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Review article

An overview of the experimental research use of lysimeters

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ABSTRACT

The lysimeter is most often defined as a box filled with soil with an intact structure for measuring the amount of infiltration and evapotranspiration in natural conditions. At the bottom of the device there is an outflow for atmospheric precipitation water infiltrating to a measuring container. Lysimeter studies are included in the group of dynamic leaching tests in which the leaching solution is added in a specified volume over a specific period of time. Lysimeter studies find applications in, amongst others, agrotechnics, hydrogeology and geochemistry. Lysimeter tests may vary in terms of the type of soil used (anthropogenic soil, natural soil), sample size, leaching solution, duration of the research and the purpose for conducting it. Lysimeter experiments provide more accurate results for leaching tests compared with static leaching tests. Unlike several-day tests, they should last for at least a year. There are about 2,500 lysimeters installed in nearly 200 stations around Europe. The vast majority of these (84%) are non-weighing lysimeters. There are a few challenges for lysimeter research mostly connected with the construction of the lysimeter, estimating leaching results and calibrating numerical transport models with data obtained from lysimeters. This review is devoted to the analysis of the principal types of lysimeters described in the literature within the context of their application. The aim of this study is to highlight the role of lysimeters in leaching studies.

KEY WORDS: lysimeter, leaching tests, waste, soil, hydrogeology

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1. Introduction

Currently the lysimeter is defined as a device (or box) filled with soil with an intact structure for measuring the amount of infiltration and evapotranspiration in natural conditions (Fig. 1). There is an outflow in the bottom for infiltrating atmospheric precipitation water to a measuring container (MACIOSZCZYK, 2002). Unfortunately, this definition is adapted for devices that only allow the determination of the water balance. The definition proposed by MULLER (1996), which describes the lysimeter as "a device that isolates a volume of soil or earth between the soil surface and a given depth and includes a percolating water sampling system at its bottom" seems to be more accurate despite the failure to specify the technical design of the device and its intended use.

Lysimeter studies belong to the group of dynamic leaching tests in which the leaching liquid (in most cases water) is added as a specified volume for a specific period of time (DABROWSKA ET AL., 2018a; KALEMBKIEWICZ & SITARZ-PALCZAK, 2015; KIM, 2002; SOLTYSIAK ET AL., 2017, 2018). Lysimeter studies are more accurate than other leaching tests due to the size of the sample and the duration of the experiment (QIANG ET AL., 2015; PLOŠEK ET AL., 2017). In the case of lysimeter studies, their precision and reliability are extremely important (DABROWSKA ET AL., 2016, 2018b, c).

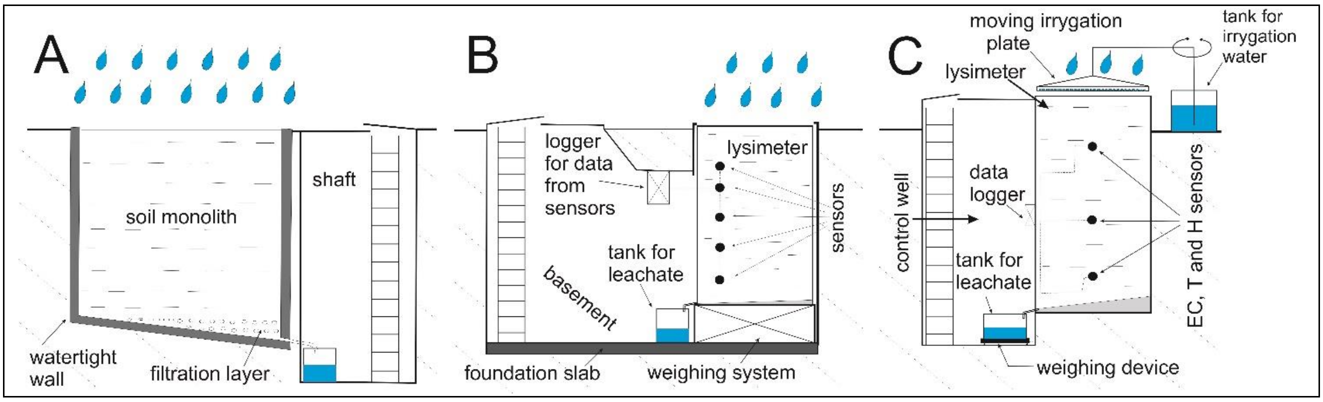

Fig. 1. Examples of lysimeter construction
A– box lysimeter (according to: Pazdro, Kozerski, 1990), B– weighing lysimeter, C– construction of a lysimeter made at the University of Silesia

It should be noted that due to its specificity, there is also no universal methodology for conducting lysimeter research – research teams usually design and make their own, unique constructions suitable for their needs and use their own methodologies. The basic parameters that differ in the lysimeter structures are: diameter (<0.5 m^2, 0.5-1.0 m^2,> 1 m^2), depth, measuring instrumentation and equipping the weighing mechanism.

The first lysimeter was probably constructed by Johann Baptist Van Helmont from the Netherlands in around 1620 (HOWELL ET AL., 1991). He raised a tree in a precisely weighed amount of soil, feeding it with water and observing its growth. Due to the fact that these studies did not concern the water balance, some take Filip De La Hire as the true creator of the first lysimeter (CEPUDER & SUPERSBERG, 1991) whose research concerned water consumption.

There are no unambiguous conditions for the construction of a lysimeter, but several conditions must be met in order to properly choose the location of the lysimeter (OECD, 2000). When planning the lysimeter station attention should be paid to organizational factors, such as the materials used and climatic factors (DVWK, 1980). When choosing the location of an experiment, it is also important to consider the purpose of the test. There are several areas of research where lysimeters can be used. These are mainly: hydrology and hydrogeology (ZUREK & MOSCICKI, 2017), agronomy and agrotechnics (ELBL ET AL., 2014), ecology and environmental protection (MEISSNER ET AL., 2000) and geochemistry and waste management (DABROWSKA ET AL., 2018a; SOLTYSIAK ET AL., 2017).

There are about 2,500 lysimeters installed in nearly 200 stations in Europe but this type of methodology is still avoided in favor of dynamic leaching tests. The aim of this study is to highlight the role of lysimeters in leaching studies and to provide the best technical solutions for lysimeters.

2. Types of lysimeters

Initially, the most popular form of the lysimeter was the structure designed by Baca and Ostromecki. This lysimeter was a box with the soil to be tested placed inside a barrel filled with water. The main purpose of the study was to evaluate the evaporation from the surface of the soil (TARKA, 1997). The second most popular lysimeter construction was the box lysimeter. This was a tight box with intact ground buried in the ground. The bottom of the box sloped in one direction, so that the water infiltrating through the soil flowed into a collecting vessel. As a result, the volume of the effective infiltration could be measured (ZUREK, 2010).

Classic lysimeter. Currently, a "classic" lysimeter (Fig. 2) is considered to be made up of columns of materials resistant to moisture (eg. PVC, stainless steel), most often with a diameter of 0.5 meters to 2 meters and a length from 1 to 3 meters (CEPUDER & SUPERSBERG, 1991). This kind of lysimeter is sometimes called a gravitation lysimeter, however, it should be remembered that a lysimeter in which water flows under the influence of gravity may have a completely different construction (MEISSNER ET AL., 2010).

Weighing lysimeter. The weighing lysimeter should be considered a more advanced type of classic lysimeter. Its design is usually similar to a classic lysimeter, but it is expanded with weighing devices. This allows for more accurate studies of the water balance, particularly for determining the evaporation in dry periods. In addition, it is possible to determine the changes in the humidity of the material being tested on the basis of continuous weight measurements (MARTINS ET AL., 2017).

Fig. 2. Classic lysimeters

In both classic and weighing lysimeters, additional measuring equipment is often installed, which allows the measurement of, for example, the humidity of the material being tested or its temperature. It is possible to determine not only seepage time through the aeration zone, but also to correlate this with soil moisture content (Soltysiak et al., 2018). Meteorological stations are often located near the lysimeters in order to obtain precise data on the amount of rainfall or changes in air temperature. These data can be used to make forecasts on water balance or leaching, e.g. based on artificial neural networks (Nourani et al., 2017a b; Polap et al., 2018) Lysimeter stations are often created that are equipped with several or even several dozen lysimeters. Filling the lysimeters with different types of material and planting different types of vegetation on them - most often different types of crops - allows the experimenter to obtain, amongst others, enormous amounts of data on the dependence between the plant species and their demand for water and soil type and the numerical value for evapotranspiration.

There are about 2,500 lysimeters installed in nearly 200 stations across Europe. The vast majority of these (84%) are non-weighing lysimeters. A lysimeter containing a monolithic sample constitutes about 30% of all lysimeter vessels and amongst these, almost half are weighing lysimeters. More than half of lysimeter studies concern agriculture. Almost all groundwater lysimeters are located in Germany (Lanthaler, 2004) where there are about half of the European lysimeters. A third fewer of are located in Hungary (368). The third highest country in terms of the number of lysimeters is France with 218 lysimeters (www.lysimeter.at; Lanthaler, 2004). The biggest lysimeter station in Europe, is the Lysimeter Research Station belonging to the National Agricultural Research and Innovation Centre is located in Szarvas (Hungary). There are 320 non-weighable backfilled lysimeters (Jancsó et al., Lanthaler, 2004). Another example is a lysimeter station in Zurich-Reckenholz, which has 72 lysimeters, 12 of which are weighing lysimeters (Valtenena et al., 2017) and Falkenberg, where 145 lysimeters are still in existence (Lanthaler, 2004).

The weighing lysimeters allow for a much more precise knowledge of the components of the water balance, especially for evapotranspiration, than the classic lysimeters. However, the cost of their construction is significant. In response to the need to conduct agrotechnical research at a relatively low cost, the need arose to build alternative weighing lysimeters (Ruiz-Penalver et al., 2015).

Tension lysimeter. The next group is the tension lysimeter (or temperature-controlled tension lysimeter). It is assumed that water movement in the soil is to a large extent defined by the current (time-varying) soil matrix potential. In addition, temperature changes in the soil profile play an important role. The design of the tension lysimeter allows for the temperature to be controlled inside the lysimeter, which results in the entire experiment better reflecting the field conditions (Barkle et al., 2011). Tensiometers allow to cover a much larger ground volume during measurements, due to the fact that the measured pressure potentials spread out spherically.

Hillside lysimeter. A special type of lysimeter that can only be installed in the field is the hillside lysimeter (Meissner et al., 2000; Rey et al., 2014). There are a few advantages of this lysimeter such as adjusting the slope (protecting the flow processes on the soil surface against the influence of unnatural obstacles) or the fact that it is possible to build this construction without using heavy equipment (this kind of lysimeter can even be used in alpine terrains).

Groundwater lysimeter. A groundwater lysimeter is a specific type of lysimeter. In contrast to typical lysimeters that study the flow of water in the aeration zone, the bottom parts of these types of lysimeter are intentionally located below the groundwater table (Schwaerzel & Bohl, 2003). This design aims: to determine the dynamics of the groundwater formation, especially in alluvial soils, to determine the impact of flooding on the formation of groundwater and the balance between water and dissolved substances and to define the conditions under which this balance is disturbed, and to determine the mobility of heavy metals, nutrients, pesticides and other pollutants caused by a change in redox conditions (MEISSNER ET AL., 2000). There are two types of groundwater lysimeters – one with a constant groundwater level and one with a variable groundwater level which should provide a better adaptation to the actual field conditions.

Moor lysimeter. An interesting technical solution is the moor lysimeter designed for peat tests. Measurement of lateral flow and the associated transport of substances in the lysimeter allows for the determination of the conditions of thermodynamic equilibrium between water and substances dissolved in peat soils with a very high resolution, both temporal and spatial (http://lysimeter.info/).

Microlysimeter. A microlysimeter is an effective method for measuring evaporation rate (UCLES ET AL., 2013). High-resolution sensors connected to data loggers facilitate accurate mass measurements of microlysimeters. They are also used in the study of non-rainfall water input (MALTERRE ET AL., 1997). These lysimeters have gained application in finding an improved temporal measurement scheme for the identification of parameters governing the degree of preferential flow in a physically based one-dimensional dual-permeability model for water flow and solute transport through the unsaturated zone. The following parameters can be taken into account: the mass exchange coefficient, the saturated micropore hydraulic conductivity and the kinematic exponent governing the flow in macropores (LARSBO & JARVIS, 2006).

3. Applications of lysimeters

HOFFMANN (2016) used lysimeters to determine the best method for measuring the amount of rainfall. In 2012-2013, a comparative study of rainfall measured on 1 m above the ground, used three Hellman rain gauges installed on the ground and three lysimeters for 417 days. Fallout caught by a lysimeter, which showed a slight deviation (0.5%), was considered a reference point.

Sources of non-rainfall water input (NRWI) were also measured using a lysimeter. The scientific community attempts to investigate the duration and quantification of the contribution of these sources, but there is no universally accepted methodology for such research. An example of research on NRWI is from an experiment conducted in Balsa Blanka, in Spain. For 49 days, from May to June 2012 measurements were conducted in 12 microlisymeters, covered with various types of vegetation or containing no plants. The temperature and humidity of the air at ground level and the amount of rainfall were measured at the same time. Data were collected at 15 second intervals by data loggers and averaged every 15 minutes. Studies showed little background interference during data collection. It has also been shown that there may be small evaporation episodes during a dew event. It was also observed that during the day, during evaporation, small amounts of water can condense. Studies have also shown that in the case of soil not covered by vegetation, participation condensing water vapor in non-rainfall water input is 66%, with 34% falling on dew (UCLES ET AL., 2013).

In order to minimize the growing impact of transport infrastructure on urban areas it is beneficial to plant vegetation along communication routes. Lysimeters built along communication routes (the so-called Urban Track Lysimeter) are designed to assess the water retention of these areas depending on the substrate and the type of vegetation growing on it, and to determine the optimal water conditions for such an environment. These lysimeters allow the determination of the amount of water accumulated by the urban greenery and its substrate and the size of infiltration and evapotranspiration in relation to rainfall. In addition, tensiometers continuously inform about the under pressure in the ground and on this basis, it is possible to determine the moisture of the substrate and estimate the amount of water available for the plants (MEISSNER ET AL., 2010; http://lysimeter.info). In addition to water balance measurements, it is also possible to perform qualitative measurements to record the flow of dissolved substances on a city road. A related type of lysimeter is the so-called green roof lysimeter, which is used to assess the ability of plants to collect suspended dust (one of the main components of smog).

An example of lysimeter studies on mountain slopes has been conducted in the Sowie Mountains and the results of this research have been described in STASKO & CHODACKI (2014). Groundwater recharge measurements were carried out at a research station located at 520 m above sea level. The lysimeter was located on a slope at a depth of 90 cm, above farms and arable fields and away from tourist routes.

Lysimetric studies in mountain areas can also be used to understand the dynamics of water circulation in the soil on the slopes in order to predict floods and other hydrological events in mountain water catchments. In addition, they can help to identify natural vegetation patterns and optimize the use of agricultural land in these areas (AUGENSTEIN ET AL., 2015).

Lysimetric studies are also used in research on water flow and the solute transport processes in the vadose zone. Stable isotopes as environmental tracers are often used in these kinds of studies. Data acquired in these experiments are used for numerical flow modeling (MACIEJEWSKI ET AL., 2006; MALOSZEWSKI ET AL., 2006; STUMPP ET AL., 2007, 2009a, b; STUMPP & MAŁOSZEWSKI, 2010; STUMPP ET AL., 2012). Also other tracers like bromide, chloride, nitrate and pesticides may be used in lysimeter investigations (SCHOEN ET AL., 1999; BROWN ET AL., 2000).

In the context of hydrogeology, lysimeter studies on waste are extremely important. Information on the time and volume of the processes involved in the leaching of toxic substances from waste, especially heavy metals, is crucial for determining the scale of the impact of waste on the environment (SOLTYSIAK ET AL., 2017; RETH, 2016). Large accumulations of waste, such as in landfill sites, can lead to irreversible changes in the chemistry of groundwater in a given region. Lysimetric studies are more accurate than other leaching tests (DABROWSKA ET AL., 2018a).

Lysimeter studies are long-term studies. An example of these can be found at the Academy of Mining and Metallurgy in Krakow where testing was taking place on lysimetric mining wastes Samples were tested from two coal mining wastes, collected from the Smolnica landfill site one of which was fresh and the other was 10 years old. The processes of leaching were observed for three decades (WITCZAK & POSTAWA, 1993a, b; SZCZEPANSKA, 1987; SARGA-GACZYNSKA, 2007). Similar lysimeter studies on metallurgical waste samples have been conducted since 2004 in the Department of Hydrogeology and Engineering Geology of the University of Silesia. The first experiment was carried out on a sample of freshly deposited waste and compared with an old waste sample stored since 1989 (SOLTYSIAK & DABROWSKA, 2016). Both samples were taken from landfill of ironworks slag. The aim of the research was to characterize the chemical composition of the water seeping through the metallurgical waste repository. These tests were preceded by laboratory tests. In 2015, the lysimeter test stand was extended with two new lysimeters equipped with sensors for measuring humidity, conductivity and ground temperature. Data from these sensors will be used to predict leaching using artificial intelligence methods (POLAP, 2018; SOLTYSIAK ET AL., 2016). The diameter of each lysimeter is 1 metre, and the thickness of waste placed in them is 1.6 metres. About 2 000 kg (2 tons) of slag was used to fill one lysimeter. Tested slags were taken from landfill of lead zinc smelters. The new experiments were divided into two phases. During the initial phase of the experiment the lysimeter was supplied with demineralized water. Then the experiment was conducted in the natural hydrological cycle. Leachates from the lysimeter were regularly collected and their volume and field parameters were measured. At the end of each month the averaged leachate was subjected to chemical analysis. This experiment was interdisciplinary and was a combination of hydrogeological and mineralogical studies, in which not only the chemical composition of leachates was determined, but also the phased composition of the slags and the precipitates covering slags were also examined. Experience from this research facilitated the design and construction of a stand equipped with a sprinkler to simulate atmospheric precipitation. An additional element to the research was the weighed system for leachate, which allows for the continuous measurement of the weight. The lysimeter itself has been equipped with a set of humidity, temperature and electrical conductivity sensors (Fig. 1c).

The first lysimeter studies in Poland were conducted at the beginning of the 1960s. In 1963 the Limnological station in Borucin was equipped with a lysimeter (BOROWIAK, 2016), under the supervision of the Department of Physical Geography of the State Higher School in Gdańsk (currently the University of Gdańsk).

Five years later lysimeter studies began at the Scientific Station of the Institute of Geography and Spatial Organization of the Polish Academy of Sciences in Szymbark. The devices were installed in such to enable the investigation of surface and intra-ground runoff processes as well as leaching of mineral components from the soil (SŁUPIK, 1973).

In 1971, lysimeter studies began at the Institute of Soil Science and Planting in the Centre of Agricultural Sciences in Puławy. The aims of these studies were to find out the relationship between soil species, cultivated plants, fertilization and the balance of micronutrients in soil (SYKUT, 1988). In the 1980s, lysimeters were also used in air quality studies (CHMIELEWSKI ET AL., 1985). In 1984 a lysimeter station was initiated at the Academy of Mining and Metallurgy in Krakow (WITCZAK & POSTAWA, 1993a, b). Mining waste has been subjected to many years of research. A new lysimeter station was built there in 2005 (ZUREK, 2010).

More recent lysimeter studies have concerned hydrogeological issues and were mainly water balance studies (MALEK, 2005; ZUREK, 2010; ZUREK &

Czop, 2010; Stasko, 2014; Soltysiak, 2009, Soltysiak et al., 2017; Zurek & Moscicki, 2017). Lysimeter studies have been conducted on natural soils, such as sands (Zurek, 2010) or on anthropogenic soils, e.g. metallurgical waste (Soltysiak, 2009, Soltysiak et al., 2017), coal - mining waste (Witczak & Postawa, 1993a, b; Szczepanska, 1987; Sarga-Gaczynska, 2007) or municipal waste (Dabrowska et al., 2018a, b; Slezak et al., 2015).

4. Conclusions

Lysimeter studies are types of dynamic leaching tests on large soil samples. A typical application of a lysimeter is found in water balance research. They can be used in various fields of science, such as climatology, hydrology, hydrogeology, agrotechnics, forestry and environmental protection.

In the case of leaching tests, the lysimeter experiment gives greater reliability of results than in static tests. In the lysimeter test, many parameters can be determined at various places in the ground profile and their variability can be studied over time. Lysimeter studies usually faithfully imitate environmental conditions. Lysimeter studies last much longer than static leaching tests, are expensive, require special installations and the interpretation of results is much more difficult. Research gives results relating to a specific profile and they refer to specific points. In the case of testing of natural soils, their structure is usually disturbed when soils are placed in a lysimeter. Lysimeter studies also require detailed observations of meteorological conditions in the immediate vicinity of the lysimeter. Lysimetric testing of waste, or materials planned for use in engineering works, usually require geochemical and mineralogical research. Also, the interpretation of hydrogeochemical studies, including model tests, requires geochemical characteristics of tested solid state.

Lysimeter studies conducted on waste provide an estimate of the impact of pollution on the soil and water environment. They can play a significant role in the acceptance of construction materials for use in civil engineering.

A thorough assessment of the environmental effects of the use of a given material reduces the risk of environmental pollution and, in extreme cases, reduces the risk to human health. This argument is justified, as it is often possible to find in literature information about environmental contamination due to the use of unchecked or inadequately tested material. Results from research can be used to create forecasts as well as environmental impact assessments – both for existing facilities (e.g. old landfill) as well as for planned facilities (e.g. embankments, macro-leveling areas).

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