HISTORY of LYSIMETER DESIGN and USE for EVAPOTRANSPIRATION MEASUREMENTS [1/]

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Abstract

Lysimeters are devices for measuring percolation of water through soils and sampling soil water for chemical analyses. Lysimeters have been used for over 300 years to determine water use by vegetation. Precision lysimetry for measuring evapotranspiration (ET) has developed mainly within the past 50 years. Weighing lysimeter designs are quite varied to suite individual research requirements. Surface areas from 1.0 m^2 to over 29 m^2 have been used. ET accuracy depends directly on the lysimeter area, mass, and the type of scale, but many lysimeters have accuracies better than 0.05 mm. Few weighing lysimeters exceed 2.5-m profile depth. Mechanical, floating, hydraulic, and electronic scales have been used in weighing lysimeters with varying types of data recording methods. Lysimeter wall construction can affect heat transfer to the lysimeter and water flow along the walls. ET accuracy of weighing lysimeters can be affected by many additional factors (personnel traffic, cultural operations, crop height, etc.).

Introduction

Lysimeters have become standard tools in evapotranspiration (ET) and water quality research. An excellent review of the history of evaporation research and experimental methods is found in Brutsaert (1982). Historical accounts of ET research, in particular lysimeter developments, are found in Kohnke et al. (1940), Harrold and Dreibelbis (1951, 1958, and 1967), Tanner (1967), and Aboukhaled et al. (1982). Soileau and Hauck (1987) reviewed lysimetry research with an emphasis on percolate water quality, and Bergström (1990) discussed lysimetry applications for pesticide leaching research.

Lysimeter is defined in Webster's ***New Collegiate Dictionary*** as *a device for measuring the percolation of water through soils and for determining the*

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soluble constituents removed in the drainage. The word *lysimeter* is derived from the Greek words *lysis* which means the dissolution or movement and *metron* which means to measure (Aboukhaled et al., 1982). Clearly, the word lysimeter means the measurement of the percolation of water in soil; although, other devices to remove water samples from soil are called "lysimeters". The lysimeter is foremost a device, generally a tank or container, to define the water movement across a soil boundary. The water use (evaporation, transpiration, or ET) can be determined by a balance of the water above this boundary. *Weighing lysimeters* determine ET directly by the mass balance of the water as contrasted to *non-weighing* lysimeters which indirectly determine ET by volume balance.

Kohnke et al. (1940) and Aboukhaled et al. (1982) attributed the first lysimeter for the study of water use to De la Hire of France in late 17th century. Salisbury and Ross (1969) described a lysimeter study conducted in the Netherlands in early 17th century (probably about 1620) by Van Helmont[3/]. Principle advances in ET lysimetry have centered on the measurement of the lysimeter mass and vacuum drainage and deeper lysimeters to more closely duplicate field conditions. The weighing mechanisms -- mechanical, floating, hydraulic, or electronic -- can be automated for electronic data recording. Major advances have occurred in the past 20 years in recording weighing lysimeter data.

Lysimeter designs have been copied or duplicated; however, Kohnke et al. (1940) cautioned "*that no one construction should be regarded as standard in a lysimeter and that a proper design can be made only by having an accurate knowledge of both the purpose of the experiment and of the pedologic, geologic, and climatic conditions.*" Pruitt and Lourence (1985) cautioned each lysimeter user to critically evaluate all agronomic aspects to ensure the representative high quality ET data since major errors in ET data are possible even with an accurate lysimeter.

In ET research, lysimeters are simply containers or tanks filled with soil in which plants are grown. Kohnke et al. (1940) classified lysimeters according to type of soil block used, surface drainage, and methods of measuring soil water content. The method of drainage may be gravity or vacuum, or a water table may be maintained (Dugas et al., 1990). Lysimeters for ET research are usually classified as monolithic or reconstructed soil profiles, as weighing or non-weighing, and as gravity or vacuum drainage.

This paper will describe the evolution of design parameters commonly used for weighing lysimeters for ET measurements. Although non-weighing lysimeters are important and discussed in other papers in this proceedings, we have limited our discussions here to weighing lysimeters with *in situ* scales. Weighable lysimeters, which can be weighed periodically, are not discussed.

[3/] **Personal communication from Dr. C.H.M. van Bavel pointed out this reference.**

Lysimeter Design

ET Accuracy. ET measurement accuracy is dictated by the intended measurement period, i.e. for hourly, daily, or weekly time periods, etc., and few weighing lysimeters have ET accuracies better than 0.02 mm. The desired ET accuracy influecnes many weighing lysimeter design parameters, especially the type of scale. Three descriptions of lysimeter accuracy are often used and sometimes confused. *Resolution* is the last significant definable increment of the measurement; *precision* is the stated level of the measurement (variability among numerous measurements); and *accuracy* is the definable verification of the stated measurement compared to a "true" value (Fritschen and Gay, 1979).

Shape and Area. Lysimeter shape and area are based on the expected crops to be studied and their rooting depths. Many weighing lysimeters are rectangular in shape with a surface area that varies from 1.0 to over 29 m^2. When drainage flux measurements are important, the macro-porosity of the soil may dictate the area of the lysimeter necessary to provide a suitable soil sample (Ritchie et al., 1972). Circular lysimeters are inherently much stronger per unit container mass, but they pose questions about the "representativeness" of the lysimeter surface area in relation to row crop geometry. Differences between lysimeter and crop geometry can bias the soil water evaporation and crop transpiration relationship. Circular lysimeters should have a diameter several times the expected row width to minimize this bias. Lysimeter shape and area may not critically affect ET measurements for grass, alfalfa, or small grains or other broadcast planted crops. Width of a rectangular lysimeter should be an integer multiple of the row spacing. For an orchard or tree crop, the lysimeter area might be limited practically to only a single tree or vine (Green and Bruwer, 1979) in which case the plant to plant differences and soil variability must be carefully considered.

Depth. Lysimeter depth is a critical design parameter and will depend on the intended purpose of the lysimeter. For hydrological studies under periods of droughts and irrigation studies with significant soil water deficits, lysimeter depth should permit normal root development and soil water extraction. The deepest U.S. lysimeters range from 2.5 to 2.7 m (Harrold and Dreibelbis, 1958; Dugas et al., 1985). Van Bavel (1961) advised that lysimeter depth should permit the development of normal rooting density and rooting depth and provide similar "available" water profiles to the field profile. This applies whether or not a water table is maintained within the lysimeter. If shallow lysimeters (depth < 1.5 m) are used and representative field conditions are desired, then vacuum drainage must be used to establish or equalize the water potential at the lower boundary to that in the surrounding soil (Pruitt and Angus, 1960; Van Bavel, 1961; Tanner, 1967). Dugas et al. (1990) described a constant water table weighing lysimeter and separately measured the upward flow to a soybean crop.

Soil Profile Characteristics. Selection of lysimeter profile type -- monolithic or reconstructed -- often determines the representativeness of the ET data. Bergström (1990) provided an excellent discussion of monolithic versus reconstructed lysimeters. Exact soil physical, chemical, and/or vegetation characteristics can only be preserved by soil monoliths (Armijo et al., 1972; Fritschen et al., 1973; Reyenga et al., 1988; and Schneider et al., 1988). Naturally occurring differences (both vertically and horizontally) may affect soil monolith characteristics, particularly hydraulic conductivity (Ritchie et al., 1972). Schneider and Howell (1991) discuss monolith lysimeters and convenient methods for obtaining large soil monoliths. Kohnke et al. (1940) argued that future lysimeter designs should utilize soil monoliths. However, many weighing lysimeters have utilized reconstructed soil profiles for ET measurements, which have been verified with independent energy balance measurements as well as uniform visual crop appearance. Carefully reconstructed soil profiles have provided accurate ET data (Pruitt and Angus, 1960; Van Bavel and Myers, 1962) in many situations.

Weighing Mechanisms. Mechanical scales have been widely used in weighing lysimeters since the installation of the USDA Coshocton, OH lysimeters (Harrold and Dreibelbis, 1951). Many others have been constructed since then (Morris, 1959; Pruitt and Angus, 1960; McIlroy and Sumner 1961; Van Bavel and Myers, 1962; England and Lesesne, 1962; Libby and Nixon, 1963; McIlroy and Angus, 1963; Ritchie and Burnett, 1968; Mukammal et al., 1971; Armijo et al., 1972; Mottram and De Jager, 1973; Bhardwaj and Sastry, 1973; Von Hoyningen-Huene and Bramm, 1978; Hutson et al., 1980; Dugas et al., 1985; Marek et al., 1988; Reyenga et al., 1988). Mechanical scales permit large counter-weights to offset the container and soil mass to permit precise measurement of the mass change of the water within the lysimeter. Typical ET accuracy with mechanical lysimeter scales is 0.05 mm to 0.02 mm depending on counter-balancing and the lysimeter area and mass. Mechanical scales permit tracking of load cell drift, but also can be damaged by corrosion from condensation and rust at pivot points. Several weighing lysimeter installations have used air conditioning/heating/dehumidification equipment to prevent condensation on mechanical scales.

King et al. (1956) constructed a floating lysimeter using the principle of buoyancy. The lysimeter floated within a water-filled tank and the mass change was measured by the depth change of the fluid in a stilling well. McMillan and Paul (1961) used a $ZnCl_2$ solution (specific gravity of 1.9) instead of water to reduce the need for buoyancy chambers within the lysimeter, but $ZnCl_2$ solutions were found to have larger thermal expansion errors than water (Tanner, 1967). Aslyng and Kristensen (1961) used flotation to partially offset the *dead* mass of a lysimeter. Brooks et al. (1963) constructed a floating lysimeter at Davis, CA to measure ET (Lourence and Goddard, 1967) as well as surface drag (Goddard, 1970). ET accuracy of these floating lysimeters is 0.025 mm, which is often more accurate than mechanical scale weighing lysimeters.

Various types of hydraulic weighing lysimeters have been built since the 1950's (Ekern, 1958; Glover and Forsgaste, 1962; Swan, 1964; Hanks and Shawcroft, 1965; Black et al., 1968; Rose et al., 1966; Hillel et al., 1969; Fritschen et al., 1973; Dylla and Cox, 1973; Sammis, 1981). Hydraulic weighing lysimeters have inherent limitations due to the thermal stability of the measuring fluid. They typically have accuracies of 0.05 to 0.1 mm depending on the lysimeter area and mass, and are suitable to daily or less frequent ET measurements.

Strain-gage load cells have been used to measure the total mass of lysimeters (Frost, 1962; Green et al., 1974; Green and Bruwer, 1979; Sammis, 1981; McFarland et al., 1983; Kirkham et al., 1984; and Howell et al., 1985) as well as the final mass of mechanical scales (Van Bavel and Myers, 1962; Libby and Nixon, 1963; Ritchie and Burnett, 1968; Mukammal et al., 1971; Armijo et al., 1972; Hutson et al., 1980; Dugas et al., 1985; Marek et al., 1988). Load-cell scale lysimeters usually measure the total lysimeter mass without counter-weights, so the accuracy is dictated by the load-cell accuracy and data processing and recording instrumentation. Load cells seldom are more accurate than 0.01% (1 part in 10,000), so the final lysimeter accuracy is determined by the area to mass ratio of the lysimeter. A limitation of load cell scales is the temporal zero stability of the load cell (Sammis, 1981). Howell et al. (1985) periodically lifted a lysimeter above a scale using hydraulic jacks to check the load cell zero.

Construction. Many weighing lysimeters have used steel materials for the soil containers. Reinforced-fiberglass and plastic have been used for lysimeter containers to minimize heat conduction down the lysimeter walls (Pruitt and Angus, 1960). Black et al. (1968) found about 30 W/m^2 of energy consumed in heating steel lysimeter walls for two lysimeters in Wisconsin with bare soil conditions (the worst case) . Wall heating caused a lag between the lysimeter ET and field ET during the morning and the opposite effect during the afternoon. This error was about the same magnitude as the ET accuracy (30 W/m^2 is equivalent to about 0.04 mm/h of ET) and should be much less under vegetated conditions. Dugas and Bland (1991) found much greater apparent diurnal damping depths for soil temperature in small (0.25 m by 0.7 m by 1.7-m deep) and medium (0.5 m by 1.5 m by 1.7-m deep) lysimeters (0.21 m and 0.25 m, respectively) compared to a larger weighing lysimeter (Dugas et al., 1985) and the field soil (0.14 m and 0.12 m, respectively) for bare soil conditions and steel-walled lysimeters. Concrete has been used for lysimeter walls to minimize cost. Concrete walls must be much thicker than steel. Concrete walls should end about 0.3 m below the ground and thinner steel walls extended to the surface to avoid wall heating errors.

The gap between the outer and inner containers should be as narrow as practical to limit wall heating; however, sufficient clearance should be provided to avoid any wall contact. This gap has been as small as 8 mm (Van Bavel and Myers, 1962) to as large as 38 mm (Harrold and Dreibelbis, 1967). The total wall-gap width (outer wall thickness plus gap width plus lysimeter wall thickness) is greatly affected by the wall material. For instance, the Coshocton, OH lysimeters (Harrold and Dreibelbis, 1951) used thick concrete walls which had a total wall-gap width greater than 300 mm (about 25% of lysimeter area). These lysimeter walls were modified in 1962 (Harrold and Dreibelbis, 1964) to remove the grease seal, which interfered with the lysimeter mass determinations, and reduce the near-surface wall-gap width (Harrold and Dreibelbis, 1967). Total wall-gap area to lysimeter surface area has been as small as 1.5% in several lysimeter designs.

Various lysimeter wall construction designs have been used to prevent direct water flow along the walls. The Coshocton, OH lysimeters had 38-mm wide steel bars located inside the soil monoliths to prevent direct wall flow (Harrold and Dreibelbis, 1958). Brown et al. (1985) used a 50-mm wide tape barrier about 75-mm below the rim of their lysimeters to retard wall flow. The Bushland, TX lysimeters used 102-mm "drainage collars" placed 230 mm beneath the soil surface (Marek et al., 1985) to minimize direct wall water flow in the expansive Pullman clay loam soil. The Bushland weighing lysimeters like the Coshocton lysimeters segmented the lysimeter bottom. Although drainage through the Pullman clay loam profile at Bushland is a small part of the water balance, considerably greater drainage flux has been observed from the wall sections (50% of lysimeter area) compared to the inner section (remaining 50% of lysimeter area) indicating some wall flow.

Siting. Lysimeters are intended to represent soil and plant conditions in fields or natural environments. They should be located away from taller obstructions that may alter incident radiation and wind patterns, and the topography should be as level as practical. The site should have uniform soil conditions to permit uniform crop development. Hill-top locations may have non-representative wind regimes. The lysimeter buffer area must be large enough to provide a typical micro-environment. A larger buffer area (or fetch of the same vegetation) is required in arid settings than in humid settings. Many investigators recommend an upwind fetch distance greater than 50 m and site area of 1 ha. An example of the effect of inadequate fetch was reported by Dugas and Bland (1989) in which ET was 44% greater in relation to total net radiation and soil heat flux for a 0.01 ha soybean plot surrounding a 3-m^2 weighing lysimeter at Temple, TX when the surrounding fallow soil was dry compared to similar conditions with a wet surrounding soil.

Lysimeter Operation

Cultural Operations. Cultural operations (fertilizing, tilling, planting, harvesting, etc.) are normally preformed on the lysimeter and the immediate surrounding area by hand to simulate field practices and to assure that crop development is similar to that in the surrounding field. Common problems involve service personnel and visitor traffic to the site. Trails in the crop can change the hydrology of the site and crop development surrounding the lysimeter. Many investigators use walkways (boards, light steel, bricks, etc.) to permit personnel traffic to the lysimeter site when the soil surface is wet.

Representativeness of lysimeter vegetation greatly affects ET. Pruitt and Lourence (1985) showed examples where even small differences between the lysimeter and surrounding crop greatly affected the ET. Meyers et al. (1990) reported a 30% ET reduction for soybean in a lysimeter with 0.1-m shorter crop. The ET reduction was removed when 0.1 ha of the surrounding crop around the lysimeter was shortened by 0.15 m (Meyer and Mateos, 1990). Van Bavel et al. (1963) demonstrated the dramatic effect of an intentional crop height discontinuity on ET measured with a weighing lysimeter.

Data Recording. Lysimeter data recording methods have changed dramatically over the past 20 years with developments of portable, d.c.-powered data acquisition systems using micro-computers. The Coshocton, OH lysimeters (Harrold and Dreibelbis, 1958) were the first weighing lysimeters to continuously record lysimeter mass. The Phoenix, AZ lysimeters (van Bavel and Myers, 1962) were the first to utilize automated data recording. Many weighing lysimeters still use hand recording techniques, but computerized data acquisition systems can process lysimeter and meteorological data and perform control functions (drainage, etc.) (Howell et al., 1985). The integration period for lysimeter mass has varied considerably from a few minutes to an hour depending on data recording methods. Since wind interferences limit weighing lysimeter accuracy to about 0.02 mm or greater, lysimeter mass measurements more frequent than 15 min. to 30 min. are seldom required.

Conclusions

Lysimeters have been used for centuries, but measurement and instrumentation technologies have been improved greatly during the past 50 years. Large potential errors can be reduced by designing lysimeters to meet specific requirements, by proper lysimeter operation, and by managing the lysimeter site according to design requirements. Many problems can be avoided by reviewing lysimeter literature before designing new lysimeters.

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