USE OF SOPHISTICATED LYSIMETER TYPES TO MEASURE SOIL WATER BALANCE PARAMETERS WITH HIGH ACCURACY

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Abstract
Intensive cultivation has resulted in an accumulation of nutrients and hazardous substances in the soil. These solutes represent a potential risk to the quality of both surface and groundwater. It is of vital interest to know the quantity and quality of seepage water which leaves the root zone, then enters the aquifer and finally the surface water system. To solve the problem we carried out trials at different scales to get information on how different land management methods influence the amount and quality of seepage water. We used direct lysimetry methods for measuring water and solute fluxes in soils. The combination of lysimeter studies with field experiments at different scales opens new possibilities for modelling and management of watersheds. The paper informs about advances in lysimeter techniques and technology and gives a practical application of this technique to measure the amount of dew. Based on an example the combination of lysimeter measuring results with the WebGIS based model STOFFBILANZ for calculating nutrient balances at catchment scale will be shown.

KEYWORDS: LYSIMETER, MEASURING TECHNIQUE, SOIL WATER REGIME, WATER FLUX, SOIL MOISTURE, ACTUAL EVAPOTRANSPIRATION, UP-SCALING, WATER AND SOLUTE MODELLING

1. Introduction
In the international literature the term “lysimeter” is used for different measuring devices. According to our understanding it belongs to the direct methods to measure water and solute fluxes in soil. The German Industrial Standard DIN 4049-3 defines a lysimeter as a device to collect drainage water for mass and solute balances in relation to soil, parent rock, vegetation, local climate and other site conditions. In general, it consists of a square or round vessel filled with soil and a mechanism to collect and quantify the amount of water leaving it at the bottom. Only lysimeters permit a direct determination of the water amount percolating through a soil profile and of the type and amount of solutes contained in it. Hence, they allow a much more reliable calculation of solute loads carried towards the groundwater than any other method [1]. If the lysimeter is weighable, actual evapotranspiration can be calculated from its weight (mass) change.

A wide range of lysimeters have been developed and used in the past, ranging from small, free-draining pan lysimeters or tension-controlled lysimeters that only often capture a small portion of the drainage water, to large drainage lysimeters that limit divergence and capture most or all of the drainage water within a prescribed area. The main difference between the used lysimeter types are:
- soil filling procedure (disturbed – undisturbed)
- weighability (weighable or non-weighable)
- lysimeter size (depends on scientific question and scale of observation)
- lower boundary conditions (free drainage or suction controlled drainage)

The design of a lysimeter (required surface and length) depends mainly on scientific question, manner of vessel filling (disturbed or undisturbed), lower boundary, and location of installation. Small scale heterogeneity of a site will be averaged using a larger lysimeter base area. Furthermore, lysimeters with vegetation should represent natural crop inventory and maximal root penetration depth should be taken into account. Except the generation of well-defined recurrences of the same soil conditions it is recommended to fill the lysimeter vessel monolithically. According to our knowledge a large weighable lysimeter is the best method for obtaining reliable data about seepage water quantity and quality. However, the construction and maintenance of large drainage lysimeters (especially the weighing type) is expensive. To solve these problems new lysimeter techniques have been developed and used in different countries [2].

The objectives of this paper are i) to inform about advances in lysimeter techniques and technology, ii) to demonstrate its use for measuring of soil water balance parameters (for example dew) and iii) to give an example for the combination of lysimeter measuring results with the WebGIS based model STOFFBILANZ for calculating nutrient balances at catchment scale.

2. Material and methods
An optimal soil-monolith extraction with minimal disturbance during the filling procedure of the lysimeter vessel is of critical importance for establishing flow and transport conditions comparable to natural field conditions. In the past, several methods were used to extract and fill lysimeter vessels vertically - including hand digging, employing sets of trihedral scaffolds with lifting blocks and ballast, or using heavy duty excavators, which could shear and cut large blocks of soil. More recently, technologies have been developed to extract cylindrical soil monoliths by using ramming equipment or screw presses. One of the great disadvantages of the mentioned methods is the compaction or settling of soil that occurs during the “hammering” or “pushing”.

For this reason a new technology was developed, which cuts the outline of the soil monolith employing a rotary cutting system [3]. The principal scheme of this technology is shown in Figure 1. The newly developed cutting tool makes it possible to cut out soil monoliths with high precision. The soil monolith is not damaged during the cutting process and the extraction site is only minimally affected. A tripod frame is used to bring the lysimeter vessel into a vertical position and hold it vertical during cutting. The vessel is made of stainless steel and can be coated on the inside with an inert protective surface. At the top of the frame there is a hydraulic cylinder, which in conjunction with guard and adjustable slip rails guides the lysimeter vessel during the cutting process. At the bottom of the vessel there is a rotary cutting tool. It is driven by a small hydraulic motor, also located at the bottom of the vessel, using a chain and sprocket arrangement. The cutting tool can be fitted with various types of chisels to adjust it to soil and site conditions.

While rotating, the cutting tool carves out the soil some 4 cm wider than the diameter of the lysimeter vessel, i.e. it leaves an excess of 2 cm of soil all around the rim of the vessel. With its own mass as the driving force, the vessel concurrently penetrates into the carved soil and shears off the aforementioned excess in the process. If necessary, an additional force can be applied by the hydraulic cylinder on top of the frame. Because the vessel slides over a soil core, which is slightly larger than itself, a tight fit
between soil and vessel results. This precludes gaps, which may act as preferential flow paths.

On one side of the vessel a pit needs to be dug, which is 20 cm wider and 40 cm longer than the diameter of the lysimeter vessel, and some 10 cm deeper than the vessel will eventually penetrate into the soil. This is necessary to accommodate the metal plate and the accompanying hydraulic pushing device for cutting the base of the monolith. Furthermore, the peelings from the cutting process are discarded into the pit, though a much smaller size would be sufficient for that. After the desired depth is reached, the cutting tool stops rotating and the chisels are detached. Next, the monolith is severed at the bottom and the cutting plate left attached to the bottom of the vessel. Then a crane is employed to lift the whole assembly out of the pit. Smaller monoliths (e.g. surface area < 0.5 m² and depth < 1.0 m) can be lifted by aforementioned hydraulic cylinder, without any additional lifting device. Once on the soil surface, the rotary cutting tool and the hydraulic motor, which drives it, are removed. After a lid has been fixed on top of the vessel, it is turned upside down. Now the lower 15 cm of soil in the monolith are removed and replaced with a graded filter layer made of quartz sand and gravel (0.1 - 0.5 mm, 0.71 - 1.25 mm and 3.15 - 5.6 mm in diameter). The time required to collect a soil monolith depends on soil, site conditions and size of the soil column. Usually it takes one day for the whole procedure to obtain a large undisturbed soil monolith. This technology has been used successfully for different soil types (from gravel to sand to clay) and for different lysimeter sizes (surface area 0.03 – 2 m² and depth until 3 m). Different types of cutting tools are available to cut out the soil monoliths; the most important tools are displayed in Figure 2. Until now more than 400 monoliths (from sand to gravel to clay) have been extracted with this method. Preferential flow did not occur in any of them.

Lysimeters are usually located in a special lysimeter station with an access for functional inspection as well as for the accommodation of measurement, control and weighing devices. In most cases such a station involves an expensive steel or concrete cellar. To reduce cost and secure mobility a containerised polyethylene (PE-HD) lysimeter station was developed. The principle scheme of PE-HD lysimeter station, where four lysimeter vessels are located in a clover type arrangement around one side of the vessel a pit needs to be dug, which is 20 cm wider and 40 cm longer than the diameter of the lysimeter vessel, and some 10 cm deeper than the vessel will eventually penetrate into the soil. This is necessary to accommodate the metal plate and the accompanying hydraulic pushing device for cutting the base of the monolith. Furthermore, the peelings from the cutting process are discarded into the pit, though a much smaller size would be sufficient for that. After the desired depth is reached, the cutting tool stops rotating and the chisels are detached. Next, the monolith is severed at the bottom and the cutting plate left attached to the bottom of the vessel. Then a crane is employed to lift the whole assembly out of the pit. Smaller monoliths (e.g. surface area < 0.5 m² and depth < 1.0 m) can be lifted by aforementioned hydraulic cylinder, without any additional lifting device. Once on the soil surface, the rotary cutting tool and the hydraulic motor, which drives it, are removed. After a lid has been fixed on top of the vessel, it is turned upside down. Now the lower 15 cm of soil in the monolith are removed and replaced with a graded filter layer made of quartz sand and gravel (0.1 - 0.5 mm, 0.71 - 1.25 mm and 3.15 - 5.6 mm in diameter). The time required to collect a soil monolith depends on soil, site conditions and size of the soil column. Usually it takes one day for the whole procedure to obtain a large undisturbed soil monolith. This technology has been used successfully for different soil types (from gravel to sand to clay) and for different lysimeter sizes (surface area 0.03 – 2 m² and depth until 3 m). Different types of cutting tools are available to cut out the soil monoliths; the most important tools are displayed in Figure 2. Until now more than 400 monoliths (from sand to gravel to clay) have been extracted with this method. Preferential flow did not occur in any of them.

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There are different newly developed lysimeter types available. Figure 3 shows a schematic of a weighable gravitation lysimeter equipped to measure water and solute flux and to calculate actual evapotranspiration. This type of lysimeter can be produced with surface areas from 0.5 to 2.0 m² and total depths of 1.0 to 3.0 m; in Germany the lysimeter type with the size of 1.0 m² surface area and a total depth of 2.0 m is often used. The lysimeter vessel was extracted out of the investigation site as an undisturbed soil monolith with the collection technology described before. As described above, a 15 cm thick filter layer (sand over coarse sand over gravel) was placed at the lysimeter bottom to minimize natural flux disturbances.

Instead of a mechanical weighing system, our lysimeters are equipped with three shear stress cells, which are placed on top of aluminium pedestals. Even at a total lysimeter mass of 4.000 to 4.500 kg this weighing system can register mass changes of ± 20 g [4]. Tensiometers, TDR (time-domain reflectrometry) probes, thermometers and suction cups are installed at depths of 0.30 m, 0.90 m and 1.50 m. Measured values are consolidated and stored in a data-logger, whose recording interval is chosen by the user. It permits a very high temporal resolution (< 1 minute). The amount of baseflow water is measured with a tipping bucket (values are stored by data logger) and collected in a storage container from which water samples can be taken for chemical analysis. The tube leading from lysimeter bottom to the tipping bucket has a large diameter and is open to the atmosphere to allow free drainage out of the lysimeter. There is no hanging water column. On overview regarding further newly developed lysimeter types as a weighable groundwater lysimeter or a large fen lysimeter is described in [3] and [5].

3. Results and discussion

3.1 Measuring the amount of dew

In water balance studies, lysimeters are typically used to quantify rainfall, actual evapotranspiration and drainage. However, if the weighing precision is high enough as in case of the lysimeters introduced here, precipitation in the form of dew, fog and rime can be measured accurately [4].

As an example of the high precision of the new weighing technique Figure 4 shows the chart of the lysimeter mass (the mass change allows to calculate the change in the amount of water stored in the soil column) recorded at northern Germany over a 5-day-period in April. No rainfall occurred during April 16 until the
evening of April 18 so that the lysimeter mass decreased due to evapotranspiration. In the early morning of April 17 dew formation is visible because the mass of the lysimeter increased slightly. The rising sun’s radiation leads to increasing evapotranspiration with a typical day-night rhythm. In the late evening of April 18 a rain event occurs, which led to an increased mass change of the lysimeter. Nine further rain events with different amounts of precipitation were registered until the afternoon of April 19. Altogether 5.5 mm of precipitation were measured, leading to an increased mass of 5.5 kg. Furthermore, the installed computer software allowed the presentation of all measured parameters in detail (for example average, minimum and maximum values of the measured data). The measuring process is individually adjustable (depending on the problem in question) and allows a highly sophisticated spatial and temporal resolution.

3.2 Combination of lysimeter measuring results with modelling

Based on an example from a research project in China the combination between lysimeter – field and sub-catchment measurements with the WebGIS based model STOFFBILANZ for calculating nutrient balances at the total catchment scale will be shown [6]. The software STOFFBILANZ [7] was used to calculate runoff, soil loss, sediment and nutrient input into the Sheyuchuan experimental sub-catchment (about 28 km²) as well as in the entire Miyun catchment area (about 15,600 km²). The approach requires a minimum of parameters to run the model and is suitable for modelling at the meso-scale. To guarantee a sufficient temporal resolution of the simulation in the monsoon influenced region, the following procedures were carried out on a daily basis:

- calculation of the FAO dual crop evapotranspiration undersoil water stress conditions
- direct runoff calculation according to the Curve Number Approach
- estimation of erosion yield according to the USLE-M approach
- sediment input into surface water according to [7]

Fig. 4 Example of the diurnal mass change of a weighing gravitation lysimeter planted with grass

Particulate P inputs into surface waters were calculated considering sediment input, nutrient enrichment and total P (TP) content in topsoil, which was derived from land use type and soil texture. In addition, we simulated diffuse dissolved P losses with the help of estimated P export coefficients for seepage water and direct runoff. The simulation of N surplus in the root zone, N input via direct runoff and N input via deep percolation is based on mass balances calculated for each grid cell [7].

Calibration and testing of the modelling approach STOFFBILANZ was done on the basis of the continual monitoring at the lysimeter station and at a gauge measuring station at the end of the small sub-catchment Sheyuchuan as part of the total Miyun reservoir. The lysimeter data revealed a substantial amount of seepage water in July 2011, caused by a heavy rainfall of more than 100 mm/d (Fig. 5). The monitoring results underline that the episodic character of the rainfall pattern and the processes which this sets into motion have to be modeled with high resolution at the meso-scale in order to properly depict critical source areas, transport pathways and solute loads. The lysimeter as well as field and sub-catchment observations were used to learn from the processes of runoff generation and to calibrate the crop evapotranspiration under soil water stress conditions (ETadj) and deep percolation simulation. Figure 5 depicts the result of this calibration. The simulation of evapotranspiration corresponds well with the observation. In summertime the amplitude of simulated evapotranspiration is much lower than the one observed by the lysimeter. This is due to the fact that the simulated soil moisture as well as the evapotranspiration term remains at a constantly high (maximum) level during that period. Plant interception and the evaporation from the plant surface are not included in the modelling in an adequate way, because it is focusing on soil-water-plant-interactions. In contrast to that the lysimeters give continual (every 10 min) information about the changes of mass, caused by the fluctuating evapotranspiration term. A positive peak appears after the rainfall event and shows, how much water is evaporated from the wetted soil, but also from the wetted plant surface. The observed evapotranspiration by the lysimeter is therefore a little bit higher compared to the simulated one.

Fig. 5 Comparison of measured lysimeter data and model results with STOFFBILANZ for actual evapotranspiration and deep percolation for 2011

The simulated values were compared to the observed ones for average values of periods of 7 days. The calculated Nash–Sutcliffe model efficiency coefficient is 0.78. According to the soil-water-fluxes, which are more important from our point of view, the results of the simulated deep percolation correspond well with the observed one with a calculated Nash–Sutcliffe model efficiency coefficient of 0.75 for the 7 day periods. A daily comparison was neglected, because flow distance and retention time is neither included in the soil-water-budget of the ETadj approach nor in the curve number approach.

After successful calibration with lysimeter results, the knowledge of local process generation was transferred to the total catchment area of Miyun. According to the meteorological data set all calculations are based on the climate data pool of 1960-1990, combined with the event-based daily meteorological data for the year 2009 from the central Shixia meteorological station in the Miyun catchment area. The results of the FAO-grass reference evapotranspiration modelling range from 970 mm/a in the South-Eastern part to 1.293 mm/a in the North-Western part. The average value of direct runoff for the total catchment area is about 11.7 mm/a. Percolation from the evaporating layer into the root
zone was calculated by the ETcadj approach with an average value of 132.5 mm/a for the total catchment. Percolation from the root zone into groundwater is about 3.1 mm/a (Fig. 6).

Fig. 6 Simulation of deep percolation (groundwater recharge) in the Miyun catchment area (reference year 2009)

According to information from our Chinese partner, the Beijing Water Authority, the annual water inflow into the Miyun reservoir is about 200,000,000 m³, corresponding to a total runoff of 13 mm/a. These results correspond to runoff values from comparable rivers in the catchment (e.g. Bai river, 17.3 mm/a or Chao river, 15.4 mm/a). Water abstractions, which can be estimated to be at least 20 % of the total runoff, have to be added to compare the observed values with the simulated total runoff in the Miyun basin of 15 mm/a. According to these estimations the simulation results are in good agreement with the range of the literature and monitoring data.

The estimation of nitrogen (N) surplus was realized by a very soft balancing approach due to the lack of more precise data to agricultural management and waste water treatment in the region. Average values of N input into surface waters via direct runoff and deep percolation are about 2.7 kg N/ha and 2.2 kg N/ha, respectively (Fig. 7). Nitrate concentrations in leachate (deep percolation) were calculated with app. 409 mg/l on temporary cropland of the dry bottom of the Miyun reservoir. These values are well in the range of the first observed seepage nitrate concentrations of the lysimeter (average of 398 mg/l). Diffuse N input into surface waters from all land use types was approximately 7,833 t/year in total (4,217 t/year by direct runoff; 3,616 t/year by deep percolation).

Fig. 7 Simulation of the total diffuse N input in the Miyun catchment area with the model STOFFBILANZ (reference year 2009)

5. Conclusions

There is an international tendency towards a wider use of direct drainage lysimetry methods for measuring water and solute fluxes in the soil. This technique ensures reliable drainage data, but requires relatively large investment and maintenance costs. Progress is visible in the technological development of newly lysimeter types with a high precision weighing technique. More efforts are necessary to reduce the costs for the application of the lysimeter technique.

Lysimeter investigations will be an essential tool for scaling up results achieved in small-scale experiments to larger geographical units. Combination of lysimeter studies with direct measurements in the field or catchment and in combination with modelling approaches allow scenario simulation of topical climatic and hydrologic questions (e.g. climate change, different land management, groundwater recharge etc.).

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6. References


