Measuring water and solute balance with new lysimeter techniques

Ralph Meissner[1] and Manfred Seyfarth[2]

[1]UFZ Centre for Environmental Research Leipzig-Halle, Department of Soil Science, Lysimeter Station, Dorfstrasse 55, D-39615 Falkenberg, Germany. www.ufz.de Email: ralph.meissner@ufz.de
[2]UGT Ltd., Eberswalder Str. 58, D-15374 Muencheberg, Germany. www.ugt-online.de Email: info@ugt-online.de

Abstract
A prerequisite to develop sustainable strategies for land use and protection of water resources in quantity and quality is the exact measurement of water and solute fluxes below the root zone. Water flux densities are often measured indirectly (for example with water balance methods, water content - water storage change methods, tracer methods etc.) and are often predicted with notable uncertainties. In the last years, particularly in Europe, direct lysimetry methods are being used more and more for studying water and solute migration in soil. A large weighable lysimeter is the best method to obtain reliable drainage or vadose zone water flux data but it is connected with relatively high investment and additional expenses for maintenance. To tackle this problem, new lysimeter techniques have been developed. It is possible now to collect large monolithic soil columns and to measure the soil water balance of these monoliths (surface area of 1 m^2 and depth of 2 to 3 m) with high precision (± 30 g). The weighing function of the lysimeters is used to determine actual evapotranspiration. In addition to weighable gravitational lysimeters weighable groundwater lysimeters have been developed. The two different lysimeter types which are in use are presented and evaluated here.

Key Words
Lysimeter, percolation, solute flux, soil monolith, floodplain, soil hydrology.

Introduction
Because water supplies throughout the world are rapidly diminishing in quantity and quality there is a need for greater conservation of water resources (Haygarth and Jarvis 2002; WISPAS 2002). To develop ways to use water more efficiently and, at the same time, reduce the potential for groundwater pollution is an important scientific challenge. Exact information about the soil water balance is needed to quantify solute transfer within the vadose (unsaturated) zone. Different methods exist for measuring water and solute flux in and below the root zone and have been critically reviewed (Fuehr *et al.* 1998; Meissner *et al.* 2000). Gee *et al.* (2003) differentiate between indirect (water balance estimates, physically-based methods, environmental tracer method) and direct (drainage-type lysimeter, water fluxmeter) methods. A large weighable lysimeter is the best method for obtaining reliable data about seepage water quantity and quality but it is connected with significant investment and additional expenses for maintenance (ATV-DVWK 2002). However, in recent years in Europe the use of direct lysimetry methods for measuring water and solute balance in soils has increased (ALSG 2004). The combination of lysimeter studies with field experiments at different scales opens new possibilities for modelling and management of watersheds (Meissner *et al.* 2002).

The aim of this paper is to (i) describe a method for obtaining undisturbed soil monoliths for lysimeters, (ii) to present two newly developed lysimeter types and (iii) to present examples of the preliminary results.

Methods
Soil monolith collection
An evaluation of different methods to obtain large undisturbed soil cores is given by Derby *et al.* (2002). One of the great disadvantages of the presented methods is the compaction or settling of soil that occurs during the hammering procedure. The newly developed cutting tool makes it possible to cut out large soil monoliths with high precision (Figure 1). During the cutting procedure the contour of the soil monolith is pre-bladed by a rotating tool which is connected with the lysimeter vessel. The soil monolith is not damaged during the cutting process. The forces needed for cutting the soil monolith are small due to reduced wall friction. The extraction site is only minimally affected. After finishing the cutting procedure a metal plate is placed under the lysimeter vessel and a crane is used to lift the whole assembly. 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^2 and depths from 2 to 3 m).

In comparison to 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 the preparations for cutting the soil monolith are minimal. The time required to collect a soil monolith depends on the soil and site conditions. Usually we calculate one day for the whole procedure to obtain a large undisturbed soil core.

Figure 1. Cutting tool for obtaining large undisturbed soil monoliths.

Weighable gravitation lysimeter

If the lysimeter is weighable a direct measurement of actual evapotranspiration is possible. Additional recording of the amounts of percolating water and precipitation permits the quantification of the water balance of the soil column. The actual evapotranspiration can easily be derived using the following equation:

$$ETa = P - D \pm \Delta S \quad (1)$$

ETa actual evapotranspiration (mm)
P precipitation (mm)
D amount of seepage (drainage) water (mm)
ΔS change in the amount of water stored (mm, based on measuring the weight change of the soil column over time; 1 kg ≈ 1 L m^{-2} = 1 mm)

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

$$L = Cs * D \quad (2)$$

L solute load of (mg m^{-2})
Cs solute concentration in the seepage water (mg L^{-1})
D amount of seepage water (L m^{-2} = 1 mm)

The UFZ Centre for Environmental Research Leipzig-Halle operates 8 weighable lysimeters with a surface area of 1.0 m^2 and a total depth of 2.0 m each, which allow the gravimetric measuring of water flux (Figure 2).

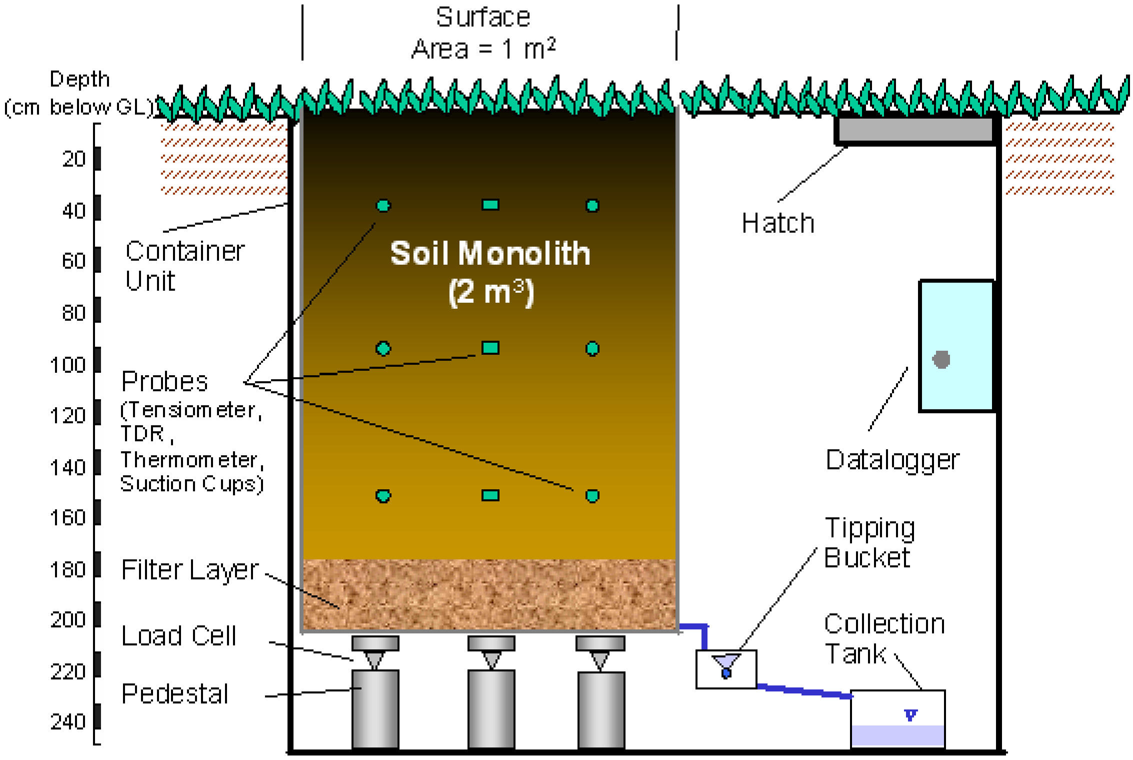

Figure 2. Schematic of a weighable gravitation lysimeter.

Four lysimeters were filled manually with typical soils from post-mining areas. The other 4 lysimeters contain undisturbed soil monoliths (extracted from an agricultural site with the collection technology described above). A 0.25 m filter layer (sand, coarse sand, gravel) was placed at the bottom of each lysimeter to avoid disturbances to natural flux. The lysimeters were equipped with an improved weighing device consisting of three special digital load cells, which were situated on top of three aluminium pedestals. TDR (Time Domain Reflectrometry) probes, suction cups, tensiometers and thermometers recording hourly values were installed at depths of 0.30 m, 0.90 m and 1.50 m beneath the surface (at each depth one set of instruments). The amount of seepage water was measured continuously with a tipping bucket and collected in a storage container for taking water samples for chemical analysis. All frequently measured parameters were stored in a data-logger.

The vegetation at the surface of the lysimeters was matched to the vegetation of the extraction sites. It is possible to establish the lysimeters in situ, i.e. directly in the field. However, lysimeters are usually located in a special lysimeter station with an access for functional inspection as well as for the accommodation of measuring, control and weighing devices. In most cases such a station involves an expensive steel and concrete cellar. To reduce costs and secure mobility, we developed a polyethylene (PE-HD) lysimeter station as a container, where 4 lysimeter vessels are located in a clover-leaf arrangement around the access (Figure 3). Variations regarding the amount and arrangement of lysimeter vessels are possible (at present from 2 to 4 lysimeters at one station).

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

Weighable groundwater lysimeter

The dynamics of soil water have a substantial impact on groundwater recharge as well as the concurrent process of solute movement. Knowledge of these processes is essential for long-term planning with regard to floodplains that serve for obtaining drinking water from bank filtrate. In the event of flooding, the parameters which influence groundwater dynamics need to be quantified as completely as possible so that the water absorption capacity of adjacent floodplains can be predicted more accurately. The precise measuring of pedohydrological parameters in the floodplain itself is very difficult. For this reason a weighable groundwater lysimeter was developed (Bethge-Steffens *et al*. 2004). It is the basis for recording the water balance quantities precipitation, evapotranspiration, groundwater recharge, capillary rise, and interaction with the water course.

For floodplain sites, the water balance equation can be specially adapted. Surface runoff can be neglected. The rate of outflow and inflow can be recorded in the saturated zone. During a flood, floodwater is an additional input. The modified water balance equation for groundwater-influenced and temporarily water-logged sites reads:

$$P + Pond = ETa + (R_{out} - R_{in}) \pm \Delta S \qquad (3)$$

P	precipitation	R_{out}	groundwater outflow
Pond	surface floodwater	R_{in}	groundwater inflow
ETa	actual evapotranspiration	Δ S	change of storage capacity

The UFZ Centre for Environmental Research Leipzig-Halle operates 4 groundwater lysimeters. The lysimeters were filled monolithically using the excavation technique described above and located in a PE-HD container lysimeter station (Figure 4). They include weighable lysimeters, as described in the previous section, and additional features to maintain and record groundwater levels.

In order to balance groundwater inflow and outflow, weight changes need to be recorded with as little delay as possible. Weight is recorded every minute. The measurements are condensed to 15-minute averages (rolling average) to reduce external effects, for example caused by wind (oscillation of the soil in the lysimeters) or brief weight increases (due to passing animals etc.).

TDR probes, tensiometers and thermometers recording hourly values are installed at depths of 0.30 m, 0.60 m, 0.90 m and 1.20 m beneath the surface. Furthermore, suction cups are installed at these depths to take soil water samples. For measuring the quantity and quality of seepage water during periods when the groundwater is below the bottom of the lysimeter, a tipping bucket with a storage tank is installed. This allows groundwater lysimeter to be used as a gravitational lysimeter too. The height of the vegetation is matched to the vegetation in the floodplain by mowing, because it has a decisive influence on evapotranspiration (especially transpiration and interception).

Each lysimeter is connected to a directly adjacent balancing tank using the principle of communicating pipes. The balancing tank is fitted with a water level sensor. If the water level in the balancing tank deviates from the target water level by more than 1 cm, the valve to the lysimeter is closed and the water level is raised or lowered by a pump. A storage tank serves to provide the water required or to take up surplus water. The valve between the balancing tank and the lysimeter is then opened and the water level is adjusted. This process is repeated until the target water level has been achieved in both the lysimeter and the balancing tank.

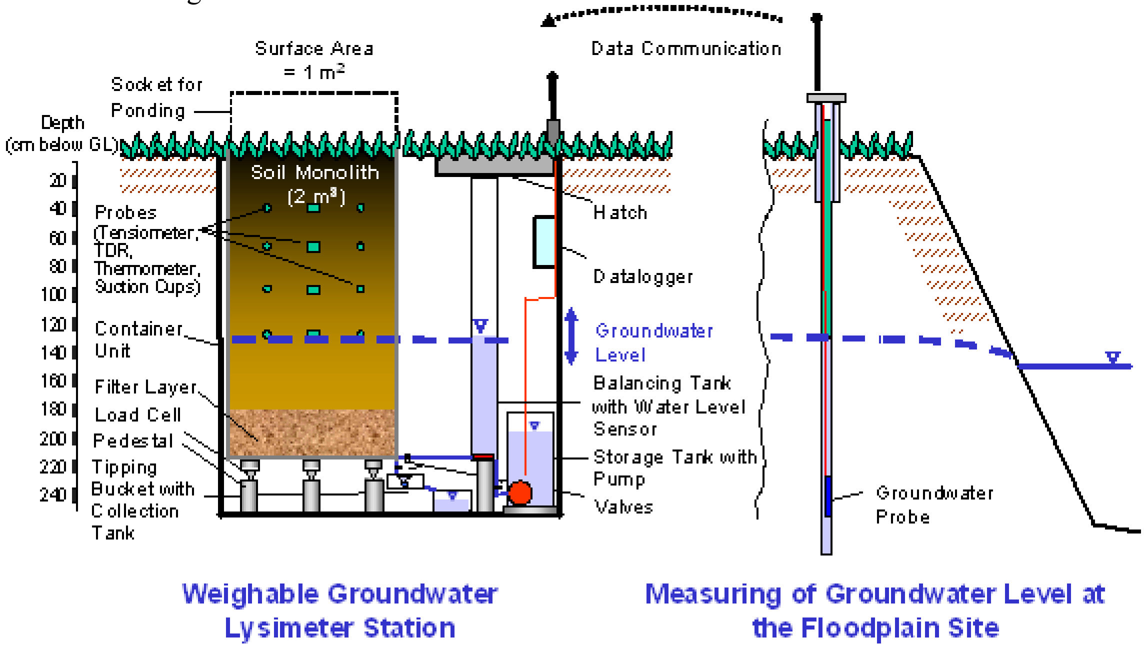

Figure 4. Schematic of a weighable groundwater lysimeter with a groundwater control system and radio data transmission.

An automatic groundwater control system was developed which allows the groundwater levels measured in the floodplain to be recreated as soon as possible in the lysimeter in order to gauge the natural course of capillary rise and groundwater recharge in the lysimeter experiments as realistically as possible. In our case the groundwater level data from the floodplain are transmitted once a day (temporal resolution is variable) by the modem to the lysimeter site and regarded as the target water level.

The differences in water level needed to achieve the target water level in the balancing tank are added together in order to determine how much water flowed into or out of the lysimeter during the period concerned. The balance is calculated using the following equation:

$$V_{efft=m} = A_{AG} * [(B_{t=m} - B_{t=0}) - (W_{t=m} - W_{t=0})] \quad (4)$$

$V_{efft=m}$ volume of water, which flowed into/out of the lysimeter at t = m (time of adjustment process)
A_{AG} base area of the balancing tank
$B_{t=0}$ value of balancing at the start of the adjustment process
$B_{t=m}$ value of balancing at the end of the adjustment process, comprising $B_{t=0}$ plus/minus the changes to the water level in the balancing tank during the period concerned
$W_{t=0}$ water level in the balancing tank at the start of the adjustment process
$W_{t=m}$ water level in the balancing tank at the end of the adjustment process

Results

Weighing precision of a gravitation lysimeter

As an example of the high precision of the new weighing technique Figure 5 shows the lysimeter weight (and the change of the water storage capacity) recorded over a 5-day-period in April 2000. Before the evening of April 18, no rainfall occurred resulting in the lysimeter weight decreasing due to evapotranspiration. In the early morning of April 17, dew formation is visible because the weight 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 occurred, which led to an increased weight 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 weight 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. During pre-investigations with a 3000.00 kg soil monolith an accuracy of ± 30 g could be reached using the new weighing technique. In contrast, mechanical and analogous scales used for lysimeter investigations enable accuracies of only ± 100 g.

This example gives an impression about the various uses of this lysimeter type. It allows an "inside view" of hydrologic process and is an essential tool for development and testing of hydrologic models. In Germany this newly developed lysimeter type is used for investigating and monitoring water and solute balances in agricultural, post-mining and forested areas at the present time (Meissner *et al.* 2001). It is used for scientific studies measuring the movement of water and chemicals (nutrients, pesticides, important contaminants) through the soil profile.

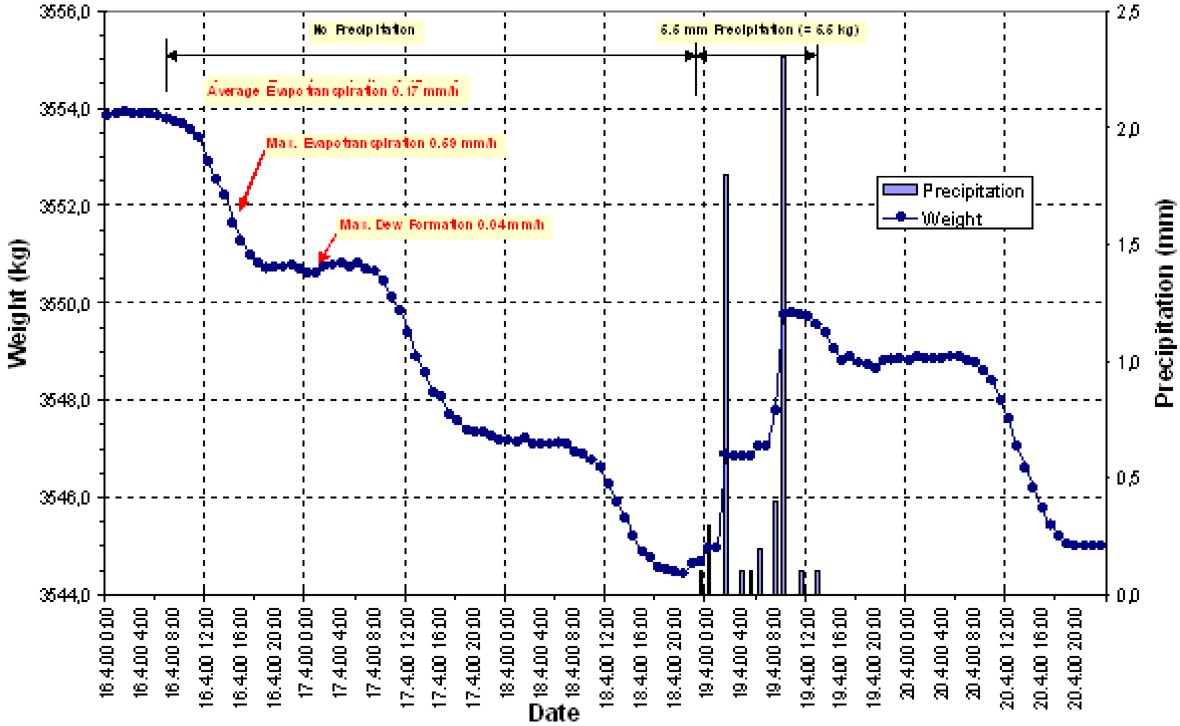

Figure 5. Example of the diurnal change of the weight of a gravitation lysimeter planted with grass.

Water balance of a groundwater lysimeter

First estimates of individual quantities of the soil water balance of the floodplain sites studied are made using the data presented below. In unadjusted periods (time intervals where the groundwater level is not influenced by groundwater control, i.e. by pumping processes), precipitation and current evapotranspiration can be directly quantified on the basis of recorded weight changes of lysimeter monoliths. These data are supplemented by groundwater control values. Figure 6 contains a summary of the hydrological parameters measured in a groundwater lysimeter in February 2003.

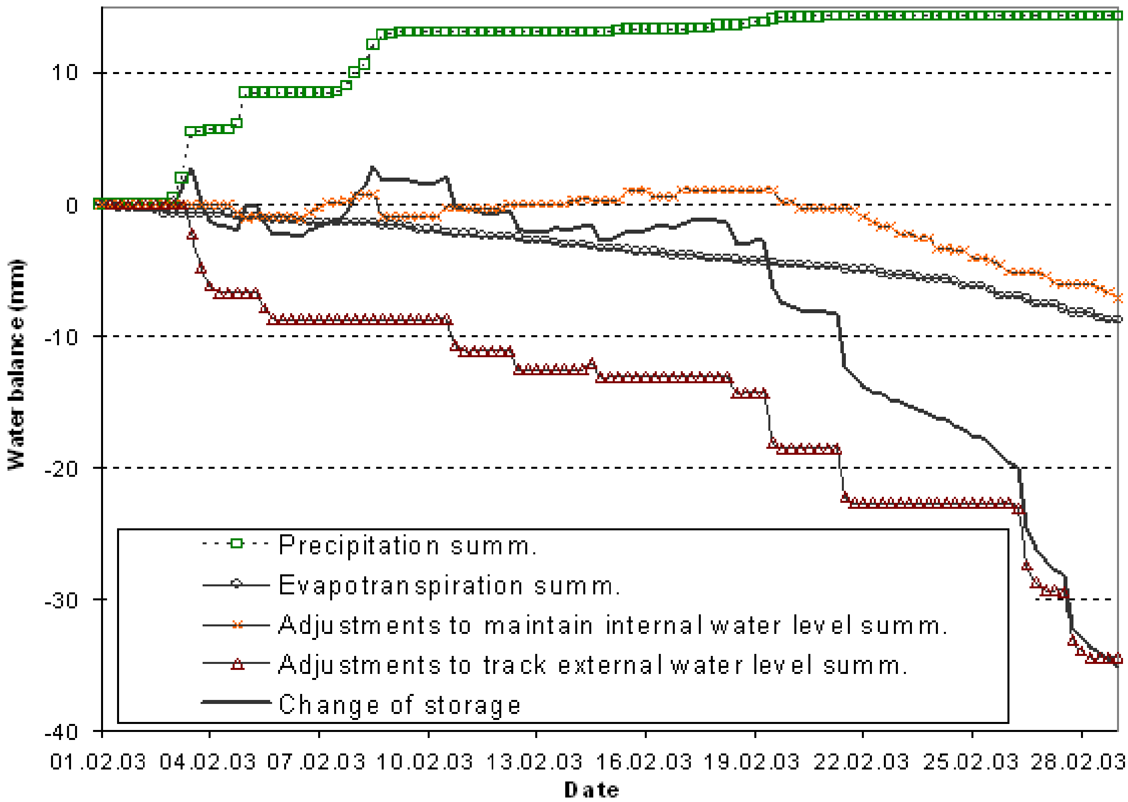

Figure 6. Water balance parameters (cumulative) in February 2003 based on measurements with the weighable groundwater lysimeter.

Using the modified water balance equation (3), the following balance can be drawn up for this period:

$P + Pond = Eta + (R_{out} - R_{in}) \pm \Delta S$

15 mm + 0 mm = 9 mm + (7 mm + 34 mm - 0 mm) - 35 mm (3)

Precipitation of 15 mm occurred as snow or sleet, mainly at the beginning of the month. It led to a short-term and slight replenishment of soil water storage. Depending on the course of the weather, daily values of evapotranspiration varied between 0.1 mm and 0.7 mm per day. In February, the total actual evapotranspiration of 9 mm had only a small effect on the reduction in soil water storage.

The water level in the balancing tank is constantly compared with the target water level. If the water level in the lysimeter deviates from the specified target water level by more than ± 1 cm an adjustment is necessary. This type of adjustment is called **"adjustments to maintain internal water level"** and classified as groundwater recharge or capillary rise. In order to maintain the target water levels, limited adjustments were necessary until 20 February 2003. As of 20 February 2003, increased seepage was observed in the lower soil layers. The outflow from the lysimeter (comparable with „groundwater recharge") reached a total amount of 7 mm by the end of the month.

The other type of adjustments are external changes of the target water level for groundwater control in the floodplain and unchanged water levels in the corresponding lysimeter. Change of groundwater level in the floodplain was caused by interaction with the water course. This kind of adjustment is called **"adjustments to track external water level"** and classified as infiltration or exfiltration.

During the investigation period "adjustments to track external water level" had the greatest share in groundwater outflow. The evapotranspiration, groundwater recharge and exfiltration into the water course resulted in a reduction of soil water storage by 35 mm, which precipitation was not able to compensate. The large groundwater level decline caused a groundwater outflow of 34 mm. This quantity is classified as "exfiltration into the water course". Hence, the findings of the lysimeter experiments can be used to determine the scale of the groundwater's interaction with river water in the study area.

Besides the described use of this lysimeter type, two new weighable groundwater lysimeters with a surface area of 1 m^2 and a depth of 3 m were constructed in spring 2004 in Germany. These lysimeters are located in situ in a post-mining area with a high groundwater table, established in a PE-HD lysimeter station. They will be used to investigate hydrogeological processes in post-mining overburden-heaps.

Conclusions

In Europe, lysimeters of various designs are used for measuring movement of water and chemicals in the unsaturated and saturated zone of the soil. There is a tendency to develop new lysimeter techniques. Progress is visible in a new technology to obtain large undisturbed soil monoliths and in the development of mobile PE-HD lysimeter stations. A high-resolution weighing technology and an automatic groundwater control system enable detailed investigations of the water balance, forming the basis for an accurate calculation of the solute balance and for modelling hydrological process.

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 scenario simulation of current climatic and hydrological events, such as a rapid rise of the water level and long-term flooding in connection with extremely hot weather or transport of contaminants during heavy rainfall in connection with the severe drying-up of the soil profile.

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