Design and Testing of a Drop Counter for Use in Vadose Zone Water Samplers

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Measuring leachate mobility in the vadose zone is necessary to understand the processes controlling groundwater and river contamination, and requires recording leachate volumes with time. Many field studies manually measure the volume of leachate with a daily, weekly, or even biweekly resolution; however, measurement of leachate at higher temporal resolution is needed for the calibration of solute transport models and is useful in identifying the contribution of preferential flow to solute transport. We designed a simple, robust, and low-cost drop counter for measuring leachate volumes at a high temporal resolution. Laboratory experiments showed a nearly perfect linear relationship between the applied flux and the number of drops per unit time, and indicate an average drop size of 35 μ L. Due to manual manufacturing, variability between drop counters is not negligible and a one-point calibration is necessary. The drop counter consists of an upper (guiding) tube from which a drop forms and a lower (capillary) tube that "sucks" the drop down before it falls. The presence of the lower tube makes the counter less vulnerable to temperature and ionic strength effects of the leachate. Counting of the drops can be easily achieved using any type of datalogger capable of logging electrical pulses.

EASURING THE natural flux of soil water and solute concentration in the unsaturated zone of the soil profile, also called the vadose zone, is challenging due to the requirement of an appropriate suction. Traditionally, suction cups are used for the sampling of leachate through the soil; however, suction cups are not capable of measuring fluxes because of their small and unknown sampling area. For estimating solute fluxes, larger sampling systems are required, which usually consist of a porous plate in contact with the soil. There are different options for controlling suction applied to the porous plates: zero tension, constant tension, or automatic tension control. As an alternative to porous plate sampling systems, passive capillary wick samplers (PCAPs) have been introduced that use the capillary properties of fiberglass wicks to exert suction on the unsaturated soil. The suction exerted by the wick is a function of the wick length, while the

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wicks themselves serve as a means to guide the sampled solute to the collecting bottle. Common to all in situ solute flux sampling systems is the requirement of measuring the percolating solute volume for a period of time. In many studies, leachate volumes are manually measured on a daily (Morari, 2006), weekly, or even biweekly (Brye et al., 2000, Mertens et al., 2007b) basis. For the purpose of calibrating a solute transport model, which forms the basis of solute management in field soils, solute fluxes at high temporal resolution are required. Additionally, high-temporalresolution flux data make the in situ identification and probable quantification of macropore flow possible.

Gee et al. (2002, 2003) and Vandervelde et al. (2005) used a tipping bucket system with a sensitivity of 4 mL tip⁻¹, placed at the end of a fiberglass wick, in their solute flux meter. The detection limit of their low-cost (<US\$60) flux meter corresponds to a pluviometry of 0.1 mm. In the calibration of the flux meter between 50 and 5000 mm yr⁻¹, they noticed a nonlinearity between the number of tips and leachate volume of about 10% (Gee et al., 2002). Masarik et al. (2004) used the ECH2O probe (Decagon Devices, Pullman, WA), which was originally designed to measure the dielectric constant of the soil to infer its volumetric water content. The probe is installed inside the leachate collecting container and the ECH2O probe output yields, after calibration, the height of the collected solute, making a calculation of the solute flux possible on a submillimeter scale. Kosugi and Katsuyama (2004) mounted the soil solute collecting containers on load cells and monitored leachate weight as a function of time.

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A new drop counter was designed and developed for a field experiment that requires the continuous measurement of the soil solute flux collected by PCAPs. Drop counters are commonly used in chemical titration experiments and are widely applied in medical applications. All drop counting systems described in the literature consist of what is called a "drip chamber." The purpose of the drip chamber is to break the fluid flow into drops. In most commercially available drop counters, the drops are counted using an optical sensor. Other systems are based on measuring the change in capacity or resistance between electrodes placed around the drip chamber when a drop passes. We intended to design a drop counter that did not require the use of any electrical sensor other than a datalogger, which has become standard equipment at any experimental field site measuring soil water fluxes. Moreover, the drop counter developed in this study had to be reliable across a range of field conditions; effects caused by changes in temperature and ionic strength of the percolating solute had to be minimized. Therefore the drop counter was designed such that temperature and ionic strength of the leachate minimally affects the drop size and therefore the number of drops corresponding to a given flux. Additionally, the drop counter described here is

inexpensive and easy to manufacture ("homemade"). Although the system was originally designed to be used at the outlet of fiberglass wicks, the drop counter can easily be used in any other vadose zone water sampler because it can be mounted at the inlet of any collecting container.

We designed and then tested the drop counter in the laboratory. Three factors could have an effect on the drop size and therefore on the relationship between drop counts and flux: the flux itself and the temperature and ionic strength of the leachate. Laboratory testing was performed to assess: (i) the linearity of the relation between the number of drops per unit time and the applied flux; and (ii) the effect of the solute water temperature on drop size. We determined that the effect of ionic strength on drop size is negligible.

Materials and Methods

The body of the drop counter (Fig. 1) is made out of polytetrafluoroethylene (PTFE or Teflon). The material is very nonreactive and reduces the risk of pesticides or any other contaminants present in the percolating soil water adsorbing onto the counter's body. Teflon is relatively soft and facilitates the manufacturing of the drop counter on a lathe. Since fiberglass wicks are usually installed inside a flexible tube, the top of the drop counter has a diameter equal to the inner diameter of the flexible tube. In this study, the instrument was installed through the screw cap of a leachate container as shown in Fig. 1 and 2. The essential part of the instrument consists of two vertical stainless steel tubes, spaced at a fixed distance of 3 mm (see Fig. 1). The upper tube (or guiding tube) has an inner diameter of 5 mm and external diameter of 6 mm, while the lower tube (or capillary tube) has a inner diameter of 3 mm. Water leaving the fiberglass wick first drips onto a small piece of fiberglass inserted on top of the upper guiding tube. The purpose of this small piece of wick is to reduce the impact of the water falling from the fiberglass wick onto the upper stainless steel guiding tube in case the fiberglass wick and the upper guiding tube do not touch. The small piece of wick enhances a constant water flow through the upper guiding tube and, by doing so, the formation of drops at the end of the guiding tube.

The size of the drops can be calculated when only the upper tube is used (see Clanet and Lasheras, 1999). Tate (1864) showed that equating surface tension forces to gravity forces at the point of detachment, the mass (*M*) of a drop falling from the tube is expressed by $2\pi\sigma r/g$, where σ is the surface tension and *r* the external radius of the tube. Harkins and Brown (1919) introduced a correction factor f(r/a) to Tate's law in which *a* is the capillary length of water equal to $(2\sigma/\rho g)^{1/2}$, with ρ being the density of water [M L⁻³]. Their highly accurate measurements revealed that f(r/a) is best described by a third-



Fig. 1. Layout of the drop counter and the two stainless steel guiding tubes.



FIG. 2. Photographs of the drop counter: (left) drop counter installed in a leachate collecting bottle; (right) the two stainless steel guiding tubes.

order polynomial $[f(r/a)/2\pi = -0.4032(r/a)^3 + 1.2256(r/a)^2$ - 1.2158(r/a) + 0.9982]. This correction factor is referred to as the Harkins and Brown factor and the mass of the drop is calculated as $M = 2\pi \sigma r/g f(r/a)$ and accounts for the deviation from sphericity of the pendant drop before its detachment. Those studies led to the well-known "drop-weight" method to determine the surface tension of a liquid. Applying the surface tension of water at 20°C (0.0728 N m⁻¹) and an external radius of 3 mm of the upper guiding tube used in this study yields a drop size of 84.5 µL. This means that freely forming drops at the end of the upper tube would have a volume of 84.5 μ L immediately before detachment. In the design presented here, drops do not detach only by gravity. As soon as the size of the water droplet at the end of the upper tube is large enough to touch the rim of the lower steel tube (capillary tube), the droplet is pulled into the lower tube by the capillary forces exerted by this lower tube. We therefore expected the size of droplets to be smaller than the 84.5 µL calculated above as a consequence of the combination of gravity and capillary forces. The droplets are transported through the lower stainless steel tube and drip into the collecting container. Tests in the laboratory revealed the possibility of air entrapment in the lower capillary tube between consecutive drops. Therefore, two rectangular slits (Fig. 2) were cut out of the wall of the lower tube on opposite sides to prevent air entrapment. This study shows that it is this unique design, consisting of the two stainless steel tubes, that makes the drop counting less dependent on the surface tension and therefore on variations in temperature and ionic strength of the fluid.

A picture of the drop counter, installed in the screw cap of a sampling bottle, and a close-up of the two stainless steel tubes is shown in Fig. 2. An electrical wire is welded to each of the stainless steel tubes and an electrical potential is supplied by a datalogger. In this study, the Campbell Scientific CR10X datalogger (Campbell Scientific, Logan, UT) was used in combination with a homemade pulse multiplexer. A current flow is generated through the electrical circuit each time a conducting drop descending from the upper guiding tube makes contact with the lower capillary tube. The water percolating through the soil must therefore be an electrical conductor. All experiments in this study were performed using tap water with an electrical conductivity of 810 μ S cm⁻¹. Using a CaCl₂ solution with an electrical conductivity of 100 μ S cm⁻¹, no stable drop counting could be obtained on the pulse channels (5 V) of the CR10X datalogger. Tests revealed that the fluid should have a minimum electrical conductivity of 200 μ S cm⁻¹ using the pulse channels of a CR10X datalogger. For fluids with lower electrical conductivity, the signal needs to be amplified, which can be achieved by increasing the applied voltage or by using smarter electrical amplifiers; however, the value of 200 μ S cm⁻¹ is close to the lower limit of electrical conductivity varied between 300 and 4000 μ S cm⁻¹ with two lower values of 126 and 165 μ S cm⁻¹).

For evaluating flux and temperature effects, an adjustable peristaltic pump was used to control the water flow of four drop counters. The temperature of the water was varied using a Cu coil inside an insulated ice bath through which the water was routed before it reached the drop counters. The ice bath was left to melt overnight and hence the temperature gradually increased. A microthermocouple was installed on one of the four drop counters at the circumference of the upper guiding stainless steel tube to record the temperature at the location where drops are formed. It was assumed that the temperature differences between the four drop counters would be negligible since water from the same source was used.

Results and Discussion

Flux Effect

The relationship between the applied water flux and the number of drops counted by each of the four tested drop counters is presented in Fig. 3. Each flux was applied for a minimum of 4 h and the drops counted during 10-min intervals. The flux was varied between 0.11 and 2.5 mL min⁻¹ (0.11, 0.22, 0.5, 1, 2, and 2.5 mL min⁻¹). A nearly perfect linear relationship (R^2 = 0.99) was observed between the number of drops counted within 10 min and the applied flux for all four drop counters. For a sampler area of 900 cm², as used in our field setup (Mertens et al., 2007a), the applied flux range corresponded to a pluviometry of 1.8 and 40 mm d⁻¹. Fluxes <0.1 mL min⁻¹ could not be tested due to the technical limitations of the peristaltic pump used; however, analysis of the field water balance tells us that, on the experimental site, fluxes >40 mm d⁻¹ (or 3.6 L d⁻¹ for a 900-cm² sampler area) seldom occur. Notwithstanding, the drop counters were briefly tested for higher fluxes, suggesting linearity up to 8 mL min⁻¹.

From the linear relations presented in Fig. 3, a drop size between 33 and 36 μ L was calculated. This is less than half of the theoretically calculated drop size of 84.5 μ L in the absence of the lower capillary tube and hence confirms the design requirement that drops are "sucked" away by the lower stainless steel tube. Although low CVs were found for the flux range applied in the drop counter tests, Fig. 3 indicates a slight increase in CV at the lower flux range. Since a CV of 2% at the 0.11 mL min⁻¹ flux is the result of a varying number of drops between 30 and 32 per 10 min and the size of drops is small, absolute errors in measured leachate volume will be negligible.



FIG. 3. Relationship between the applied flux and the number of drops counted every 10 min; average and CV for four drop counters. Horizontal bars depict the size of the standard deviation for a measurement period of 4 h and the numbers are the CV (%).

The experiment, the results of which are depicted in Fig. 3, showed that the drop counters exhibit a linear behavior in the range of relevant field leachate fluxes. A difference in drop size among drop counters, however, is not negligible. The most obvious reason is the manual manufacturing of the counters; hence, minimal differences in spacing between the two stainless steel tubes are likely. Therefore, each drop counter must be calibrated. The linearity implies that a single-point calibration is sufficient (i.e., by counting drops for one flux) for each of the drop counters. Although not tested in this study, the drop counter can be used at a higher temporal resolution than the 10 min chosen in this study. This seems only advisable, however, at relatively high fluxes (i.e., a large number of drops within one interval) because the CV will increase due to individual drops being included or not being included in the chosen time period.

Temperature Effect

Figure 4 shows the relationship between the temperature measured at the upper stainless steel tube of Counter 1 and the number of drops counted within every 10 min at a flux rate of 1 mL min⁻¹. The experiment was run using gradually increasing temperatures between 5 and 20°C, a range considerably larger than the temperature variations encountered in the field at a depth of 40 cm below the surface. A small temperature effect is seen for three of the four counters.

The size of a droplet falling from a 3-mm external radius upper guiding tube without the presence of the lower capillary tube, at 5 and 20°C, can be estimated by using Tate's law and substituting the surface tension at both temperatures (0.0749 N m⁻¹ at 5°C and 0.0728 N m⁻¹ at 20°C) in the Harkins and Brown factor. This yields a drop of size of 87.0 and 84.5 μ L and an expected difference in drop counts per 10 min of 2.9%. Linear

regression through the observed data in Fig. 4 and calculating the corresponding drop size at 5 and 20°C results in differences in drop sizes between 0.1% (Counter 1), 1.8% (Counter 4), and a maximum of 2% (Counters 2 and 3), which is smaller than the expected error of 2.9% that would be incurred in the absence of the lower tube.

Ionic Strength Effect

The effect of ionic strength on the precision of the counter was reconstructed from the relationship between ionic strength and surface tension. Figure 5 depicts the effect of temperature and ionic strength on the surface tension of water. The ionic strength-surface tension relation is the result of an experiment conducted at 35°C using a CaSO₄ and NaCl solution (Kumar et al., 2005). This figure illustrates that the effect of ionic strength within the range 0 to 1.6 mol kg⁻¹ on surface tension is negligible and considerably smaller than the effect of temperature in the range 0 to 40°C. Moreover, the range of ionic strength expected in the soil water at the experimental site in which the drop counters are used is considerably smaller and varies between 0 and 0.1 mol kg⁻¹. From this it can

be concluded that ionic strength will hardly affect the number of drops counted by the drop counter.

Conclusions

We developed a drop counter able to measure in situ the soil solute flux with high temporal resolution. The concept of the drop counter is unique and based on a low-voltage pulse generated by a drop falling from a vertical guiding tube with a 5-mm inner diameter to a capillary tube with an inner diameter



FIG. 4. Effect of water temperature on the number of drops counted in 10 min by four drop counters given a flux of 1 mL min⁻¹; water temperature was measured at the upper tube of Drop Counter 1.



FIG. 5. Effect of temperature and ionic strength (measured at 35°C using a $CaSO_4$ and NaCl solution) on the surface tension of water (ionic strength data from Kumar et al., 2005).

of 3 mm, both tubes at a vertical distance of 3 mm. It has been demonstrated that the guiding of the droplets from the upper to the lower receiving tube, combining gravity and capillary forces, makes the effect of temperature on drop size small (0.1–2%), and the effect of variations in ionic strength negligible. The effect of air bubbles is neutralized by the two vertical slits in the capillary tube. The drop counter is mounted in the screw cap of the fluid-collecting recipient and connected to a passive capillary wick sampler. It has been shown that the counter exhibits a linear response to the applied flux. The components of the counter are inexpensive. In addition, the construction of the device is simple and easy to make, increasing the accessibility of the counter to the scientific community. Further evaluation of the drop counters under field conditions is required, in particular testing its vulnerability to CaCO₃ deposition.

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