

# Lysimeter application for measuring the water and solute fluxes with high precision

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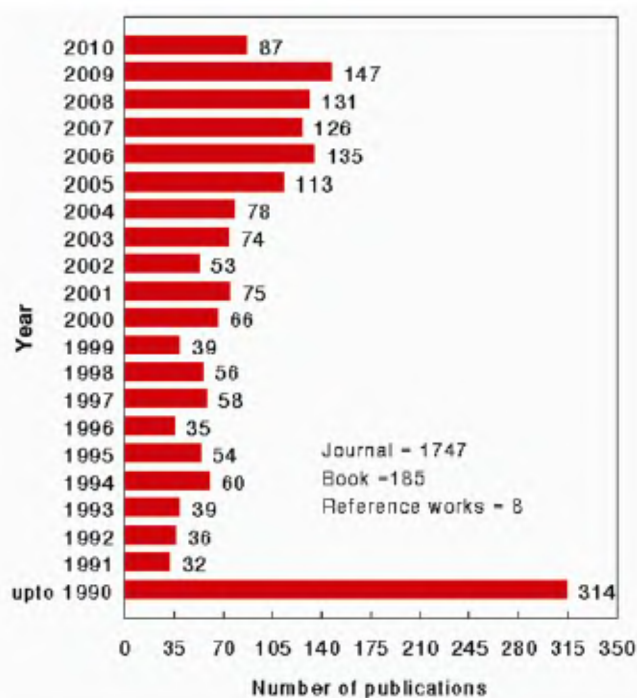
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Different methods exist for measuring water and solute flux in and below the root zone. Besides indirect methods (e.g. water balance, tensiometer, time domain reflectometry, frequency domain reflectometry and environmental tracer), direct methods (e.g. drainage-type lysimeter, water flux meter) have a long tradition and have been successfully used in seepage research. However, lysimeters are most reliable and accurate for *in situ* water and solute assessment. A large weighable outdoor lysimeter is the best method for obtaining reliable data about seepage water quantity and quality, but it involves significant investment and additional expenses for maintenance. To tackle this problem new methods for the vertical collection of large volume soil monoliths and for the placement of the lysimeter in a container lysimeter unit have been developed. The design of lysimeters typically used in Europe – a weighable gravitation lysimeter and a weighable groundwater lysimeter are explained. An example is given for the high precision of the new lysimeter weighing technique. Besides recording rainfall and seepage, its weighing precision makes it possible to register mass input by dew, fog or rime. It also permits accurate calculation of actual evapotranspiration. The newly developed lysimeter types will be an essential tool for scaling up results obtained in small-scale experiments to larger geographical units. Furthermore, the newly developed experimental set-up allows a scenario simulation of topical climatic and hydrologic questions, e.g. global warming and its impact on the water and solute balance, the influence of dew and fog on the establishment of a vegetation cover in arid areas or the transport of contaminants during heavy rainfall following a severe drying-up of the soil profile.

**Keywords.** Flux, lysimeter, seepage, solute, water.

LYSIMETER (Greek origin, lysis = dissolution or movement, and metron = to measure) is a multifaceted instrument used in a variety of investigations. Particularly, it is

widely used for the measurement of percolation of water beneath the vegetation root zone and water use through evaporative processes (Figure 1). Plant roots are phytohydraulic in function. Thus, lysimeters not only function as *in situ* water and solute quality assessing tools, but are of significant importance in a variety of fields such as agricultural management, including meteorology, agronomy, agriculture, ecosystems and environment, applied geochemistry, environmental pollution, environmental radioactivity, forest ecology and management, forest meteorology, hydrology, soil and tillage research, soil biology and biochemistry waste management and water quality management (Table 1)<sup>1–41</sup>.



**Figure 1.** There has been a gradual rise in publications using lysimeters for a variety of hydrological applications. A total of 1747 articles have been indexed in *ISI Web of Science* starting with only 32 in 1991 (source: [www.sciencedirect.com](http://www.sciencedirect.com)).

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## RESEARCH ACCOUNT

**Table 1.** Broad range applications of lysimeter in the field of sylviculture, agriculture and environment

Lysimeter applications	Reference
Drought and irrigation on the fate of nitrogen	1
Toxicity tests	2
Transport of organic compounds in macroporous soil	3
Surface impoundments and landfills	4
Weighing lysimeter	5
Water use by intensively cultivated agri-sylviculture	6
Monitoring fertilizer losses due to drainage	7
Rainfall of interception and canopy storage	8
Interception loss from forest	8, 9
Organic matter	10
Snowpack dynamics	11
Tracer release in melting snow	11
Nitrate leaching	12
Mineral fertilizers use efficiency	13, 14
Nutrient leaching from different soil types	13
Dissolved organic carbon investigation in wetlands	15
Environmental fate and behaviour of agrochemicals	16
Herbicide transport in macroporous soils	17
Transport of [ <sup>14</sup> C] benazolin and bromide	18
Soil CO <sub>2</sub> efflux	19
Solute transport	20, 21
Fulvic acid and humic acid in degraded lands	22
CO <sub>2</sub> release of peat soils	23
Diffuse pollution of water resources	24
Water dynamics	25
Anion-cation leaching	26
Behaviour of heavy metals in floodplain sites	27
Nitrogen-use efficiency	28
Performance of different genotypes under field	28
Surface sealing on hydrology and pesticide loss	29
Lysimeter soil retriever	30
Measurement of dew, fog and rime	31
Evapotranspiration in different agroclimatic regions	32, 33
Groundwater seepage	34
Hydrological studies	35
Modelling the water balance	36, 37
Nutrient transport from agricultural systems	38
Phosphorus in soil leaching and transfer	39
Salinity impacts of a bio-drainage	35
Leaching and reclamation studies	40
Nitrous oxide emissions	41

The *in situ* monitoring of water and solute fluxes is challenging because the information is of basic interest to answer both scientific and practical questions regarding environmental protection of water resources, sustainable management of areas under agriculture and forest, mining or industrial areas, reducing leachate loss from landfills or explaining the fate of environmentally harmful substances. Exact quantification of soil water flow is necessary for the accurate prediction of solute transfer within the unsaturated soil zone. Different methods exist for measuring water and solute fluxes in and below the root zone, but a standard method is lacking. A state-of-the-art review about *in situ* soil water extraction methods has been given by Weihermüller *et al.*<sup>42</sup>, providing an overview of the existing *in situ* extraction devices, to support the selection of adequate sampling systems for solute

concentration and solute transport measurement, as well as calculation of mass balances. Furthermore, Weihermüller *et al.*<sup>42</sup> showed that selection of an appropriate system depends mainly on the scientific objective, potential limitations in terms of installation efforts, maintenance temporal resolution and financial budget.

Gee *et al.*<sup>43</sup> recommend differentiation between indirect and direct measuring methods. The simplest form for the indirect estimation of the drainage is the use of the water balance equation which can be expressed as:

$$P + I = ET + \Delta S + D + RO, \quad (1)$$

where  $P$  is the precipitation,  $I$  the irrigation,  $ET$  the evapotranspiration,  $\Delta S$  the water storage change,  $D$  the drainage and  $RO$  the run-off/run-on.

In the absence of irrigation and run-off/run-on and for periods when storage change is negligible, drainage is typically determined as the difference between precipitation and  $ET$ , where  $ET$  is estimated from meteorological parameters. Elaborate schemes have been developed to measure key parameters (e.g. solar radiation, temperature, wind speed, humidity, etc.) and calculate either the potential or actual  $ET$ <sup>44</sup>. Since climatic information is generally readily available at most locations, water balance- $ET$  estimation methods have been widely used over the years. While applicable to humid areas where  $ET$  is often about 50% or less of the precipitation, these schemes have less utility in arid areas where  $ET$  is often greater than  $P$ . In dry (arid) zones, relatively small errors in  $ET$  estimates translate into large ones (often several orders of magnitude) in recharge estimates<sup>45</sup>. Another widespread indirect method is the measurement of specific soil characteristics and calculating water flux rate using data from tensiometers, time domain reflectometry (TDR), frequency domain reflectometry (FDR) or heat-pulse probes<sup>43</sup>.

The most important direct method – measuring drainage water using a buried device – is drainage lysimetry. A wide range of lysimeters and simple water samplers have been used in the past ranging from small, free-draining pan-type lysimeters, wick samplers (fluxmeters) 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<sup>21,46–48</sup>. Only lysimeters allow direct determination of the amount of water percolating through the soil profile, and also the type and amount of solutes contained in it. If they are weighable, actual evapotranspiration can be deduced from the mass (weight) change<sup>49</sup>. A large weighable lysimeter is the best method to obtain reliable data about quantity and quality of the seepage water, but this requires significant investment and additional expenses for facility maintenance. However, in Europe the use of direct lysimetry methods for measuring water and solute fluxes in soils has increased in recent years<sup>50</sup>.

The aim of this article is to demonstrate relevant developments in lysimeter techniques to improve accuracy and reduce the costs involved and also to give an example regarding the measuring precision of a sophisticated weighing lysimeter.

## Developments in lysimeter techniques

### *Undisturbed soil collection*

One of the great disadvantages of the available methods to extract undisturbed large soil monoliths is the compaction or settling of soil that occurs during the hammering procedure<sup>51</sup>. The newly developed cutting tool makes it possible to cut out soil monoliths with high precision (Figure 2). During the cutting procedure the contour of the soil monolith is pre-bladed by a rotating tool which is connected with the lysimeter vessel<sup>31</sup>. The soil monolith is not damaged during the cutting process. The extraction site is only minimally affected since due to reducing coat friction the forces needed for cutting the soil monolith are small. This technology has been used successfully for different soil types – from sand to gravel to clay – and for different lysimeter sizes (surface area of 1 m<sup>2</sup> and depths from 2 to 3 m).

In comparison to the available methods, the effectiveness of cutting out a soil monolith with the new technology is much higher and costs are lower. The efforts for transportation and preparations for cutting the soil monolith are minimal. The time required to collect a soil monolith depends on the soil and site conditions. Usually one day is required for the whole procedure to obtain a large undisturbed soil core.

### *Containerized lysimeter station*

Lysimeters are usually located at special lysimeter stations with access for functional inspection as well as for the



**Figure 2.** Cutting tool for obtaining large undisturbed soil monoliths.

accommodation of measurement, control and weighing devices. In most cases such a station involves an expensive steel and concrete cellar. To reduce costs and secure mobility a containerized polyethylene (PE-HD) lysimeter station has been developed, where four lysimeter vessels are located in a clover-type arrangement around a central access (Figure 3)<sup>48</sup>. Variation in the number and arrangement of lysimeter vessels is possible. The containerization allows the establishment of lysimeters at virtually any location, e.g. directly at the extraction site.

### *Weighable gravitation lysimeter*

The use of lysimeters is a proven method to get exact information about the soil water balance which is the precondition to quantify solute transfer within the unsaturated zone<sup>42</sup>. In connection with the additional recording of the amount of percolating water and precipitation, it also permits quantification of the water balance of the soil column. For a weighable lysimeter the actual evapotranspiration can easily be derived using the following equation

$$ET_a = P - S \pm \Delta S, \quad (2)$$

where  $ET_a$  is the actual evapotranspiration (mm),  $P$  the precipitation (mm),  $S$  the amount of seepage water (mm) and  $\Delta S$  the change in the amount of stored water (mm, based on measuring the mass change of the soil column over time;  $1 \text{ kg} \approx 1 \text{ l/m}^2 = 1 \text{ mm}$ ).

If the water balance is calculated correctly, the solute balance can be determined with sufficient accuracy using the following equation

$$L = C_s * S, \quad (3)$$

where  $L$  is the solute load (mg/m<sup>2</sup>),  $C_s$  the solute concentration in the seepage water (mg/l) and  $S$  the amount of seepage water (l/m<sup>2</sup> = mm).



**Figure 3.** Polyethylene (PE-HD) lysimeter station with four lysimeters in a clover-type arrangement with an entering hatch (centre position) during the installation process.

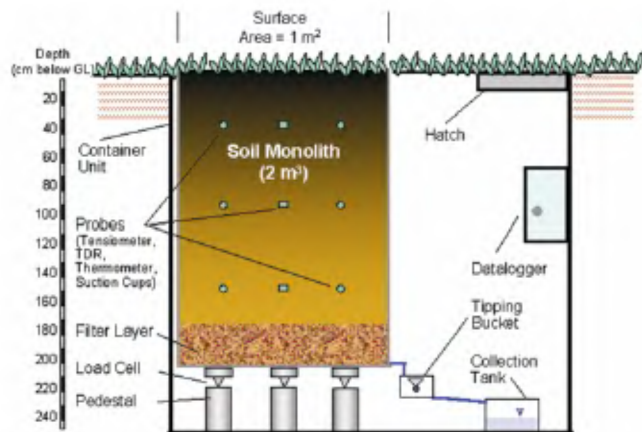


Figure 4. Schematic of a typical weighable gravitation lysimeter.

Figure 4 depicts a typical gravitation lysimeter often used in Europe<sup>50</sup>. This type of lysimeter has a surface area of 1.0 m<sup>2</sup> and a total depth of 2.0 m. A 15 cm thick filter layer (sand over coarse sand over gravel) is placed at the bottom of the lysimeter to minimize disturbances of the natural fluxes. The lysimeter is equipped with an improved high-precision weighing device. It consists of three special digital load cells, which are placed on top of aluminium pedestals. Even at a total lysimeter mass of 4–4.5 kg, they register mass changes of  $\pm 20$  g (ref. 52).

Tensiometers, TDR probes, thermometers and suction cups are installed at depths of 0.30 m, 0.90 m and 1.50 m. The amount of seepage water is measured continuously with a tipping bucket and collected in a storage container from which water samples can be taken for chemical analysis. All frequently measured parameters are stored in a datalogger. The vegetation at the surface of the lysimeter and its management can be matched to the specifics at the extraction site. However, it is also possible to choose any other vegetation type or management practice.

### Weighable groundwater lysimeter

Because accurately measuring pedohydrological parameters in a floodplain (which is used for obtaining drinking water from bank filtrate) itself is difficult, Meißner *et al.*<sup>53</sup> developed a weighable groundwater lysimeter (Figure 5). In contrast to the gravitation lysimeter, it allows to balance groundwater inflow and outflow<sup>27,48</sup>. For this reason the groundwater lysimeter is connected to a directly adjacent balancing tank using the principle of communicating pipes. Furthermore, an automatic groundwater control system has been developed, which allows the groundwater levels measured in the floodplain to be recreated quickly in the lysimeter in order to gauge the natural course of capillary rise and groundwater recharge in the lysimeter experiments as realistically as possible.

The groundwater-level data from the floodplain are transmitted once a day using a modem to the lysimeter site and regarded as the target water level.

The water balance equation is adapted for level floodplain sites. Surface run-off can be neglected. The rate of outflow and inflow can be recorded in the saturated zone. During floods, floodwater is an additional input parameter. The modified water balance equation for groundwater-influenced and temporarily waterlogged sites reads:

$$P + P_{\text{ond}} = ET_a + (R_{\text{out}} - R_{\text{in}}) \pm \Delta S, \quad (4)$$

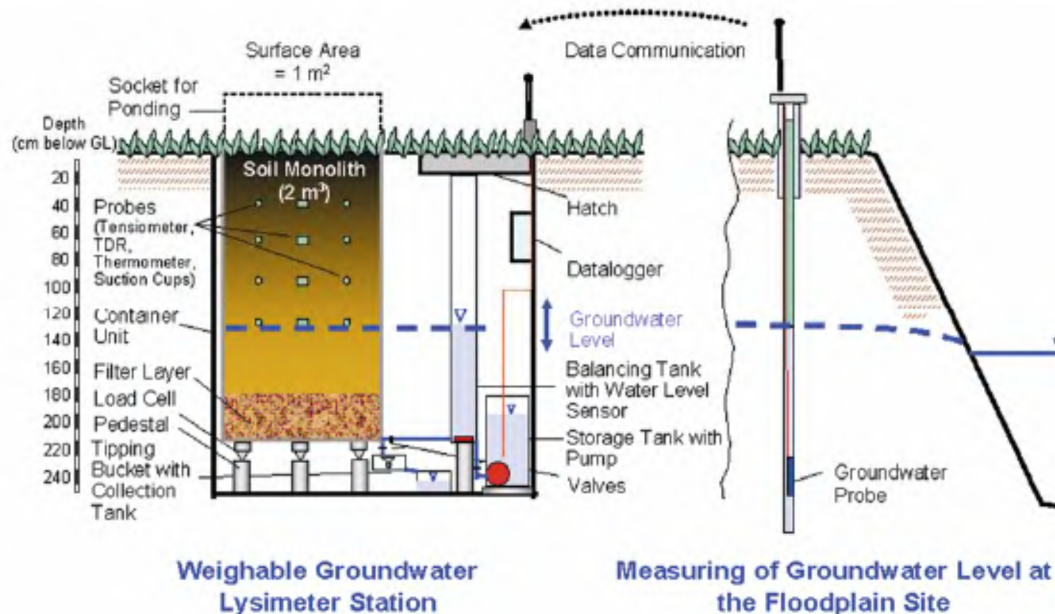
where  $P$  is the precipitation,  $P_{\text{ond}}$  the surface floodwater,  $ET_a$  the actual evapotranspiration,  $R_{\text{out}}$  the groundwater outflow,  $R_{\text{in}}$  groundwater inflow and  $\Delta S$  the change in the amount of stored water.

### Weighing precision

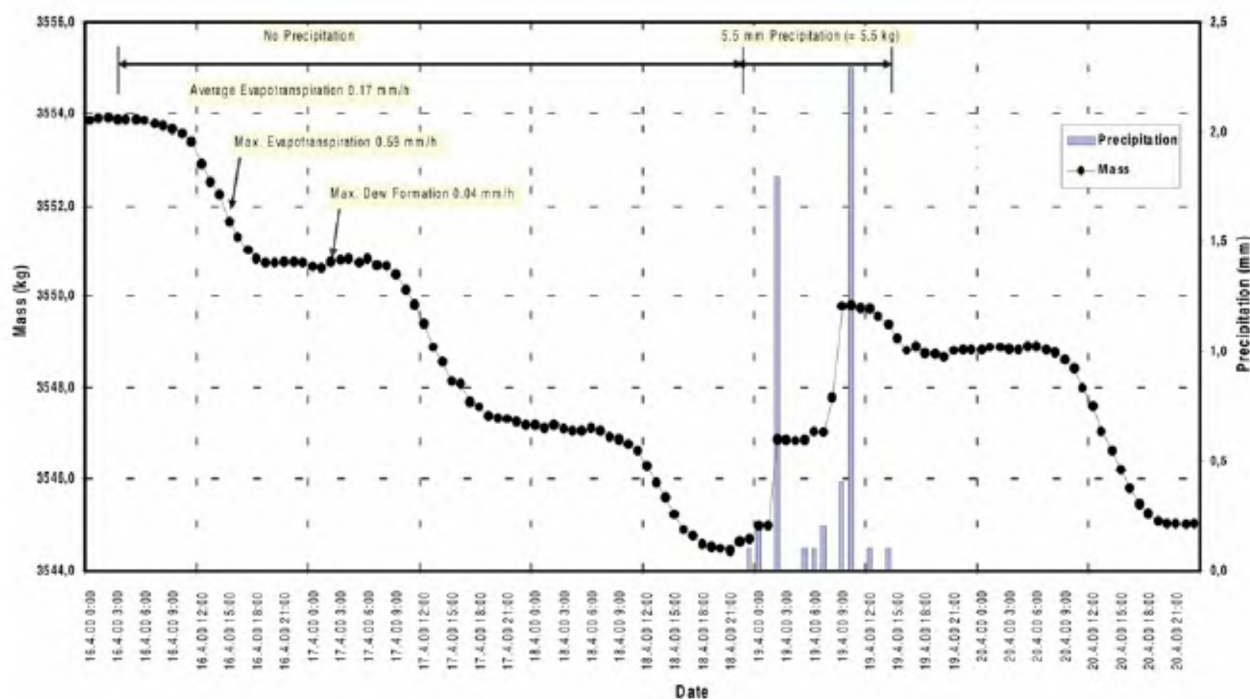
In water-balance studies, lysimeters are typically used to quantify rainfall, actual evapotranspiration and drainage. However, if the weighing precision is high enough as in the case of the lysimeters introduced here, precipitation in the form of dew, fog and rime can be measured accurately<sup>31,52</sup>. Because these new lysimeter types allow high temporal resolution, they are ideally suited to develop and test models for soil hydrologic processes.

As an example of high precision of the new weighing technique, Figure 6 shows a chart of the lysimeter mass (the mass change allows us to calculate the change in amount of water stored in the soil column) recorded in northern Germany over a 5-day-period in April 2010. No rainfall occurred during 16 April until the evening of 18 April, so that the lysimeter mass decreased due to evapotranspiration. Dew formation is visible in the early morning of 17 April because the mass of the lysimeter increased slightly. Radiation from the rising sun leads to increasing evapotranspiration with a typical day–night rhythm. In the late evening of 18 April a rain event occurred 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 19 April. Altogether 5.5 mm of precipitation was measured, leading to an increased mass of 5.5 kg. Furthermore, the installed computer software allowed presentation of all measured parameters in detail (for example, average, minimum and maximum values of the measured data). The measuring process can be individually adjusted (depending on the problem in question) and allows a highly sophisticated spatial and temporal resolution.

The above example highlights the various uses of this lysimeter type. It allows a high temporal resolution, gives an ‘inside view’ of hydrologic processes and is an essential tool for development and testing of hydrologic models. In Europe this newly developed lysimeter type is at



**Figure 5.** Schematic of a weighable groundwater lysimeter with a groundwater control system and data transmission using a modem.



**Figure 6.** Example of the diurnal mass change of a weighable gravitation lysimeter planted with grass.

present being used for investigating and monitoring water and solute balances in agricultural, post-mining and forested areas. Furthermore, it is also being used for scientific studies measuring the movement of water and chemicals (nutrients, pesticides, important contaminants) through the soil profile.

## Conclusion

In Europe the use of direct drainage lysimetry methods for measuring water and solute fluxes in soils has increased in recent years. This technique ensures reliable drainage data, but requires relatively large investment and

maintenance costs. Efforts are on to develop new lysimeter techniques in order to improve the measuring accuracy and reduce the costs. Progress is visible in a new technology to obtain large undisturbed soil monoliths and in the development of a mobile containerized polyethylene lysimeter station. A high-resolution weighing technology and an automatic groundwater control system enable detailed investigation of the water balance, forming the basis for a highly accurate calculation of the solute balance and for modelling hydrological processes.

Also, in the future lysimeter investigations will be an essential tool for scaling up results achieved in small-scale experiments to larger geographical units. Combining lysimeter studies with *in situ* measurements in the field or catchments allows a direct comparison of relevant soil hydrologic parameters. Furthermore, the newly developed experimental set-up allows a scenario simulation of topical climatic and hydrologic questions, e.g. global warming and its impact on the water and solute balance, the influence of dew and fog on the establishment of a vegetation cover in arid areas or the transport of contaminants during heavy rainfall following a severe drying-up of the soil profile.

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