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Technical Paper

Construction and evaluation of an inexpensive weighing lysimeter for studying contaminant transport

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ABSTRACT

A description is provided of an above-ground, weighing lysimeter that minimizes the edge flow of water which can occur between the soil and the wall of the casing. The lysimeter was designed to study water flux and the movement of inorganic and/or organic pollutants as they pass through and beyond the root zone. The lysimeter is instrumented at selected depths with thermistors, soil solution extractors, time-domain reflectometry probes, gas extractors and tensiometers. These sensors provide temperature measurements, soil solution samples, water content measurements, soil atmosphere samples and water potential measurements. The horizontal insertion of these instruments from the side of the lysimeter reduces any channeling that might occur along the sides of the instruments, if they had been inserted vertically. Annular-ring baffles are located at selected depths to reduce edge flow between the lysimeter casing and the column of soil. The baffles redirect water flow away from the edge of the column. Data are presented that show a reduction in the hydraulic bypass of the lysimeter compared to a lysimeter without baffles. The total cost of a single lysimeter including materials and labor is under US $4000.

INTRODUCTION

Weighing lysimeters have been used extensively in agriculture, environmental science and hydrology as a means of measuring complex soil-water-chemical-plant interactions. Allen et al. (1991) provided a compilation of papers discussing the history and application of soil lysimeters for evapotranspiration and environmental measurement.

NOTATION

List of symbols used in this paper

Symbol	Description	Unit
γ	mobility coefficient, or more specifically, the fraction of V_{BI} which is subject to piston flow (where $0 \leqslant \gamma \leqslant 1$, $\gamma = 0$ represents total bypass and $\gamma = 1$ represents complete piston-type flow)	
$(1.0 - \gamma)$	fraction of V_{BI} which is bypassed	
C_{BI}	concentration of solute in the soil water immediately before an irrigation	$(g\ m^{-3})$
C_{fc}	concentration of solute in the soil water at field capacity	$(g\ m^{-3})$
C_{in}	solute concentration of the entering water	$(g\ m^{-3})$
C_{out}	solute concentration of the exiting water	$(g\ m^{-3})$
T_{AI}	total amount of solute in a volume, V_t, of soil after an irrigation	(g)
T_{BI}	total amount of solute in a volume, V,, of soil immediately before an irrigation	(g)
V_{BI}	volume of soil water in V_t immediately before an irrigation (= $\theta_{BI} V_t$)	(m^3)
V_{fc}	volume of water in V_t at field capacity (= θ_{fc} V,)	(m^3)
V_{in}	volume of water entering V_t	(m^3)
V_{out}	volume of water leaving V_t	(m^3)

Concern is mounting over the movement of both point (such as isolated accidental spills and intentional disposal of chemicals) and non-point source pollutants (such as fertilizers, pesticides, trace elements and heavy metals) into groundwater supplies because of the increased need for groundwater by domestic, agricultural and industrial users. The assessment of the hazard to soil and of groundwater contamination by a pollutant comprises integrative levels of sequential investigation including laboratory testing, model calculations, outdoor lysimeter simulation studies and field testing (Esser et al., 1988; Klein et al., 1988). Laboratory transport studies allow comparisons between chemical substances and the identification of the critical properties that control their movement. However, laboratory-to-field extrapolations are often not valid due to temporal and spatial variations in the field. On the other hand, these variations make field tests site- and time-specific. Consequently, soil lysimeters have become increasingly important to study the fate and movement of organic and inorganic pollutants within and beyond the root zone. Indeed, guidelines for waste disposal, and for the use of pesticides and fertilizers appear to be increasingly dependent on data obtained from lysimeter experiments (Cameron et al., 1992). However, interpreting the results of lysimeter experiments is best done knowing their basic limitations and their limited extrapolation to the field.

Weighing lysimeters are particularly well-suited for the development and validation of one-dimensional solute transport models. The transport parameters essential for model input can be obtained more easily and more efficiently than in field experiments with less concern for lateral variations in transport properties of soil. An ideal approach to the study of the movement of contaminants in the root zone requires discrete sampling of the soil solution at specific times and depths within a chemically- and physically-characterized soil profile (Fermanich et al., 1991). The soil-solution sample should be free of any contaminants from the sampling equipment and should be obtained under natural water flow conditions (Fermanich et al., 1991). It is desirable to couple natural flow and dissipation conditions similar to the field with the controlled conditions found in the laboratory. Soil columns operated under unsaturated flow conditions can simulate the water flow that normally exists in field soils (Weber and Witacre, 1982). Lysimeters allow the experimenter to sample the confined soil system intensively, to control its inputs and to measure its outputs more easily. All of the processes involved in solute transport including evapotranspiration, water and solute inputs, chemical reactions, degradation, volatilization and drainage can be measured independently. Even though the measurement of these processes is more difficult in a lysimeter than in a laboratory study, it is less difficult than in a field study.

A lysimeter study must not suffer from inaccuracy due to the design of the lysimeter. Uncertainty exists about the influence of edge flow of water and solutes along the sides of a lysimeter. This can substantially increase the preferential flow of solutes in excess of levels of hydraulic bypass found under field conditions (Till and McCabe, 1976; Wild and Cameron, 1980; Cameron et al., 1990, 1992). Cameron et al. (1992) eliminated edge flow by filling the annular gap between the soil monolith and the wall of the casing with liquefied petrolatum. The liquefied petrolatum provided a water-tight seal around the edge of the lysimeter. However, the use of petrolatum as a sealant renders a lysimeter unsuitable for pesticide transport studies.

It is the purpose of this paper to present the description of a modified weighing lysimeter that was designed to reduce edge flow of water and solutes between the soil monolith and the lysimeter wall. The lysimeter is particularly well-suited for controlling water flow and determining the fate and movement of organic and inorganic contaminants within the root zone. The lysimeter is instrumented to determine water flow, drainage and evapotranspiration. Furthermore, it is a simple matter to obtain samples to determine the chemical composition of the soil solution and the soil atmosphere composition. The cost of a single lysimeter is approximately US $4000, including materials and labor.

LYSIMETER CONSTRUCTION

A photograph of a set of four weighing lysimeters is presented in Fig. 1. The lysimeters are shown encased in their insulated housings. The rail-guided, mobile hoist that straddles the first lysimeter is used to weigh the lysimeters. A plastic enclosure protects the lysimeters, the work area and the weighing apparatus from rain. The sides of the plastic enclosure can be raised or lowered to protect the lysimeters from adverse conditions without appreciably altering ambient meteorological conditions such as relative humidity, temperature, etc. The soil solution collection tubes and the soil atmosphere

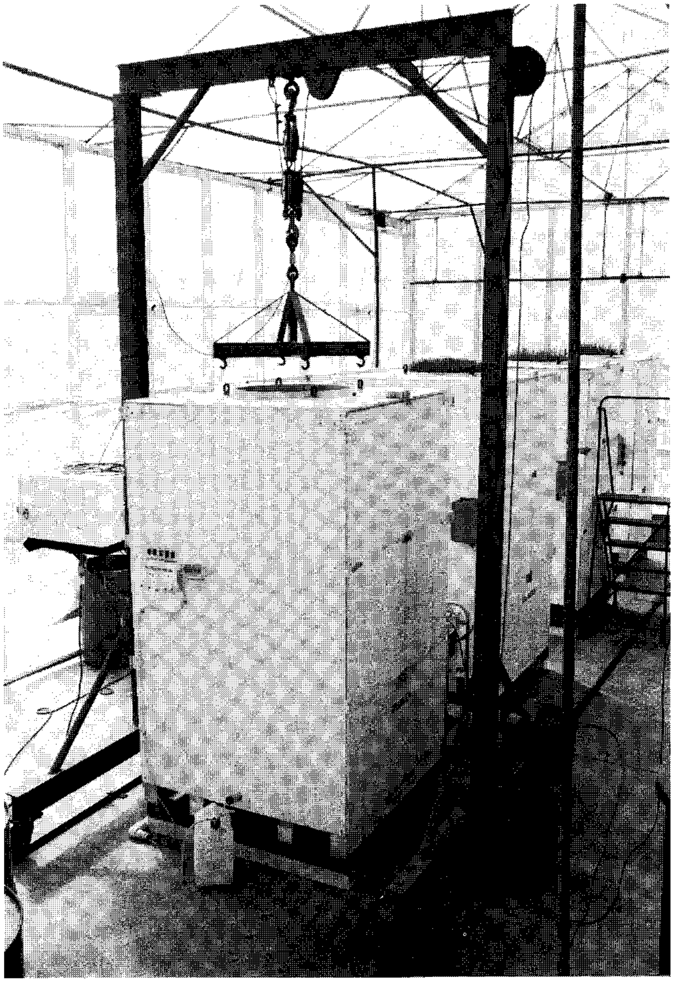

Fig. 1. A set of four weighing lysimeters showing the rail-guided, mobile hoist and the protective rain cover enclosure.

septa are visible on the left-hand side of the housing of the first lysimeter. The drainage collection bottle is seen at the base of the lysimeter.

The following is a detailed description of each structure seen in Fig. 1:

Lysimeter design

Fig. 2 presents an illustrated schematic of the lysimeter design showing

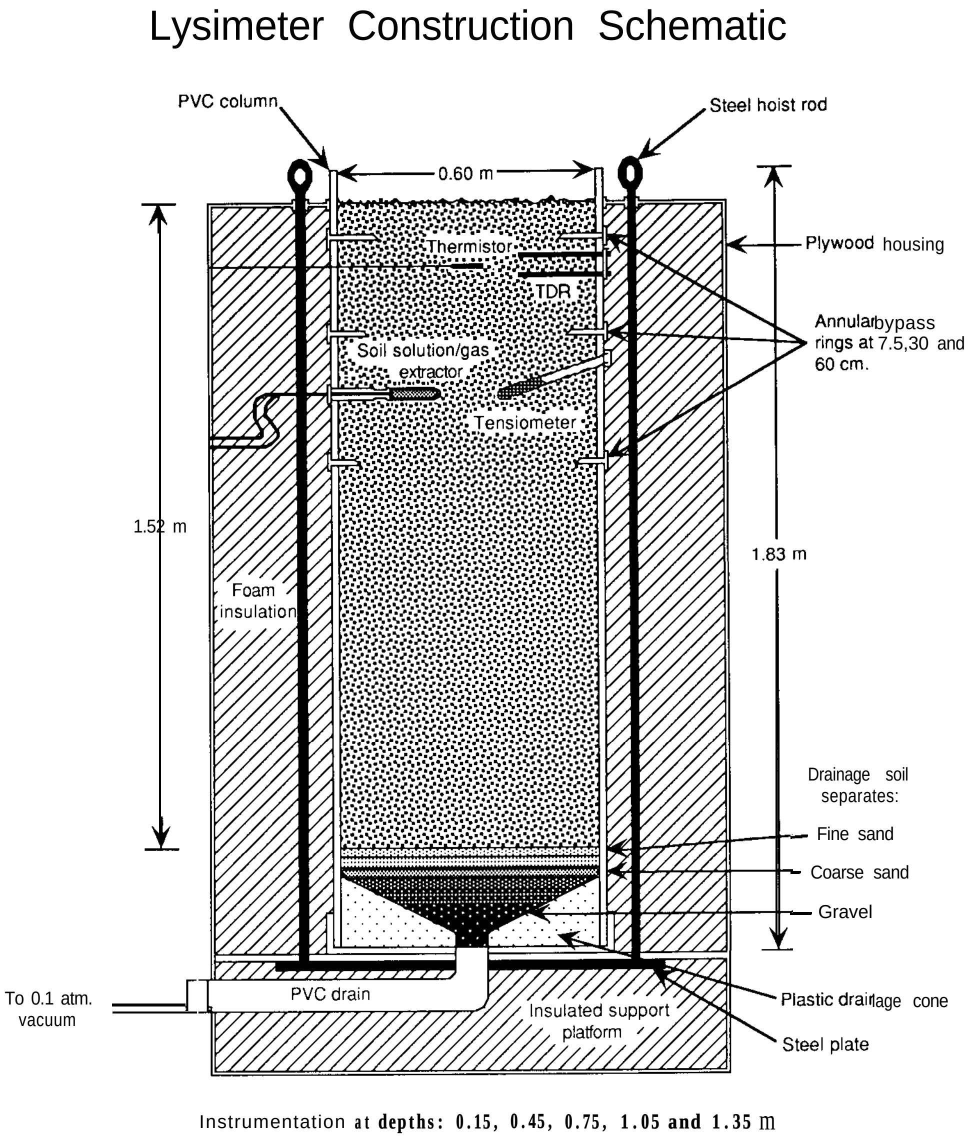

Fig. 2. A schematic of the soil lysimeter design.

the soil column, the housing and the instrument placement. The lysimeter casing is made of a column of 1.25 cm thick polyvinylchloride (PVC) which is 0.6 m in diameter and 1.83 m in length. A plywood housing (1.2 m x 1.2 m x 2.4 m) surrounds the PVC column. The housing holds the foam insulation surrounding the soil column. Sufficient foam insulation (~ 22.5 cm thick) surrounds the column so that a fluctuation in ambient air temperature of 39°C over a 12-h period will result in a fluctuation in temperature at the side of the column of only 1 °C. The column rests on a steel plate surrounded by four steel hoist rods. The rods are used to lift the entire structure for the purpose of weighing with a load cell. The column is cut into four segments of 7.5,22.5, 30 and 123 cm lengths. Between each segment an annular bypass ring made of PVC is inserted to act as a baffle to divert the flow of water along the side of the column toward the inside. The width of the annular ring decreases with depth from 7.5 cm in width at the 6.25-cm depth to 5 cm in width at the 30-cm depth, and to 3.75 cm in width at the 60-cm depth. The annular bypass rings are designed to reduce edge flow caused by the soil pulling away from the casing as the soil dries due to evapotranspiration.

Soil

A loam soil excavated from the University of California campus in Riverside, California, was used as backfill in the weighing lysimeter. The 1.83-m column was filled with 1.52 m of soil (see Fig. 2). After filling the lysimeter with soil, it was subjected to wetting-drying cycles over a 6-month period to promote the settling of soil particles. The soil reached an average bulk density of $1.61 \pm 0.06\ \mathrm{g\,cm^{-3}}$. The remaining 0.31 m of the column was composed of drainage material at the bottom of the column (23.5 cm of drainage material) and free-space at the top of the column for ponding irrigation water containing the contaminant (7.5 cm of free-space). In the past, refilled lysimeters have been criticized because of the artificial nature of the soil system and the alteration of the water and solute flow pathways (Cassell et al., 1974). McMahon and Thomas (1974) and Smith et al. (1985) have shown that the use of undisturbed soil columns better approximates field movement of water and solutes than columns of disturbed soil. Even though the task is more difficult, an intact column of soil can be placed into the column following the method of Cameron et al. (1992) and the annular bypass rings inserted in place afterward. Disruption of the undisturbed soil is minimized by keeping the bypass rings very thin and tapered.

Drainage

The bottom of the soil lysimeter column was filled with 23.5 cm of drainage material (see Fig. 2). The drainage material consists of eight different soil separates. The soil separates range from a fine sand to a gravel. A drainage cone was installed at the base of the column to channel the flow of drainage water, and thereby reduce the likelihood of the formation of a zone of saturated water at the bottom of the column. In addition, a vacuum of 0.1 atm can be applied continuously to the PVC drain to assist in the elimination of saturated conditions. The intention is to simulate a semi-infinite soil column. However, it is also possible to remove the vacuum and thereby, intentionally create a water table. The depth of the water table can be controlled with a manometer attached to the PVC drain.

Instrumentation

Each column was instrumented with thermistors, soil solutiongas extractors, tensiometers and time-domain reflectometry (TDR) probes. The instruments were placed in duplicate at five depths. The five depths were 0.15, 0.45,0.75, 1.05 and 1.35 m. The duplicates of the extractors, tensiometers and TDR probes were located on opposite sides of the column, and thereby provide a measure of the local variability. A schematic of the construction of a thermistor is illustrated in Fig. 3. The two thermistors at each depth were positioned 15 and 30 cm from the side of the column. These two locations provided a measure of both the spatial variation in temperature fluctuations moving down through the soil from the surface and the effect of temperature change along the side of the column, indicating how effectively the insulation was eliminating lateral temperature changes. Fig. 4 shows a schematic of the gas-soil solution extractor. The combination gas-soil solution extractor was designed by Suarez (1986). The design minimizes CO_2 degassing, thereby reducing any change in the pH of the soil solution once extracted from the soil. Fig. 5 is a photograph of a tensiometer and the Tensimeter® recorder

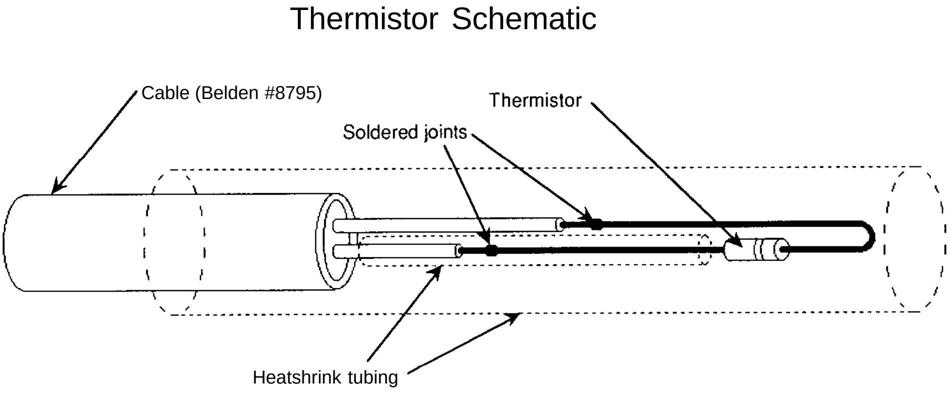

Fig. 3. A schematic of the thermistor design.

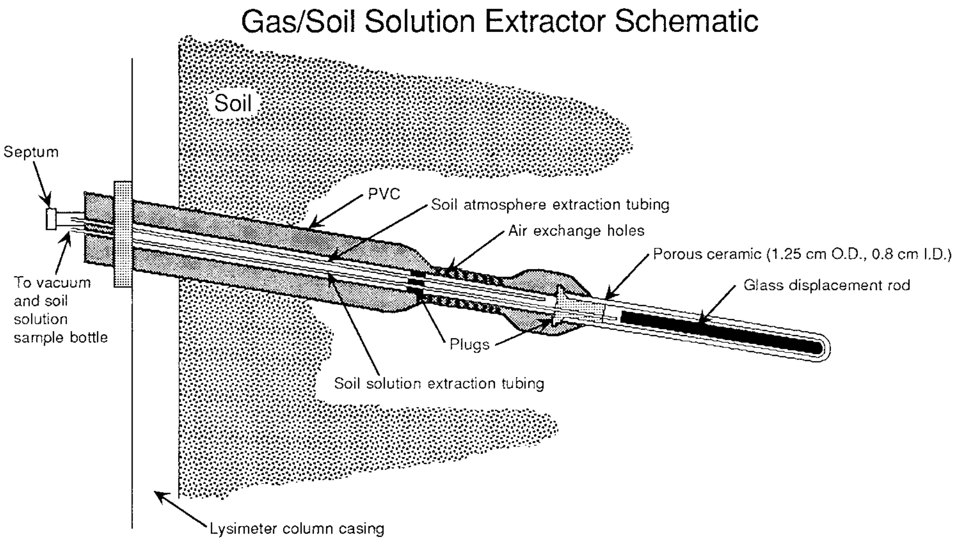

Fig. 4. A schematic of the soil atmosphere–soil solution extractor design (Suarez, 1986).

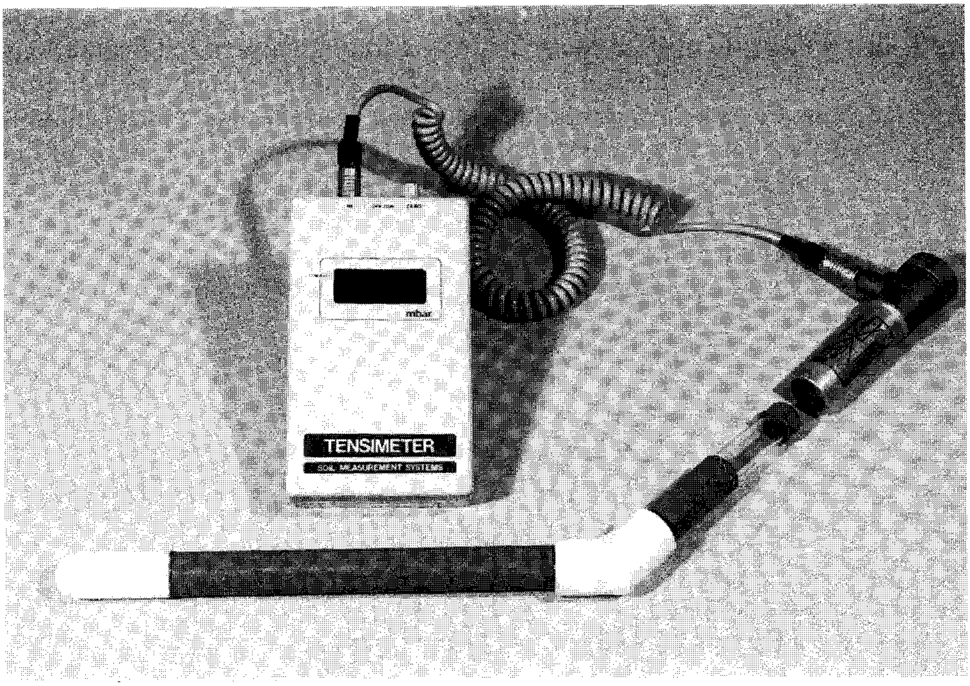

Fig. 5. Photograph showing a soil tensiometer and the Tensimeter® recorder which is used to read matric potential quickly and easily.

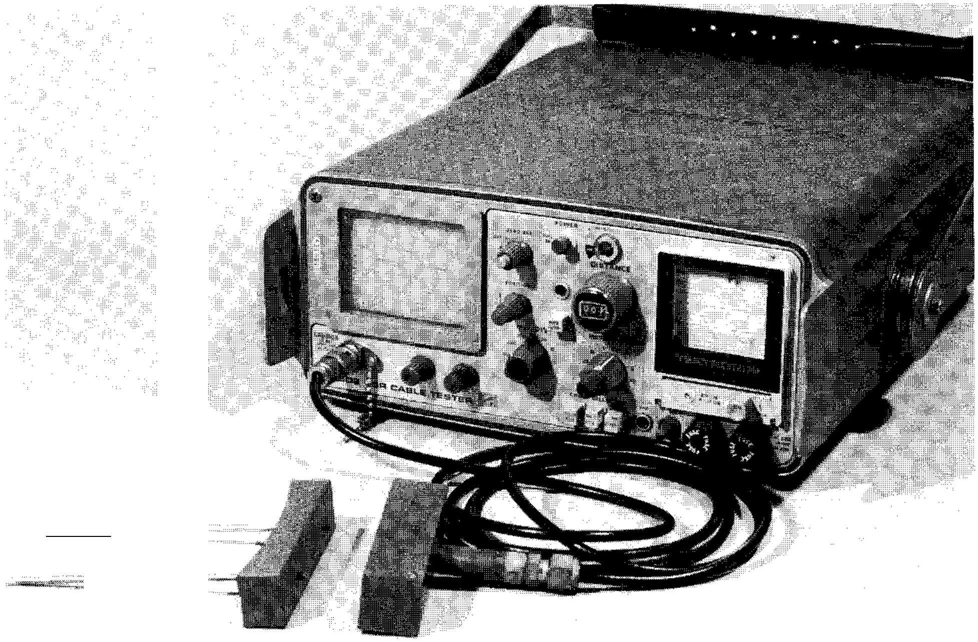

Fig. 6. Time-domain reflectometry (TDR) rods and the portable oscilloscope for reading TDR

used to quickly and easily measure the matric potential of the soil. Fig. 6 shows a set of TDR rods which can be inserted into the side of the soil column and used to measure the volumetric water content with the portable cable tester. Volumetric water content is determined from TDR by obtaining the dielectric constant of the medium through a measure of the transit time of an electromagnetic pulse launched along the rods embedded in the soil (Topp et al., 1980). Fig. 7 shows a view of the instrument location along one side of the lysimeter. In a vertical line down the center of the column are the heads of the TDR rods. Off to the left-hand side are the ends of the tensiometers protruding through the foam insulation. The soil solution and soil atmosphere collection tubes are off to the side and are best seen in Fig. 1. The thermistors are read from a terminal box with a simple resistivity meter connected to a channel selector.

Weighing apparatus

Figs. 8 and 9 show the weighing apparatus used to determine the weight loss of the lysimeter due to evaporation and transpiration. Fig. 8 shows the calibration weights of sealed drums containing dry sand, the hoist and the load cell. Fig. 9 shows the millivolt meters used to read the load cell. The load

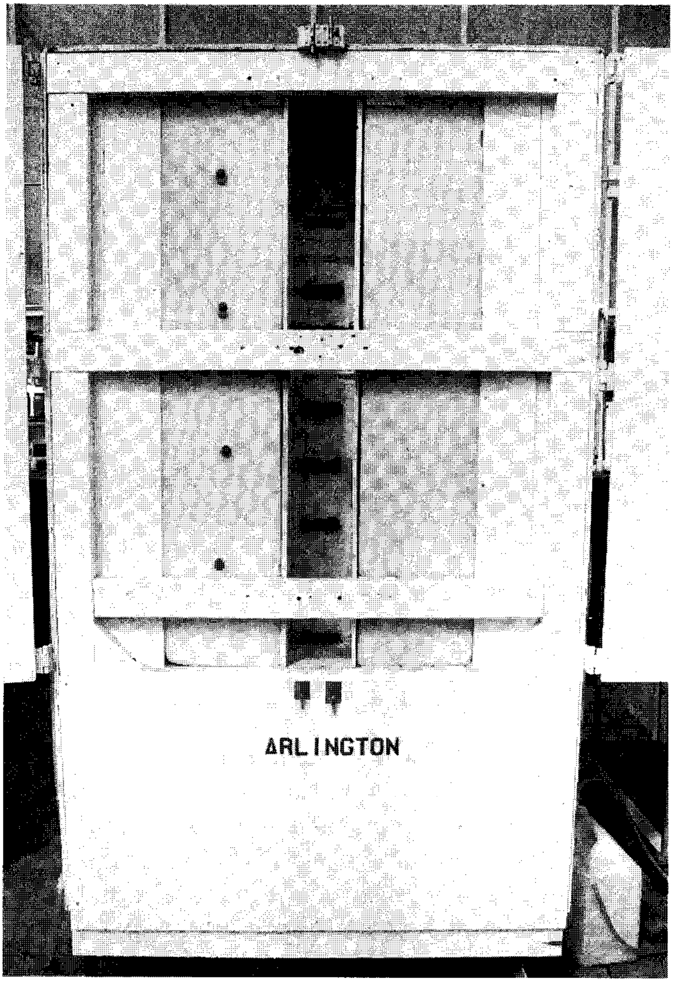

Fig. 7. Instrument placement of TDR rods and tensiometers along one side of a lysimeter.

cell is a stainless-steel 1364-kg load-capacity cell. The load cell was designed to provide automatic compensation both to reduce zero and calibration errors due to temperature. The total saturated mass of a single lysimeter was ~1300 kg or 100% of the load cell design capacity. The load cell had the following specifications: rated output of 3 mV V^{-1}, zero balance of < 2% of full scale, maximum nonlinearity of ±0.03% of full scale, maximum hysteresis of ±0.03% of full scale, maximum nonrepeatability of ±0.01% of full scale, maximum creep of ±0.03% of the load in 20 min, maximum temperature effect on zero balance of ±0.0015% $°C^{-1}$ of full scale, maximum temperature effect on output of ±0.0014% $°C^{-1}$ of load and operating temperature range of -55” to 95°C. To raise and lower the lysimeter a battery-powered winch was used.

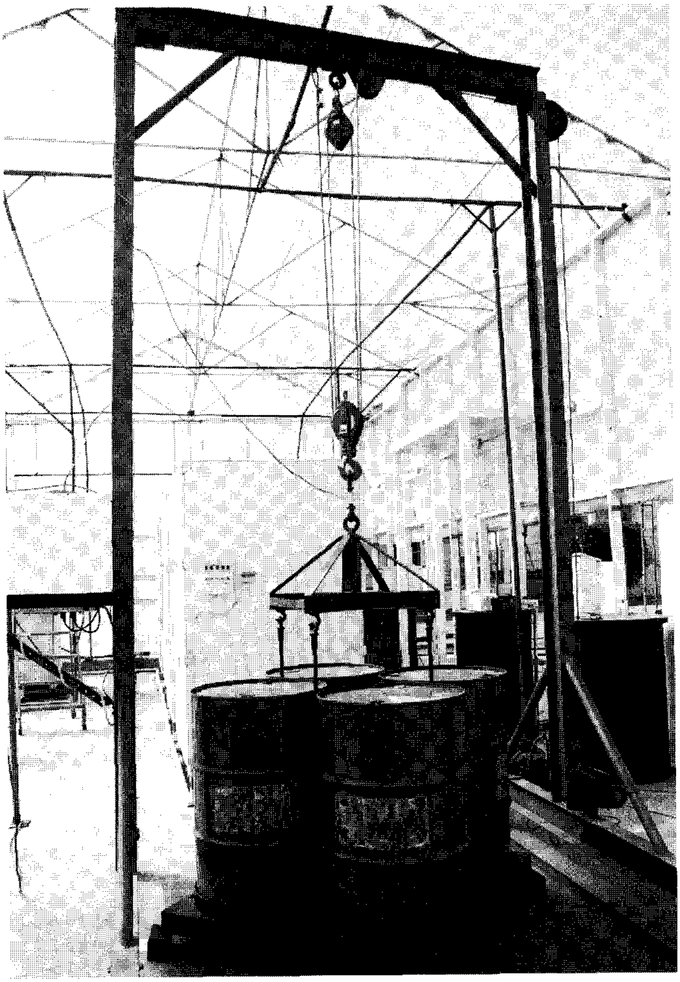

Fig. 8. Hoist, load cell and calibration weights of the soil lysimeter weighing apparatus.

Cost

An itemized list of equipment and labor costs is presented in Table 1. The cost of labor (at US \$20 h^{-1}) and materials for a single lysimeter including the instruments is under US \$4000. The weighing apparatus shown in Figs. 8 and 9 including the labor, materials for the hoist and instruments (i.e. millivoltmeter and load cell) is approximately US \$4550. The enclosure (see Fig. 1) to protect the lysimeter(s) from the rain is approximately US \$400 per lysimeter. The complete set of four lysimeters in Fig. 1 cost a total of approximately US \$22,000.

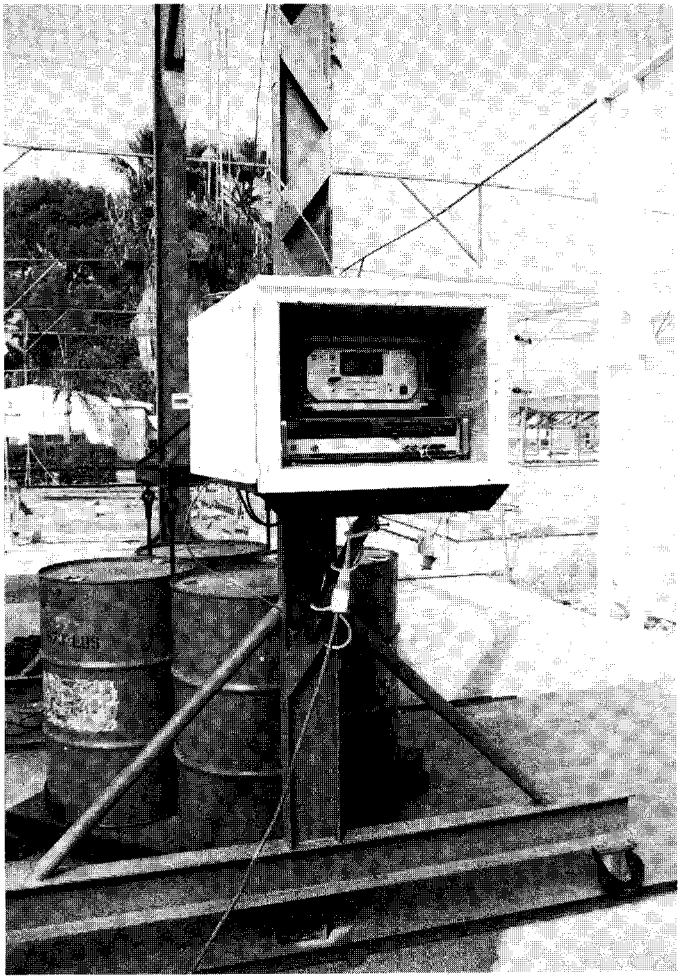

Fig. 9. Encased millivolt meters used to read the load cell

EVALUATION OF BYPASS IN THE LYSIMETER

To evaluate the magnitude of preferential flow in the constructed soil lysimeter, the transient-state solute transport model TETrans (Corwin and Waggoner, 1991; Corwin et al., 1991) was used.

It has been shown that the mobility coefficient, γ, in TETrans can be used to determine temporal and spatial variations in bypass (Corwin, 199 1; Corwin et al., 1991). The mobility coefficient, as defined by Corwin et al. (1991), represents "the fraction of the soil liquid phase which is subject to piston-type displacement."

The mobility coefficient is analogous to the volume of water theoretically

TABLE 1

Itemized list of labor (estimated at \$20 h^{-1}) and material costs for a single lysimeter, the instruments, the weighing apparatus, and the protective rain cover

	Materials	Labor
Lysimeter		
housing	\$480	\$800(40 h)
PVC column	\$565	\$800(40 h)
Total	\$1.045	\$1,600(80 h)
Instruments (cost per instrument)		
thermistor	\$4.50	\$10(0.5 h)
solution/gas extractor	\$10.00	\$60(3 h)
TDR block & probes	\$2.00	\$20(1 h)
tensiometer	\$6.00	\$30(1.5 h)
Total	\$13.50	\$120(6 h)
Weighing apparatus		
hoist	\$1,542	\$800(40 h)
load cell	\$350	
digital readout meter	\$1,865	
Total	\$3.157	
Rain cover (cost per lysimeter)	\$250	\$160(8 h)

and experimentally shown by Wierenga (1977) to be responsible for solute movement under transient water flow.

The determination of the mobility coefficient is based upon the deviation of measured soil solution chloride concentrations from calculated concentrations for each irrigation/precipitation event and each depth increment assuming complete piston-type displacement of the solute. In TETrans this deviation is assumed to be attributed in large part to bypass resulting from preferential movement through macropores and from the movement of a mobile water phase, thereby bypassing small dead end pores and a stagnant immobile phase of water. Though dispersion and anion exclusion would also account for the deviation of chloride transport from strict piston flow, these effects are assumed to be negligible. If dispersion is a significant factor then its effects are assumed to be inclusive within the bypass phenomenon, and compensated for in the mobility coefficient. To calculate the mobility coefficient, γ, for each irrigation and for each depth increment, equations (2) and (4) from Corwin et al. (1991) are used. Equation (2) from Corwin et al. (1991) can be rearranged to give the following equation (see also the Notation for symbols used in this paper):

$$C_{out} = (T_{BI} + V_{in}C_{in} - T_{AI})/V_{out} \tag{1}$$

where C_{out} is the solute concentration of the exiting water (g m^{-3}); T_{BI} is the total amount of solute in a volume of soil V_t immediately before an irrigation (g) [V_t is a unit volume of soil within the depth interval z_1 to z_2 (m^3)]; V_{in} is the volume of water entering V_t (m^3); C_{in} is the solute concentration of the entering water (g m^{-3}); T_{AI} is the total amount of solute in a volume of soil after an irrigation (g); and V_{out} is the volume of water leaving V_t (m^3). Equation (4) from Corwin et al. (1991) can be rearranged to give the following equation:

$$\gamma = (V_{out}C_{out} - V_{out}C_{in})/(V_{BI}C_{BI} - V_{BI}C_{in}) \tag{2}$$

where V_{BI} is the volume of soil water in V_t immediately before an irrigation (m^3); and C_{BI} is the concentration of the solute in the soil water immediately before an irrigation (g m^{-3}). Because T_{AI} can be calculated from the measurement of the chloride concentration of the soil solution at field capacity (for a nonreactive solute, $T_{AI} = V_{fc}C_{fc}$, where V_{fc} is the volume of water in at field capacity and C_{fc} is the concentration of the solute in the soil water at field capacity), then γ can be determined by substituting Eq. 1 into Eq. 2:

$$\gamma = (V_{in}C_{in} + T_{BI} - V_{fc}C_{fc} - V_{out}C_{in})/(V_{BI}C_{BI} - V_{BI}C_{in}) \tag{3}$$

Eq. 3 holds for the situation where $V_{in} > V_{fc} - (1.0 - \gamma)V_{BI}$ for $0 < \gamma \leqslant 1$. However, because γ is precisely the term that is being determined, then Eq. 3 can only explicitly be used when $V_{in} > V_{fc}$. If it is found that the total chloride, T_{AI}, measured for a depth increment is equal to:

$$T_{AI} = (V_{fc} - V_{in})C_{BI} + V_{in}C_{in} \tag{4}$$

then it is known that the condition:

$$V_{fc} - V_{BI} < V_{in} < V_{fc} - (1.0 - \gamma)V_{BI} \qquad \text{for} \qquad 0 < \gamma \leqslant 1$$

is the case; consequently, it is assumed that:

$$\gamma = (V_{in} - V_{fc} + V_{BI})/V_{BI} \tag{5}$$

because it is impossible to determine γ explicitly and this represents the closest logical approximation. If the total measured chloride is equal to:

$$T_{AI} = V_{BI}C_{BI} + V_{in}C_{in} \tag{6}$$

then it is known that the condition $V_{in} \leqslant V_{fc} - V_{BI}$ exists; consequently, $\gamma = 0$ is assumed. If the total measured chloride is equal to:

$$T_{AI} = V_{BI}C_{BI} + (V_{fc} - V_{BI})C_{in} \tag{7}$$

when $V_{in} > V_{fc} - V_{BI}$, then $\gamma = 0$. The only condition for which γ has not been determined is when:

$$V_{fc} - (1.0 - \gamma)V_{BI} \leqslant V_{in} \leqslant V_{fc} \qquad \text{for} \qquad 0 < \gamma \leqslant 1$$

If all other conditions are not met, then this condition is assumed to be the case and Eq. 3 is invoked. Anomalous situations could arise where γ is calculated by Eq. 3 to be outside its defined range. By definition $0 \leqslant \gamma \leqslant 1$, so if γ is calculated to be < 0, then γ is set equal to 0. Similarly, if γ is calculated to be > 1, then γ is set equal to 1.

METHODS AND MATERIALS

A solute transport experiment was conducted with a soil lysimeter column modified to minimize edge flow with annular bypass rings. The results are compared to an unmodified soil lysimeter column previously used by Corwin et al. (1991). Both modified and unmodified lysimeters contained a loam soil. The modified and unmodified lysimeters were packed to the same bulk density (1.61 g cm^{-3}) with a homogeneous mixture of the same soil to minimize differences in macropore structure and dispersion. The difference in bypass between the two lysimeters was assessed through the determination of a mobility coefficient, γ, averaged over time and depth for the movement of chloride. The differences in mobility coefficients between the two lysimeters were attributed primarily to edge flow differences.

Plugs of chloride were passed through soil lysimeter columns at intermittent intervals. From the chloride concentrations predicted by TETrans, which assumes piston-type flow and the measured chloride concentrations, optimization techniques were used to determine γ for each irrigation event and each depth.

The input data needed for TETrans included: initial chloride concentration in the soil water; initial water content of the soil; dates and amounts of irrigation water applied; total evapotranspiration lost between irrigations; horizonation of the soil with the associated bulk density, water content at field capacity and water content at the wilting point for each horizon depth increment; chloride concentration of each irrigation water applied; chloride concentration of the soil solution (at field capacity) after selected irrigations; date of planting, days to maturity, date of harvest, maximum depth of root penetration and plant root distribution for each crop.

DISCUSSION OF RESULTS

Corwin et al. (1991) reported an average mobility coefficient for a soil lysimeter with no modifications in its construction for minimizing edge flow to be 0.498 ± 0.056. This means that 50.2% [i.e. $(1 - \gamma) = 0.5021$ of the liquid phase was bypassed. The average mobility coefficient for a soil lysimeter modified according to the construction design presented in this paper was 0.709 ± 0.117. This means that only 29.1% of the liquid phase was bypassed. The reduction in the fraction of the liquid phase which is involved in bypass is attributed to the minimization of edge-flow between the soil monolith and the casing.

SUMMARY

The design of an inexpensive (i.e. approximately US $4000 in materials and labor) weighing soil lysimeter which can be used to study the movement of inorganic and organic comtaminants through the root zone is presented. The design introduces the use of three annular bypass rings which minimize the edge-flow effects between the soil and the column casing. Edge-flow effects are common in most other soil lysimeters.

The lysimeter is fully instrumented to provide for the measurement of soil matric potential, volumetric water content and evapotranspiration. Extractors installed at selected depths provide soil atmosphere and soil solution samples. The combined soil solutionsoil atmosphere extractor provides a soil solution sample that has minimal contact with the atmosphere, thereby, reducing any CO_2 exchange that will alter the pH of the soil solution. The altered pH would change the solution chemistry.

The lysimeter design and installed instrumentation make it a useful tool for contaminant transport studies and for the validation/calibration of one-dimensional solute transport models. The cost of each lysimeter is approximately US $4000 with a low operation and maintenance cost. Operation and maintenance are quick and easy because the lysimeter is above ground.

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