# 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 often only 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

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.

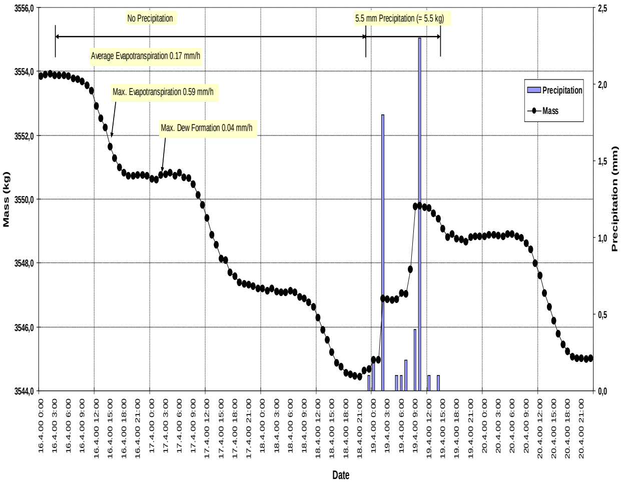

***Fig. 4*** *Example of the diurnal mass change of a weighing gravitation lysimeter planted with grass*

### 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 km$^2$) as well as in the entire Miyun catchment area (about 15,600 km$^2$). 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]

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 (ETcadj) 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.

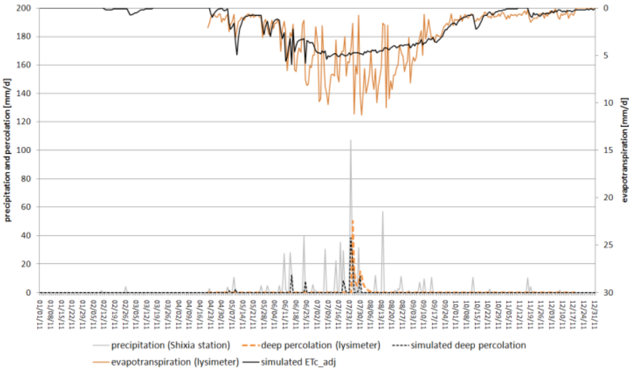

***Fig. 5*** *Comparison of measured lysimeter data and model results with STOFFBILANZ for actual evapotranspiration and deep percolation for 2011*

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 ETcadj 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).

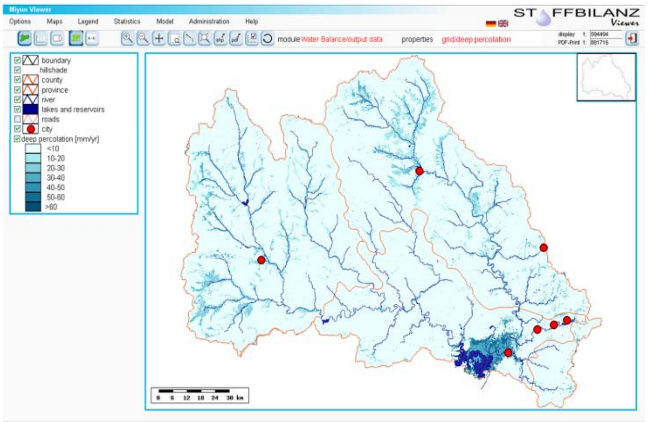

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***Fig.6*** *Simulation of deep percolation (groundwater recharge) in the Miyun catchment area (reference year 2009)*

According to information from our Chinese partner, the Beijing Water Authority, the annual water inflow into the Miyun reservoir is about 200,000,000 m$^3$, 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).

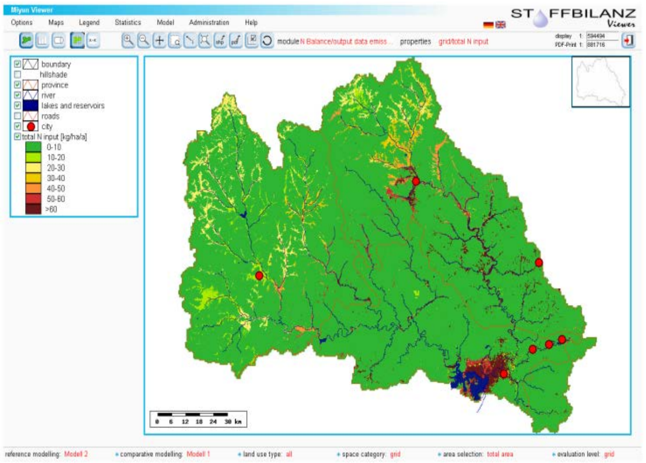

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***Fig. 7*** *Simulation of the total diffuse N input in the Miyun catchment area with the model STOFFBILANZ (reference year 2009)*

## *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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