# Third-Generation Lysimeters: Scientific Engineered Monitoring Systems

**Christian Hertel and Georg von Unold**

**Abstract** Third-generation lysimeters meet the needs of 21st century environmental research and monitoring. High-resolution sensors, field-replicating hydraulic and thermal conditions and an excavation method showing the soil inside the lysimeter cylinder are important features in their quality process chain. Older lysimeter systems are unable to provide such detailed information about the soil water budget and all linked processes. Due to an increasing awareness of climate change, water management, agronomy and soil science issues, it was essential to upgrade lysimeter systems in order to gather more detailed information about processes and fluxes. Different lysimeter station layouts were developed for specific requirements and to increase their fields of application for particular tasks such as fertilisation treatments or irrigation and reproducing identical climatic conditions. Additionally, highly engineered third-generation bespoke lysimeter types are available to support particular projects. As an example, the meteorological lysimeter precisely measures precipitation, evapotranspiration and leachate. For this, the lysimeter weighs to the nearest gramme range a surface of 1 $m^2$ and supplies results to an accuracy of 0.01 mm for water input such as rain, dew, frost or snow and water output by evapotranspiration and leachate as well as reporting the change of soil water content. Combined with additionally measured meteorological data, this enables water balance models to be developed and potential evapotranspiration can be determined.

**Keywords** Lysimeter · Types · Evapotranspiration · Filtration · Accuracy

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L. Mueller et al. (eds.), *Novel Measurement and Assessment Tools for Monitoring and Management of Land and Water Resources in Agricultural Landscapes of Central Asia*, Environmental Science and Engineering, DOI: 10.1007/978-3-319-01017-5_9,

# 1 Introduction

Formerly, lysimeters were only used for measuring leachate. Over the past 20 years, innovative technology has developed lysimeters as high-precision tools for environmental monitoring research projects such as climate research, water management, agronomy, soil science and site remediation. Today, lysimeters are more than a standard tool for evapotranspiration, and will be described in the following paper. The word *lysimeter* originates from the Greek—"lysis" means dissolution or movement and "metron" is to measure (Aboukhaled et al. 1982). It is clear that the word "lysimeter" means the measurement of the percolation of water in soils (Howell et al. 1991). The first lysimeter investigations were performed by Philippe de La Hire in 1688 and focused on determining the origins of springs. Following various studies, de La Hire found out that lysimeters in grass evaporate more water than those in fallow ground (Kohnke et al. 1940). Historically, the design of lysimeters was generally a simple container to define the water movement through a soil boundary (Howell et al. 1991). According to Kohnke et al. (1940), lysimeters can be classified into two groups: those systems that can weigh and those that cannot. In the early beginnings of lysimetry, weighing was an often stated problem. Lysimeters with weighing systems are able to determine evapotranspiration directly through the mass loss of the water within the lysimeter. In contrast, non-weighing systems determine evapotranspiration indirectly through volume balance (Howell et al. 1991). By predicting runoff and lateral flux, lysimeters can provide data for water fluxes and because of the substance concentration in relation to the water balance, the mass balances too, as shown in Fig. 1.

Modern-day lysimeters invented by UMS Muenchen (http://www.ums-muc.de) monitor water fluxes according to the hydraulic and thermal conditions of the

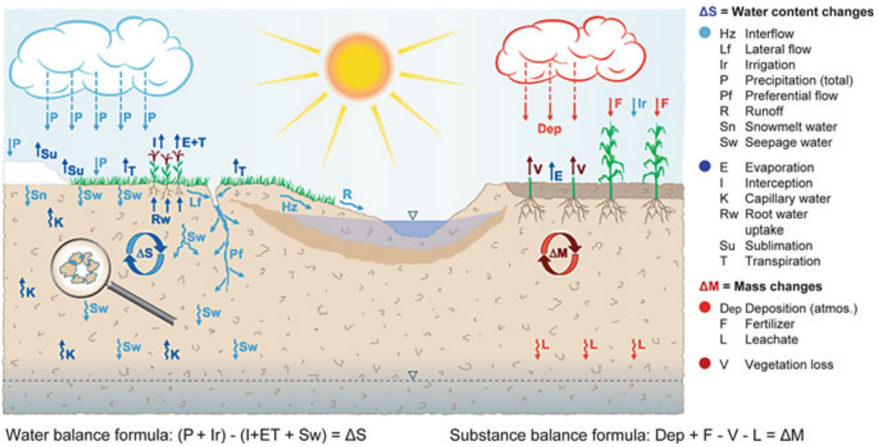


**Fig. 1** Precise water and substance balances. Soil water as well as input and output parameters of water and substance balance

surrounding field. Their sophisticated measuring, sampling, controlling and regulating instrumentation monitor the real field situation. Soil water is the decisive parameter for mass balance and any flux study. For studies on groundwater recharge or mass transport or for metabolism research, it is crucial to have a field-replicating water regime inside the lysimeter. Lysimeters offer thermodynamic comparability between field and lysimeter specially designed for climate research or for the analysis of microbial activities. Both features are important for many tasks, as well as aspects of research into conventional cultivation, snow coverage during winter operations and high substance conversion after snow melt.

Scientific engineering lysimeters use a precision weighing system that measures water fluxes in soils by weighing and calculating water input and output over time and can weigh lysimeter columns with a mass of 50 up to 6,000 kg. They can measure soil columns to a high level of precision and resolution. This absolute precision depends on the total weight of the lysimeter. The precise resolution can be even 10 g or 0.01 mm precipitation. Thus, lysimeters are exceptionally suitable for the measurement of all types of precipitation including rain, dew, frost and snow. And above all, they can measure precipitation as it occurs in the surrounding field—right on the soil surface. High-resolution data loggers store short-interval readings over extended periods of time to demonstrate ongoing processes, mass conversion or solute movements. Loggers store readings internally or on USB sticks. As an option, the logger can transmit the data to an Ethernet or Web server network via GSM or GPRS. Thus, data can be combined from numerous lysimeter sites, and this is then available as a common and substantial database for research networks. When investigating climate change, the mesocosmos containing soil, vegetation and micro-organisms is significant as it is exposed to a natural yet different climate. Thus, it reveals symptoms of climate change on soil, plants, water balance, $CO_2$ and $O_2$ dynamics, long before they may become apparent elsewhere. The following chapter describes various systems and their respective applications in this area of research.

## 2 Materials and Methods

Stations with several lysimeters increase the measuring capacity or compare the effects of various treatments of fertilisation or irrigation under identical climatic conditions. In order to determine various treatments at one site, two or more lysimeters are connected to one logger and one service well (Fig. 2a). They can compare diverse cultivation methods and crop rotations, as well as conventional and organic farming. For comparison studies on the same soil but with different treatments (fertilisation, irrigation or $CO_2$ treatment), up to six lysimeters can be connected to one logger and service well. The advantages of a tetragonal layout are an installed service well in the corner of four fields and the flexible length of the connection pipes, so the lysimeters can be placed far inside the field to minimise vegetative island effects (Fig. 2b). Another possibility is a linear layout to compare various crop rotations or variations from Fig. 2c A to F. A linear alignment and parcelling around the lysimeter is recommended as this is less disruptive to cultivation. Furthermore, lysimeters in a linear arrangement are preferable for autonomous robots or automatic systems for irrigation and tracer application or when gas treatment hoods are used. Another option is the hexagonal layout. For studies into a comparison of soils under changed climatic conditions, lysimeters can be arranged as a ring. Then, the soils can be brought in from different locations and be exposed and surveyed under changed climatic conditions. Due to the geometric similarity of the hexagonal layout, the lysimeters are exposed to equal conditions, which is especially advantageous for comparative studies. Then, lysimeters of Fig. 2d A to F are filled with a different mesocosmos from various locations, or represent the variability of one ecosystem.

Innovative solutions for delivering the best quality assurance in cutting and conserving lifting and rotation methods are important for lysimeter systems operations. As each soil is unique, it is essential to have experience in the

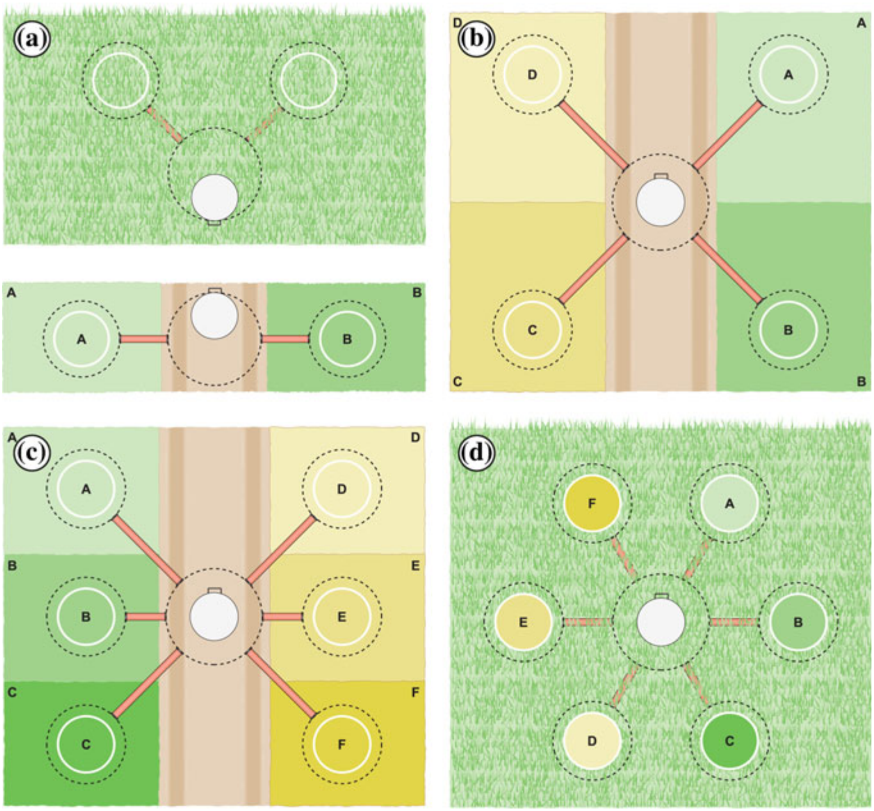


**Fig. 2** Various third-generation lysimeter layouts. **a** 90° layout and duplex field layout. **b** Tetragonal layout. **c** Hexagonal linear layout. **d** Hexagonal circular layout

excavation of lysimeter soil columns. Special cutting methods were developed to ensure quality. This method prevents soil compaction and gaps and during the cutting process shows exactly the soil that will be later inside the lysimeter. The first step is inspection borings to determine if rocks, roots, cavities or other disturbances might require preventive measures. Ideally, the site will have trenches dug with an excavator at least one metre deeper than the last lysimeter to show the exact origin of the soil in its texture, structure and any peculiarities. Furthermore, continuous observation of the cutting process by experts is crucial. A specially developed tool for cutting precise perpendicular under protection by the utility model is being used for third-generation lysimeters. Its cutting edges are made from special steel which minimises friction and prevents soil compaction inside the lysimeter column. Finally, stones or roots need to be removed by hand beneath the cutting edge so they do not create cavities or grind grooves onto the soil column. As soon as the soil is inside the lysimeter cylinder, it becomes a black box, so care needs to be taken during the cutting process to ensure its quality. The last step in cutting a lysimeter soil column is a precise shear-off procedure. A polished cutting plate with specially shaped cutting edges is driven by hydraulics to assure a careful and accurate shearing. After the cutting process, the soil column is lifted and turned upside down. The lifting force is applied evenly and close to the balance point to prevent column deformation. The soil body is kept safe and free from deformation. Third-generation lysimeter design assures that the cylinder is not deformed when lifted, as the induced load torque is reduced to a minimum. The load is carefully distributed away from the short bolts over the large welded-on base plate. The filled lysimeters are transported on special anti-shock trucks, if required. The special air suspension of the vehicles ensures that the soil column remains undisturbed. The lysimeter's innovative lifting and rotating mechanism prevents a deformation of the soil body and eliminates the development of gaps inside the cylinder—an essential quality criterion for obtaining substantial data. This prevents the need for heavy weight clamps around the lysimeter and invisible preferential gaps due to handling. After cutting and lifting, the next step in the lysimeter process is the installation and the adjustment of the field-identical water regime.

The basic design of a third-generation lysimeter has a cylindrical stainless steel surface of 1 $m^2$ and a monolith depth of 1 m. A range of different sensors are available and can be selected according to the lysimeter's task of providing a view into the black box of the soil monolith. Thanks to highly resolved weighing systems, measurements of water fractions with a resolution of 10 g can be achieved (for lysimeters with a surface of 1 $m^2$ and a length of 1.5 m). Drainage water measurements by a second cell enable high resolution (von Unold and Fank 2008). Tipping buckets for drainage measurements are applicable too, but lead to losses in resolution, depending on the tip volume. The bottom of the monolithic pillar is formed as a matric potential area to achieve field comparable fluxes. The difference between the water regime in the field and inside the lysimeter has always been criticised as a weakness in design. In conventional gravity lysimeters, the leachate simply drains out of the bottom of the lysimeter. In reality, variable matric potentials, which are the main determinants for water flow, occur in the field. In rainy seasons or wet periods, the field's soil water is pulled towards the lower groundwater. This does not happen inside the lysimeter, as the potential on the very bottom is zero. As a result, the lysimeter has more moisture than the field. In dry periods, depending on the soil type, capillary suction causes the water in the field to rise. As this is not the case in the conventional lysimeter, the soil in the lysimeter remains drier than the soil in the field. The described third-generation lysimeter has solved this problem by measuring and comparing the matric potential in both the bottom of the lysimeter and in the field at the same depth. If the lysimeter has more moisture, then water is sucked out through the rake of the suction cups. If the lysimeter is drier, then water is injected. In this way, the old problem with lysimeter bottom plates was overcome, enabling the monitoring of field water fluxes, which was exactly what was wanted.

## 3 Lysimeter Designs

Third-generation lysimeters depend on different application requirements. Special lysimeter designs are described in detail below in terms of their specific field applications.

### *3.1 Hydro-Lysimeter*

The Hydro-Lysimeter in its basic design (Fig. 3) has been devised to solve the water balance equation (von Unold and Fank 2008). It measures the weight of the lysimeter monolith as well as drainage. The standard lysimeter height is 1.5 m with a surface of 1 $m^2$. Precipitation and evapotranspiration are determined from the change in the lysimeter's weight over time. The precipitation evaluation and drainage measurement enable the determination of ground water recharge capacities (von Unold and Fank 2008). With the Hydro-Lysimeter, it is possible to obtain soil water parameter measurements and their interfaces to atmosphere and aquifer. The controlling input parameters for the lysimeter are the measured water reaching the surface and the water equivalent of snow. To prevent problems in snow measurements, the snow bridge crossing the gap between the lysimeter and its surrounding area is cut to maintain correct weight measurements. On other sites, the output parameters are real evapotranspiration and drainage rates. In addition, an identical temperature regime is available within the lysimeter field.

The design includes a lysimeter cylinder with silicon carbide porous cups' rake and a precision weighing system. Moreover, the field tensiometer measures the field situation and the lysimeter tensiometer steers the controller to keep the lysimeter at field conditions.

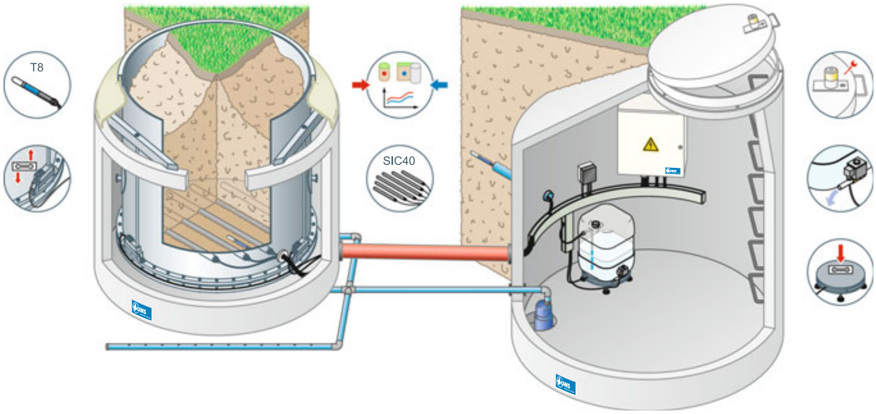


**Fig. 3** The Hydro-Lysimeter with service well

## *3.2 Meteo-Lysimeter*

The meteorological lysimeter, as shown in Fig. 4, is specially designed for determining evapotranspiration (ET) and grass reference evapotranspiration over short time intervals ($ET_0$); drainage and precipitation from lysimeter weighing data and measured peripheral meteorological data.

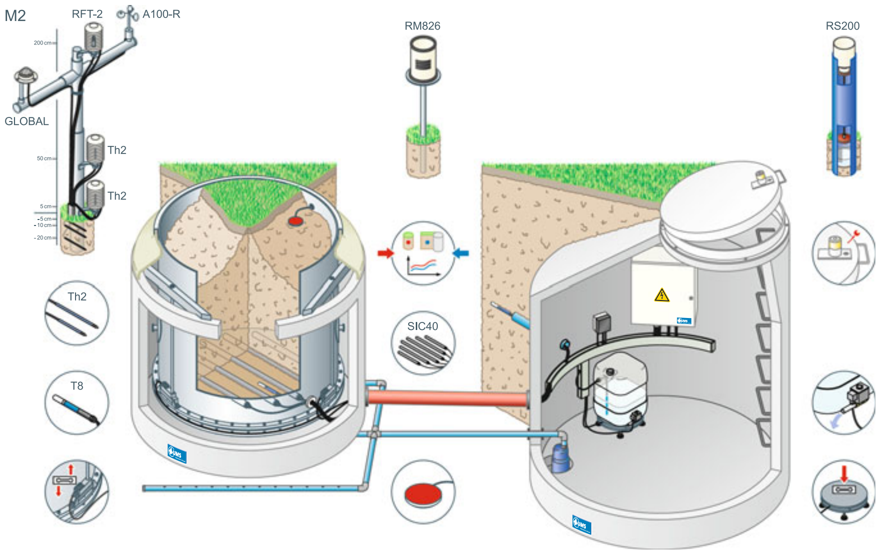


**Fig. 4** The Meteo-Lysimeter with weather station and service well

As with the Hydro-Lysimeter, the Meteo-Lysimeter measures $ET_0$ as a continuously recorded reading, calculated by a 12 cm grass cover algorithm. Furthermore, soil temperature is measured at depths of 5, 10 and 20 cm. The soil water content is measured at a level of 10 cm below the surface. The included weather station is equipped with a radiation sensor, relative humidity sensor and wind speed at 2 m height. Air temperature is measured at 5, 50 cm and 2 m. The lysimeter and the meteorological data allow the ASCE standardised reference evapotranspiration equation to be calculated. Furthermore, the combination of measured real ET and calculated $ET_0$ can determine crop coefficients and water stress coefficients (von Unold and Fank 2008).

### 3.3 Scientific Field-Lysimeter

This lysimeter, designed especially for scientific applications, has a standard depth of 2 m (Fig. 5). It has been designed as a configurable system for investigating specific properties of soil, soil utility and conservation. It combines the advantages of laboratory and field investigations, as it provides laboratory precision even under rough field conditions. Water samples and readings inside the monolith are taken from 10 cm down to 180 cm. Through its ability to supply the additional measurements of volumetric water content, matric potential and soil temperature, a detailed description of soil water fluxes within the monolith can be generated. For quality assurance, sensors are also installed in the undisturbed field to compare the significance of the lysimeter investigations with natural field conditions (von Unold and Fank 2008). For more detailed research tasks, a combination of suction cups and a tension controlled vacuum for pore water extraction can be installed,

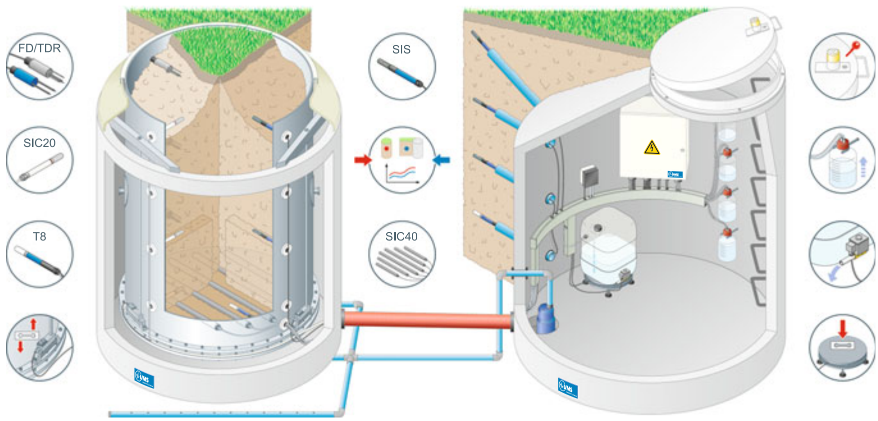


**Fig. 5** The science field-lysimeter with various types of instrumentation and reference sensors

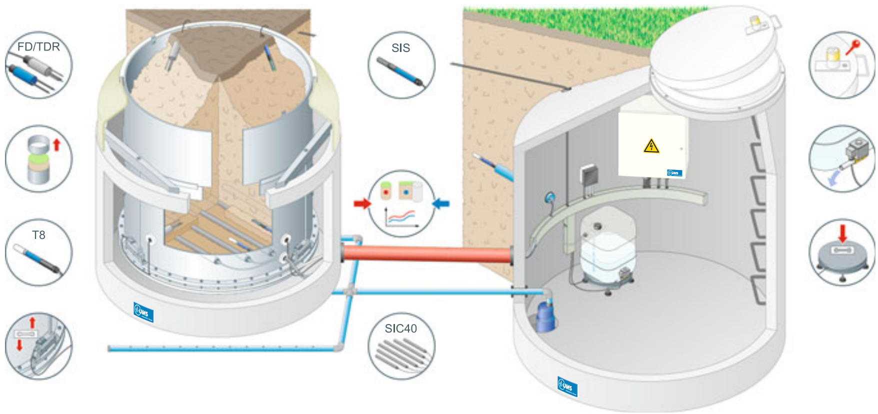


**Fig. 6** The agro-lysimeter with various types of instrumentation and reference sensors

giving detailed information about metabolisms or contamination inside the monolith.

### *3.4 Agro-Lysimeter*

The Agro-Lysimeter (Fig. 6) is adjusted to measure variables such as root water stress, drainage water and solute fluxes in cultivated field investigations. The specifications of the lysimeter are 1 $m^2$ with a depth of 1 m. The special construction of the removable upper ring means that the field can be cultivated and it can be replaced after tillage. The field matric potential is transferred into the lysimeter by the suction cup rake. The Agro-Lysimeter is not weighable and additional sensors should be adjusted in the upper soil horizon. Furthermore, seepage water measurements are detected by using a 0.1 mm capsulated tipping bucket (von Unold and Fank 2008). Its ideal application area is the recurrent monitoring of ground water recharge and solute leaching from arable land.

## 4 Conclusion

Lysimeters have been used for centuries, but only the instrumentation and innovation of the past 20 years has reduced the large water potential errors. To avoid problems in lysimetry, a detailed review is crucial to find out which configuration and layout are best suited to resolving scientific questions. The chapter above has described general operations and technical concepts to show the flexibility of lysimeters for different tasks and applications.

## References

Aboukhaled A, Alfaro JF, Smith M (1982) Lysimeters. FAQ Irrigation and Drainage Paper, no 39. Rome

Howell TA, Schneider AD, Jensen ME (1991) History of lysimeter design and use for evapotranspiration measurements. In: Proceedings of the International Symposium on Lysimetry: Lysimeters for evapotranspiration and environmental measurements, pp 1–9, July 23–25, 1991, Honolulu, Hawaii. ASCE, 345 E. 47th St., NY, 1017–2398

Kohnke H, Dreibelbis FR, Davidson JM (1940) A survey and discussion of lysimeters and a bibliography on their construction and performance, vol 372. USDA, Washington, DC, p 68

von Unold G, Fank J (2008) Modular design of field lysimeters for specific application needs. Water Air Soil Poll: Focus 8:233–242