installation point of suction cups and moisture sensor. Each installation point is covered with a vertically embedded plastic pipe (inner diameter, 250 mm; see the pipes with brown cover in Fig. 1c) protecting the suction tubes and housing the soil water collection bottles. We installed a tipping-bucket rain gauge (Kalyx, Environmental Measurements Ltd) 1 m above ground at each site next to the distribution box.

Experimental Sites

The advanced in situ soil water sampling system was developed and tested for two experimental sites in Germany, which are equipped with decentralized stormwater infiltration systems for street runoff in urban areas. Site BS1 is located in Berlin (northeastern part of Germany, urban setting; Table 2) and the other in the Ruhr valley of the federal state of North-Rhine-Westphalia (BS2, central-western part of Germany, suburban setting) (Table 2). According to the nomenclature proposed by Woods-Ballard et al. (2007), both sites can be classified as bioretention systems (also known as bioretention cells or areas, raingardens, biofilters, or bioswales). Both systems consist of a 10-cm topsoil layer and a 20-cm subsoil layer and have an organic matter content between 1 and 3% (w/w) (German Association for Water, Wastewater and Waste, 2005) (Fig. 2).

Soil textural classes and the approximate saturated hydraulic conductivity (K_{sat}) range from sand to loamy sand and from
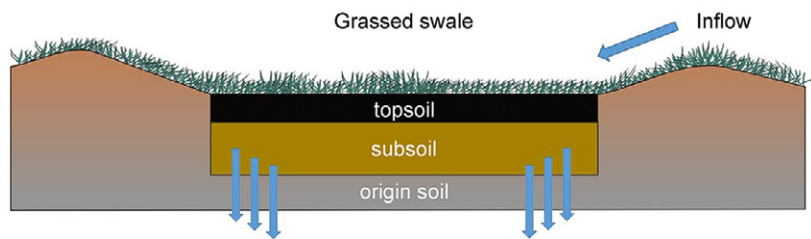
Fig. 2. Schematic construction of a bioretention system (swale) according to DWA-A 138 (German Association for Water, Wastewater and Waste, 2005) as used for testing the designed in situ soil water sampling system.

6.7×10^{-5} and 7.0×10^{-5} m s^{-1}, respectively (Table 2). The systems are covered with grasses and perennials and have been operated for more than 20 yr. The system BS1 is located in a residential area and receives stormwater runoff areally from the adjacent road and paved sidewalks. The system BS2 is located in a commercial area and receives stormwater runoff from a logistic truck maneuvering area via different point inflows. Mean temperature and annual cumulative precipitation are 10.2°C and 579.2 mm for BS1, respectively, and 10.7°C and 949 mm for BS2, respectively (reference period 1988–2017; data basis: German Meteorological Service, 2019). Table 2 gives an overview about soil parameters, drainage area types, and years of operation, and Table 3 summarizes the basic requirements for the construction of bioretention swales in Germany.

Bioretention Media Soil Sampling and Laboratory Analyses

During the field construction of each in situ soil water sampling system, composite soil samples were taken from the upper 20 cm excavated via access shaft for suction cup installation. All composite samples were sieved to 2 mm, homogenized, and oven-dried at 105°C until reaching constant weight. Soil textural classes were determined by wet sieving and sedimentation analysis according to DIN ISO 11277 (Deutsches Institut für Normung, 2002). Total organic C (TOC) was determined following DIN ISO 10694 (Deutsches Institut für Normung, 1995) by dry combustion at 1200°C in a CNS-Analyzer (Vario EL III, Elementar Analysensysteme GmbH). Before dry combustion, each soil sample was tested for calcium carbonate by adding 10% hydrochloric acid. If calcium carbonate was detected, the respective soil sample was incinerated at 550°C for 5 h prior to the dry combustion to determine the total inorganic C content. To determine TOC, total

Table 3. Requirements for constructing bioretention swales in Germany (German Association for Water, Wastewater and Waste, 2005).

Parameter	Value
Construction height	10 cm topsoil and 20 cm subsoil
Soil texture	fine and medium sand (<10% w/w clay and silt)
pH	6–8
Organic matter (topsoil)	1–3% (w/w)
Saturated hydraulic conductivity	10^{-4}–10^{-5} m s^{-1}
Max. initial load of pollutants	<Z0 soil quality standard (Jaron and Kossmann, 2003)

inorganic C was subtracted from total C content. If no CaCO$_3$ was detected, TOC was set to total C.

For determining the soil moisture at a matric potential of −0.1 and −6.3 kPa as well as the dry bulk density, undisturbed soil core samples of 100 cm^3 were taken at a depth of 25 to 30 cm with six repetitions each. Soil retention properties were determined on the drying branch according to DIN EN ISO 11274 (Deutsches Institut für Normung, 2014) for two points on the retention curve (−0.1 and −6.3 kPa) by using suction plates. The in situ infiltration rate was determined in a former project (Kluge et al., 2016) by using double ring infiltrometer (Eijkelkamp) according to DIN 19682-7 (Deutsches Institut für Normung, 2015).

Results and Discussion
Application of the Advanced In Situ Soil Water Sampling System

Results of the 4-mo test phase (24 Apr. 2018–31 Aug. 2018) are presented in Fig. 3a and 3b. The bioretention systems differ significantly regarding their soil moisture dynamics due to different weather conditions. The rainfall amount at Site BS1 was 125 mm (long-term mean of same months, 249 mm; reference period 1988–2017; data basis: German Meteorological Service, 2019), whereas the rainfall amount was twice as high for Site BS2 with 243 mm (long-term mean of same months, 306 mm; reference period 1988–2017; data basis: German Meteorological Service, 2019). This cumulative rainfall corresponds to an average volume of 2056 mm infiltrated per square meter of bioretention system for Site BS1 and 4652 mm for Site BS2. According to the pronounced weather conditions, soil leachate was sampled only twice at Site BS1 due to the dry spring and summer season but was sampled 17 times at Site BS2 with a cumulative rainfall slightly below long-term mean. At Site BS1, only two storm events with 20 mm in 3 h and 51 mm in 9 h yielded enough precipitation runoff to increase soil moisture values at a depth of 30 cm above the threshold of soil water sampling initiation (θ_{ST}) because in all other precipitation events infiltrating water was retained in the bioretention media above.

By contrast, most precipitation events at Site BS2 increased soil moisture values above the threshold of sampling initiation (θ_{ST}) regardless of precipitation amount and intensity. In addition to climatic conditions, the main causes are the significantly higher connected drainage area and the punctual inflow conditions, both leading to high water inflow at the installation point of the moisture sensor at Site BS2. Therefore, it was necessary to
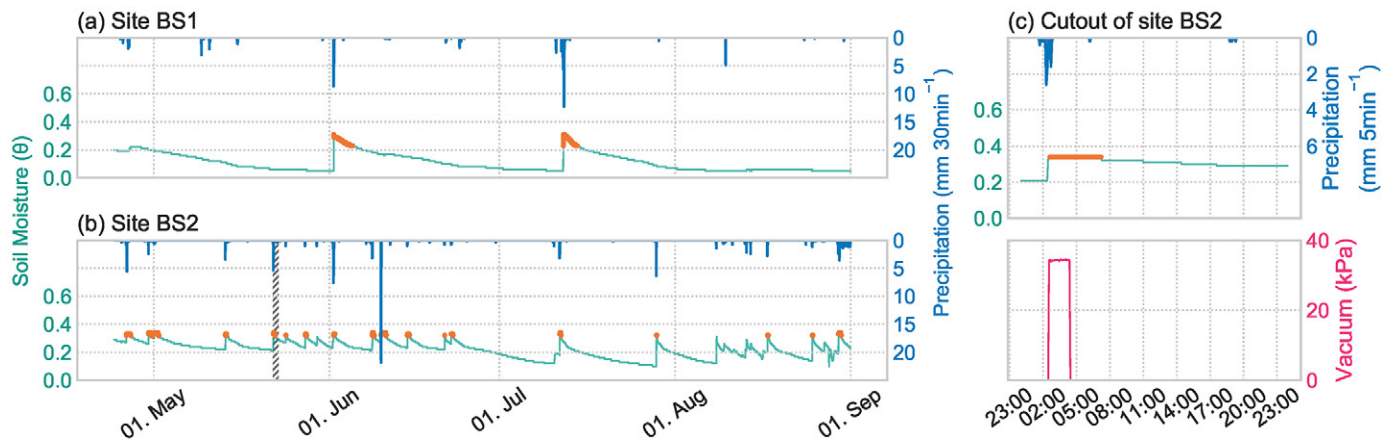
Fig. 3. Time series of the 4-mo test phase for precipitation and soil moisture at a depth of 25 to 30 cm for (a) Site BS1 (located in the northeastern part of Germany, urban setting) and (b) for Site BS2 (located in the central-western part of Germany, suburban setting) and (c) example query for 1 d (hatched area in subplot b) of a precipitation event, soil moisture increase, and automatically applied vacuum for soil leachate extraction. The bold and orange colored sequence of all three subplots indicates moisture values exceeding θ_{ST}, the threshold defined for sampling initiation (volumetric soil water content at a matric potential of −6.3 kPa plus offset).

set θ_{ST} for Site BS2 to a moisture content of 0.33 $m^3 m^{-3}$ (22% higher relatively to the soil moisture at field capacity), whereas the θ_{ST} for Site BS1 was set to a moisture content of 0.23 $m^3 m^{-3}$ (15% higher relatively to field capacity) to ensure a clear separation of single infiltration events based on the actual soil moisture.

An example illustrating the schematic performance of the designed sampling system is given in Fig. 3c for a single nocturnal precipitation event of 8.4 mm 2 h^{-1}. About 100 min after precipitation started, θ_{ST} (0.33 $m^3 m^{-3}$) is exceeded at the sampling depth of 30 cm, and the vacuum system starts regulating the given pressure of −35 kPa for the next 4 h. This extraction duration was set as default for both measurement stations because it yielded enough soil water for our analysis objectives (100–150 mL per event per suction cup; average 500 mL per event in total with five suction cup parallels per measurement point). However, the extraction duration should be adjusted individually in consideration of the soil hydraulic properties and the soil leachate volume required for analysis.

Quantitative Evidence and Limitations

The functioning of the advanced in situ soil water sampling system was successfully tested at the two sites with differing soil properties (Table 2) and rainfall regimes (Fig. 3a and 3b), indicating a general transferability of the approach.

One potential reason for the uncertainty regarding our approach is the use of only one moisture sensor. However, in our application with constructed and therefore more or less homogeneous soils, the clear correlation of precipitation input and soil moisture response demonstrates that one sensor is sufficient. If our approach is transferred to larger sampling areas, more moisture sensors might become necessary to accommodate variations in soil properties. Another alternative is to replace the moisture sensor with a tensiometer. Thus, no water retention properties must be determined because θ_{ST} can be directly set near to field capacity.

However, tensiometers require periodic service and are prone to malfunction during dry conditions.

A further discussion point is the threshold defining the onset of a drainage period (θ_{ST}). Other alternatives than field capacity include a sampling triggered by precipitation. However, in such a case the threshold for sampling initiation could not be defined ad hoc because the infiltration depth and velocity of the respective wetting front depends on the antecedent soil moisture. Hence, for each precipitation event, data pre-processing would be necessary to calculate if and when the wetting front would reach the sampling depth. Another possibility would be to calculate the delta between two consecutive moisture measures to identify drainage periods based on the actual soil water flow rate. A thorough overview of different approaches to predict infiltration is given by Assouline (2013). Both approaches to identify drainage periods might be technically feasible but require a programmable controller unit and more technical development effort. Hence, one future-oriented modification would be to convert our approach to an open source microcontroller platform such as Arduino. This would have two main advantages: (i) Controlling and data logging would be merged to one device, with the possibility to telemeter both and a more flexible configuration of the whole system compared with user-ready components, and (ii) the project codes would be published under a Creative Commons Attribution–Share Alike (CC BY-SA 3.0) license to allow the easiest possible reconstruction and the further development of the system.

Because various definitions of field capacity exist, we choose a simple and practicable laboratory standard according to the German soil classification (Eckelmann et al., 2006) but verified the laboratory-derived values with the value soil moisture attained after a given precipitation period in spring (negligible evaporation). In our case, the field-derived values aligned the laboratory measures of field capacity. Other possibilities to define and determine field capacity are for example given by Assouline and Or (2014).

Another critical point is to define the ideal offset of θ_{ST} concerning field capacity. We had the trade-off between a sufficiently high offset for clear event segregation and the risk of omitting small precipitation events, as is the case for example in August at Site BS2 (Fig. 3b). Furthermore, our testing period currently covers only the vegetation period with pronounced moisture dynamics. It is conceivable to choose a higher offset outside the vegetation period due to reduced moisture decreases after rainfall or snow events. Vice versa, a lower offset is thinkable for natural soils without runoff input. Because the threshold is key element of the introduced system, special attention should be paid to the field capacity determination regarding the accuracy and representativeness of the selected method and sample size to ensure the restriction of soil leachate sampling to drainage periods. The ideal threshold offset should be at least as high as the absolute measurement error of the moisture sensor, controller unit, and determined field capacity. In our case, we added an extra offset for Site BS2 because of the high inflow conditions. Otherwise, the sampling intervals would have exceeded our contingent of laboratory analyses and maintenance.

Currently, the application of our approach is not suitable for soils prone to preferential flow (i.e., macroporous soils and soils with strong structural heterogeneities) because the preferential flow is likely to bypass the suction cup (Grossmann and Udluft, 1991) or the soil moisture sensor and hence the flow field will not be captured. An alternative would be to use sampling devices with a larger cross-sectional sampling area, such as porous suction plates (Ciglasch et al., 2005; Singh et al., 2017; Weihermüller et al., 2007), instead of suction cups and to increase the number of soil moisture sensors.

Conclusions

The present study introduces an in situ soil water sampling approach to automatically extract soil water during drainage periods for drainage quality analysis. Soil leachate is sampled discontinuously with active devices regulated by the actual moisture. The 4-mo testing phase with 19 individual infiltration events on two different monitoring sites demonstrates good performance and indicates a general transferability of our approach to sample soil leachate in mid-latitude climates. However, to fully evaluate our approach, the application should be extended to different natural soils and outside the vegetation period. Nonetheless, our approach clearly demonstrates the feasibility of automatically restricting soil water sampling in the vadose zone to drainage periods on the basis of the actual soil moisture value. The main advantages are (i) automatic in situ soil water extraction of defined soil moisture states, (ii) ease of technically duplicating with commonly available sampling equipment components, (iii) the possibility to receive soil water samples for varying meteorological boundary conditions, (iv) minimal disturbance of the natural flow field due to the discontinuous operation mode, and (v) remote control of the sampling system using a mobile phone and SMS notification in the case if soil water is collected.

The fifth point is especially important if concentrations of easily degradable substances (e.g., dissolved organic C) or volatile contaminants (e.g., chlorinated hydrocarbons or aromatic hydrocarbons) are an objective of the investigation. Hence, our soil water sampling system is suitable to provide robust soil leachate pollutant loads, which are required for the assessment of pollution risk areas where potentially contaminated water or stormwater is infiltrated or where contaminated sites such as brownfields or landfills need to be monitored.

References

Assouline, S. 2013. Infiltration into soils: Conceptual approaches and solutions. Water Resour. Res. 49:1755–1772. doi:10.1002/wrcr.20155

Assouline, S., and D. Or. 2014. The concept of field capacity revisited: Defining intrinsic static and dynamic criteria for soil internal drainage dynamics. Water Resour. Res. 50:4787–4802. doi:10.1002/2014WR015475

Bundes-Bodenschutz- und Altlastenverordnung. 1999. Federal site protection and contaminated sites ordinance. (In German.) Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin.

Berry, Z.C., J. Evaristo, G. Moore, M. Poca, K. Steppe, L. Verrot, et al. 2017. The two water worlds hypothesis: Addressing multiple working hypotheses and proposing a way forward. Ecohydrology 11(3):31843. doi:10.1002/eco.1843

Bradl, H.B. 2004. Adsorption of heavy metal ions on soils and soils constituents. J. Colloid Interface Sci. 277:1–18. doi:10.1016/j.jcis.2004.04.005

Brooks, J.R., H.R. Barnard, R. Coulombe, and J.J. McDonnell. 2009. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. Nat. Geosci. 3:100–104. doi:10.1038/ngeo722

Carlon, C., editor. 2007. Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonization. EUR 22805-EN. European Commission, Joint Res. Ctr., Ispra, Italy.

Cheng, S. 2003. Heavy metal pollution in China: Origin, pattern and control. Environ. Sci. Pollut. Res. Int. 10:192–198. doi:10.1065/espr2002.11.141.1

Ciglasch, H., W. Amelung, S. Totrakool, and M. Kaupenjohann. 2005. Water flow patterns and pesticide fluxes in an upland soil in northern Thailand. Eur. J. Soil Sci. 56:765–777. doi:10.1111/j.1365-2389.2005.00712.x

Deutsches Institut für Normung. 1995. Soil quality: Determination of organic and total carbon after dry combustion (elementary analysis). ISO 10694:1995. Beuth, Berlin.

Deutsches Institut für Normung. 2002. Soil quality: Determination of particle size distribution in mineral soil material. Method by sieving and sedimentation. ISO 11277:1988 + ISO 11277:1998/Cor.1:2002. Beuth, Berlin.

Deutsches Institut für Normung. 2014. Soil quality: Determination of the water-retention characteristic. Laboratory methods. ISO 11274:1998 + Cor 1:2009 (German version EN ISO 11274:2014). Beuth, Berlin.

Deutsches Institut für Normung. 2015. Soil quality: Field tests. Part 7: Determination of infiltration rate by double ring infiltrometer. DIN 19682-7. Beuth, Berlin.

Eckelmann, W., H. Sponagel, W. Grottenthaler, K.-J. Hartmann, R. Hartwich, P. Janetzko, et al., editors. 2006. Bodenkundliche Kartieranleitung. 5th ed. Schweizerbart Science, Stuttgart, Germany.

Fang, W., R.C. Delapp, D.S. Kosson, H.A. van der Sloot, and J. Liu. 2017. Release of heavy metals during long-term land application of sewage sludge compost: Percolation leaching tests with repeated additions of compost. Chemosphere 169:271–280. doi:10.1016/j.chemosphere.2016.11.086

FAO. 2006. Guidelines for soil description. FAO, Rome.

Flury, M., M.V. Yates, and W.A. Jury. 1999. Numerical Analysis of the effect of the lower boundary condition on solute transport in lysimeters. Soil Sci. Soc. Am. J. 63:1493–1499. doi:10.2136/sssaj1999.6361493x

German Association for Water, Wastewater and Waste. 2005. Design, construction and operation of rainwater drainage systems. (In German.) DWA-A 138. German Assoc. for Water, Wastewater and Waste, Hennef, Germany.

German Meteorological Service. 2019. Historical monthly climate data retrieved for the meteorological stations "Berlin Tempelhof" (ID 433) and "Essen-Bredeney" (ID 1303). Climate Data Center of the German Meteorological Service. https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/monthly/kl/historical/ (accessed 8 July 2019).

Grossmann, J., and P. Udluft. 1991. The extraction of soil water by the suction-cup method: A review. J. Soil Sci. 42:83–93. doi:10.1111/j.1365-2389.1991.tb00093.x

Holt, M. 2000. Sources of chemical contaminants and routes into the freshwater environment. Food Chem. Toxicol. 38:S21–S27. doi:10.1016/S0278-6915(99)00136-2

Jaron, A., and C. Kossmann, editors. 2003. Requirements governing the recycling of mineral residues: Technical report of the Federal Waste Working Group Germany. (In German.) Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin.

Kluge, B., A. Markert, M. Facklam, H. Sommer, M. Kaiser, M. Pallasch, and G. Wessolek. 2016. Metal accumulation and hydraulic performance of bioretention systems after long-term operation. J. Soils Sediments 18:431–441. doi:10.1007/s11368-016-1533-z

Kumpiene, J., L. Giagnoni, B. Marschner, S. Denys, M. Mench, K. Adriaensen, J. Vangronsveld, M. Puschenreiter, and G. Renella. 2017. Assessment of methods for determining bioavailability of trace elements in soils: A review. Pedosphere 27:389–406. doi:10.1016/S1002-0160(17)60337-0

Lapworth, D.J., N. Baran, M.E. Stuart, and R.S. Ward. 2012. Emerging organic contaminants in groundwater: A review of sources, fate and occurrence. Environ. Pollut. 163:287–303. doi:10.1016/j.envpol.2011.12.034

McDonnell, J.J. 2014. The two water worlds hypothesis: Ecohydrological separation of water between streams and trees? Wiley Interdiscip. Rev.: Water 1:323–329. doi:10.1002/wat2.1027

McGuire, P.E., and B. Lowery. 1994. Monitoring drainage solution concentrations and solute flux in unsaturated soil with a porous cup sampler and soil moisture sensors. Groundwater 32:356–362. doi:10.1111/j.1745-6584.1994.tb00651.x

Nielsen, D.R., M.Th. van Genuchten, and J.W. Biggar. 1986. Water flow and solute transport processes in the unsaturated zone. Water Resour. Res. 22(9S):89S–108S. doi:10.1029/WR022i09Sp0089S

Nimmer, M., A. Thompson, and D. Misra. 2010. Modeling water table mounding and contaminant transport beneath storm-water infiltration basins. J. Hydrol. Eng. 15:963–973. doi:10.1061/(ASCE)HE.1943-5584.0000256

Pitt, R., S. Clark, and R. Field. 1999. Groundwater contamination potential from stormwater infiltration practices. Urban Water 1:217–236. doi:10.1016/S1462-0758(99)00014-X

Science Communication Unit. 2013. Soil contamination: Impacts on human health. Science for Environment Policy in-depth report. Univ. of the West of England, Bristol, UK. http://ec.europa.eu/environment/integration/research/newsalert/pdf/IR5_en.pdf (accessed 8 July 2019).

Singh, G., G. Kaur, K. Williard, J. Schoonover, and J. Kang. 2017. Monitoring of water and solute transport in the vadose zone: A review. Vadose Zone J. 17:160058. doi:10.2136/vzj2016.07.0058

USEPA. 1996. Soil screening guidance: Technical background document. EPA/540/R95/128. USEPA Office of Solid Waste and Emergency Response, Washington, DC.

Weihermüller, L., J. Siemens, M. Deurer, S. Knoblauch, H. Rupp, A. Göttlein, and T. Pütz. 2007. In situ soil water extraction: A review. J. Environ. Qual. 36:1735–1748. doi:10.2134/jeq2007.0218

Wilcke W. 2000. SYNOPSIS polycyclic aromatic hydrocarbons (PAHs) in soil: A review. J. Plant Nutr. Soil Sci. 163:229–248. doi:10.1002/1522-2624(200006)163:3

Wong, C.S.C., X. Li, and I. Thornton. 2006. Urban environmental geochemistry of trace metals. Environ. Pollut. 142:1–16. doi:10.1016/j.envpol.2005.09.004

Woods-Ballard, B., R. Kellagher, P. Martin, C. Jefferies, R. Bray, and P. Shaffer. 2007. The SUDS manual (C697). CIRIA, London.

Zhang, K., A. Randelovic, A. Deletic, D. Page, and D.T. McCarthy. 2016. Stormwater biofilters: A new validation modelling tool. Ecol. Eng. 87:53–61. doi:10.1016/j.ecoleng.2015.11.014

Zia, A., L. van den Berg, M.N. Ahmad, M. Riaz, D. Zia, and M. Ashmore. 2018. Controls on accumulation and soil solution partitioning of heavy metals across upland sites in United Kingdom (UK). J. Environ. Manage. 222:260–267. doi:10.1016/j.jenvman.2018.05.076

Zimmermann, J., C. Dierkes, P. Göbel, C. Klinger, H. Stubbe, and W.G. Coldewey. 2005. Metal concentrations in soil and seepage water due to infiltration of roof runoff by long term numerical modelling. Water Sci. Technol. 51:11–19. doi:10.2166/wst.2005.0027