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Rainfall Simulator - Grid Lysimeter System for Solute Transport Studies Using, Large, Intact Soil Blocks

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ABSTRACT

A grid lysimeter system and sample collection, containment and storage techniques were developed for detailed laboratory studies of water and solute movement through intact soil blocks. This was done because existing designs and techniques had important deficiencies and were limited in their range of capabilities. Intact 46-cm soil cubes were isolated, then contained within a polyurethane foam shell, which formed a stable, intimate soil bond, was impermeable to water and strong enough to support a large soil block, while sufficiently elastic to accommodate soil shrink-swell with changing water content without rupturing. The soil blocks were instrumented with solution delivery, collection and monitoring systems. A dripper-based simulator delivered steady rainfall ranging from 4.8 to 30.0 mm hr^{-1}. The solution collection system was a 10 by 10 grid of cells (3.8 by 3.8 by 1.3 cm deep) milled into an aluminum block which individually drained into collection tubes housed within a vacuum chamber. The collection grid permitted characterization of spatial and temporal water and solute movement through the block. The solution monitoring system consisted of side-by-side tensiometer pairs and TDR probes inserted horizontally through the foam shell at four depths in the block. As a partial test of the system, a bromide (Br^-) tracer breakthough curve (saturated flow) was generated at a simulated rainfall rate of 19.2 mm hr^{-1}. Flow data indicated that 85% of the water in the block was "bypassed" by the Br^-, and that >99% of the water flow passed through only 26% of the basal area of the block. The water flow pattern in the solution collector exhibited no evidence of preferential flow along the interface between the soil and the outer polyurethane shell. It was concluded that the rainfall simulator-grid lysimeter system was operating effectively.

Index Words: preferential flow, solute transport, macropore, by-pass flow

INTRODUCTION

During recent years there has been increasing interest in preferential water flow through soils and the resulting potential for rapid transport of pesticides, nutrients and other solutes to tile drains and groundwater. A well established technique for characterizing preferential water and solute movement is the use of instrumented, intact soil cores or blocks (Murphey *et al.*, 1981; Buchter *et al.*, 1984; Lewis *et al.*, 1990; Isensee and Sadeghi, 1992; Tindall *et al.*, 1992). Inherent in the successful use of this method, however, are several difficult and critically important steps, including the choice of adequate block size, the use of effective techniques for isolating, transporting and storing the block, and the instrumentation of the block with appropriate, effective solution delivery, collection and monitoring systems.

Many studies have concluded that preferential water and solute movement in undisturbed field soils is caused primarily by extreme variability in the sizes, shapes, connectivity and distributions of soil pores, and by "fingering", "wetting front instability" or "funneled flow" at soil layer or horizon boundaries (Baker and Hillel, 1990, 1991; Kung, 1990a, 1990b; Steenhuis and Parlange, 1991; Selker et al., 1992). Because of this, Bouma and Wösten (1979) have suggested that accurate representations of preferential flow behaviour can only be obtained from intact soil cores and blocks ($ 13 L) that contain the major soil horizon and layer boundaries. Beven and Germann (1981) further suggested that "representative elementary volumes" (REV) which encompass macropore variability may approach or exceed 1 m^3, whereas 1 cm^3 volumes may suffice to represent micropore variability. Such large intact soil volumes require elaborate and specialized techniques for successful isolation, transport and storage.

A variety of materials have been used to form protective shells around intact soil blocks. Murphey et al. (1981) used layers of polyester resin and fiberglass cloth, which required very careful operation of a bandsaw to prevent soil breakage, smearing or compaction upon subsequent opening of the resin-cloth shell. Buchter *et al.* (1984) encased their soil block in concrete, using a paraffin seal between the soil and concrete, which had the obvious inconvenience of the added weight and bulkiness, as well as the inability to shrink and expand with soil

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Abbreviations: TDR, time domain reflectometry, REV, representative elementary volumes, BTC, breakthrough curves, SS, stainless steel.

moisture changes. Andreini and Steenhuis (1990) and Ogden *et al.* (1992) used a plaster of paris shell around their block, which had the potential for forming shrinkage cracks upon drying, being permeable to water, and being too rigid to accommodate shrink and swell of the soil during wetting-drying cycles. Lewis *et al.* (1990) used triple-expanding polyurethane foam to form a seal between a polyvinylchloride pipe (46-cm. diam.) and free-standing circular soil pedestals 60 to 90 cm in length. The foam formed a very effective, light-weight, inert, water-proof seal around the pedestal. Shipitalo *et al.* (1990) also used liquid polyurethane foam to encase their 30 by 30 by 30-cm soil blocks, using a plywood box for the outer form.

Isensee and Sadeghi (1992) and Tindall et al. (1992) used metal cores to isolate soil pedestals. Isensee and Sadeghi drove 10.2-cm diam. aluminum cores of various lengths into the soil, while Tindall *et al.* pressure-inserted 30-cm diam. by 38-cm long stainless steel core barrels using a vehicle-mounted hydraulic press. Important limitations of this approach are potential compaction and macrostructure collapse in the soil due to frictional resistance and vibration during the core insertion process. We have frequently noted in pan lysimeter studies that although the soil matrix tends to have considerable resistance to deformation forces, the soil macrostructure is quite fragile and easily damaged with very little penetrating force. Isensee and Sadeghi (1992) used an epoxy cement sleeve to encase the soil blocks, which was strong, impermeable to water, and formed a stable, intimate epoxy-soil seal by penetrating 0.2 to 0.3 cm into the soil. Like plaster of paris, it would be too rigid to accommodate soil shrink-swell. Tindall *et al.* (1992) cast melted paraffin wax sleeves around their pedestals which, like epoxy or plaster of paris, would be too rigid to accommodate soil shrink-swell. Furthermore, it tends to shrink upon cooling which might result in partial or complete rupture of the soil-paraffin seal.

To study spatial and temporal variability of water and solute movement through intact soil blocks, one must interface the block with solution delivery and collection systems. Andreini and Steenhuis (1990) constructed a grid collector (6 by 6 array of 2.5- by 2.5-cm square cells, surrounded by two courses of 5- by 5-cm cells), which was filled with 1-cm diam. chipped limestone, used for both support and as an interface to conduct percolate away from the base of the block. Their solution delivery device was a single 18-gauge catheter mounted on a trolley riding back and forth on a set of rails. The grid collector used by Shipitalo *et al.* (1990) consisted of an 8 by 8 array of 3.75- by 3.75-cm square funnels, covered by a fine screen to support the soil block. They delivered solution to the block via a syringe-grid applicator capable of X-Y translation similar to the rainfall simulator used by Römkens *et al.* (1975). Isensee and Sedeghi (1992) used a rainfall simulator consisting of a single line of eleven, 0.1-cm i.d. teflon drippers (1.5 cm spacing). A gearmotor produced a 2-cm oscillation for the entire assembly. Tindall *et al.* (1992) used a single stationary dripper centered over a tripod that distributed the solution over the soil surface. Both Isensee and Sadeghi (1992) and Tindall et al. (1992) employed membrane-based solution collectors, Isensee and Sadeghi using a filter paper disk and Tindall *et al.* using a ceramic plate. Membranes allow vacuum to be applied to the soil for unsaturated flow studies, but do not allow determination of the spatial and temporal distributions of water and solute flow through the base of the soil samples. The reverse applies to the grid collectors of Andreini and Steenhuis (1990) and Shipitalo *et al.* (1990).

In this report, we combine and refine the best elements of the above techniques and equipment to construct a rainfall simulator-grid lysimeter system for use with large, intact soil blocks (46-cm cubes; about 145 kg). The system includes a highly-detailed grid-type solution collector that allows vacuum to be applied to the base of the block, a rainfall simulator that can deliver a wide range of rainfall rates with high uniformity, and networks of tensiometers and TDR probes for non-destructive in-situ measurement of matric potential and volumetric water content, respectively. A brief test of the system for saturated flow is also given.

MATERIALS AND METHODS

Soil Block Collection

Soil blocks (46-cm cube) were carefully isolated from a soil profile using a flat shovel to cut straight, smooth surfaces. An open-ended plywood box (51-cm cube I.D., 2-cm wall thickness lined on the inside with polyethylene film) was positioned over the block, maintaining a uniform space of about 2.5 cm on each vertical side. A polyethylene-covered "protector plate" 46 by 46 by 10 cm high, was positioned on the top of the soil pedestal to prevent expanding foam from flowing onto the soil surface. One-L volumes of both polyurethane foam components (isofoam® A and B, I.P.I. Div. of Kingsley and Keith (Canada Inc.) were mixed vigorously for 10 s, then poured into the cavity between the soil block and the plywood box. Within 10 min, the foam had expanded and hardened sufficiently to remove the protector plate and to trim the excess foam from the top of the box with a corrugated blade. Small bags of vermiculite pellets were carefully packed onto the top of the block to maintain the antecedent soil surface conditions during transport and manipulation, then a plywood cover was screwed onto the top of the box.

A 1-m^2 area of soil adjacent to the block was excavated to the full depth of the block so that its base could be cut off using an hydraulically operated, 76 by 71 by 0.3 cm, "cutoff" plate. Adjustable angle iron strips, separated by the width of the plywood box and parallel to the insertion direction, were bolted to the cutoff plate to stiffen it and to prevent bending when lifting the soil block out of the pit. The angle iron also acted as guides for the cutoff plate during the insertion process. Prior to cutoff plate insertion, several 3-cm diameter horizontal holes were bored beneath the pedestal at right angles to the direction of plate insertion. This served to loosen the soil below the block thereby minimizing damage to the block base during the insertion process. A backhoe bucket was used to prevent movement of the block during plate insertion. After the cutoff plate was inserted, the entire box-cutoff plate assembly with its contained soil block was lifted onto a wooden skid covered with a foam cushion and transported to the laboratory for storage at -5/C.

Solution Collector Design and Installation

The solution collector consisted of an anodized aluminum plate 60 by 60 by 2 cm, into which was machined a grid of 10 by 10 (100) square funnels, (3.8 by 3.8 by 1.3 cm deep), each leading to a central tubular drain hole (Leesta Industries, Montreal, QUE) (Fig. 1). To avoid possible edge effects, the grid of funnels was confined to the centre 38- by 38-cm area of the soil block. The flow in the 4-cm wide boundary area between the edges of the funnel array and the edges of the soil block was also collected via four, 6.35-cm wide, sloping edge-flow channels machined into the edges of the solution collector (Fig. 1). Collection of the edge flow ensured that vertical rectilinear flow within the soil block was maintained, and that water and solute mass balances could be calculated. A stainless steel (S.S.) drain-tube (29 by 4 mm i.d.), a fine S.S. screen and a retaining ring were press-fitted into each funnel drain hole (Fig. 2, inset). The grid funnels and edge-flow collection channels were filled with a borosilicate glass sphere slurry (53 to 105 :m sphere size), and allowed to drain for 2 hr prior to installation of the collector onto the soil block.

The solution collector was attached to the block by first rotating the block on its side (using a rotary clamping frame and a hydraulic shop crane) and removing the cutoff plate to expose the soil at the block base. Approximately 1.5 cm of soil was cut away using a coarse tooth pruning saw to expose a fresh, uncompacted soil surface which was not smeared or structurally damaged by the cutoff plate. A vacuum cleaner was used to remove loose soil and to reopen worm holes, root channels, cracks and other macrostructure. All visually significant macrostructure in the block base was then recorded for future reference by tracing their shapes and positions on an oriented, clear, 4-mil acetate sheet. To ensure good hydraulic contact between the soil and the collector, the soil surface was levelled using a borosilicate glass sphere (53 to 105 :m sphere size) slurry to fill in depressions, etc., and then the collector, filled with the same glass sphere slurry, was brought in contact and secured. The soil block-grid assembly was then rotated upright, mounted on a mobile trolley (0.9 m high), and the outer plywood box dismantled to expose the polyurethane foam shell around the block. A bead of exterior silicone caulking was then

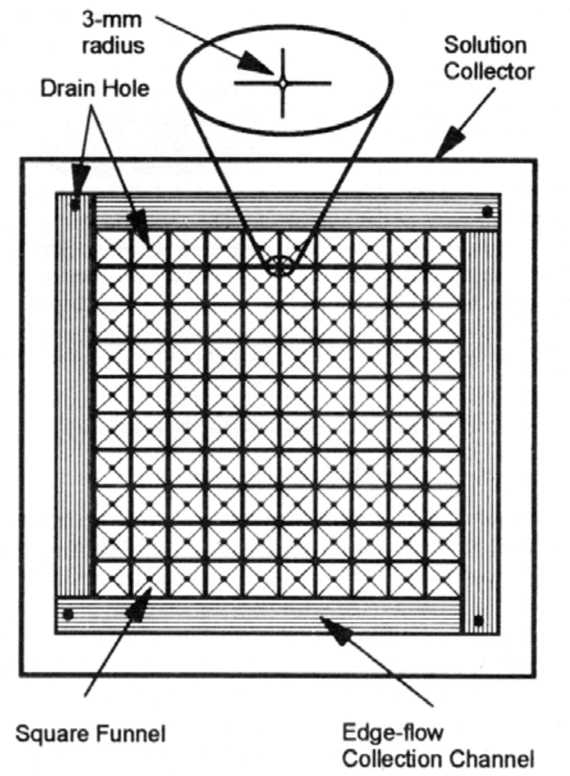

Fig. 1. Solution collector with a 10 by 10 grid of 3.8-cm square funnels 1.3 cm deep, and with outer edge-flow collection channels for maintaining water and solute balance information.

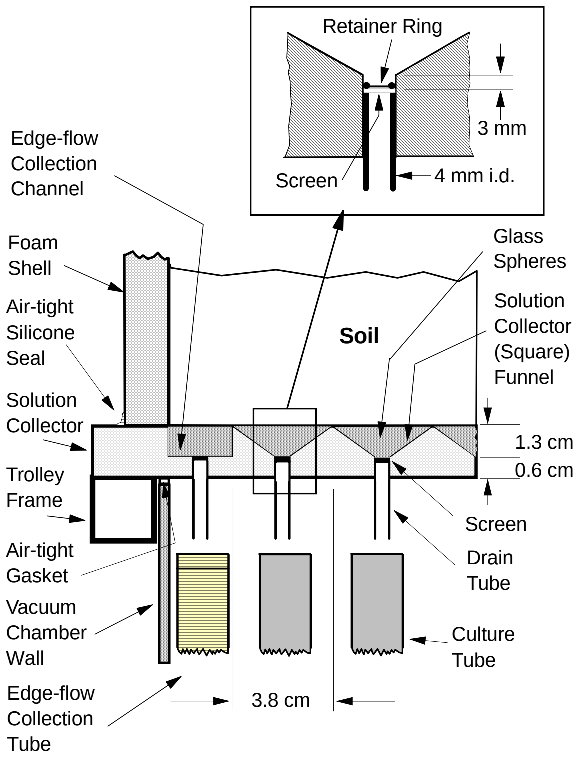

Fig. 2. Detailed schematic of the mounted solution collector and vacuum chamber. *Inset,* the schematic representation of a single funnel with drain tube assembly.

applied to ensure an air-tight seal between the foam shell and the solution collector (Fig. 2).

An acrylic vacuum chamber (51 by 51 by 24 cm deep) was sealed to the underside of the solution collector using a neoprene gasket and clamps (Fig. 2). The vacuum chamber allowed, through adjustment of the applied vacuum, control of the range of soil pore sizes participating in water and solute flow (i.e. the degree of unsaturation during unsaturated flow). A removable door on the front of the vacuum chamber permitted quick access to a percolate collector tray containing a 10 by 10-array of Pyrex glass culture tubes (150 by 25 mm) arranged on the same spatial grid as the drain tubes in the solution collector (Fig. 2). Water volumes delivered by the four edge-flow collection channels were bulked into a separate container (Fig. 2). The suction in the vacuum chamber was controlled by a precision sub-atmospheric vacuum-pressure regulator (110 kPa vacuum to 0 to 34.5 kPa pressure, Model 44-20, Moore Instruments, Brampton, ON) connected to the building vacuum system. A water-filled manometer was used for precise monitoring of the applied vacuum (0 to 20 cm water). Provision was made for sampling of individual funnels in the solution collector via an access tube through the side of the vacuum chamber to a secondary vacuum chamber, permitting continuous measurement of water and solute flow in individual solution collector funnels (not shown in Fig. 3). After the vacuum chamber was installed, the trolley-mounted soil block was wheeled into the solution delivery-collection-monitoring system (Fig. 3).

Solution Delivery (Rainfall Simulator) System

Water was delivered to the soil block surface via a 10 by 10-grid of syringe needles (drippers) arranged on the same 3.8-cm spacing as the solution collector funnels (Fig. 3). The drippers were attached on the underside of a S.S. reservoir (50 by 50 by 1.25-cm deep) using male Luer-Loc® to 10/32 standard thread adapters (Popper and Sons, New Hyde Park, NY). Either 22-gauge (0.406 mm bore), 25-gauge (0.254 mm bore), or 27-gauge (0.203 mm bore) drippers were used for water delivery, depending on flow requirements. In order to provide as uniform coverage as possible, the entire dripper grid was rotated (1.25 cm radius) and X-Y translated (2.5 cm translation limits) using variable speed DC motors. The dripper grid was supported approximately 20 cm above the soil surface, and water was applied over the entire 46- by 46-cm soil surface. Reverse osmosis, deionized water spiked with 0.005 M $CaSO_4$ (to minimize clay deflocculation in the soil) was delivered to the dripper grid through a surgical rubber tube (3.2 mm I.D.) using a variable speed peristaltic pump (0.15 to 1020 mL min^{-1}). Parallel in-line glass-fiber filters (0.7 :m) prevented suspended particulates from clogging the drippers. The upper surface of the dripper reservoir was dome-shaped to facilitate bleed-off of air exsolved from solution. For some experiments, the soil surface was covered with a nylon mesh (53 by 53 :m openings), and the mesh covered with a levelled, . 2 cm thick layer of sand (425 to 840 :m). This was done when it was desired to maximize the uniformity of solution infiltration across the soil surface by minimizing the effects of surface irregularities.

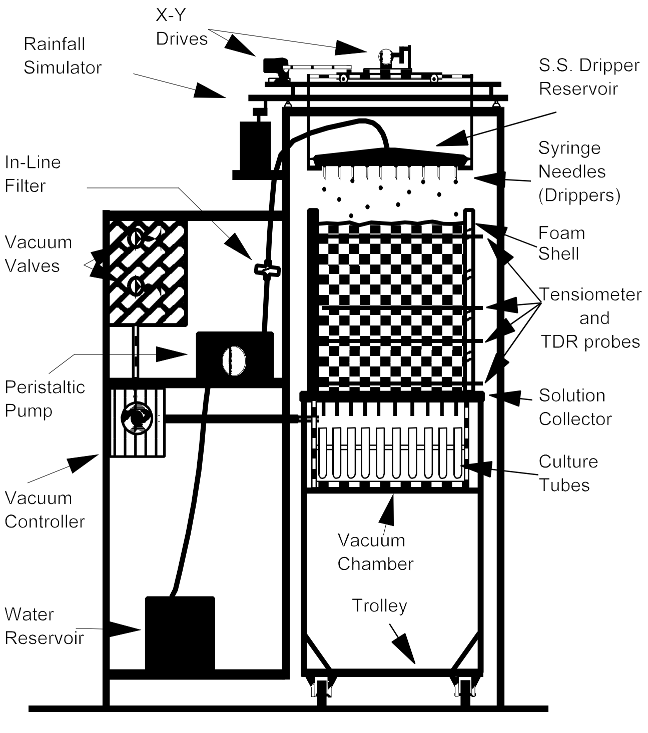

Fig. 3. Schematic of the soil block positioned within the solution delivery-collection-monitoring system.

Soil Water Monitoring

Soil water matric potential and volumetric water content were measured in-situ at several depths in the soil block (Fig. 3) in order to monitor changes in soil water status during experimentation, and to determine the hydraulic properties of the soil (i.e. the soil water characteristic and the hydraulic conductivity-pressure head relationship). Matric potential was measured using fast-response tensiometers consisting of acrylic tubing (22 cm long, 0.95 cm o.d., 0.32 cm wall) fitted on one end with a ceramic cup (SoilMoisture Equipment Corp., 3 cm long, 0.95 cm o.d., 0.159 cm wall, high flow, 1 bar bubbling pressure), and on the other with a pressure transducer (Motorola, temperature compensated 0 to 10 kPa differential pressure sensor, ± 0.15% full scale linearity) wired directly to a microcomputer.

Volumetric water content was measured using the TDR method (Topp et al., 1993) and parallel-pair probes (0.3 cm thick, 46 cm long, stainless steel, 2.5 cm spacing between probes) connected to a cable tester (Tektronix, 1502B). The tensiometers and TDR probes were installed horizontally through the foam wall of the soil block as side-by-side pairs at four depths below the soil surface (2.5, 25, 33, 40 cm in the example discussed below). The depths were chosen to allow monitoring near the soil surface, near the base of the Ap horizon, near the top of the B horizon, and near the base of the soil block. The tensiometers were inserted a distance of 22 cm from the side of the soil block to avoid possible edge effects, and to provide a "mid block" matric potential. The TDR probes extended to within 5 cm of the opposite wall of the block (probe length of 41 cm within the soil) to yield an "average" block water content at each of the selected depths.

RESULTS AND DISCUSSION

Soil Block Containment

Containment of an undisturbed soil block is one of the most critical and fundamental steps in constructing a grid lysimeter system. Many different approaches to block containment have been tried with varying degrees of effectiveness and convenience, as noted in the introduction. The material used to contain the block should ideally have the following properties: i) it should form a stable, intimate bond with the soil, ii) it should be water-repellent, neither degrading nor softening with extended exposure to high moisture contents, iii) it should have sufficient strength to support the soil block, while being sufficiently flexible to allow the block to swell and shrink with changing moisture contents without rupturing the bond with the soil, iv) it should not shrink nor crack with aging, v) it should be an electrical insulator to avoid interference with voltage-based instrumentation (e.g. TDR probes) and, vi) it should neither adsorb materials from the soil nor release materials to the soil. Our experimentation thus far suggests that the polyurethane foam used (i.e. isofoam®) satisfies the first five criteria (discussed further below). We do not as yet have information on the chemical sorption and release characteristics of the foam.

The isofoam consistently produced uniform foam shells, providing no loose soil fell into the reacting liquid foam during the expansion phase, and providing the liquid foam was uniformly distributed around the base of the block. It is important that the shell be created in one operation, as freshly reacted foam does not adhere well to cured foam (M.J. Shipitalo, personal communication, 1991), and for this reason it was preferable to use a bulk source of foam rather than small aerosol cans. The moderate pressures created by the foam during expansion (maximum expansion of about 12 fold occurred at 15 to 20/C) caused about a 0.5 cm penetration of foam into the soil, resulting in a very strong, water-tight foam-soil bond. Rupture of the foam-soil bond was not observed, provided that the soil block did not completely air dry. For this reason, it is advantageous to obtain the soil blocks at relatively low moisture content so that any further drying would not likely cause shrinkage problems with the foam shell. The foam was usually hard enough for easy trimming with a knife within 10 min of mixing, and the foam did not appear to deform, soften, shrink, crack or degrade with time. The dielectric constant of the cured foam is sufficiently low (. 1.2) as to not interfere with water content determination using TDR.

It was important that earthworm activity cease at the time of block collection, since it was not possible to use the soil blocks immediately following their collection (we collected either pairs or triplicates), and since it was also necessary to run a number of successive water flow experiments on each block over a period of weeks to months. It was decided that freezing at -5/C was the simplest and most effective means to stop adult earthworm activity, recognizing that freezing-induced changes might take place in the soil itself. As the soil was moderately dry at collection time (i.e. well below field capacity), it is believed that a single freezing would not result in significant and/or "un-natural" changes in the soil structure.

Solution Collection System

Important features of a grid-type solution collector for measurement of saturated-unsaturated water and solute movement through a lysimeter include: i) minimal flat area on the grid surface which can cause impeded drainage and perturbed (non-rectilinear) flow at the soil interface; ii) minimal volume in each collector cell to minimize solute mixing within the collector; iii) contact material between the collector and the soil that has appropriate air entry and saturated hydraulic conductivity values, and that neither reacts with the solutes being studied nor causes significant additional dispersion of the solute as it passes from the soil to the collection tubes; and iv) precise and accurate control of the matric potential at the soil-collector interface so that the size range of soil pores conducting water and solutes can be controlled and characterized.

The ideal of zero flat area on the collector grid was not feasible due to the practicalities of collector construction. However, the present design with 3-mm radius corners at the top of each square funnel produced only 0.088 cm^2 of flat area per four-unit set of funnels (Fig. 1 insert). This resulted in a total flat area at the soil-collector interface of only 8.8 cm^2, which was only 0.6 % of the total collector surface. In contrast, many earlier collector designs had total flat areas that comprised more than 13 % of the collector surface (e.g., Andreini and Steenhuis, 1990; assuming a tubing wall thickness of 3 mm). Each cell (i.e., square funnel) in our collector (Fig. 2) has a volume of only 9-ml, whereas other designs often have volumes of over 30-ml per cell (e.g., Andreini and Steenhuis, 1990), and thus much greater potential for significant within-cell mixing of solute.

The borosilicate glass spheres used as contact material between the solution collector and the soil have an air entry value of approximately 60 cm of water and a saturated hydraulic conductivity of about 0.03 cm s^{-1}. This air entry value is sufficient to study unsaturated water and solute flow over the pore water tension range that involves soil macropores (i.e., tensions # 20 cm), and the hydraulic conductivity value is large enough to be not limiting for most agricultural soils. The glass spheres were also found to be virtually non-reactive to most tracers (e.g., chloride, bromide, difluorobenzoates) and many pesticides (e.g., atrazine, metolachlor), and to have a saturated dispersivity of only 0.023 cm (53 to 105 : m range in sphere diameters). This material should therefore not add significant artifact effects onto the water and solute transport behaviour produced by the soil block.

The vacuum system attached to the underside of the solution collector provided precise, accurate and stable control of the matric potential (tension) at the soil-collector interface through the combined use of a precision vacuum-pressure regulator and a water manometer. The system was capable of maintaining tensions between zero and 30 cm of water for extended periods of time with a precision of ± 0.2 cm of water. This high degree of control is essential for detailed studies of soil macropores, which are known to exert a strong influence on water and solute movement, but which are believed to be operative only at pore water tensions less than about 15 to 20 cm of water.

Solution Delivery System

A new needle-based rainfall simulator was developed for this study because none of the existing spray nozzle or syringe-needle systems that were considered could deliver the desired range of rainfall rates (5 to 30 mm hr^{-1}) with the desired degree of uniformity (uniformity coefficient, $C_u > 95\%$, see below) over an extended period of time. The main problems with the existing designs included dripper (needle) plugging with exsolved air and/or suspended particles, and increasingly erratic solution delivery due to aging and binding of simulator components (e.g. syringe plungers). These problems were reduced by developing a dripper reservoir that could accept a range of needle sizes to produce a range of drop sizes (Chow and Harbaugh, 1965), by use of a precision variable-speed peristaltic pump to provide a range of uniform pumping rates, by incorporation of provisions for bleeding off exsolved air and for filtering out suspended particulate, and by use of both rotation and X-Y translation of the dripper grid to produce more uniform surface coverage (Römkens *et al.*, 1975). Rainfall uniformity was quantified by the coefficient C_u, (Andreini and Steenhuis, 1990) which exceeded 98% for rainfalls ranging from . 5 mm hr^{-1} to . 25 mm hr^{-1} over time periods of up to 72 hr, where:

$$C_u = 100\,\{1.0 - (|x|/m \bullet n)\} \qquad (1)$$

where $|x|$ = absolute deviation of the individual rainfall rates from the mean
m = mean rainfall rate
n = number of observations of rainfall rate

Soil Water Monitoring System

The tensiometer and TDR instrumentation was installed to allow nondestructive, in-situ measurement of porewater matric potential, volumetric water content, the soil water characteristic, and the hydraulic conductivity-pressure head relationship. Due to the sensitivity of tensiometers, monitoring of matric potential is the most precise way of determining if unsaturated flow is transient or steady state, especially in the macropore flow range (tensions ≤ 20 cm) where the soil is near-saturated and water content is nearly constant. Matric potential is also required for the determination of hydraulic head gradients and the range of pore sizes conducting solution during unsaturated flow. The TDR instrumentation provides measurements of average volumetric water content within a relatively large volume of soil (approximately 100 cm^3 in this study), which in turn allows more relevant calculation of average linear pore water velocity and solute velocity, and percentages of soil water "bypassed" by solutes. The combined use of tensiometers and TDR probes to determine the soil water characteristic and hydraulic conductivity relationship allows the water storage and transmission characteristics of the soil to be determined, which are required (among other things) for simulation modelling and for calculating macropore volumes. Since the tensiometers had an equilibration time of only 2 min (90 % response), they should be able to provide an accurate representation of even fairly rapid changes in matric potential. The TDR technique can measure volumetric water content with a full-scale accuracy of 1 to 2 % (Topp et al., 1993), which should be more than adequate for our purposes.

Example of Lysimeter Operation

An intact 46 by 46 by 44-cm deep block of structured Embro silt loam soil (gleyed Gray Brown Luvisol), which had been planted to alfalfa for the previous three years, was collected and instrumented as discussed above. The tensiometer and TDR probes were installed as side-by-side pairs at depths of 2.5, 25.0, 33.0 and 40.0 cm below the soil surface, the middle two pairs lying on either side of the boundary between the Ap and B horizons. A constant simulated rainfall of 19.2 mm hr^{-1} was applied until quasi-steady saturated flow throughout the block was achieved (at approximately t = 2000 min), as indicated by nearly constant and positive tensiometer readings (Fig. 4). (The solution collector vacuum chamber was set at ambient atmospheric pressure). At t = 2040 min, a 275 cm^3 slug of KBr tracer solution (Co = 1031 mg L^{-1} bromide) was added via the rainfall simulator as a square wave pulse (pulse duration of 4.6 min), and then followed by tracer-free rainfall. Both the tracer pulse and the following tracer-free solution were applied at the same rate as the original rainfall (i.e.,19.2 mm hr^{-1}), and with only two, 5-s interruptions in flow. Collection of effluent from the base of the soil block into a single pan was initiated at t = 2040 min and continued until the termination of rainfall at t = 3060 min (Fig. 4). The effluent was analyzed for bromide concentration and areal distribution of water flow within the collection area.

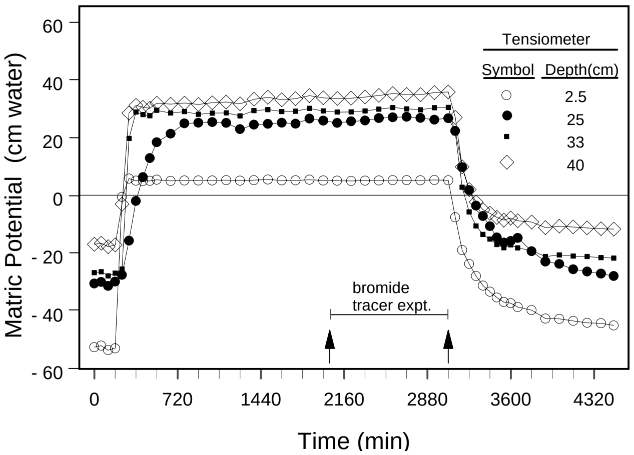

Fig. 4. Response of tensiometers to a constant simulated rainfall of 19.2 m hr^{-1} on saturated intact soil block. Quasi-steady state, saturated flow within the block occurred after 2000 min.

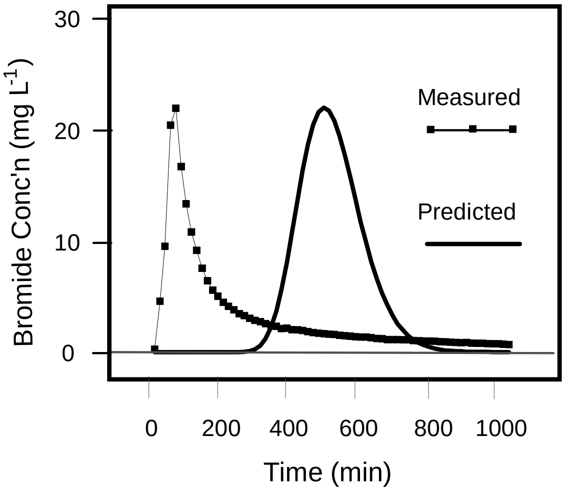

Fig. 5. Comparison of measured and predicted bromide breakthrough curves (BTC) resulting from the addition of a square wave pulse (275 mL) of KBr tracer (Co = 1031 mg L^{-1}). The t = 0 time corresponds to t = 2040 min in Figure 4.

The Br$^-$ breakthrough curve (BTC) was found to be extremely asymmetric, with first Br$^-$ appearing in the effluent (0.25 mg L^{-1}) after only 15 min and the peak concentration (22 mg L^{-1} Br$^-$) appearing after only 75 min (Fig. 5). In addition, only about 70% of the input tracer mass (283.8 mg Br$^-$) was recovered over the 1020 min. effluent collection period. In contrast, the BTC predicted by an analytical solution of the convection-dispersion equation (Kirkham and Powers, 1972) was nearly symmetrical, with the 0.25 mg L^{-1} Br$^-$ concentration not appearing until 300 min, the 22 mg L^{-1} (peak) concentration not appearing until 495 min, and 100% mass recovery of the tracer over the 1020 min. collection period (Fig. 5). These discrepancies suggest extreme preferential flow of Br$^-$ (and water) through the soil block, with some portion of the solute (and water) moving rapidly (presumably through macropores) while the remainder moved slowly (presumably though micropores). Using the average TDR-measured volumetric water content in the soil block (0.365 ± 0.050) and the calculated velocity of the measured BTC peak, approximately 85% of the water in the soil block was "bypassed" by the bromide.

The distribution of water flow in the solution collector confirms that extensive preferential flow of water and solute occurred. Figure 6 shows that over 99% of the water flow was conducted through only about 26% of the basal area of the block. In addition, 13 of the solution collector cells conducted water at rates exceeding 0.1 cm min^{-1}, while 49 cells flowed at less than 0.001 cm min^{-1}. The distribution of flow rates through the solution collector appeared to be random with no evidence of preferential flow along the interface between the soil and the foam shell.

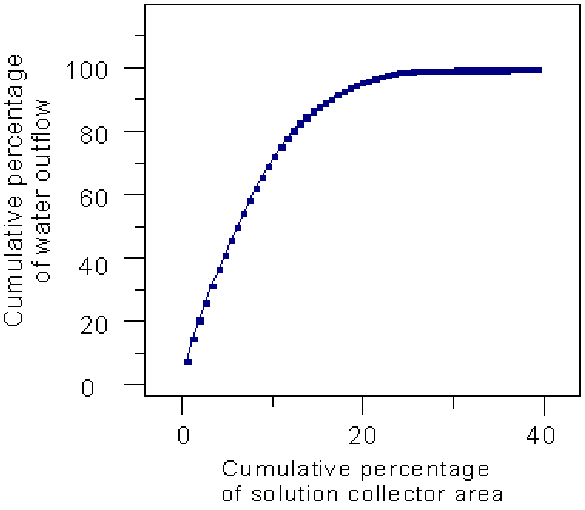

Fig. 6. Distribution of water flow within the solution collector for the quasi-steady saturated flow conditions of Figure 4.

Although this example considers saturated flow only, it demonstrates nonetheless that the grid lysimeter has the desired measurement capabilities, and that the solution delivery, monitoring and soil containment components of the system are operating effectively.

Concluding Remarks

Elucidation of the mechanisms controlling the preferential movement of water and solutes through soil require extensive and careful experimentation on intact soil samples that are large enough to be representative of true field conditions. Detailed and accurate measurements through space and time of the water and solute storage and transmission properties of the soil must be made, and the initial and boundary conditions relevant to water and solute movement must be both known and controllable. The grid lysimeter system and the sample collection, containment and storage techniques described in this report are an attempt to satisfy these requirements. Future papers will describe the use of this grid lysimeter system and the associated methodology to characterize the preferential movement of water and various agrochemicals through agricultural soils.

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