AN ABSTRACT OF THE THESIS OF

Weidong Cao for the degree of Master of Science in Civil Engineering presented on December 6, 1994. Title: Nitrate and Pesticide Transport under Pear Production in Clay and Sandy Soil

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Abstract Approved: ______________________

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Groundwater contamination on irrigated land is of concern in this nation and around the world. In order to reduce the potential of groundwater contamination by agricultural practices such as irrigation, fertilizer and pesticide application, vadose-zone monitoring and sampling are needed. The main objective of this study was to evaluate impacts of current irrigation treatments and soil structures on the migration of pollutants to groundwater. Passive CAPillary wick pan Samplers (PCAPS) and suction cups were installed in two cracking clays and one sandy soil under the pear tree root zone. PCAPS and suction cups were used to collect nitrate-nitrogen and tracer samples. Tracers were applied to track the spatial and temporal patterns of compounds that mimic nitrate-nitrogen and pesticide movement.

The observed magnitude of water leaching over 3 months differed between irrigation methods and soil structures and decreased in this order: flooding over 3 months in clay soil (22.8 cm) > micro-sprinkler in clay soil (16.1 cm) > over-head sprinkler in sandy soil (4.1 cm). Leaching patterns were varied spatially; soil structures, irrigation methods, preferential flow, and high water table may have been responsible for the spatial variation of leaching.

Mass recovery of all three tracers, including bromide, blue dye, and rhodamine had the same decreasing order: flooding in clay soil > micro-sprinkler in clay soil > over-head sprinkler in sandy soil.

Average blue dye and rhodamine concentrations had the following order: flooding in clay soil > micro-sprinkler in clay > over-head sprinkler in sandy soil. Since blue dye and rhodamine have similar properties to some moderately adsorbed pesticides, we may infer that the risk of pesticide movement in three sites should also decrease in this order. Presumably pesticide movement in clay soil would have been more pronounced for flooding than sprinkler irrigation.

On the annual/seasonal basis, the total mass of nitrate-nitrogen leaching differed between irrigation methods and soil structures and decreased in the following order: over-head sprinkler in sandy soil > flooding in clay soil > micro-sprinkler in clay soil. The annual average nitrate-nitrogen concentration observed under over-head sprinkler in sandy soil was 15 mg/l over the maximum allowed concentration level (10 mg/l) by the EPA while seasonal nitrate-nitrogen concentration was low in clay soil under current irrigation practices.

Strong evidence suggested the occurrence of preferential flow in this study. Preferential flow may contribute to high water leachate, nitrate and pesticide migration.

High correlation coefficients between paired PCAPS indicated that PCAPS have similar responses to water and solute leaching.

Several improvements in PCAPS are needed to obtain representative samples under severe flooding conditions.

Limited data suggested that ultra-low rate irrigation devices could reduce the water leaching and the potential of pollutant migration to the groundwater because ultra-low rate application devices minimize the soil macropore flow.

Nitrate and Pesticide Transport under Pear Production in Clay and Sandy Soil

by

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Weidong Cao

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CHAPTER 1 INTRODUCTION

Groundwater provides approximately 50% of the nation's drinking water. Groundwater contamination is a growing concern both in the United States and around the world. Sources of groundwater pollution include agricultural nutrients (e.g. nitrate and phosphate) and pesticides, heavy metals and organic compounds released by industrial processes, and radioactive materials released by production of nuclear materials. Groundwater pollution is extremely difficult and expensive to remediate. Thus, prevention of groundwater contamination is crucial.

Agricultural practices, such as irrigation, fertilization and pesticide application, often contribute to groundwater contamination. Preferential flow can vastly accelerate solute and pollutant migration to the groundwater when soil macropores such as cracks and root holes are present. Preferential flow refers to any transport process by which water and solutes obtain enhanced movement while matrix flow refers to the flow through the bulk soil. In order to reduce the potential of groundwater contamination by nitrate and pesticides, we must monitor the vadose zone and evaluate the impact of current agricultural practices and soil structures on the migration of pollutants from the soil surface to the groundwater. Existing methods of vadose-zone sampling have certain disadvantages. For instance, they can not collect true flux of leached water and solutes. Good estimation of contaminant loading in irrigated agricultural land requires a feasible and reliable soil sampling device for monitoring in the vadose zone. Passive CAPillary Samplers (PCAPS) are new vadose-zone monitoring samplers which are capable of collecting both preferential and matrix flow.

Preferential flow is a function of irrigation practices and soil structures. In order to reduce/eliminate the preferential flow observed in this study, ultra-low rate irrigation devices (pulsators) were used to apply water on the experimental plots. PCAPS were installed below the root zone on the experimental plots to collect the leached water.

This project consists of two parts. The first part includes: 1) investigation of the impact of irrigation methods and soil structures on nitrate and pesticide transport through the vadose zone to the groundwater; 2) evaluation of the spatial variability of water leaching below the root zone under current irrigation practices in clay and sandy soils; 3) evaluation of the performance of Passive CAPillary Samplers (PCAPS) which are new soil solution samplers. The second part of the project evaluated the use of ultra-low application devices to eliminate the macropore flow during irrigation. PCAPS and pulsators were installed in the cracking clay and sandy soils for both parts of this study. The materials and methods of parts one and two are presented in the same section.

CHAPTER 2 MATERIALS AND METHODS

Site Description

The study areas were located on the Southern Oregon Agricultural Research Center (SOARC) at the Hanley and Medford farms. The two soils under study at these sites were expansive (cracking) clay and sandy loam (Table 1). Each soil was underlain by a shallow aquifer at a seasonally dependent depth varying from 1.5 to 4 meters. Of these soils, cracking clay tends to shrink and swell with wetting and drying. This unique physical property may have significant impact on contaminant movement through the vadose zone. Many studies show that the soil macropores, such as cracks and roots increase the loading and speed of contaminants to the groundwater. Because sandy soils have relatively high conductivity, we expected heavy irrigation and high intensity rainfall to result in high solute transport. If we understand the characteristics of solute transports in these soils, we can extend our understanding to other soils and estimate the nitrate and pesticide loading to the groundwater.

Irrigation practices under study are over-head sprinkler, flood, micro-sprinkler, and pulsator irrigation. These irrigation practices, except pulsator, are very commonly used in Oregon. The overhead sprinklers were installed in Hanley Farm pear orchard. They applied water at about 3.75 mm/hour with a wetting circle of 7-10 m. Micro-sprinklers installed in Medford Farm Block 4 ran at 2.8 mm/hour with a wetting circle of 3 m. Flood irrigation was upset in Medford Farm Block 2 and typically ran 1-2 days under ponded infiltration. The pulsator supplied water at extremely low surface irrigation rate (<0.2 mm/hr), and it continuously ran from a few hours to 24 hours per day through the irrigation season. From the outset it was apparent that the flood irrigation had a high potential to carry nitrate and other chemicals through the extensive fissures found on the clay soil site. When large continuous fissures were present preferential flow would dominate before the soil completely swelled, which included much of the period of irrigation. Alternation in irrigation practices can significantly change the soil physical properties and the characteristics of solute transport in the vadose zone. This is especially true on expansive clay soils. Also, because different irrigation methods produce vastly different infiltration conditions which are the leading factors in generating preferential flow, the behavior of nitrate and chemical movement for different irrigation methods is expected to be strongly effected by irrigation practices.

Table 1. Study site information

Study Site	Hanley Farm	Block 2 (Medford)	Block 4 (Medford)
Soil Type	Central Point Sandy Loam	Carney Clay with Cracks	Carney Clay with Cracks
Plant Type	Pear	Pear	Pear
Irrigation Practice	Over-Head Sprinkler & Pulsator	Flood & Pulsator	Micro-Sprinkler & Pulsator
Number of PCAPS	4,8,11,12	3,5,6,9	1,2,7,10
Total Pulsators	5	4	4
Total Suction Cups	15	12	12

The crop planted on the site is pear, an economically important crop in Oregon. In the adjacent new and old orchard at Medford farm, soil structures are almost exactly the same while only differences between B2 and B4 are irrigation practices.

PCAPS Construction and Installation

Passive CAPillary Samplers (PCAPS) obtain groundwater samples from unsaturated soil using the capillary suction created by a hanging woven fiber glass wick. The underlying idea of this sampling method is that the capillary wicks mimic the capillary properties of the soil (Boll et al., 1992; Knutson et al., 1993; Knutson and Selker, 1994) (Figure 1). An assembled PCAPS consist of five parts: 1) the top unbraided wick and vertical braided wick, 2) the stainless steel collection pan, 3) the sampling withdrawal tube, 4) the sample collection bottle, and 5) the fiberglass support box. The PCAPS were built using a 9.5mm fiberglass wick (part no. 1380, Pepperell Braiding Co., Pepperell, MA). A stainless steel panel (1 mm thick, 310 x 845 mm) sat on a custom molded epoxy coated fiber glass box (320 x 855 x 620 mm) with an 8 by 3 grid of 24 100 mm square stainless steel plates sat on the top of the panel. The plates supported the upper portion of the unbraided wick, the filaments of which were covered in a symmetrical radial pattern. A stainless steel compression spring supported the stainless steel plates. A 420 mm of wick passed through a 9.5 mm diameter stainless steel pipe attached to each plate and PVC flexible tubing. The lower end of each wick was sealed into a 500 ml sampling bottle glued to the bottom of the fiberglass box. A vacuum pump with about 300-600 mm Hg suction withdrew water samples from sampling bottles via 6.3 mm (1/4") O.D. Low Density Polyethene (LDPE) tubing. The large catchment pan of PCAPS would be able to intercept the preferential and matrix flow and allow analysis of the spatial and temporal variability of nitrate and pesticide transport.

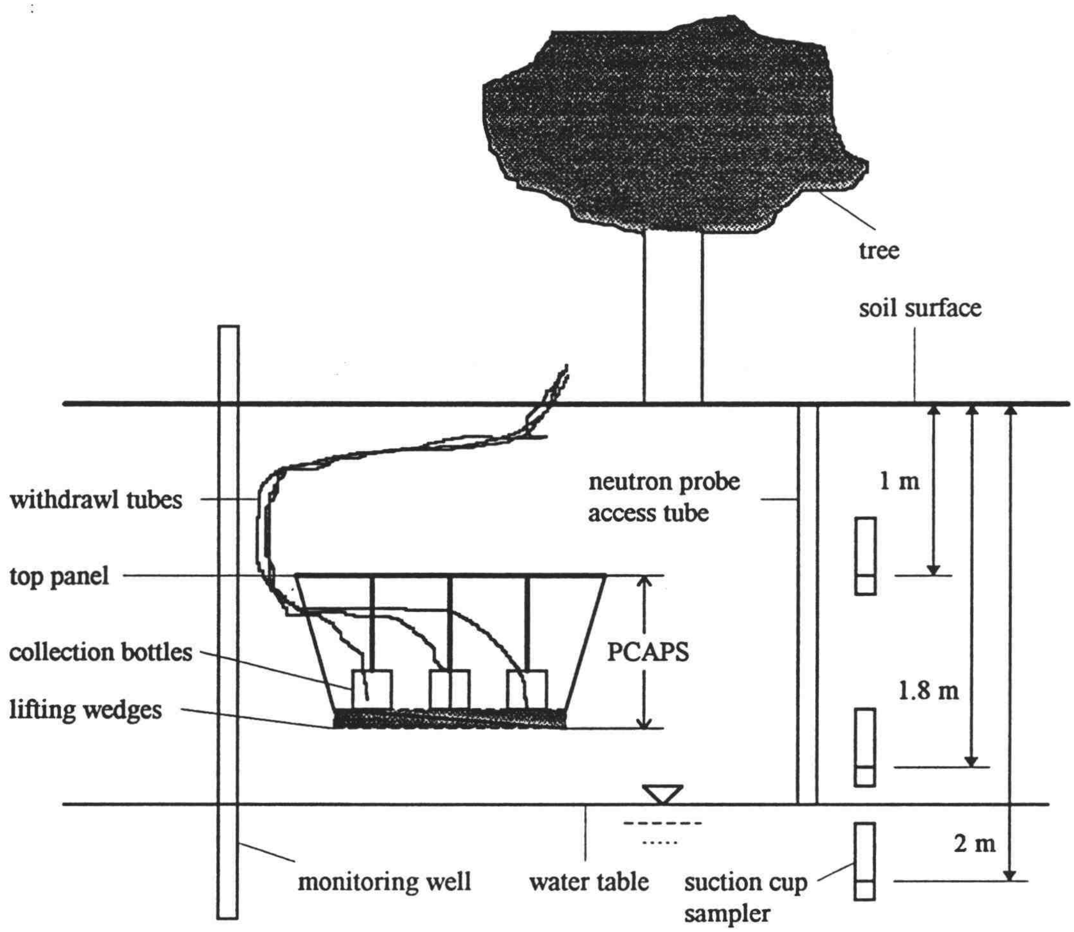

Figure 1. Section view of PCAPS and other samplers as installed at each site.

A total of 12 PCAPS (4 of which had a different design-using a 5 by 5 grid of 25 65 mm square stainless steel plates instead) were installed under the root zone (about 1 m below soil surface) at SOARC. In 1992 four PCAPS per site were installed in sandy loam soil under overhead-sprinkler irrigation, in cracking clay soil under flooding irrigation, and in cracking clay soil under micro-sprinkler irrigation. In 1993 a pair of two PCAPS from each site were adapted to pulsator irrigation (Figure 2). The major steps involved in PCAPS installation were:

1. Dig a 2 m deep trench parallel to the tree row with size from 1 by 4 m in Block 4 to 1 by 7.5 m in Block 2 using a back hoe;
2. Excavate two 1.1 m long tunnels perpendicular to the trench at 1.1 m below soil surface using a chipping hammer and a flat shovel;
3. Put the PCAPS in the tunnel and lift the wedges;
4. Inject liquid foam into PCAPS to make sampler water-proof;
5. Fill soil back into the tunnel;
6. Use bentenite clay to seal the tunnels;
7. Lead all the sampling tubes to trees nearby;
8. Fill soil back to the whole the trench.

The roof of the tunnel was leveled and smoothed. The top panel of PCAPS was filled with sieved, native soil. Two 100 by 100 mm, 1 m long wedges were used to bring the sampler into very firm contact with the roof of the tunnel.

The samplers were isolated from the trench by applying a 50 mm thick bentonite clay seal between sampler and trench. The access tubings were attached to the trench wall and buried at a depth of 150 mm to avoid damage during backfilling and mowing operations.

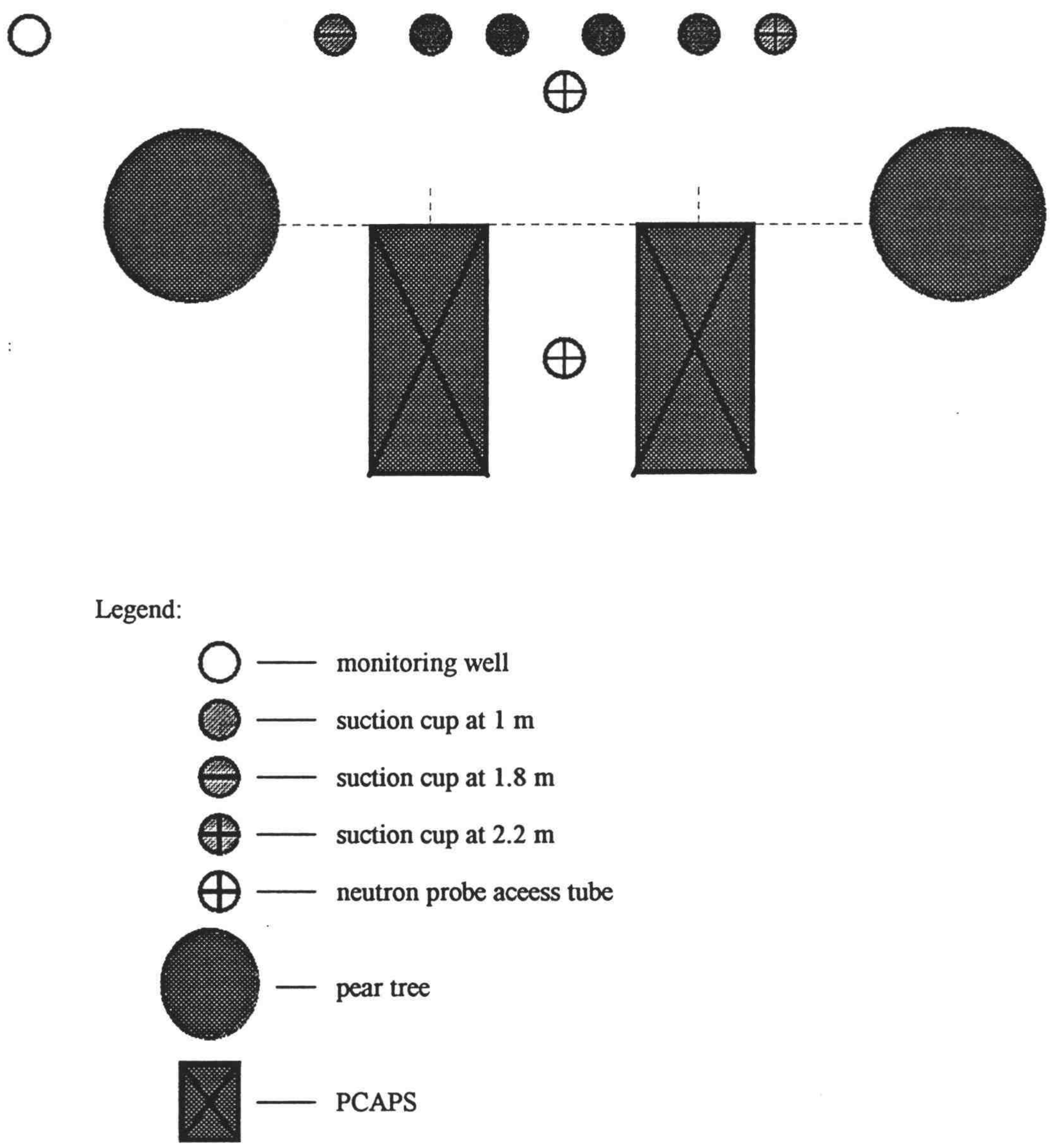

Figure 2. Plane view of the experimental setup at each site.

Suction Cup Construction and Installation

The suction cup samplers consisted of a 60 mm length of 50 mm O.D. porous ceramic cup (no. 653X01.B1M3, Soil Moisture Equipment, Santa Barbara, CA.) cemented with epoxy to a fifteen centimeter length of 50.8 mm (2") schedule 40 PVC pipe. A 6.3 mm (1/4") O.D. Low Density Polyethylene (LDPE) black tubing was attached through a two hole black rubber stopper for collecting the sample solution and for creating a vacuum (Figure 3). A hand vacuum pump was used to create a suction in the cup samplers. This method tended to accurately sample the water concentration but it could not collect the total water volume passing through the vadose zone per unit area.

A Giddings drill rig and hand and gasoline powered augers were used to drill holes with diameter of 7.5 cm for neutron probe access tubes, suction cups and monitoring wells. Suction cup samplers were inserted into 7.5 cm holes. A small amount of silica flour slurry was poured into the hole through a long funnel and the suction cup was placed firmly into the slurry to ensure good soil contact with the porous ceramic cup. After native material was filled in, suction cup sampler was isolated by placing a bentonite plug to avoid channeling of water down the side of the suction cup sampler.

Suction cup lysimeters were installed at three depths including root zone (1.1 m), capillary fringe (1.8 m) and groundwater (2 m) (Figure 1 & 2).

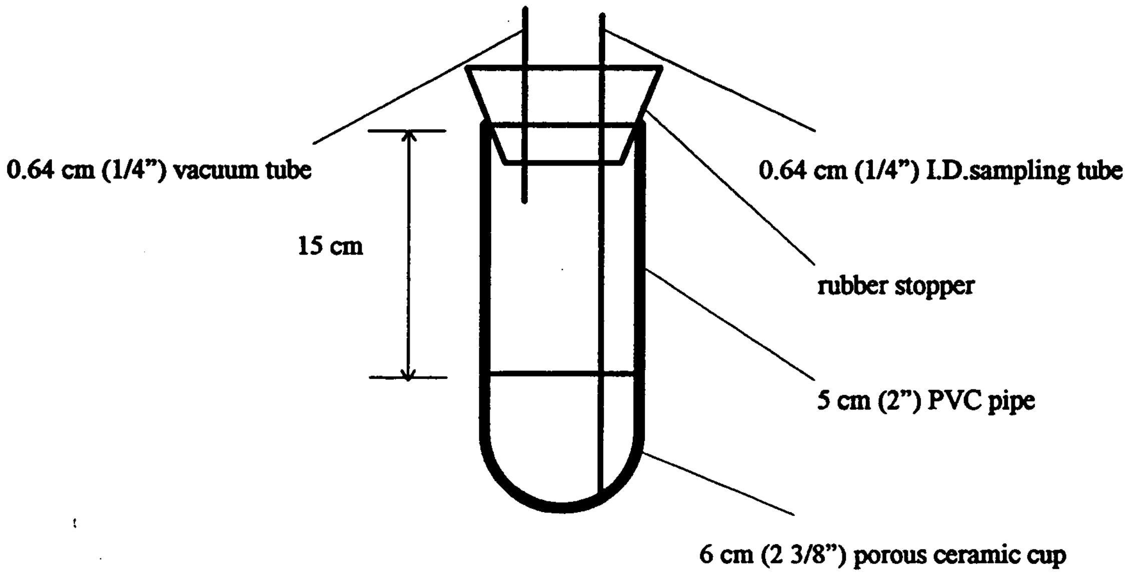

Figure 3. Schematic diagram of suction cup assembly.

Pulsator System Establishment

The pulsator system is an ultra-low-rate application device. The underlying idea was to eliminate macropore flow by applying water at low enough rates to avoid ponding. There are no previous reports on the evaluation of effects of pulsators on macropore flow. Pulsators were available in a variety of application rates, and were selected to obtain the irrigation rate required by the plant type and density (Cuenca, et al., 1992), such that the maximum rate of application was no greater than 0.25 times the saturated conductivity of the soil. A typical pulsator irrigation system installed in a pear orchard is shown in Figure 4. Based on pear tree spacing and water requirements, two types of ultra-low rate pulsators were used: flow rates of 0.24 mm/hour were used on the clay soils and rates of 0.73 mm/hour were used on the sandy soil. Pressure regulation and filtering were employed following manufacturer's specifications. Pulsator operating pressure was 760 mm Hg. Below this pressure, the pulsator would shut off automatically. Digital irrigation timers allowed irrigation control on a plot-by-plot basis. Running time for pulsator varied from month to month, Typically, pulsators ran from 15 to 25 days per month and 10 - 24 hours per day.

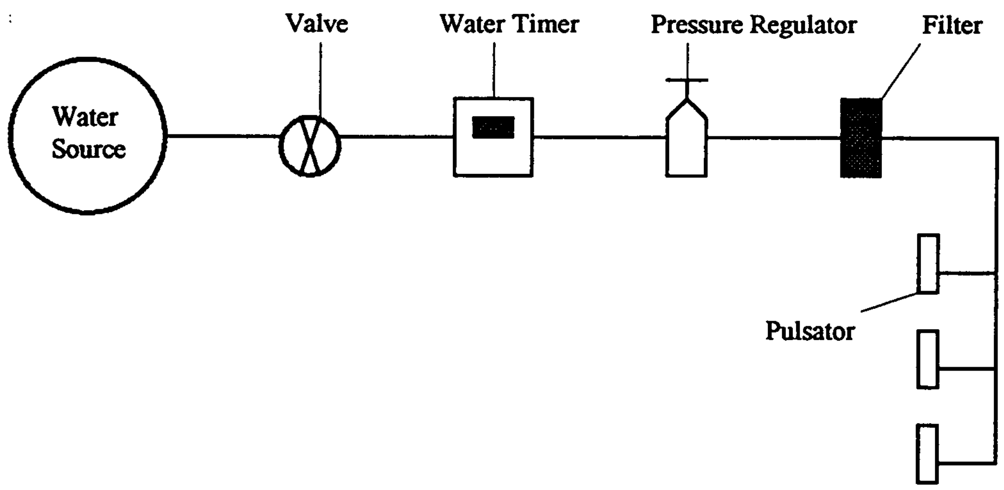

Figure 4. Schematic diagram of pulsator control system.

Tracer Application

Tracers were employed to track subsurface flows. The nitrate and pesticide movement pattern in this study would be expected to resemble the tracer movement through the vadose zone. Various tracers, including FD&C blue dye #1, Rhodamine WT, bromide and chloride were utilized in the SOARC to characterize the movement of nitrate and pesticide. The adsorption characteristic of FD&C blue dye #1 is equal to atrazine, a common pesticide (Andreini and Steenhuis, 1990); the adsorption of Rhodamine WT (selected as a backup tracer) was slightly less than that of atrazine. By the observation of breakthrough of Rhodamine WT and blue dye, we could estimate the pesticide traveling time and loading to groundwater. Bromide, as a non-adsorbed anionic tracer, had desirable characteristics for use as a NO_3^- surrogate in some soil studies. Bromide has been shown to move similarly to NO_3^- in soil (Smith and Davis, 1974) and had other desirable characteristics such as low background concentration kept in soil and irrigation water, high solubility, low plant toxicity, ease of analysis, and low cost.

We applied 1081 g calcium bromide, 854 g blue dye, and 0.194 g rhodamine WT in each trench in early September 1992. We mixed these three tracers in a 20 liter bucket and stirred them for 20 minutes using an electrical dispersator. Then we poured tracer solutions into a compressed air (210 kPa) bicycle sprayer with 4 nozzles. In 10 passes we were able to uniformly apply 13.4 L of the tracer solution in a 3 m by 10 m rectangular area where each PCAPS pairs was located.

Soil Water Sampling and Analyses

Water samples were taken before and after the application of tracer and nitrate fertilizer. Generally, water samples were withdrawn from 12 PCAPS and 39 suction cups at three sites on a weekly basis. During irrigation and heavy rain, water samples were extracted twice a week. The procedures of sampling from suction cups were:

1. apply a suction to the vacuum tube of at least 650 mm Hg using electrical vacuum pump;
2. close off both pipes leading to the samplers in such a way as to assure maintained vacuum;
3. let the sampler collect water for 1-7 days;
4. pull the sample from the device through the sampling tube while leaving the vacuum tube open;
5. close the sampling tube and go to step 1.

The procedures to withdraw water samples from PCAPS were a little bit different from the suction sup. The major steps to take samples from PCAPS were:

1. match the sampling tubings from PCAPS with the tubings of the set of sampling cylinders;
2. exert 300-600 mm Hg suction on sampling cylinder for a couple minutes using an electrical vacuum pump;
3. record volume obtained from each sample bottle;
4. take samples into 20 ml vials from sampling cylinders.

Samples were frozen and transported on ice to the Department of Bioresource Engineering Water Quality Laboratory, where they were analyzed for applied tracers and nitrate. Blue dye tracer concentrations were measured on a Milton Roy Spectronics 20 spectrophotometer. Rhodamine WT concentrations were measured on the Turner 111 fluorometer. Bromide concentrations were analyzed by using an Orion Model 94-35 bromide electrode and a Model 90-01 single junction reference electrode. A Dionex 2000I ion chromatograph with a Dionex AS4A-SC separator column and an AG4A-SC guard column was used to determine nitrate concentrations. Vadose-zone water movement was indicated both through observation of the breakthrough of bromide and dye tracers and by the quantity of water collected by the PCAPS. The potential of nitrate contamination of groundwater was analyzed using the nitrate nitrogen data. The effect of preferential flow was investigated by the observation of breakthrough of tracers and analyses of solute concentration distribution. These data provided reference points for the time required for bulk water and conservative adsorbed compounds to move from the soil surface to groundwater.

CHAPTER 3 TRANSPORT OF NITRATE AND PESTICIDES IN THE VADOSE ZONE

INTRODUCTION

Groundwater as a valuable natural resource provides 50% of the nation's drinking water, 40% of our irrigation water, and drinking water for 90% of rural households (Goodrich et al., 1991). Its importance can hardly be overestimated. However, there is increasing concern about groundwater pollution. Awareness of the pollution potential of nitrate and pesticides has been increased recently by the discovery of their widespread appearance in the groundwater (Goodrich et al., 1991; Spalding and Exner, 1993). According to USGS and USEPA, there are a number of areas where nitrate-nitrogen (NO_3-N) concentration in the groundwater exceeds the maximum contaminant level of 10 mg/l while most of those areas are associated with irrigated cropland. A recent USEPA survey indicated that 74 pesticides have been detected in groundwater in 38 states which could be traced to agricultural or other non-point sources (Goodrich et al., 1991; Williams et al., 1988). Large areas within the state of Oregon have also been found to be contaminated by fertilizer nitrogen and pesticide application.

Once nitrate and pesticides pollute the groundwater, residence times in groundwater are very long since degradation rates under saturated conditions tend to be very slow. In addition, it is extremely difficult and expensive to remediate polluted groundwater. Due to such potential risk to groundwater contamination, understanding of how nitrate and pesticide are transported through the vadose zone to the groundwater is needed to make sound resource management strategies and minimize groundwater contamination for the present and future.

The study of vadose-zone solute transport has increased during the last few decades. Environmental and economic concerns have inspired the development of numerous methods to quantify the nitrate and pesticide movement by observing and modeling the processes that affect contaminant migration in the vadose zone. For more information on solute transport, Nielson et al. (1986) gives an excellent review. The majority of research studies on nitrate and pesticide transport have been conducted under the laboratory conditions which do not adequately represent the natural field condition. There have been a limited number of experiments conducted in unsaturated field soil (Butters et al., 1989). Few field experiments have been carried out on the solute transport in swelling and shrinking clay soils. So far, there is little information on actual flux of nitrate and pesticides below the rooting zone in Oregon soils. It is important to determine the impact of irrigation regimes and soil types on nitrate and pesticide movement through vadose zone by monitoring nitrate and pesticide flux before they reach the groundwater through the field study (Wilson, 1990).

Many studies have connected high nitrate and pesticide levels in vadose zone with irrigated agriculture, especially if the soils are highly permeable with many macropores. Irrigation methodology is a contributing factor in determining amount of leaching of water and solutes. Flood irrigation may lead to high leaching rates in vadose zone, especially when the soil cracks are present. Sprinkler irrigation may cause the closure of cracks near the soil surface, and it therefore would reduce water intake compared with flood irrigation (Mitchell and van Genuchten, 1993). Micro-irrigation is more efficient in supplying the water and has far lower potential in generating leaching of water and solutes.

As we mentioned above, to protect the groundwater, it is important to measure water flow and solute transport through the vadose zone between soil surface and the groundwater table because it provides a good estimation of total contaminant loading and risk to the groundwater. However, current models can not successfully predict the contaminant loading to the groundwater in the occurrence of the preferential flow. Therefore, sampling of soil water in the vadose zone is needed to determine and monitor contaminants that may be moving toward the groundwater.

There are a variety of vadose-zone sampling methods, including soil cores, suction cup samplers, zero-tension pan samplers, and passive capillary pan samplers (PCAPS). Boll et al.(1990) summarized the sampling techniques and their features. Soil coring is a destructive method and does not allow for repetitive measurements at the same point, thus limiting its usefulness when monitoring changes over time. A large number of samples must be taken to sufficiently identify spatial variability.

Suction cup sampler extracts water from the soil by an applied vacuum pressure within a porous ceramic cup. This sampling method is widely used due to ease of installation and sampling as well as low cost. Suction cup samplers work well in most permeable soils. However, this method has several limitations. A measurement of the water flux is not available, since the soil volume sampled by a suction cup is unknown (England, 1974). Also, preferential and funneled flow may not be captured spatially (small cross-section area) and temporally (non-continuous vacuum-collects water for only a short time period). This may lead to underestimating of contaminant pulses after heavy rainfall or other agricultural practices such as fertilization or pesticide applications (Barbee and Brown, 1986). Because the suction is typically only applied for a short time before and during sampling, the resulting samples may not necessary represent the true concentration of pollutants in the vadose zone (Lowery et al., 1992). Finally, adsorption, desorption, and cation exchange of porous ceramic cups have been reported as causes of sampling errors (Bottcher et al., 1984; ASTM, 1992).

Zero-tension or gravity pan lysimeter samplers collect water by gravitational force (e.g., Jemison and Fox, 1992). Therefore the soil matrix above the sampler must become saturated prior to sample collection and bypassing of the samplers may occur under conditions of considerable unsaturated flow (Kung, 1988). A gradient in matrix potential can lead to diversion of flow away from the sampler. Collection efficiency of zero-tension pan sampler is typically low, ranging from 45% to 58% (Jemison and Fox, 1992). This sampler requires an open trench for installation and typically samples are removed manually by removing sampling bottles. Thus installation and sampling cost is high. However, the zero-tension lysimeter can collect macropore flow and flow from high moisture soils because of the capability of intercepting zero-tension flow (Simmons and Backer, 1993).

Use of wicks for sampling was introduced by combining the ideas of applying tension to the soil-water and intercepting a large area of flow by a pan (Brown et al., 1986). PCAPS uses a wick as a hanging water column to apply capillary suction (Brown et al., 1986; Holder et al., 1991; Gee and Campbell, 1991). The properties of the wick allow accurate measurement of both concentration and volume of flow through the vadose zone. Among those mentioned sampling methods, only PCAPS give superior results to existing vadose-zone samplers in terms of long-term mass balance of water and chemical loading (Holder et al., 1991; Boll et al., 1992). PCAPS do not require continuous vacuum pressure for sampling and samples can be taken continuously over time. Disadvantages of PCAPS are: 1) the high cost of installation, 2) the potential for over or under sampling duo to poor matching of soil and sampler characteristics, 3) bypassing can occur if the sample bottle is totally full, 4) sidewall flow along trenches may occur if they are not compacted or sealed carefully (Brown et al., 1986).

Tracers have been widely used to characterize many hydrological properties of soil and water. An excellent review of groundwater tracers has been provided by Davis et al. (1980; 1985).

The project reported here sets out to test three hypotheses:

1. irrigation practices and soil types have significant impact on the nitrate and pesticide leachate through the vadose zone;
2. PCAPS are capable of measuring soil solute flow processes for both matrix and preferential flow which significantly contribute to the vadose-zone solute transport;
3. the pulsator irrigation system is capable of eliminating irrigation driven macropore flow in clay soils.

OBJECTIVES

The primary objective of this investigation was to study the NO_3-N and pesticide leaching behavior under irrigation and rainfall through unsaturated zone in the field. This goal was achieved through field experiments conducted at three sites and two different soil types. PCAPS and suction cup lysimeters were installed under the root zone to collect soil water samples. Tracer tests were run through three sites to characterize the nitrate and pesticide movement. Achievement of these goal will assist in predicting the contaminant loading to the groundwater and provide guidance for improved management strategies. The secondary objective was to evaluate the ability of PCAPS in measurement of the spatial and temporal variability of nitrate and pesticide transport in cracking clay and sandy soils and to investigate impact of preferential flow through soil macropores on nitrogen and pesticide leachate. The final objective was to produce a set of observational data on vadose-zone solute transport for the usage of future model validation and research efforts.

RESULTS

Limitations of PCAPS

As mentioned early, comparing with other vadose-zone sampling techniques, PCAPS usually have several advantages.

However, in this study certain field condition precluded use of PCAPS. One example was a seasonal high water table. When the water table rose over PCAPS level, the PCAPS could not collect true flux through vadose zone. PCAPS collected infinite water from the groundwater instead and the goal of monitoring vadose-zone was not fulfilled. Initially, we did not expect high water table conditions in these experiments. Even though we injected closed-cell liquid foam into the inside of PCAPS to seal the sampling bottles and sealed the tubing into the bottles, the samplers were not completely water-proof. When we exerted a high suction to withdraw water samples during times when the water table was above the PCAPS, water from outside PCAPS appeared to have been drawn into the PCAPS and the sample bottles. This was evident when many samples were obtained which had volume far in excess of the bottle capacity. It was difficult to distinguish true flux from such a sample. When the PCAPS sample bottles were overflowed during heavy irrigation or prolonged rainfall, the excess water stayed inside PCAPS instead of draining out of PCAPS. Some of this water also entered the sample bottles, making it impossible to determine the true flux. Even when the water table receded, overflow water inside PCAPS could not drain out of PCAPS because the injected foam blocked the drainage hole. In this matter, the injected foam worsened the situation. Foam may have also formed local flow channels to allow the excess water into some bottles while isolating others. If this case were true, it would increase the difficulty of correctly interpreting the true spatial flux through the vadose zone. When samples were withdrawn from a particular sampling bottle, overflow around other bottles might have entered that bottle. Therefore, sampling volume may not have reflected the true flux from sampling unit.

It would be necessary to improve PCAPS design to make them function under such severe field conditions. First, PCAPS must be completely waterproof. In order to do so, each PCAPS must be tested in the lab to assure that there is no leakage. Second, the metal tubing should be big enough to avoid any barrier for water movement through the wick down to the sampling bottles. Wang (1993) found that small diameter of tubing in PCAPS physically constrained the diameter of the wick. This caused a large differences in pressure between the top of the wick and the wick near the bottom of plate. Third, the sampling bottles should be larger or the sampling frequency increased to avoid overflow. Fourth, a drainage hole with a drainage tube should be installed to avoid the mixture of overflow and true flux through the wick. Finally, the sampler should be installed carefully to avoid any disturbance or damage to the samplers.

Because of limitation of PCAPS, only general conclusions were drawn for this specific experiment.

Impact of Soil Structures and Irrigation Methods on Leaching Behavior

Leaching is a common phenomenon in irrigated land. Many processes are known to contribute to high leaching rates. Soil structures and irrigation methods are likely to be the major factors responsible for high leachate in most agricultural sites. Figures 5 through 7 and Tables 2 and 3 summarize the water balance over 3 months observed by site and by sampler. From early September to early December 1992, cumulative water input was almost balanced with cumulative evaportranspiration at both Hanley and B4 while cumulative water input is higher than cumulative ET at B2. We collected average cumulative leaching volume of 4.1 cm over 3 months under the overhead-sprinkler irrigation in the sandy soil, compared to 22.8 cm collected under flood and 16.1 cm under micro-sprinkler irrigation in clay soils over the same period. Note that later leachate was due to rainfall and first month irrigation resulted in early leachate. Comparing overhead-sprinkler in sandy soil at Hanley with micro-sprinkler in clay soil at B4, significantly higher percolation occurred at B4 than at Hanley even though cumulative irrigation at both sites roughly matched ET. Deep percolation observed at B4 is almost 4 times greater than that at Hanley. The infiltration capacity in the sandy soil is much higher than the clay soil due to its much higher conductivity. However, the amount of leachate in clay soil is higher than that in the sandy soil over the same period. How did this happen? First, It suggests that soil type has tremendous impact on leachate. The higher leaching rate in clay soils may have resulted from macropore flow due to the extensive cracks which were present in the clay soils. When a swelling clay soil is dry, deep extensive macropores in the form of cracks arise. When intensive water is supplied to a field over a relatively short time period and irrigation rate is much higher than the infiltration rate of the soil matrix, ponding was formed and macropore flow occurred. By our field observations, the width of cracks ranged from a few millimeters to several centimeters and the depth was from a few centimeters to several meters. Before the irrigation following harvest, clay soil was dry and intensive cracks were present. Thus, preferential flow could occurred in clay soil. Second, the shallow water table may have contributed to upward flux into soil profile at B2 and B4. Water could flow upward into the soil profile where water balance was calculated whenever the hydraulic head gradient is negative, thus altering the water balance calculation. This upward flux could be quite significant in certain situations, such as if water is located at a shallow depth below the surface profile (Jury et al., 1991). In B2 and B4, we have relatively high water table which may induce upward flux. Over-irrigation occurred at B2 while there was almost no over-irrigation at B4. Leachates under flood (B2) and micro-sprinkler (B4) on the same clay soil were approximately the same after one month of irrigation season, even though the amount of irrigation at B2 is significantly higher than that at B4. We may draw a conclusion that the impact of over-irrigation on leachate is not as important as soil type. It should be noted that estimation of irrigation rate at B2 was obtained using neutron probe data due to difficult measurement of irrigation rate under flood condition. This estimation may have caused some errors because neutron probe readings were not taken exactly on the days irrigation was begun and ended. Thus, actual irrigation rate at B2 could be higher.

Table 2. Summary information of water balance over 3 months at three sites

Site	Irrigation Type	Sum-ET (cm)	Sum-PC (cm)	Sum-(I+P) (cm)	Sum-I (cm)	Sampling Period
Hanley	O-S	23.0	4.1	30.4	12.2	9/92-12/92
B2	Flood	23.0	22.8	41.2	23.0	9/92-12/92
B4	M-S	23.0	16.1	32.1	14.0	9/92-12/92

Note: O-S - Overhead-Sprinkler; M-S - Micro-Sprinkler; Sum-ET - cumulative ET Sum-PC - Cumulative Percolation; Sum-(I+P) - Cumulative Irrigation and Precipitation; Sum-I - Cumulative Irrigation

Table 3. The cumulative depth of water collected by PCAPS at each location over three months.

Sampler Location	Sampler No.	Cumulative Water (ml)	Period of Sampling
B2 West	S3	43638	9/92-12/92
	S9	51533	9/92-12/92
B2 East	S5	33306	9/92-12/92
	S6	38465	9/92-12/92
B4 West	S2	26131	9/92-12/92
	S7	33535	9/92-12/92
B4 East	S1	34650	9/92-12/92
	S10	32115	9/92-12/92
Hanley West	S4	20837	9/92-5/93
	S12	36879	9/92-5/93
Hanley East	S8	8709	9/92-5/93
	S11	16711	9/92-5/93

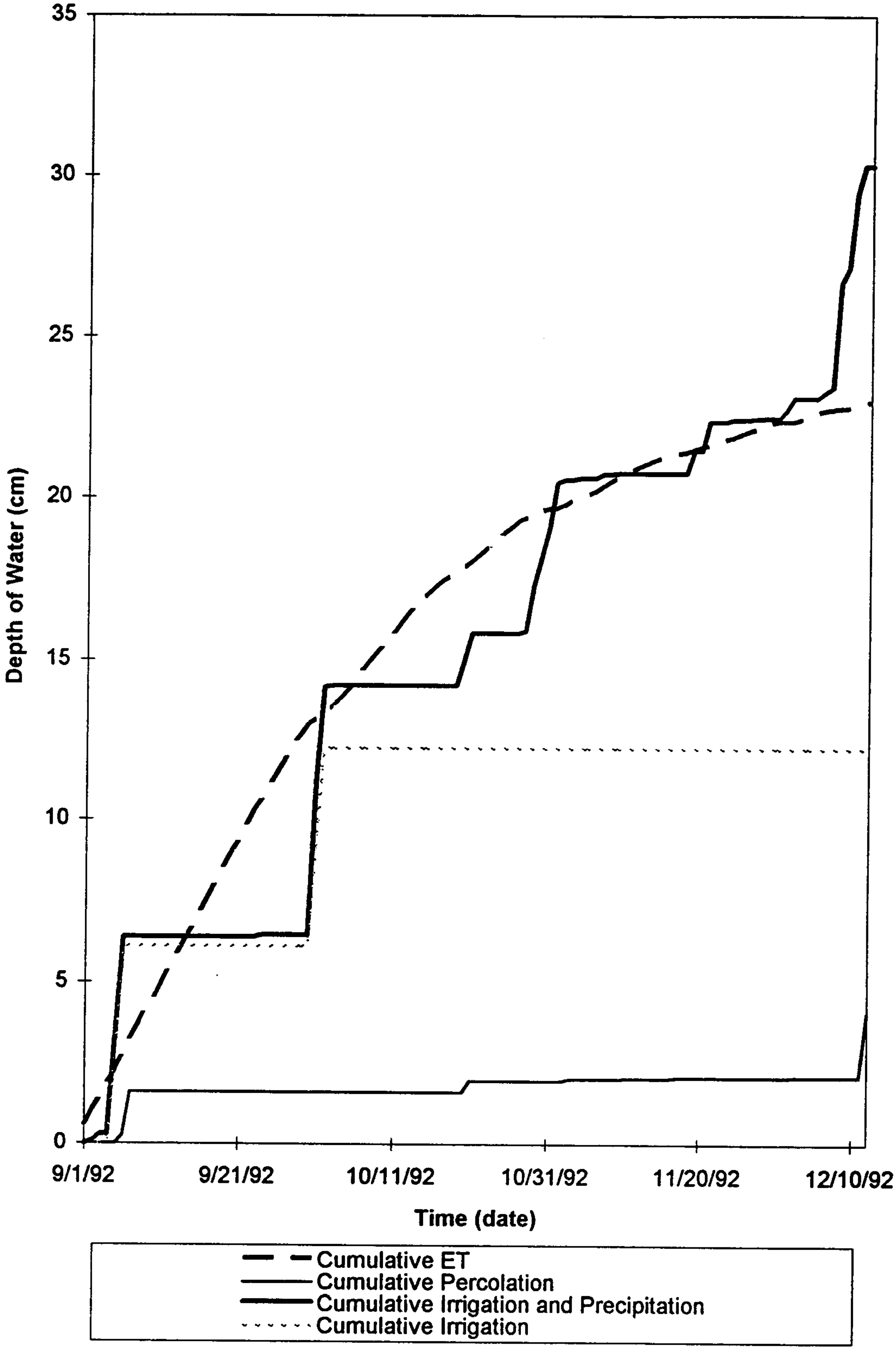

Figure 5. Water balance information over 3 months at Hanley

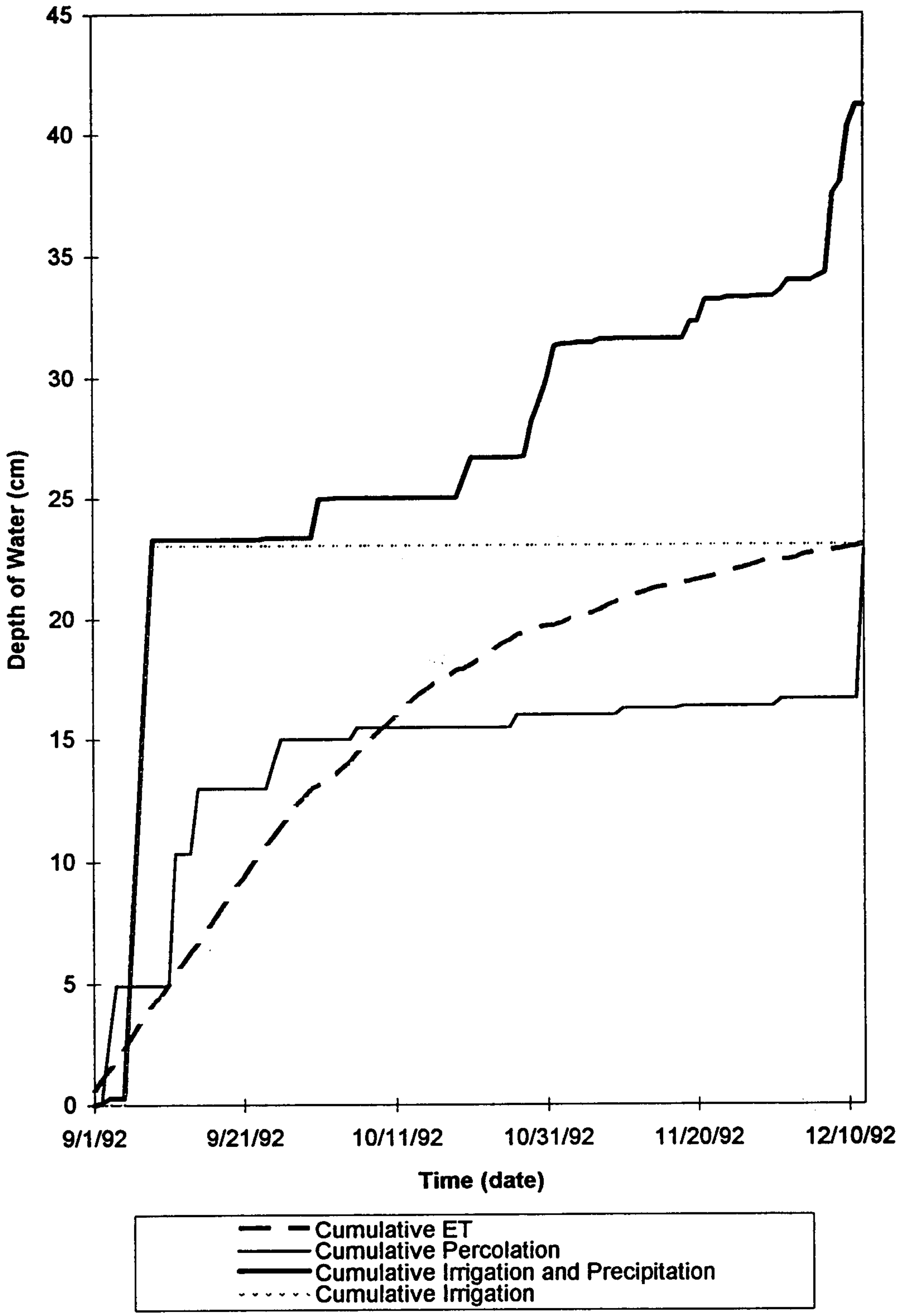

Figure 6. Water balance information over 3 months at B2

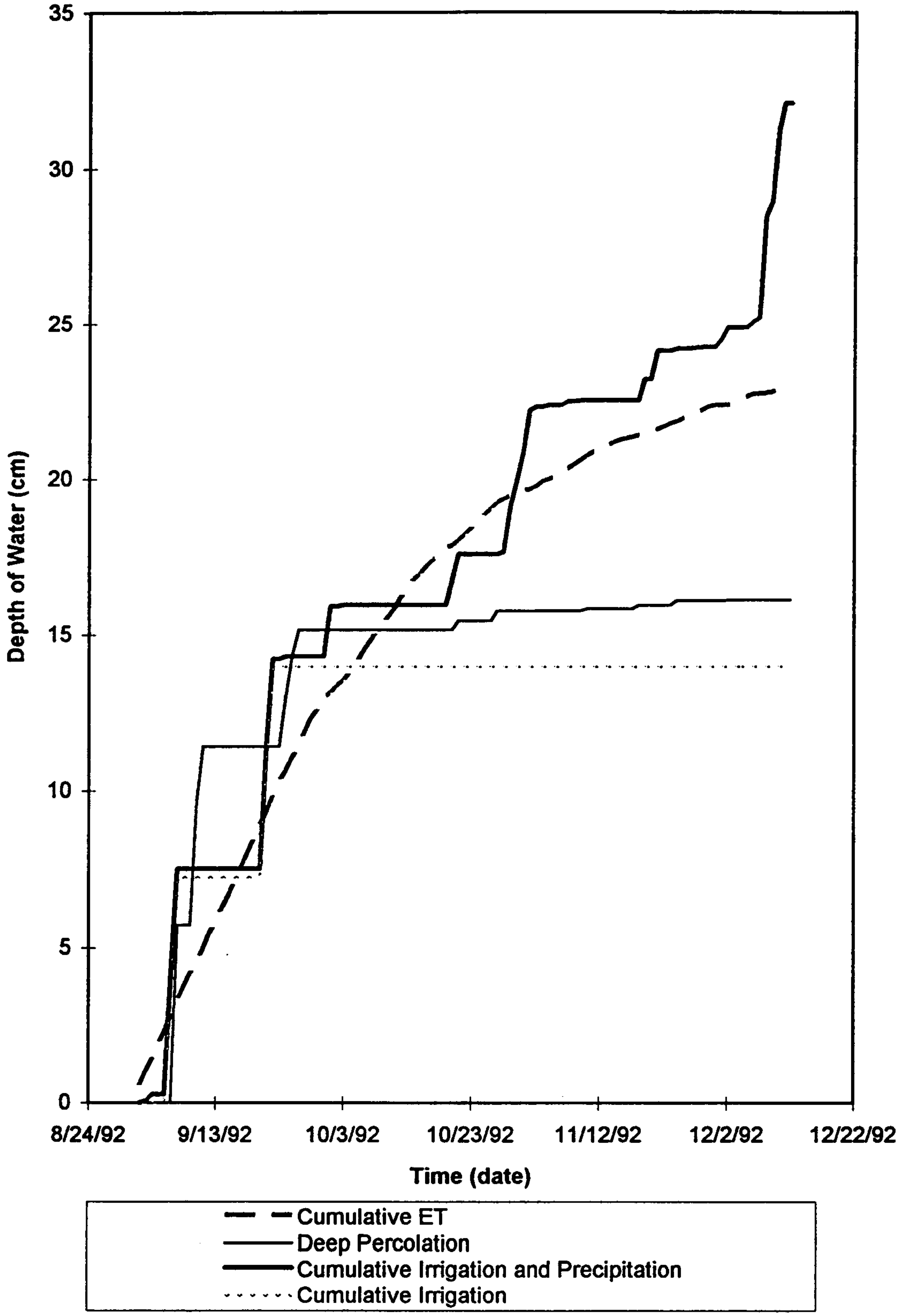

Figure 7. Water balance information over 3 months at B4

Spatial Variability of Sampling Volume within PCAPS

Because of soil heterogeneity and different irrigation practices, water leaching may behave differently with respect to the time and space. Division of the capturing area of PCAPS into many sub-sampling areas allowed us to analyze the spatial variability of water leaching. Table 4 and Figures 8 through 19 show the variability of cumulative volume observed in these experiments. Among three sites, the Hanley farm showed the largest variability in terms of cumulative volume of water in each cell. This may be explained as follows: 1) Fingered flow may have occurred in the sandy soils which would lead to the non-uniformity; 2) Oversampling from early September to later September in 1992 may have been responsible for less variability in Medford, even though higher variability in cracking clay soil was expected. As was pointed out earlier, when soil is dry and heavy irrigation is applied, large leaching may have occurred and filled up all the sampling bottles. Due to limited sampling bottle volume, leaching volume over 550 ml could not be caught and bypassing through the trench wall may have occurred.

On the Medford farm, almost every sampler collected less water in cells nearest the trench than cells furthest from the trench. Two reasons may probably explain this finding. First, the height of the water table at Medford farm varies from 3 to 0 meters from surface, often being over the level of the PCAPS. Unfortunately, the PCAPS were not completely water-proof and high water table may have had an impact on the variability of water leaching patterns. Second, the soil near the trench may have been disturbed by the backhoe and repacking the soil may have broken the continuity of macropore and diminished the role of macropore structures such as large crack formations near the trench. In contrast, this type of situation would not arise on the Hanley farm because of the unstructured sandy soil. Instead, we found that more water was collected in cells near the trench than cells away from the trench. This was particularly true for PCAPS 4 and 8 where 44% and 98% greater recharge was observed in the cells closest to the trench compared to the overall sampler. The back-filled soil may not have been brought back to native bulk density leaving soil with greater pore space near the trench. Big pores have low capillary force to hold water, which may result in higher leaching when over-irrigation or heavy rainfall occurred. PCAPS 11 and 12 were of smaller size and were installed further from the trench (The samplers were at least 55 cm from the trench whereas the other PCAPS were as close as 15 cm to the trench). These PCAPS did not obtain more water near the trench.

In each plot, we found that three of the four square PCAPS collected 18% to 92% more water than the rectangular PCAPS, although the rectangular PCAPS have a larger catchment area. We are not sure of why this occurred.

Table 4. Variability of cumulative volume water in each cell within PCAPS.

Site	PCAPS	Mean* ml	Standard Deviation	Coefficient of Variation	95% Confidence Level
B2	S3	1777	267	0.2	107
	S9	2061	210	0.1	82
	S5	1388	662	0.5	265
	S6	1603	509	0.3	203
B4	S1	1444	421	0.3	168
	S10	2267	245	0.1	96
	S2	1089	542	0.5	217
	S7	1397	433	0.3	173
Hanley	S4	868	586	0.7	234
	S12	1475	696	0.5	273
	S8	363	507	1.4	203
	S11	668	816	1.2	320

Mean*:Average Cumulative Volume of Water in Each Cell within PCAPS

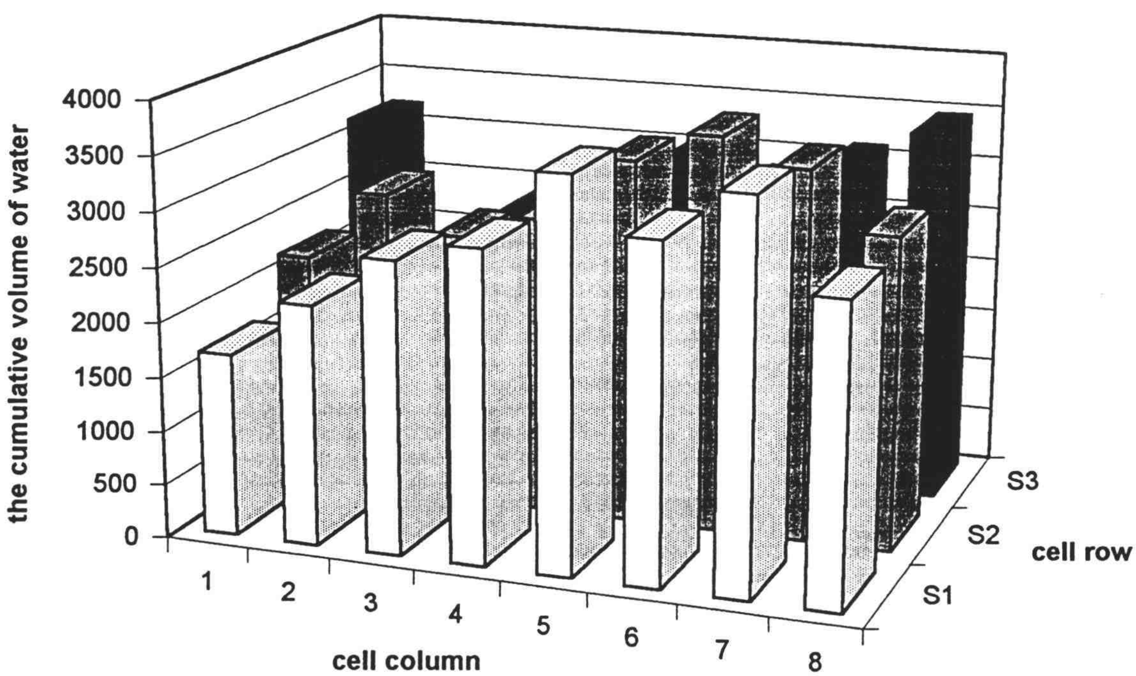

Figure 8. The cumulative depth of water observed by PCAPS 1 in each cell over 3 months under micro-sprinkler in clay soil.

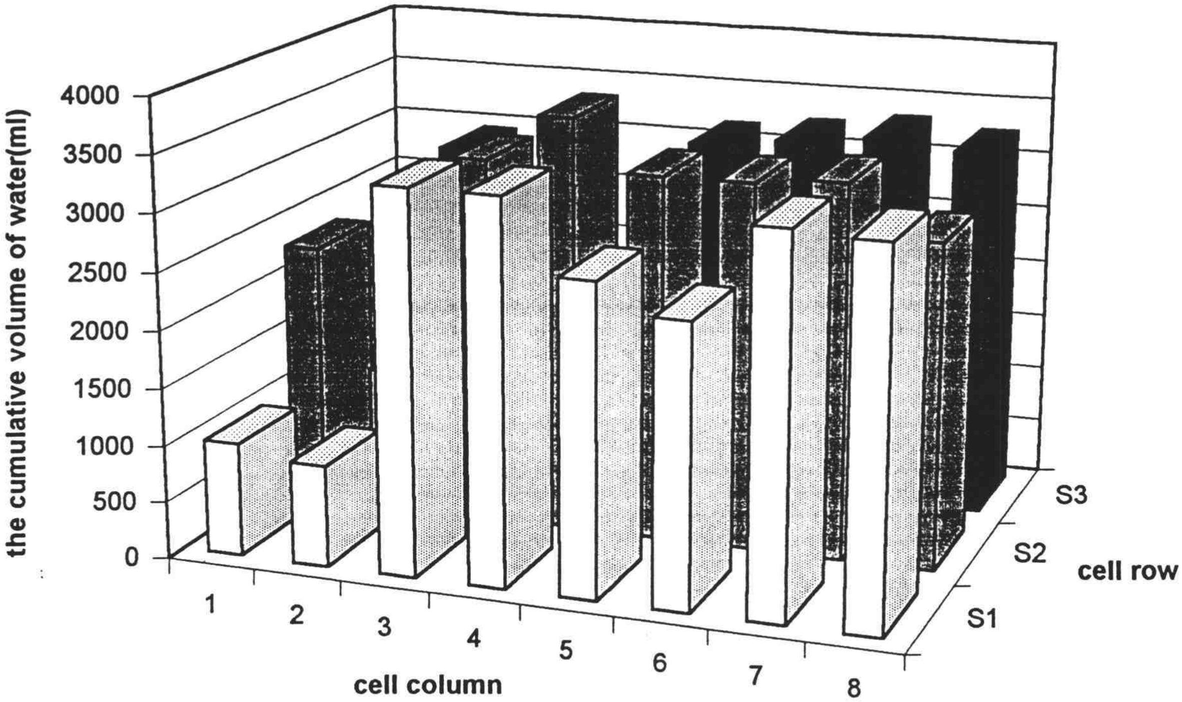

Figure 9. The cumulative depth of water observed by PCAPS 2 in each cell over 3 months under micro-sprinkler in clay soil.

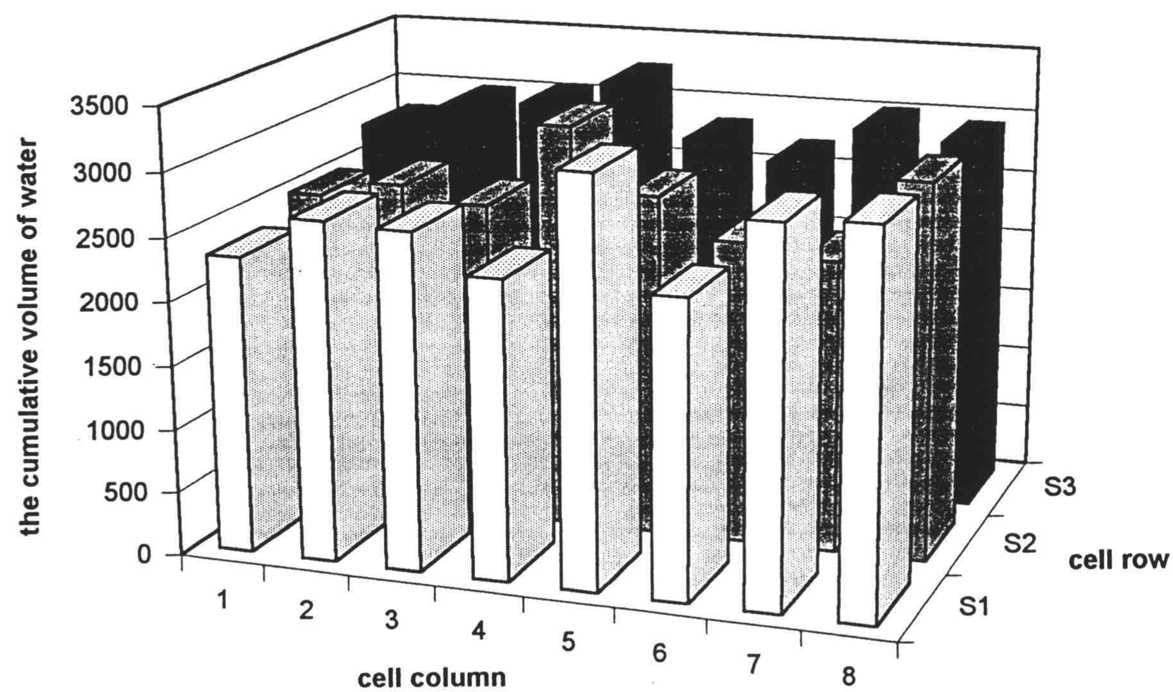

Figure 10. The cumulative depth of water observed by PCAPS 3 in each cell over 3 months under flood in clay soil.

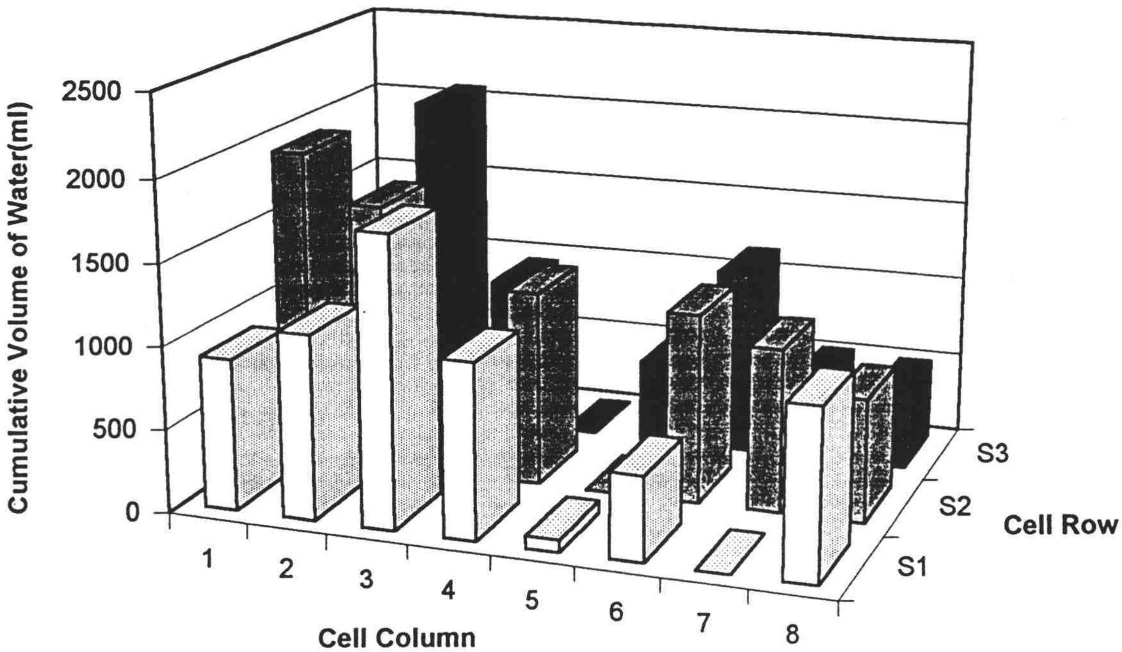

Figure 11. The cumulative depth of water observed by PCAPS 4 in each cell over 9 months under overhead-sprinkler in sandy loam soil

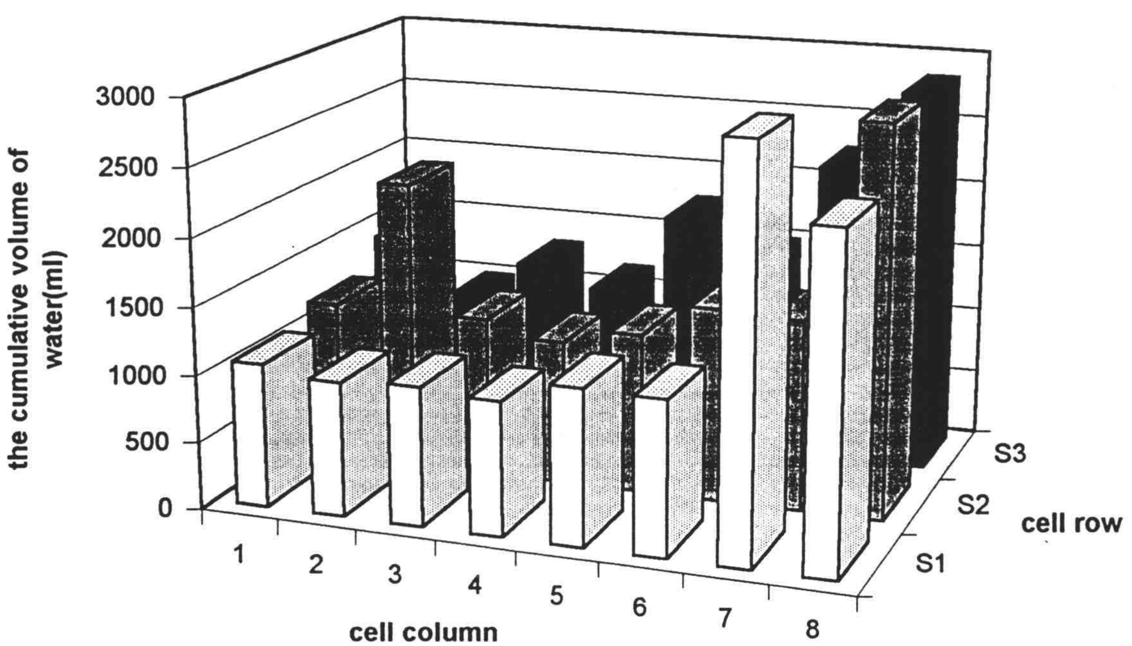

Figure 12. The cumulative depth of water observed by PCAPS 5 in each cell over 3 months under flood in clay soil.

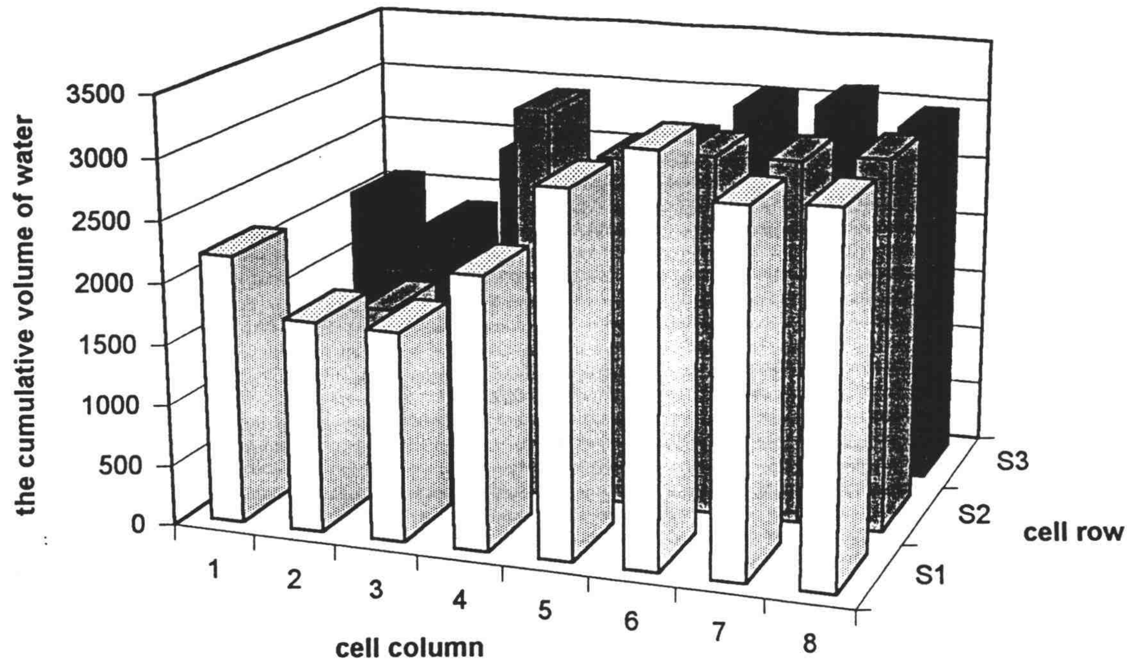

Figure 13. The cumulative depth of water observed by PCAPS 6 in each cell over 3 months under flood in clay soil.

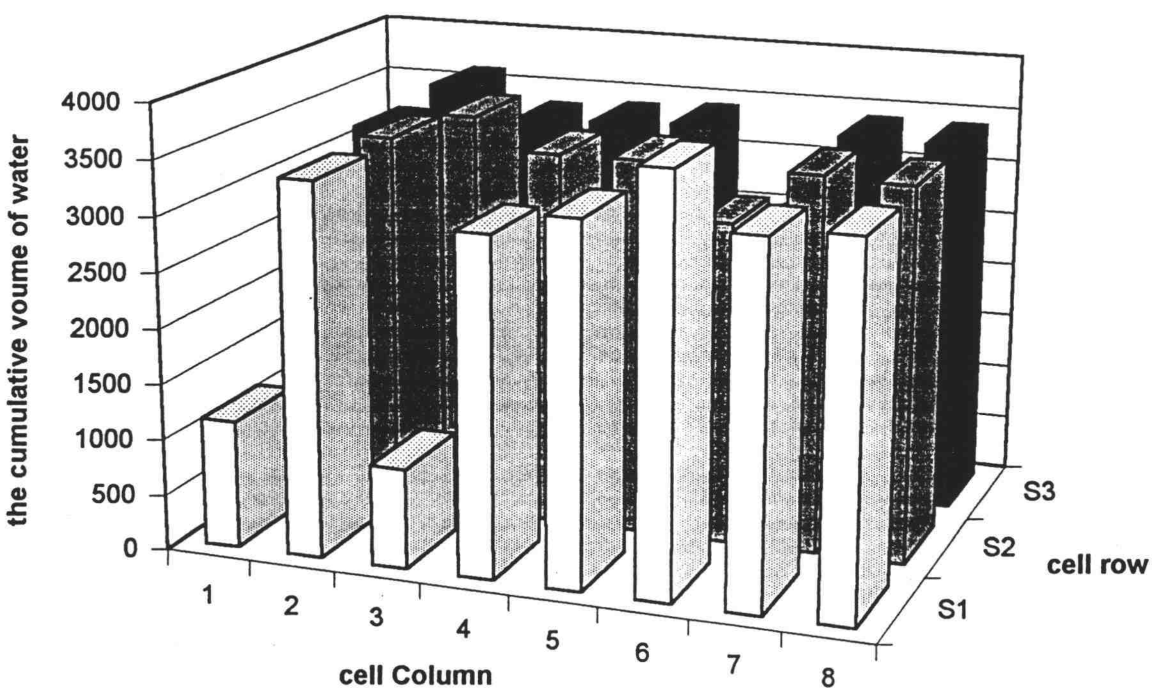

Figure 14. The cumulative depth of water observed by PCAPS 7 in each cell over 3 months under micro-sprinkler in clay soil.

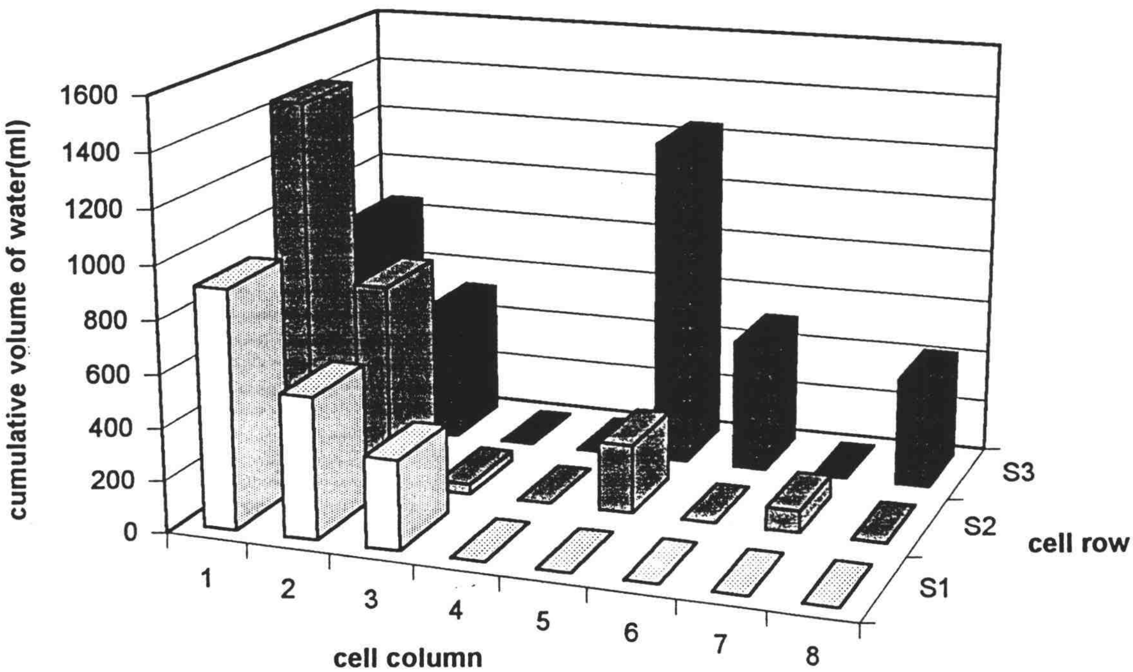

Figure 15. The cumulative depth of water observed by PCAPS 8 in each cell over 9 months under overhead-sprinkler in sandy soil.

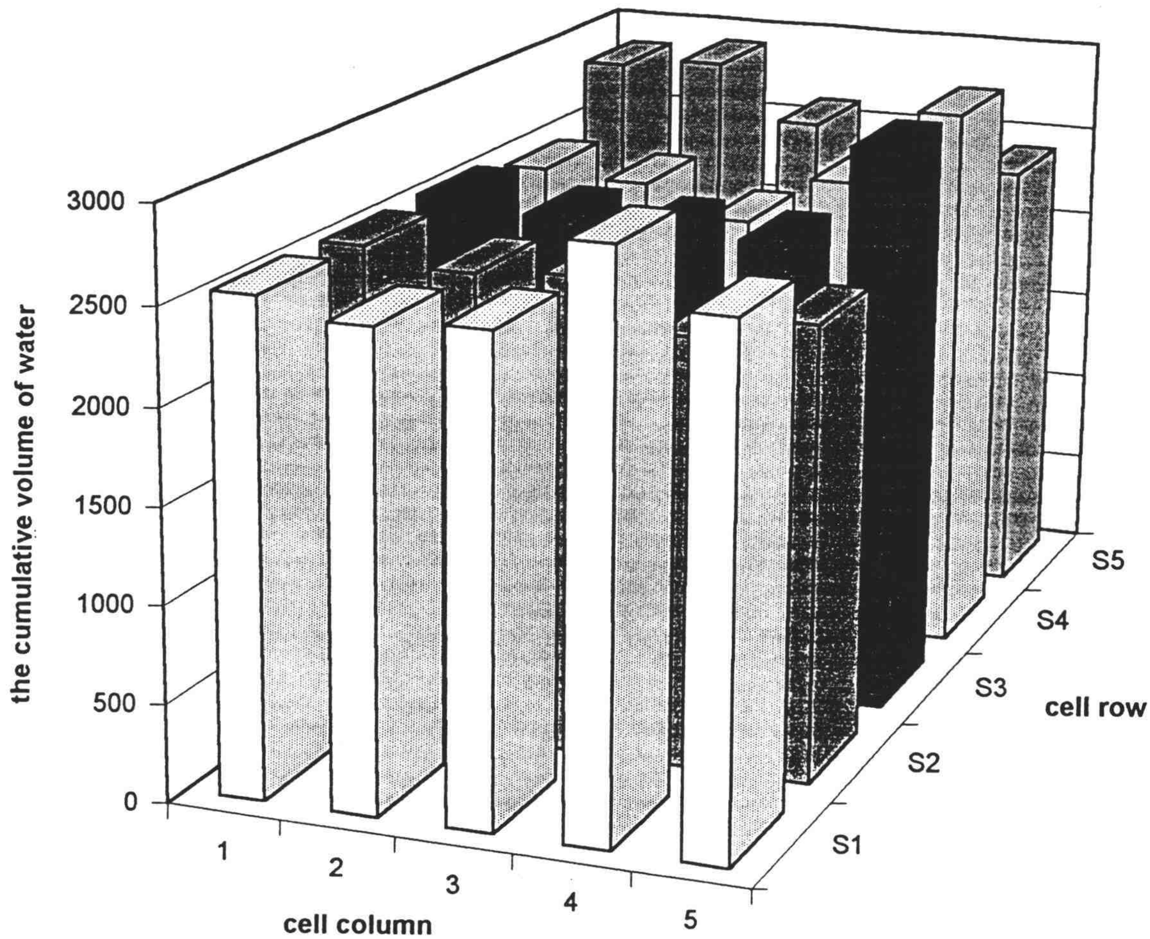

Figure 16. The cumulative depth of water observed by PCAPS 9 in each cell over 3 months under flood in clay soil.

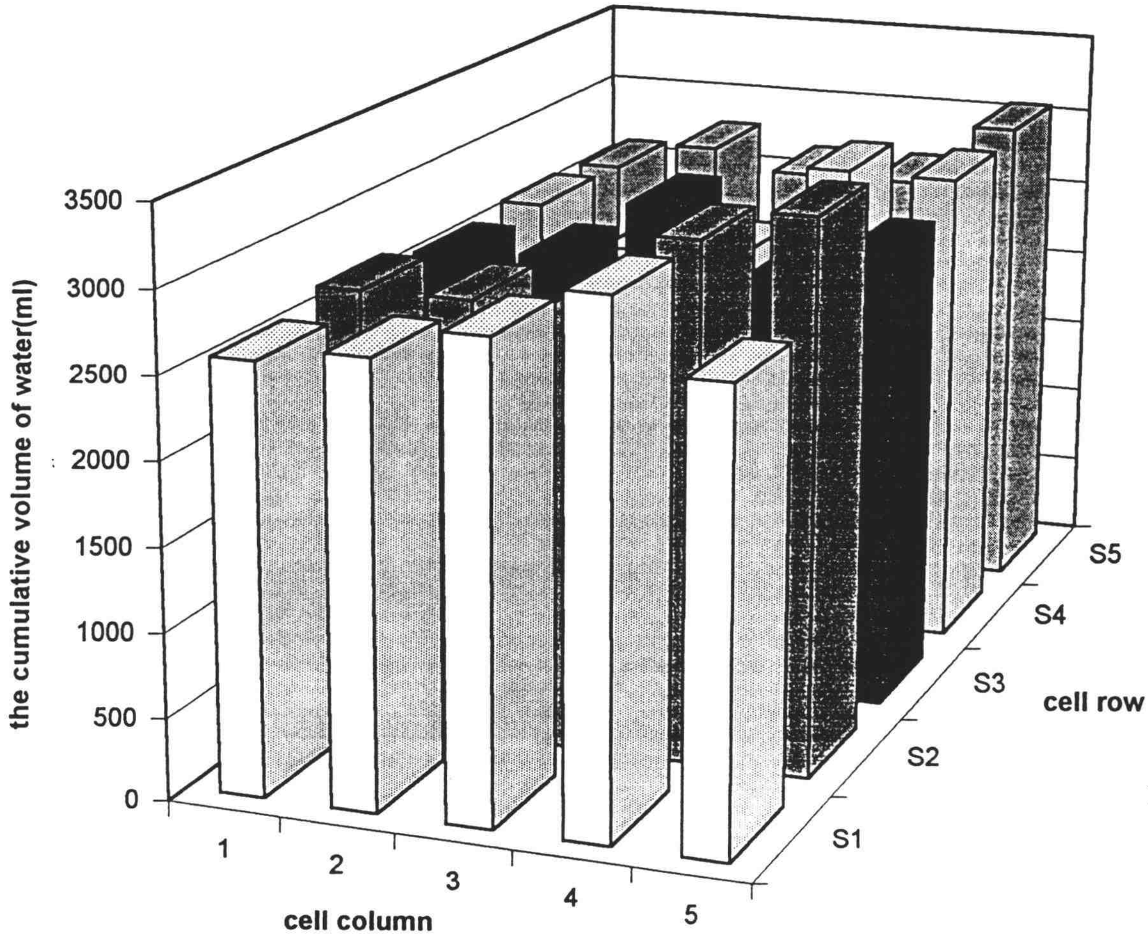

Figure 17. The cumulative depth of water observed by PCAPS 10 in each cell over 3 months under micro-sprinkler in clay soil.

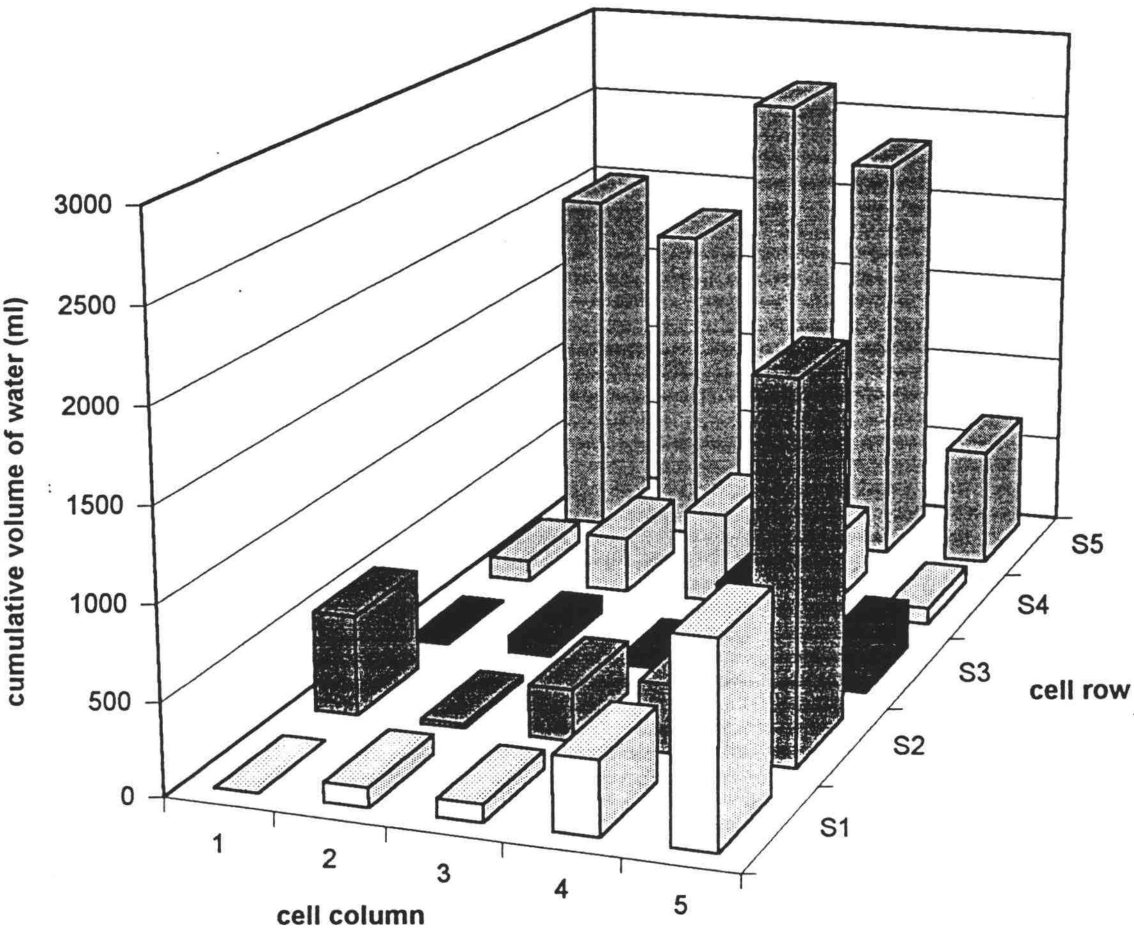

Figure 18. The cumulative depth of water observed by PCAPS 11 in each cell over 9 months under overhead-sprinkler in sandy soil

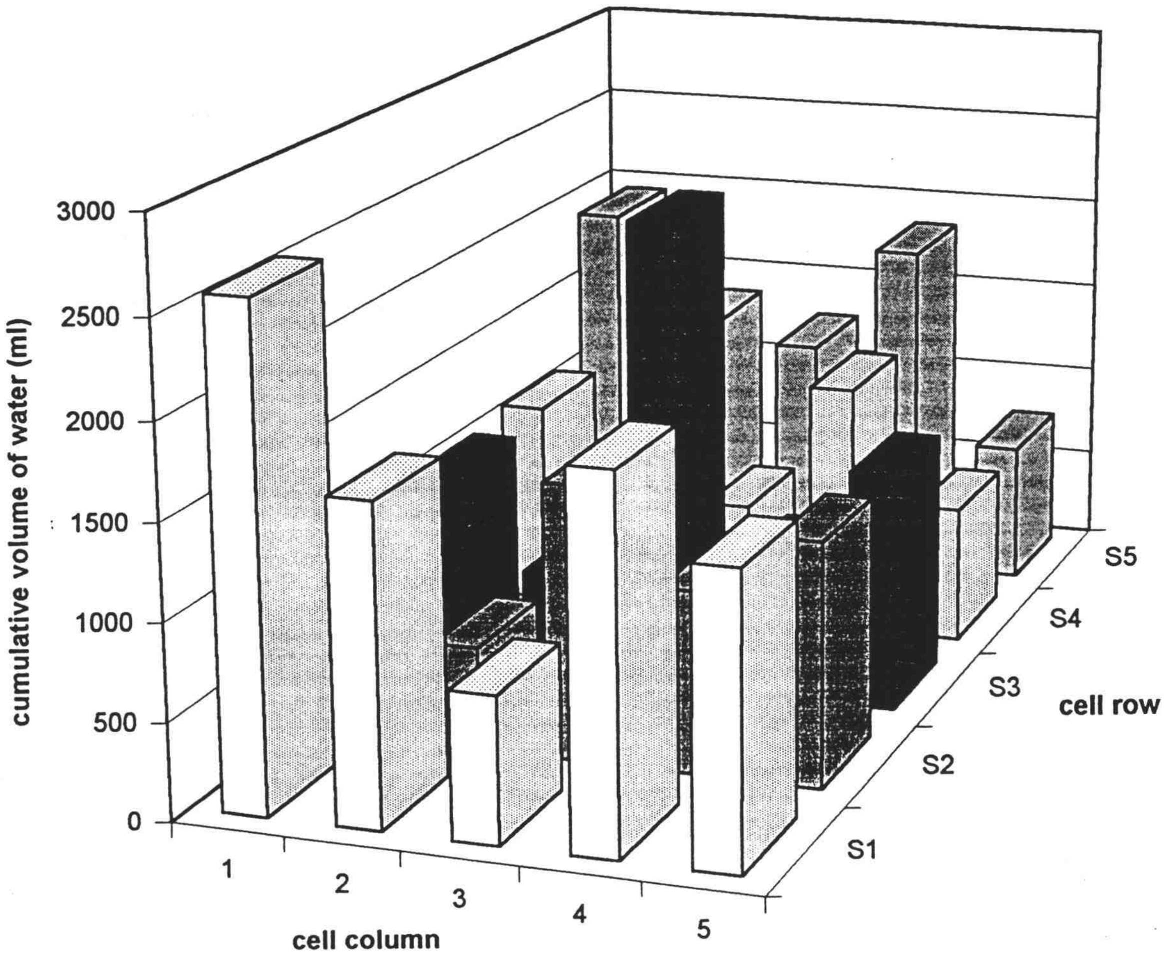

Figure 19. The cumulative depth of water observed by PCAPS 12 in each cell over 9 months under overhead-sprinkler in sandy soil.

PCAPS Sampling Ability and Mass Recovery

In terms of sampling volume, pairs of PCAPS on each plot were very consistent in their sampling results (Table 5 and Figures 20 to 25). The correlation coefficient between flux observed by pairs of PCAPS at each plot ranged from 0.965 to 0.997 which indicates that PCAPS were highly correlated. PCAPS at the Hanley farm collected little water (3.5 cm depth) during 1992 irrigation season while PCAPS at Medford collected tremendous leaching water (18.6 cm depth at B2 and 14 cm at B4). The cumulative volume over time at PCAPS in each plot represents similar trend. Before the early fall irrigation, soil at Medford was many cracks were present. When irrigation application rate was greater than the infiltration rate of clay soils, water movement could be accelerated through the macropore flow pathways. This mechanism may explain why leaching is high in clay soils in early fall. Amount of water applied in the field decreases in the order: flooding > over-head sprinkler > micro-sprinkler. However, leachate at three sites did not reflect this order. Once again, soil structures was thought to be responsible.

The correlation coefficient between PCAPS was high. However, it would have been lower if oversampling did not occur in September 1992. Because of limited sampling bottle volume and sampling frequency, high leaching in that time period may not have caught and bypassing may have occurred. Therefore, variability of cumulative volume may have been decreased and correlation coefficient may not necessarily have been this high.

Tracer mass recovery varied between sites (Tables 6, 7, and 8). The average blue dye recovery in three sites was 2.75% in B2, 0.367% in B4, and 0.024% in Hanley. The average rhodamine recovery was 1.68% in B2, 0.44% in B4, and 0.196% in Hanley. The average bromide recovery was 9.45% in B2, 7.2% in B4, and 7.2% in Hanley. The low bromide mass recovery may be explained by as follows: 1) bromide losses have been reported due to the plant uptake of bromide. For orchard grass pastures 32% uptake of applied bromide have been reported (Owens et al., 1985), and for potatoes 53% (Kung, 1990). 2) high water table may have made lateral movement of water and solutes more important, leading less bromide collection at PCAPS. 3) the refilled trench with a completely different structure and soil hydraulic properties from the surrounding soil acting as a drain for laterally moving water. Thus, for all sites blue dye and rhodamine recovery has the following order: B2 > B4 > Hanley. Note that uneven time periods were used between sites. If we only consider irrigation season, then average bromide recovery also decreased in the order: B2 > B4 > Hanley. In other words, all tracer mass recovery declined in the order: flooding in clay soil > micro-sprinkler in clay soil > over-head sprinkler in sandy soil. Because some pesticides have similar properties as the blue dye and rhodamine, total pesticide recovery rates would be expected to have the same decreasing order as the above.

Table 5. The correlation coefficient between PCAPS in terms of the cumulative volume of water.

Sampler Location	Sampler Number	Correlation Coefficient
B2E	5,6	0.979
B2W	3,9	0.997
B4E	1,10	0.977
B4W	2,7	0.997
Hanley East	8,11	0.988
Hanley West	4,12	0.965

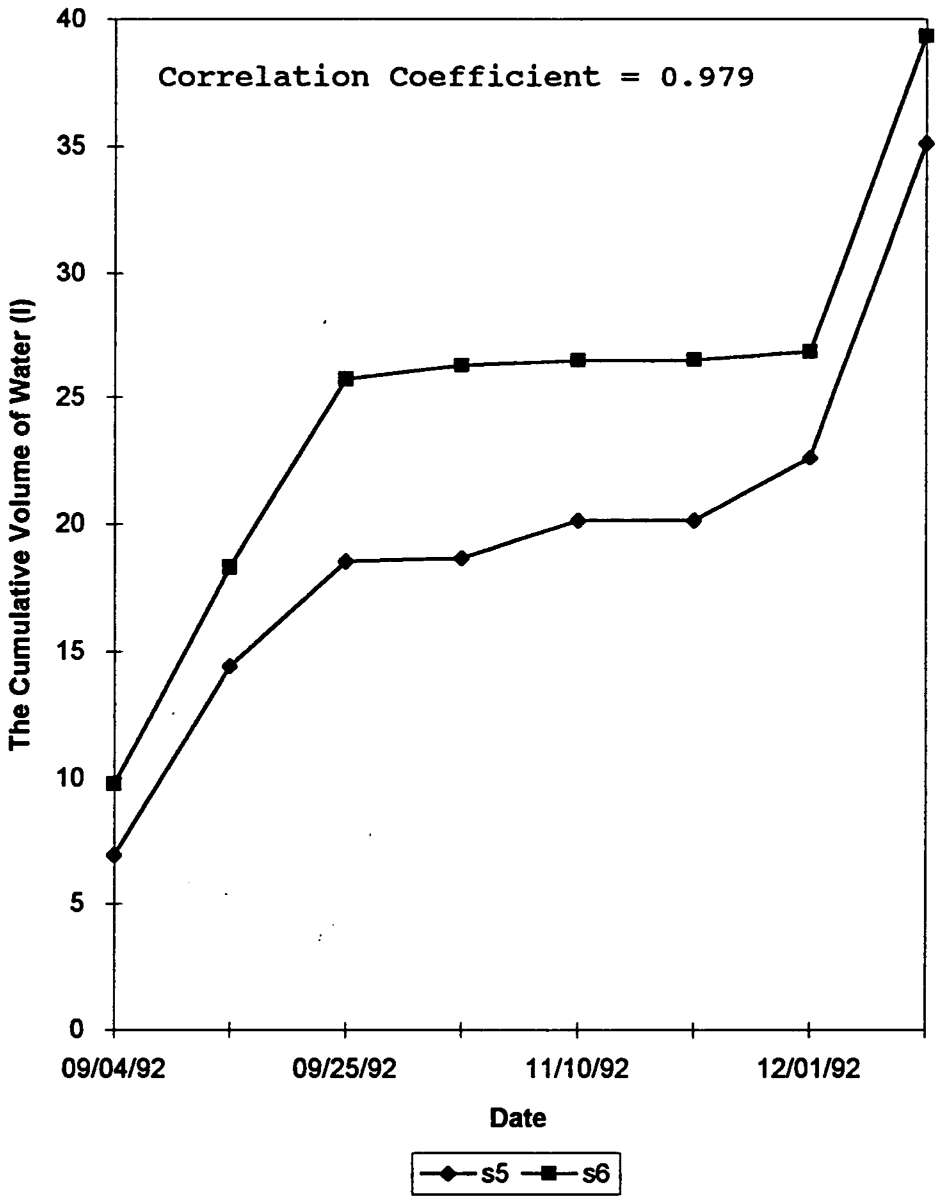

Figure 20. The cumulative volume of water vs. time at B2 East.

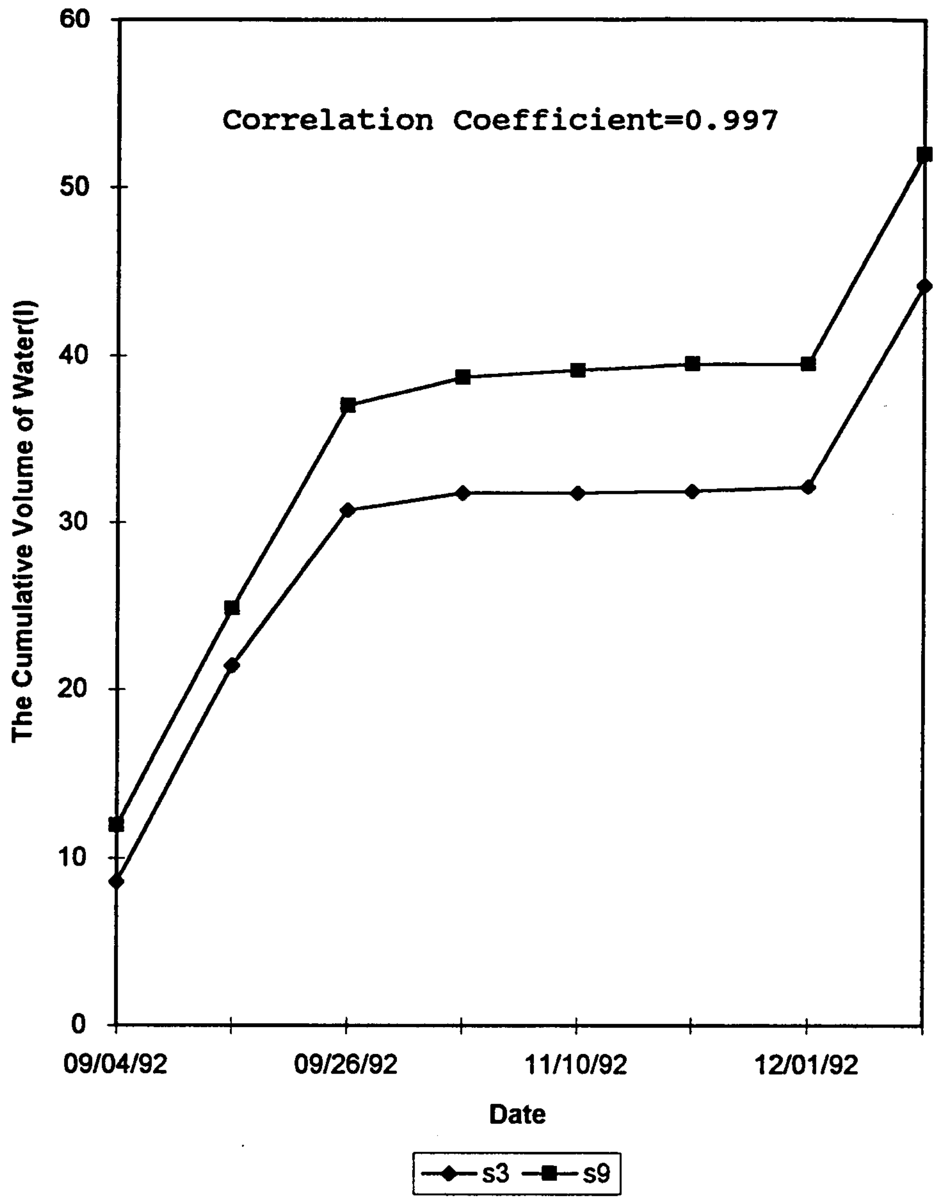

Figure 21. The cumulative volume of water vs. time at B2 West.

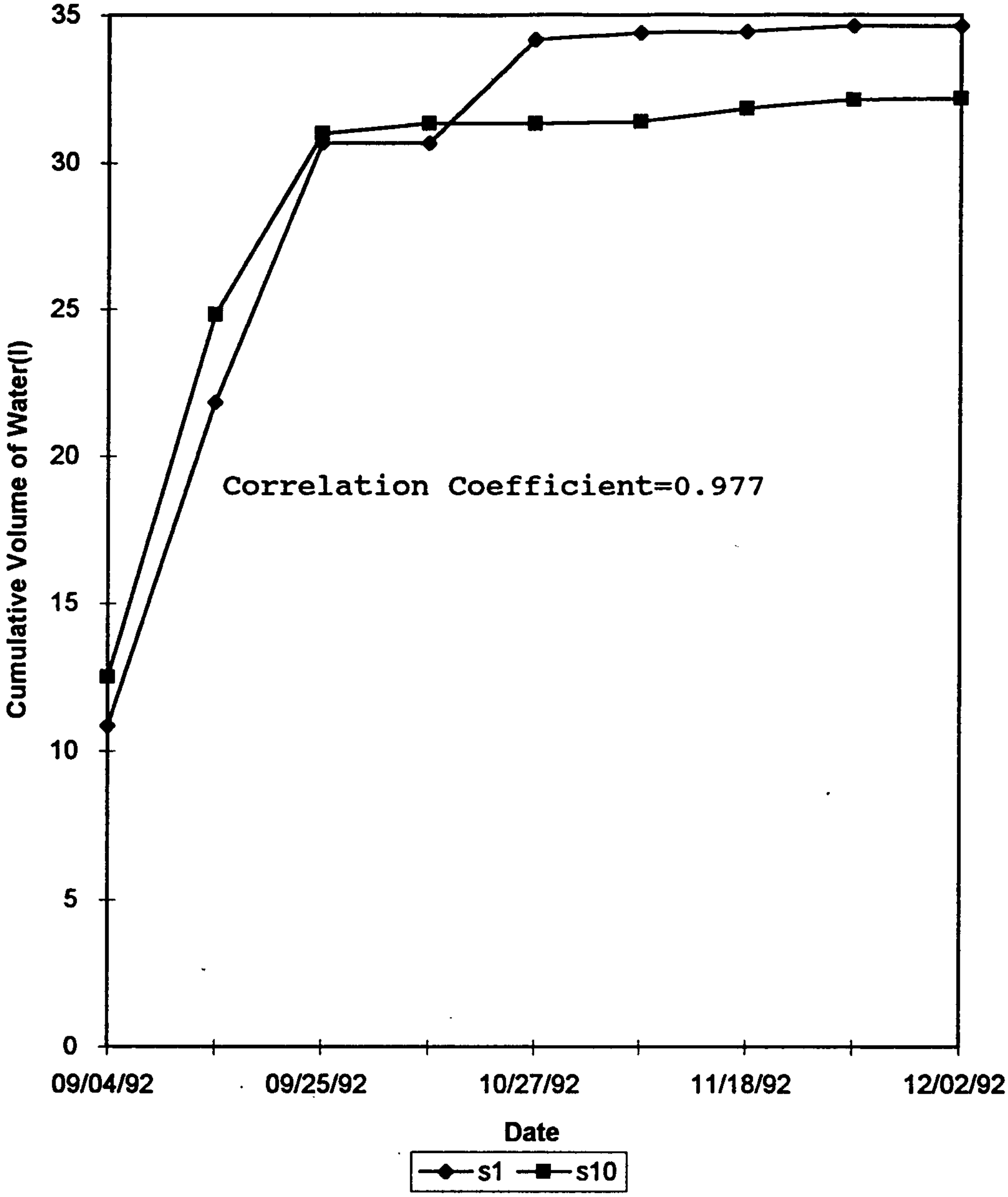

Figure 22. The cumulative volume of water vs. time at B4 East.

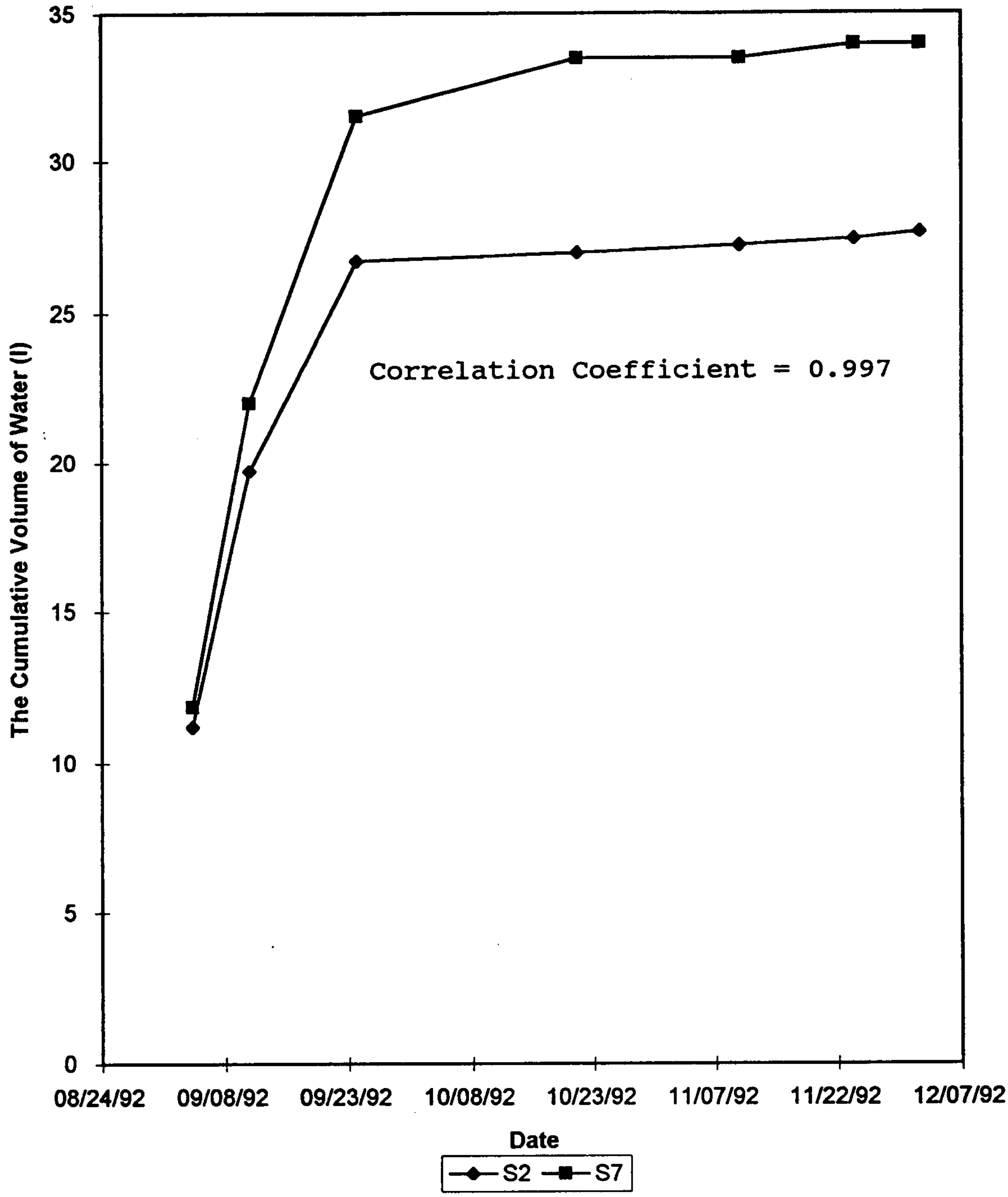

Figure 23. The cumulative volume of water vs. time at B4 West.

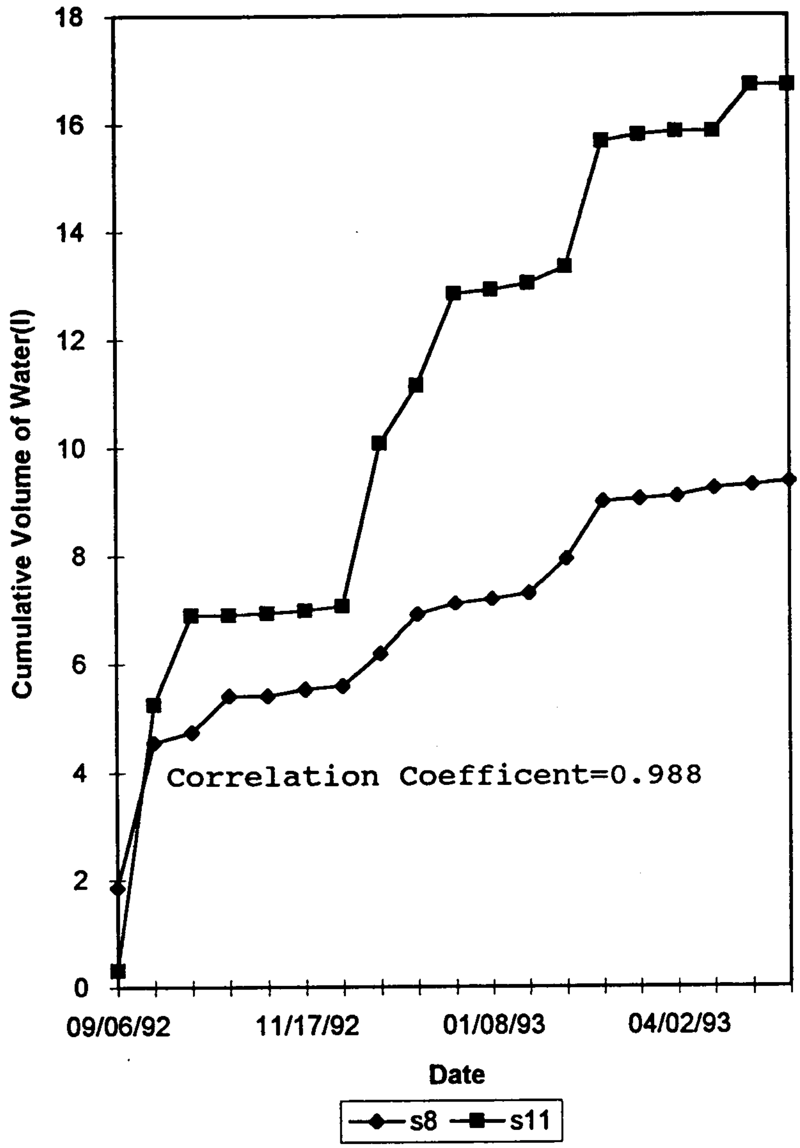

Figure 24. The cumulative volume of water vs. time at Hanley East.

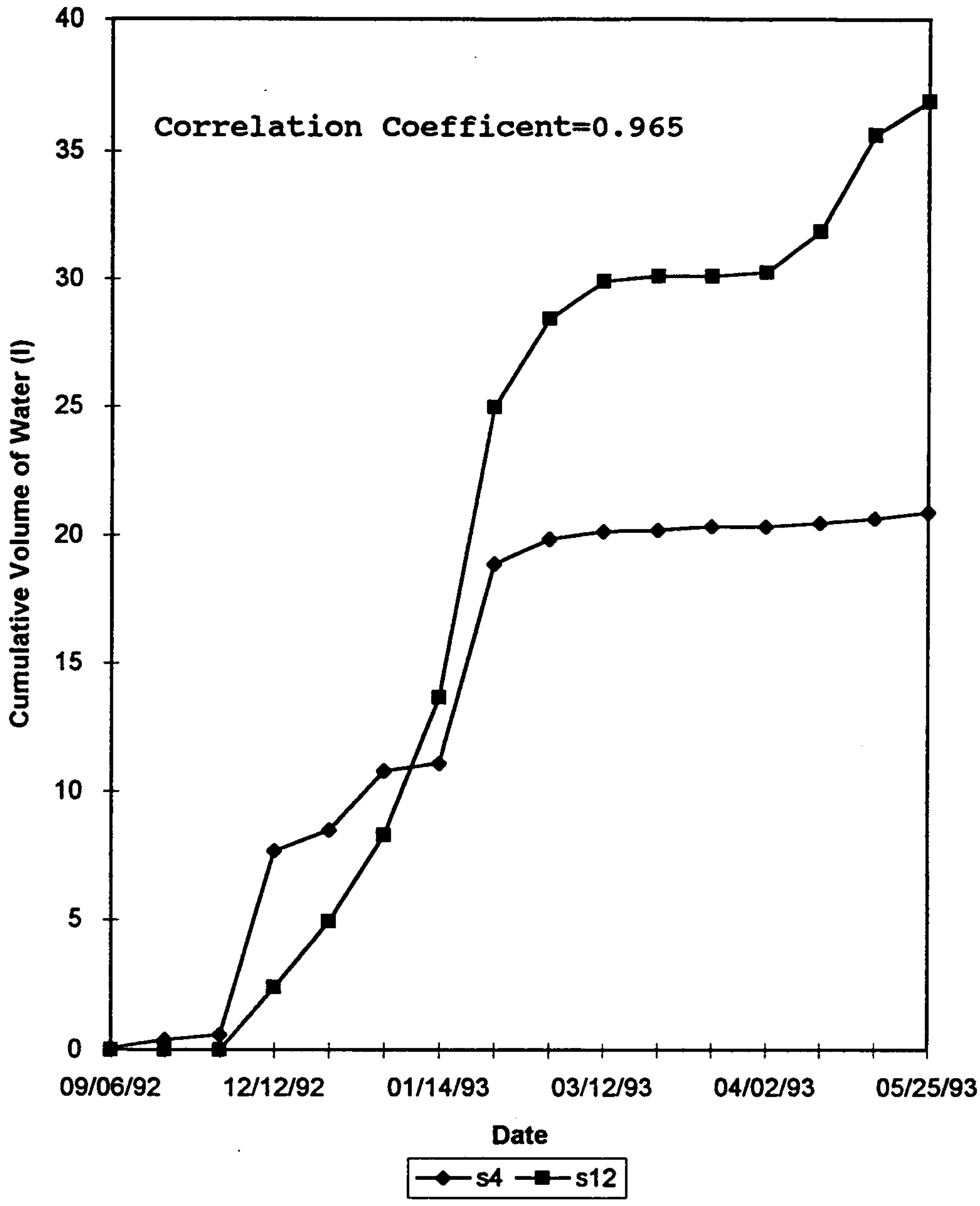

Figure 25. The cumulative volume of water vs. time at Hanley West.

Table 6. Bromide mass recovery at three sites.

Samper Location	Sampler No.	Br Collected (mg)	Br Applied (mg)	% of Recovery*
B2 West	S3	333	7991	4.2
	S9	532	3444	15.4
B2 East	S5	586	7991	7.3
	S6	868	7991	10.9
Average % of Recovery				9.4
B4 East	S1	1091	14300	7.6
	S10	744	6465	11.5
B4 West	S2	711	14300	5.0
	S7	664	14300	4.6
Average % of Recovery				7.2
Hanley West	S4	420	12339	3.4
	S12	1013	5319	19.1
Hanley East	S8	302	12339	2.5
	S11	496	12339	4.0
Average % of Recovery				7.2

*-- between 9/92 and 12/92 in B2 and B4, and between 9/92 and 5/93 in Hanley.

Table 7. Blue dye (BD) mass recovery at three sites.

Samper Location	Sampler No.	BD Collected (mg)	BD Applied (mg)	% of Recovery*
B2 West	S3	127.0	7727	1.64
	S9	251.0	3425	7.33
B2 East	S5	94.6	7727	1.22
	S6	62.0	7727	0.80
Average % of Recovery				2.75
B4 East	S1	52.5	14125	0.37
	S10	58.1	6089	0.95
B4 West	S2	3.4	14125	0.02
	S7	17.0	14125	0.12
Average % of Recovery				0.37
Hanley West	S4	2.8	8133	0.03
	S12	0.8	3506	0.02
Hanley East	S8	0.4	8133	0.004
	S11	1.2	3506	0.03
Average % of Recovery				0.02

*-- between 9/92 and 12/92 in B2 and B4, and between 9/92 and 5/93 in Hanley.

Table 8. Rhodamine (Rh) mass recovery at three sites.

Samper Location	Sampler No.	Rh Collected (ug)	Rh Applied (ug)	% of Recovery*
B2 West	S3	25	1794	1.4
	S9	28	773.46	3.6
B2 East	S5	17	1794	1.0
	S6	14	1794	0.8
Average % of Recovery				1.7
B4 East	S1	11	3211	0.3
	S10	10	1384	0.8
B4 West	S2	4	3211	0.1
	S7	8	1384	0.5
Average % of Recovery				0.4
Hanley West	S4	5	2775	0.2
	S12	4	1195	0.3
Hanley East	S8	2	2775	0.1
	S11	3	1195	0.3
Average % of Recovery				0.2

*-- between 9/92 and 12/92 in B2 and B4, and between 9/92 and 5/93 in Hanley.

Nitrate-Nitrogen and Predicted Pesticide Transport

As mentioned earlier, nitrate-nitrogen and agrochemical leachate are affected by the soil structures and irrigation methods. Table 9 summarizes seasonal and annual nitrate-nitrogen concentrations observed at the three sites. The annual nitrate-nitrogen concentration observed at Hanley farm, calculated as flow weighted mean, was 15 mg/l which slightly exceeded the maximum allowable drinking water level of 10 mg/l. Even though the total mass of migration of nitrate-nitrogen movement at Hanley was not very high, the low leaching volume results in a high nitrate-nitrogen concentration. By contrast, the seasonal nitrate-nitrogen concentration observed under flood (B2) and micro-sprinklers (B4) on clay soil was 3 mg/l and 2 mg/l, respectively. Figures 26 to 31 show the flow weighted nitrate-nitrogen calculation with time for each site. In B2 and B4, There are only a few dates for which nitrate-nitrogen concentration was over 10 mg/l. In contrast, nitrate-nitrogen concentration was over 10 mg/l at the Hanley sites of about 40% of the time. In B2, B4, and Hanley East, we find that nitrate-nitrogen concentration showed a significant increase in early fall. The early arrival of nitrate-nitrogen could have been attributed to preferential flow of water through the larger channels of the wetted pore space, causing water to flow more rapidly than if the water in the entire soil matrix were displaced. The current agricultural practice is to fertilize following the pear harvest. At that time soil is dry and extensive cracks were present, When heavy irrigation is applied, water could carry available nitrate through cracks without contacting with the bulk soil. If the solute had moved through the soil matrix, the early arrival of nitrate would not have been seen.

Table 9. Seasonal or annual nitrate-nitrogen concentration and mass at three sites.

Sampler Location	Sampler No.	Total Mass	Total Volume	Seasonal Conc.
		NO3-N (mg)	(l)	NO3-N (mg/l)
B2 East	S5	141	33	4
	S6	272	39	7
B2 West	S3	21	44	0
	S9	107	52	2
[NO3-N] @ B2				3
B4 East	S1	35	42	1
	S10	78	45	2
B4 West	S2	61	34	2
	S7	129	44	3
[NO3-N] @ B4				2
Hanley West	S4	200	21	10
	S12	867	36	24
Hanley East	S8	66	9	8
	S11	69	16	4
[NO3-N] @ Hanley				15

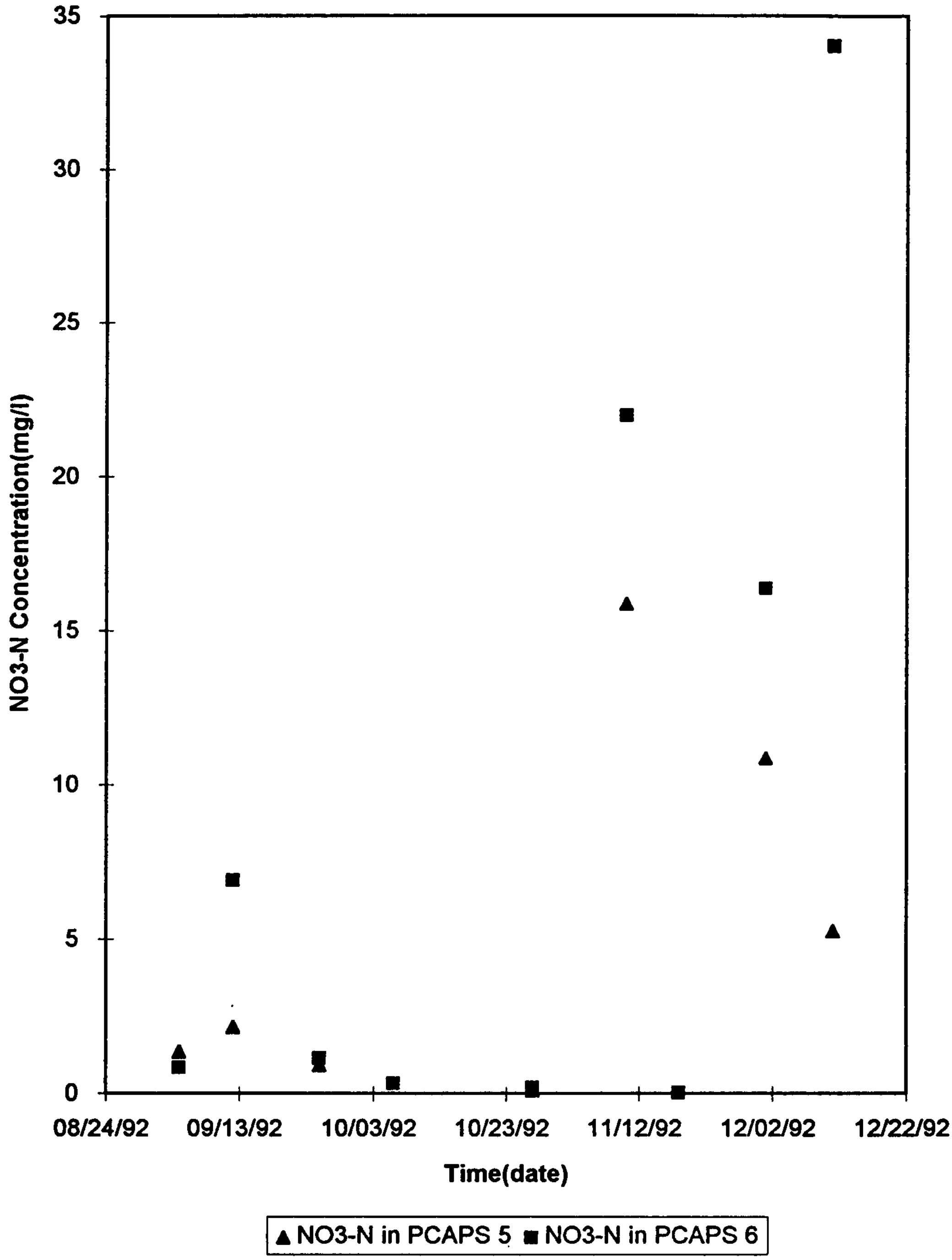

Figure 26. Nitrate-nitrogen concentration vs. time at B2 East.

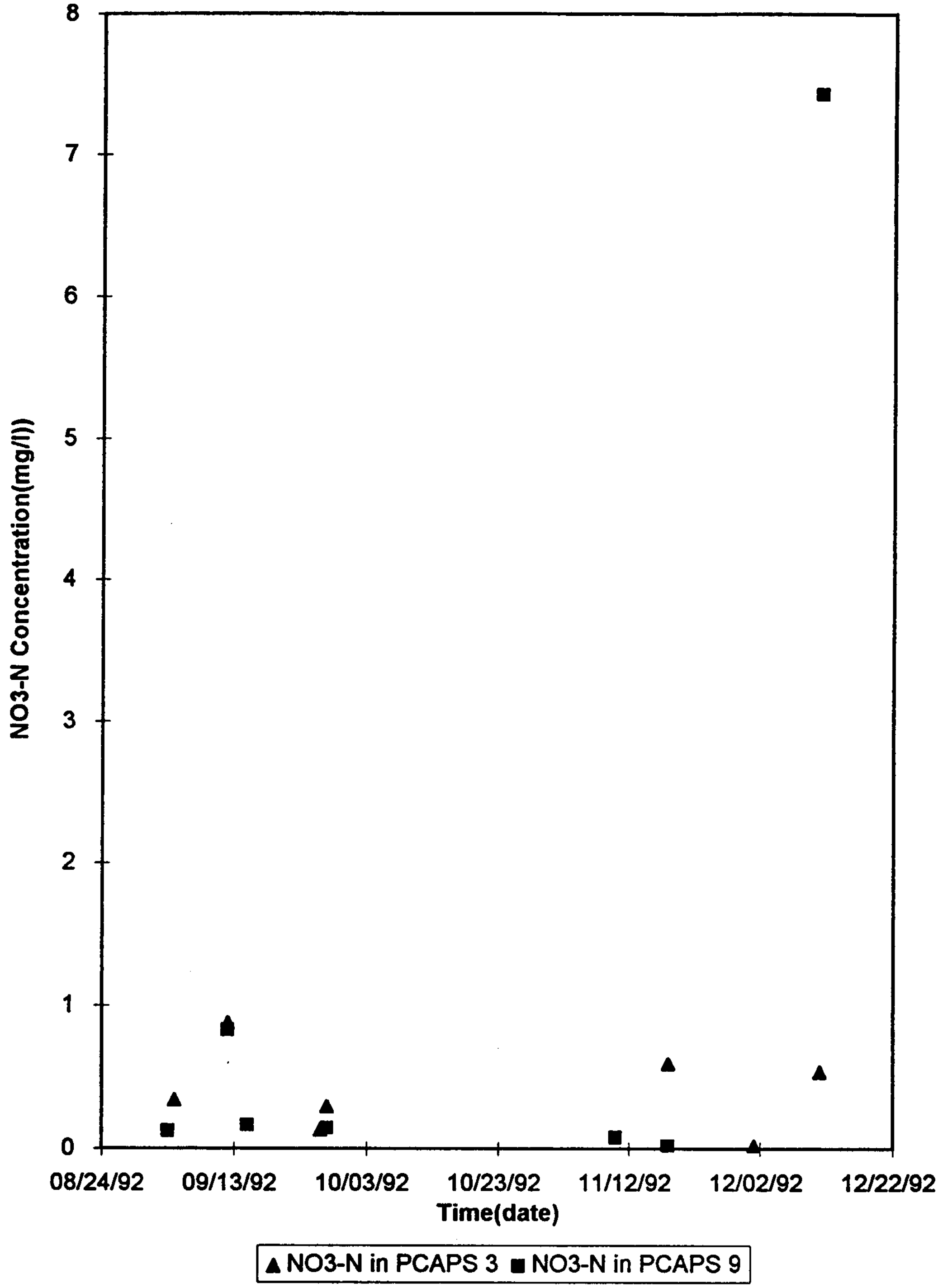

Figure 27. Nitrate-nitrogen concentration vs. time at B2 West.

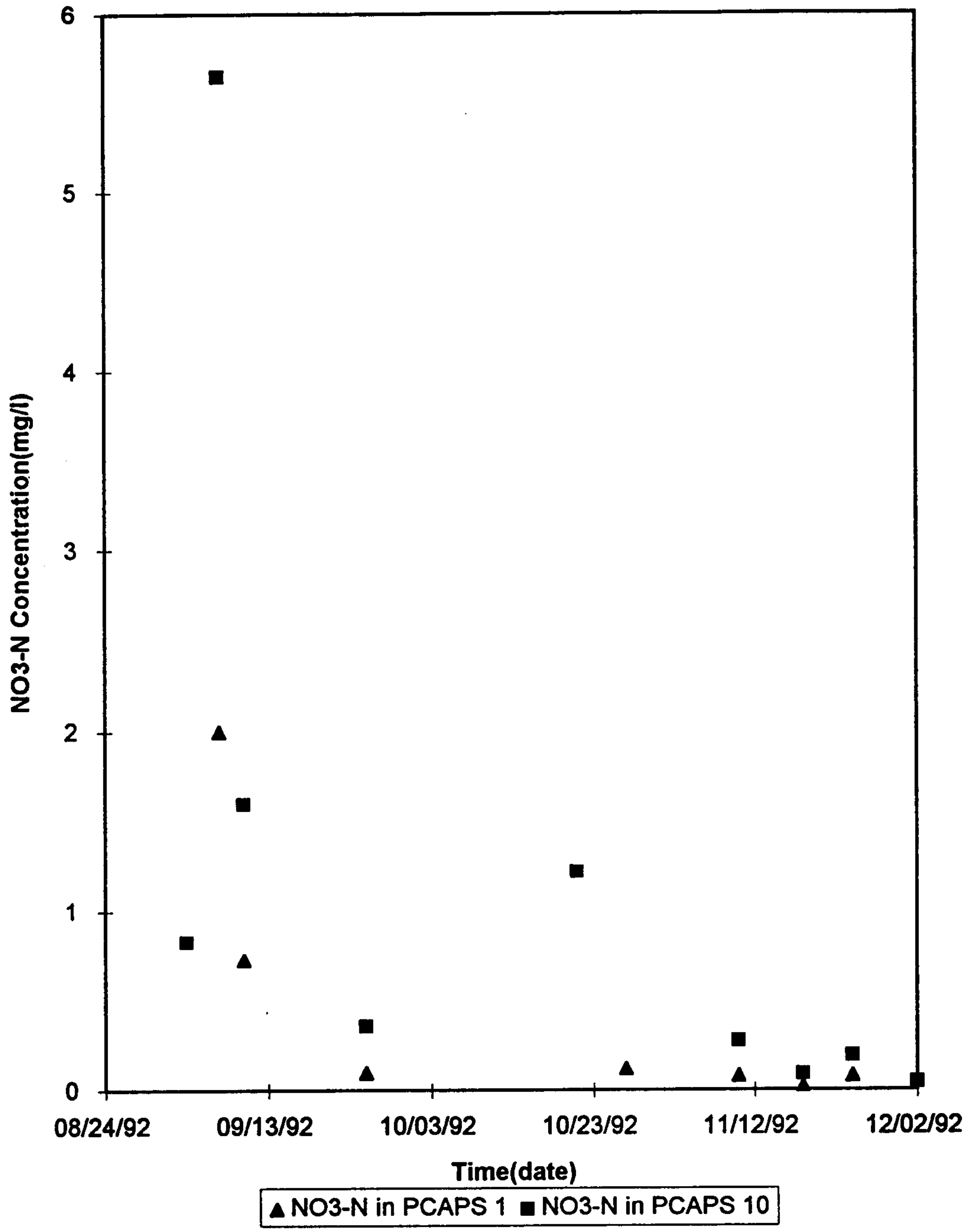

Figure 28. Nitrate-nitrogen concentration vs. time at B4 East.

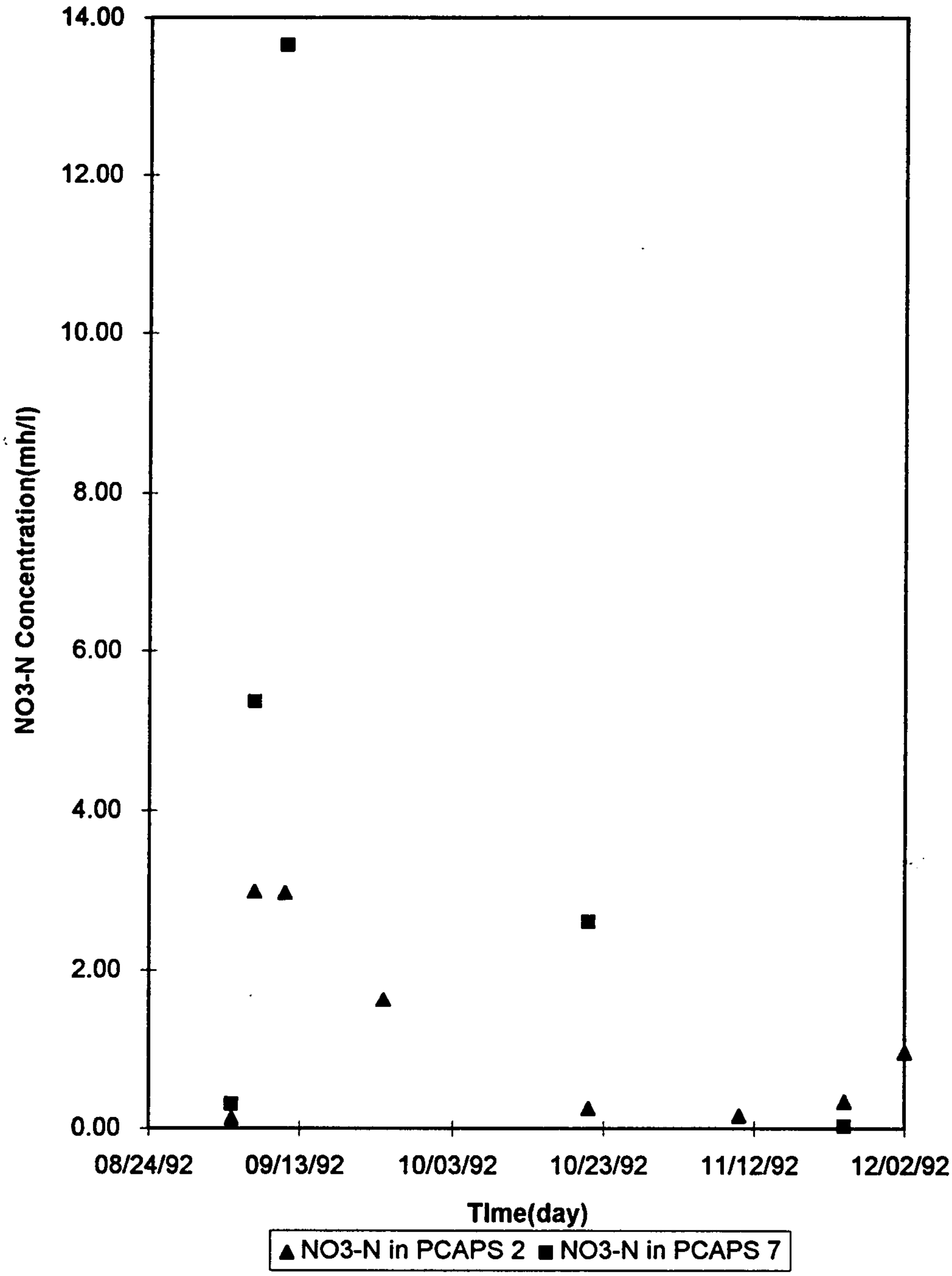

Figure 29. Nitrate-nitrogen concentration vs. time at B4 West.

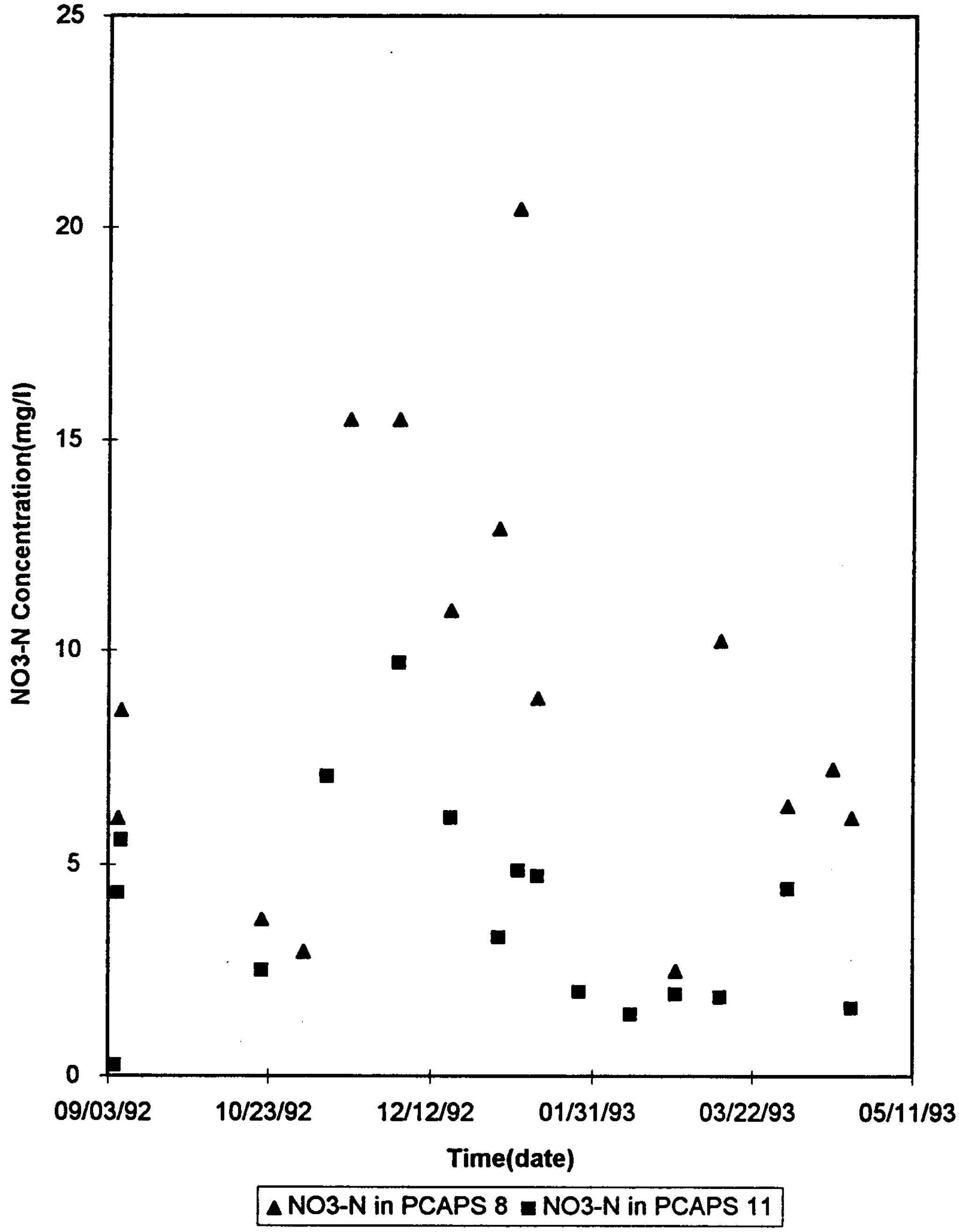

Figure 30. Nitrate-nitrogen concentration vs. time at Hanley East.

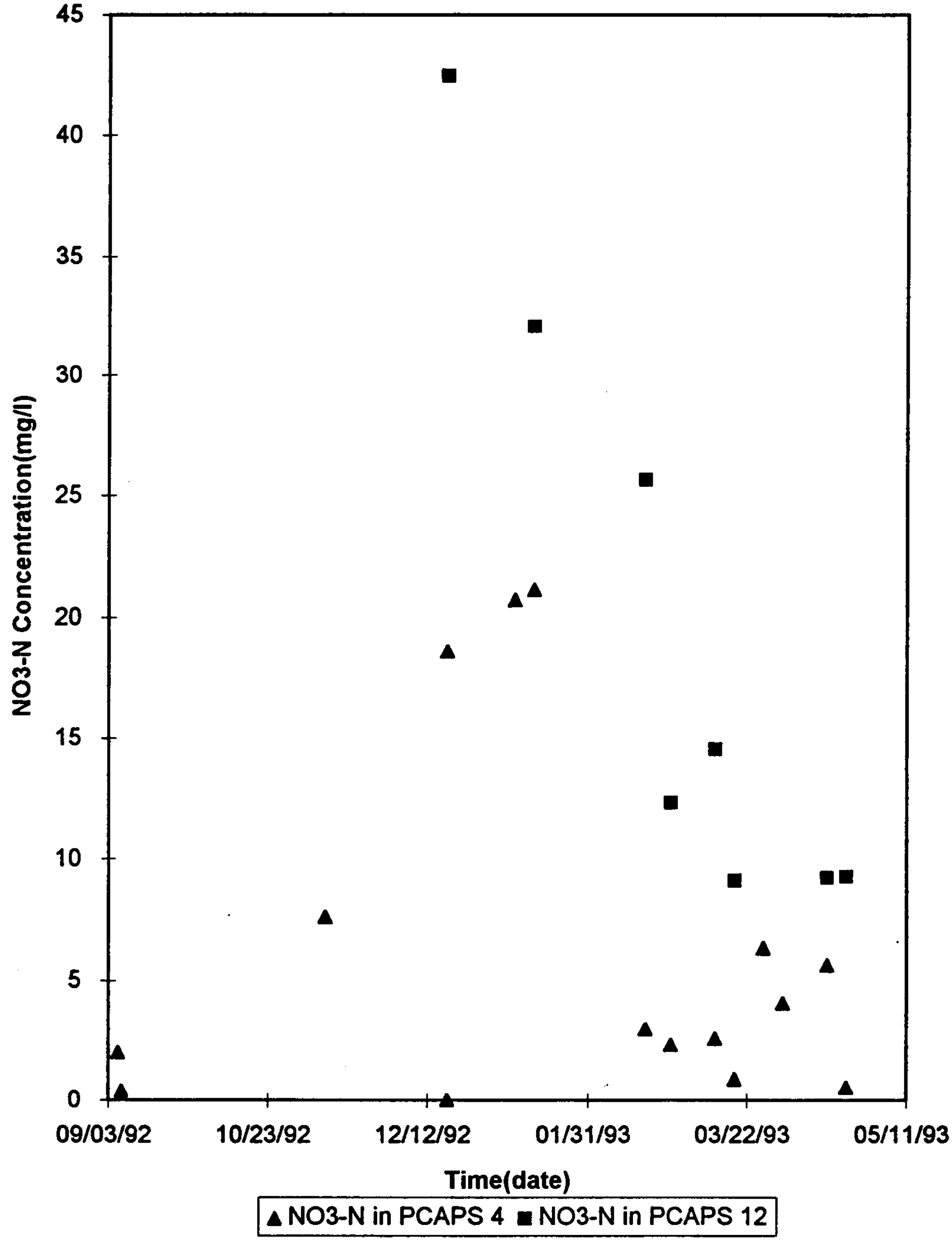

Figure 31. Nitrate-nitrogen concentration vs. time at Hanley West.

As demonstrated above, the potential for pesticide transport was observed in each of the three sites. The amount of pesticide or blue dye transport through the vadose zone decreased in the order: flooding in clay > micro-sprinkler in clay soil > over-head sprinkler in sandy soil. Blue dye transport in the sandy soil was very low (0.024% recovered) while blue dye in clay soil was over 100 times higher. While the same pattern was observed for rhodamine, the clay soil moved only 8.6 times more than the sandy soils. Because clay soils have high adsorption rate for organics and low infiltration rate while sandy soil has low adsorption and high infiltration rate, sandy soil is usually considered more susceptible to pesticide leaching than the well-structured clay soils (Flury et al., 1994). Higher blue dye and rhodamine mass found in clay soil probably resulted from the macropore flow. Low blue dye or rhodamine recovery rate in sandy soils could be caused by many factors such as degradation, the duration of sampling (most is still about the elevation of the samplers), runoff, and lateral flow. Troiano et al. (1993) found that leaching of Bromide, Chloride, and atrazine in a Delhi loamy sand was larger for flooding than for sprinkling irrigation. For example, they found that atrazine mass recovered for flood was three time higher than for sprinkler under low percolated water treatment in 1988. Smith and Parrish (1993) found no evidence of migration of any of pesticides (aldicarb and metolachlor) into the saturated zone in a sandy loam soil in their field study.

Bromide Transport

Bromide concentration were quite variable (Figures 32 to 37). These figures display typical properties of solute transport through vadose zone influenced by preferential flow, e.g., a rapid transport downward of the bromide pulse and tailing phenomena. There is a tendency that high bromide movement is observed in early fall. This occurrence may have been due to the preferential flow. This behavior was similar to the nitrate-nitrogen. Because of low leaching in early fall, this phenomenon was diminished at Hanley East. In B2 East, consistently higher bromide concentrations reached 2.2-m depth than 1.8 -m depth. In B2 West, higher bromide concentration was found at 2.2-m depth than at 1.8-m depth in early fall. This phenomena was also seen in B4 in early fall. When water was added to the cracking clay soil surface at rates higher than the infiltration rate of soil matrix, part of the water may have moved rapidly through the cracks to the deep zone. In general, over time the bromide concentration in B2 and Hanley was higher than B4. It may suggest that flooding irrigation in Block 2 may have enhanced the preferential flow. Micro-sprinkler irrigation may have reduced the preferential flow to some degree.

Because of lack of overall mass balance, it was difficult to determine the exact impact of irrigation methods on water and pollutant leaching. For example, missing sampling during high water table resulted in an incomplete breakthrough curve of the tracer on the clay soil sites. This made it difficult to explain the traveling time for pollutants to migrate to groundwater. With overall mass balance, we would have been able to illustrate how rapidly the contaminants traveled to the groundwater under different irrigation methods.

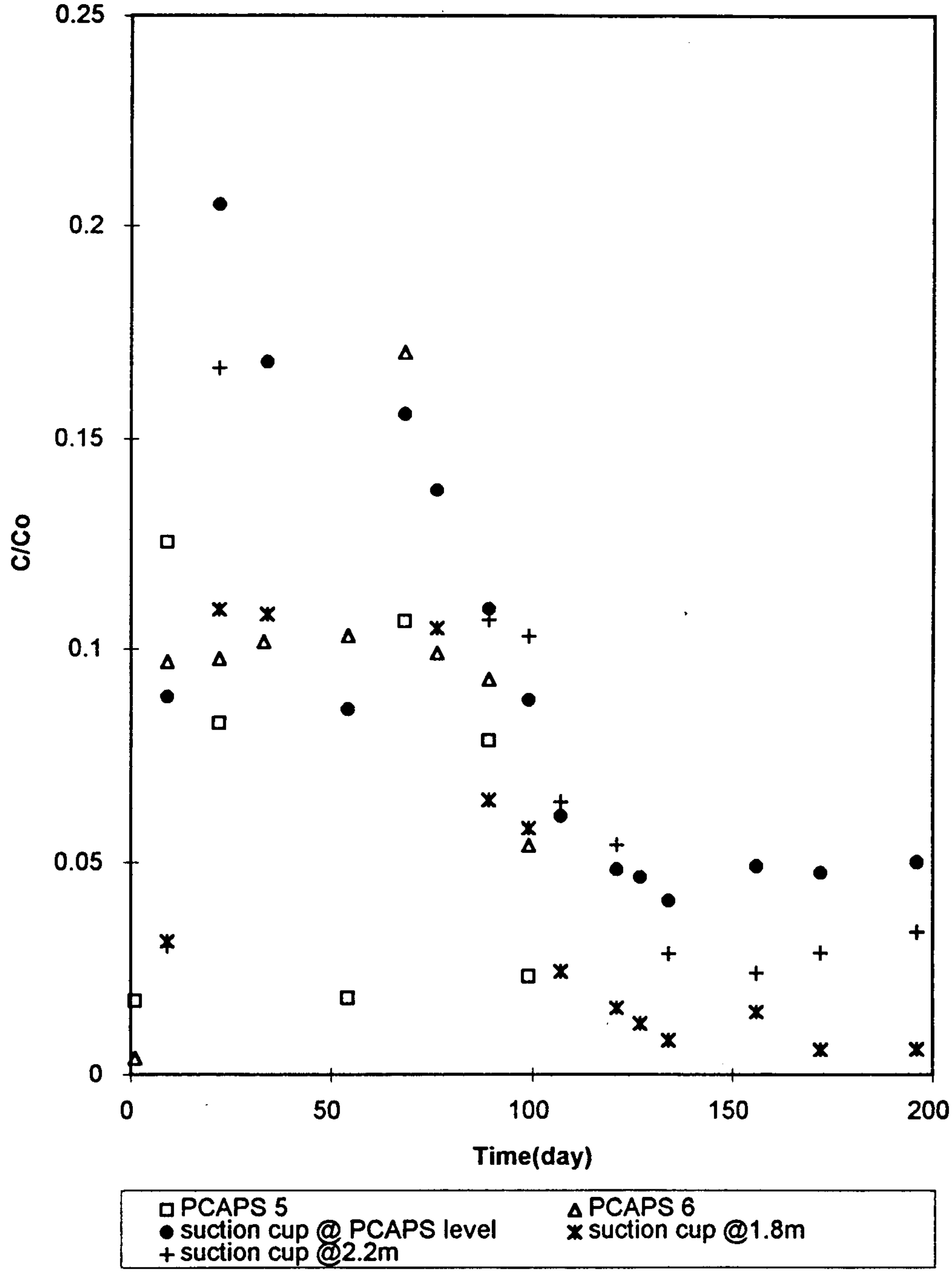

Figure 32. Bromide concentration vs. time at B2 East.

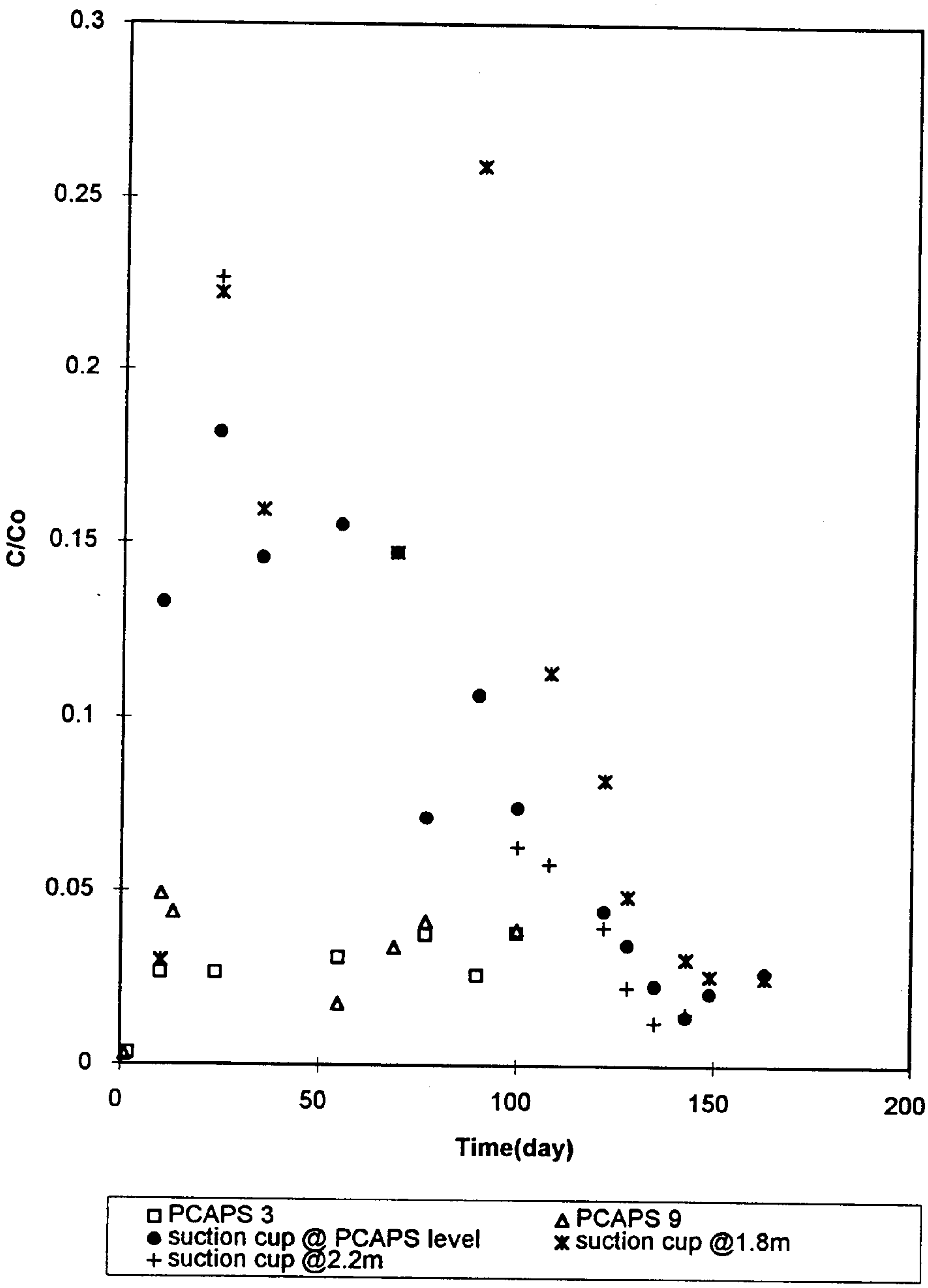

Figure 33. Bromide concentration vs. time at B2 West.

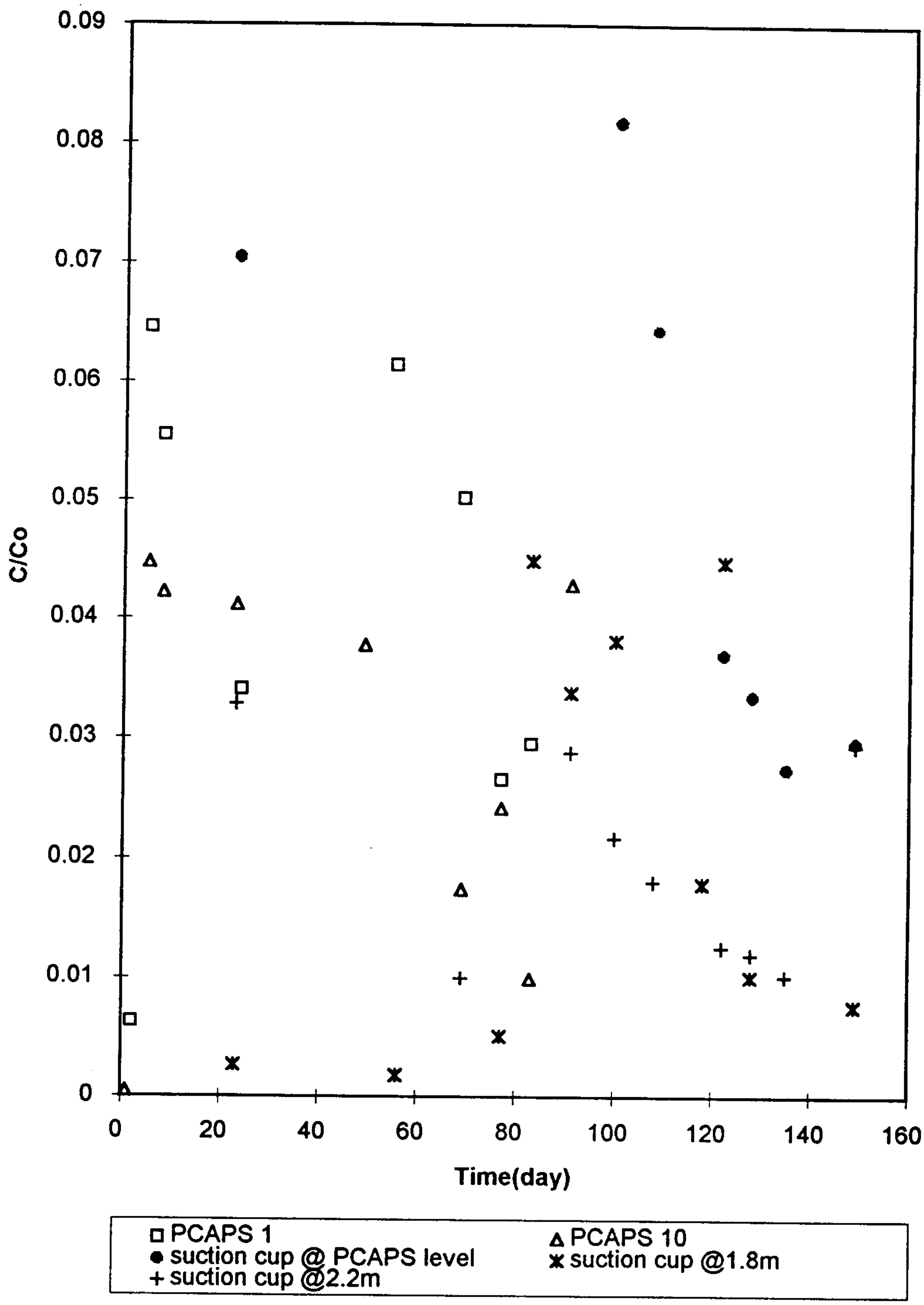

Figure 34. Bromide concentration vs. time at B4 East.

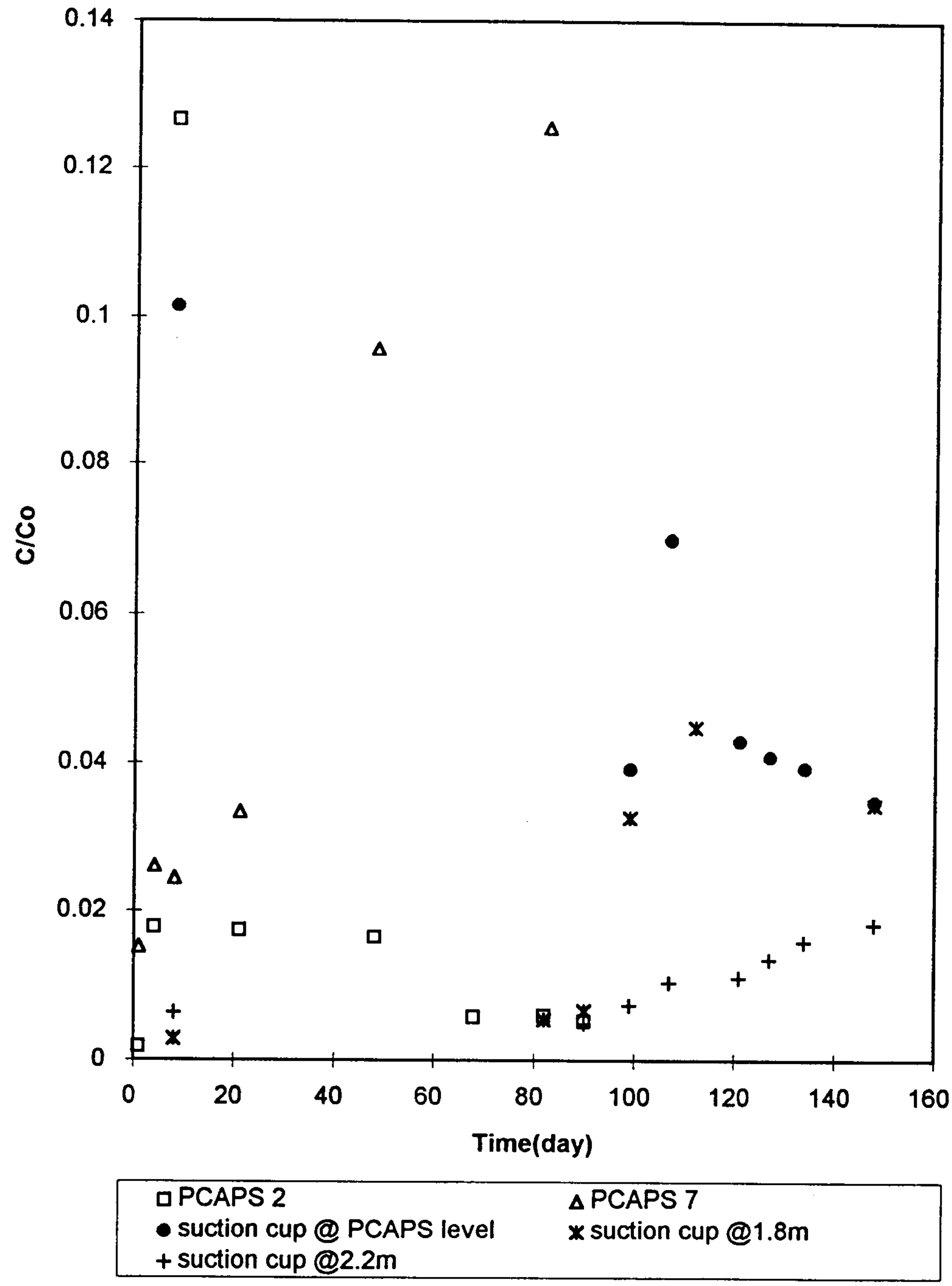

Figure 35. Bromide concentration vs. time at B4 West.

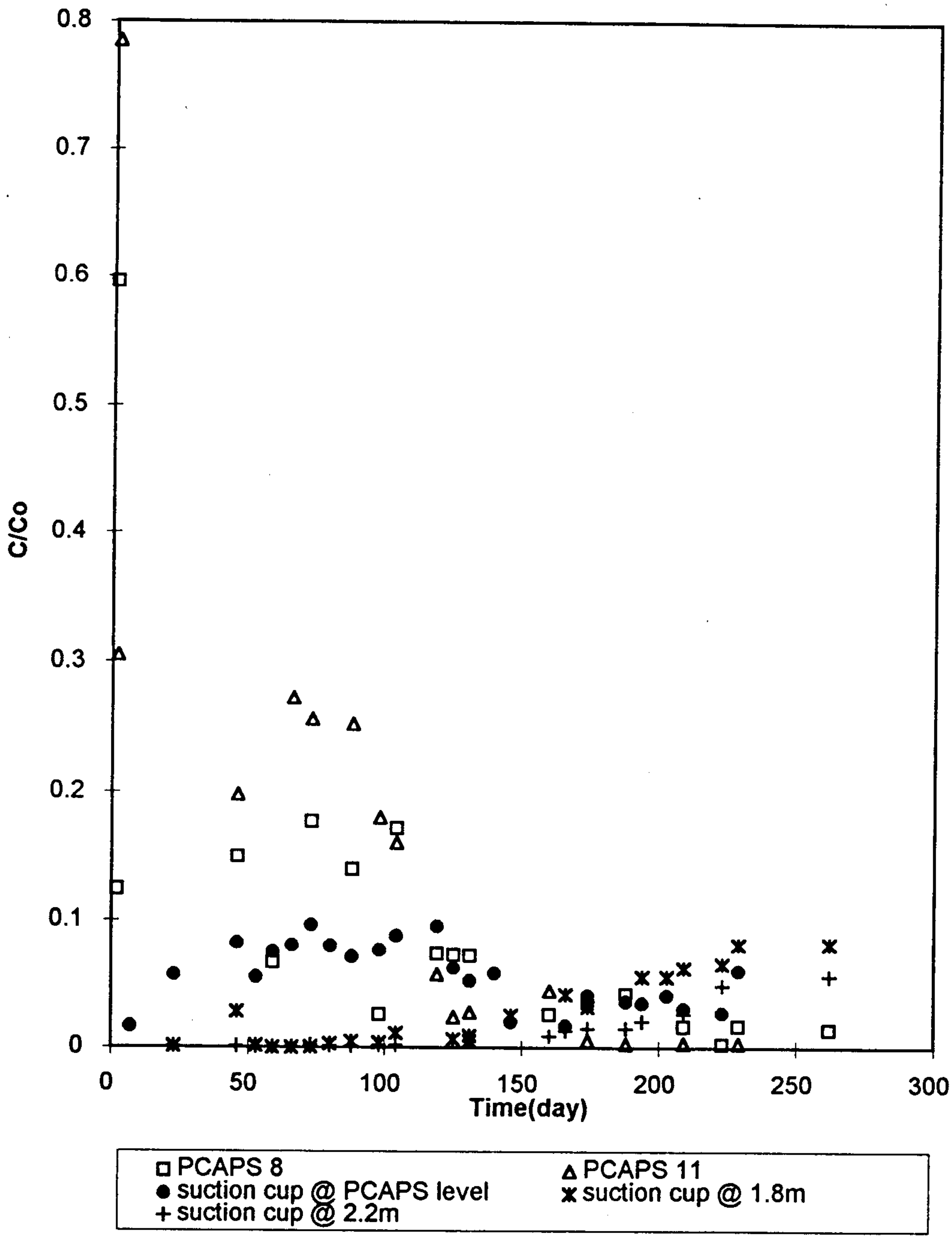

Figure 36. Bromide concentration vs. time at Hanley East.

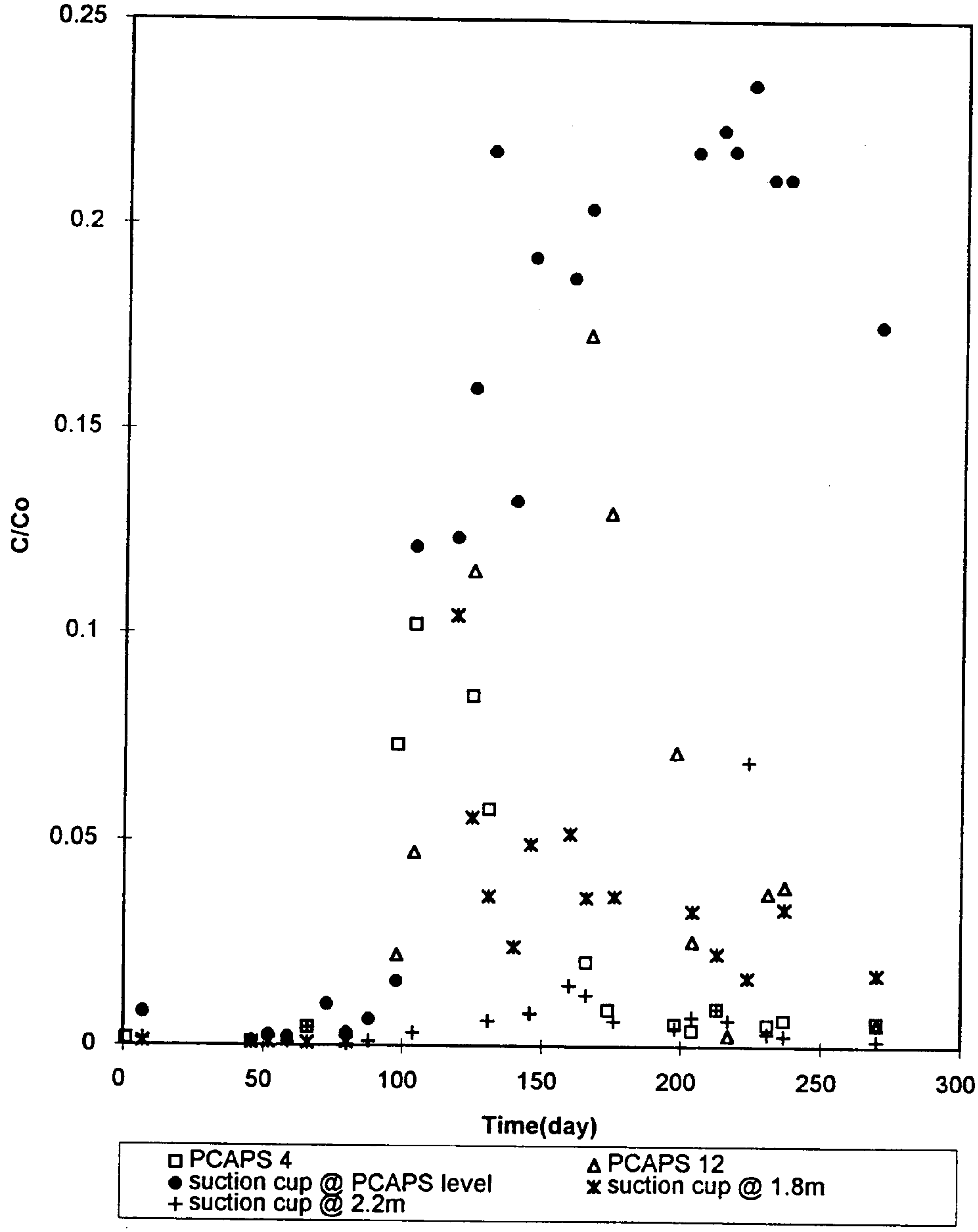

Figure 37. Bromide concentration vs. time at Hanley West.

Blue Dye Transport

The blue dye migration observed was quite limited (Figures 38 to 43). In terms of total mass recovered in PCAPS, blue dye transport followed the order: B2 > B4 > Hanley. For most time from early September to December, 1992, Five of six PCAPS collected higher blue dye concentration than suction cups installed at same level as PCAPS. This may suggest that PCAPS are able to collect both preferential flow and matrix flow while suction cups may not do so. PCAPS had large catchment areas (31 cm by 84.5 cm and 33.8 cm by 33.8 cm in our case) while suction cup had much smaller section area (about 5 cm diameter in our case). Thus, PCAPS had much higher probability to collect both preferential flow and matrix flow than suction cups.

Looking only at data from suction cups, occasionally a higher blue dye concentration at 1.8-m or 2.2-m depth was observed than at 1-m depth from early September to December, 1992. At this early stage, it was impossible for matrix flow to reach higher concentration at deeper layer than at shallow layer. In B4 East and Hanley West, there was higher blue dye peak concentration at 2.2-m depth than at 1.8-m depth. Also at these plots, during most of the time from later November, 1992 to early April, 1993, blue dye at 2.2-m depth had higher concentration than at 1.8-m depth. Again, these data strongly suggest that blue dye was not carried by the matrix flow but by macropore flow.

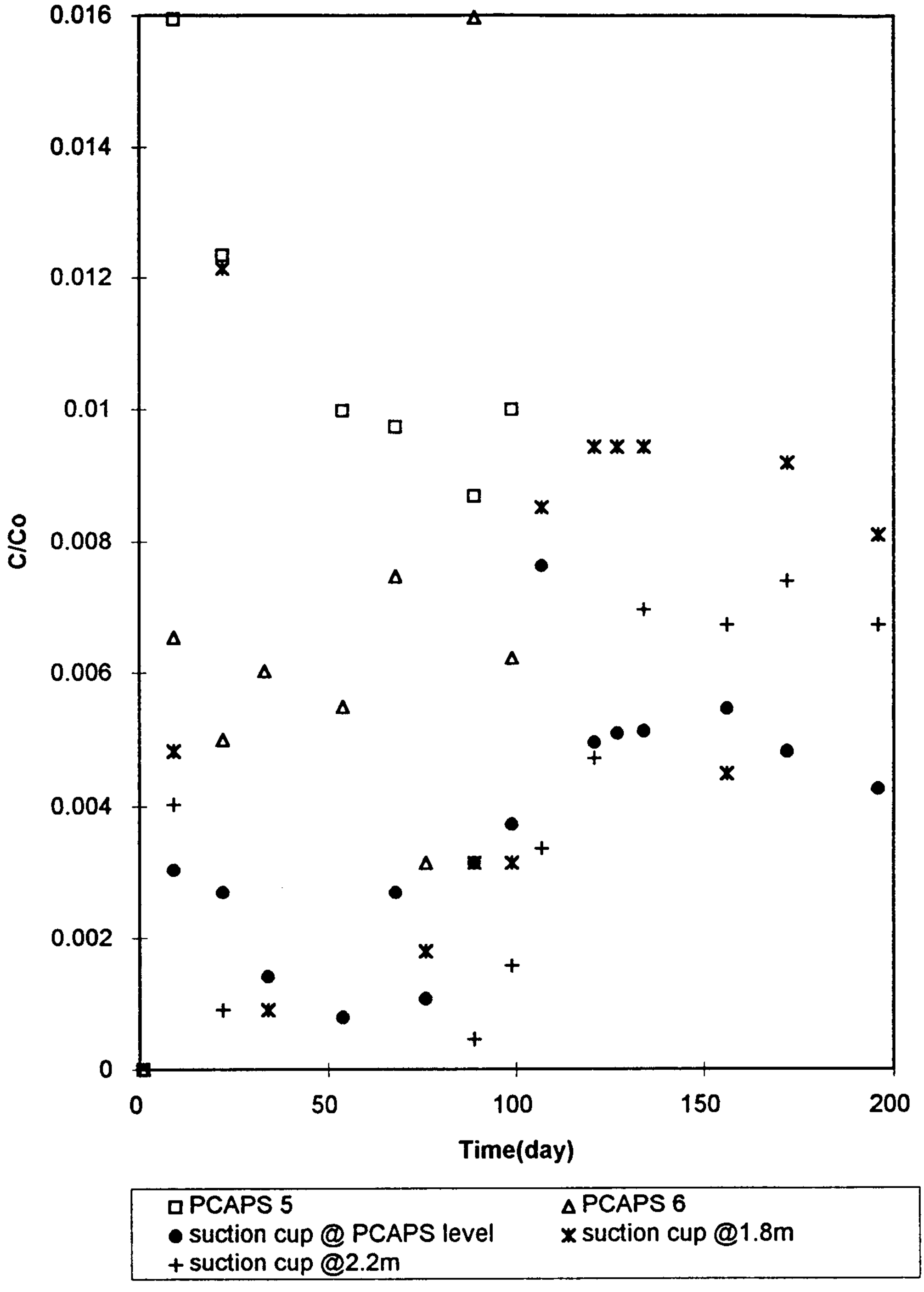

Figure 38. Blue dye concentration vs. time at B2 East.

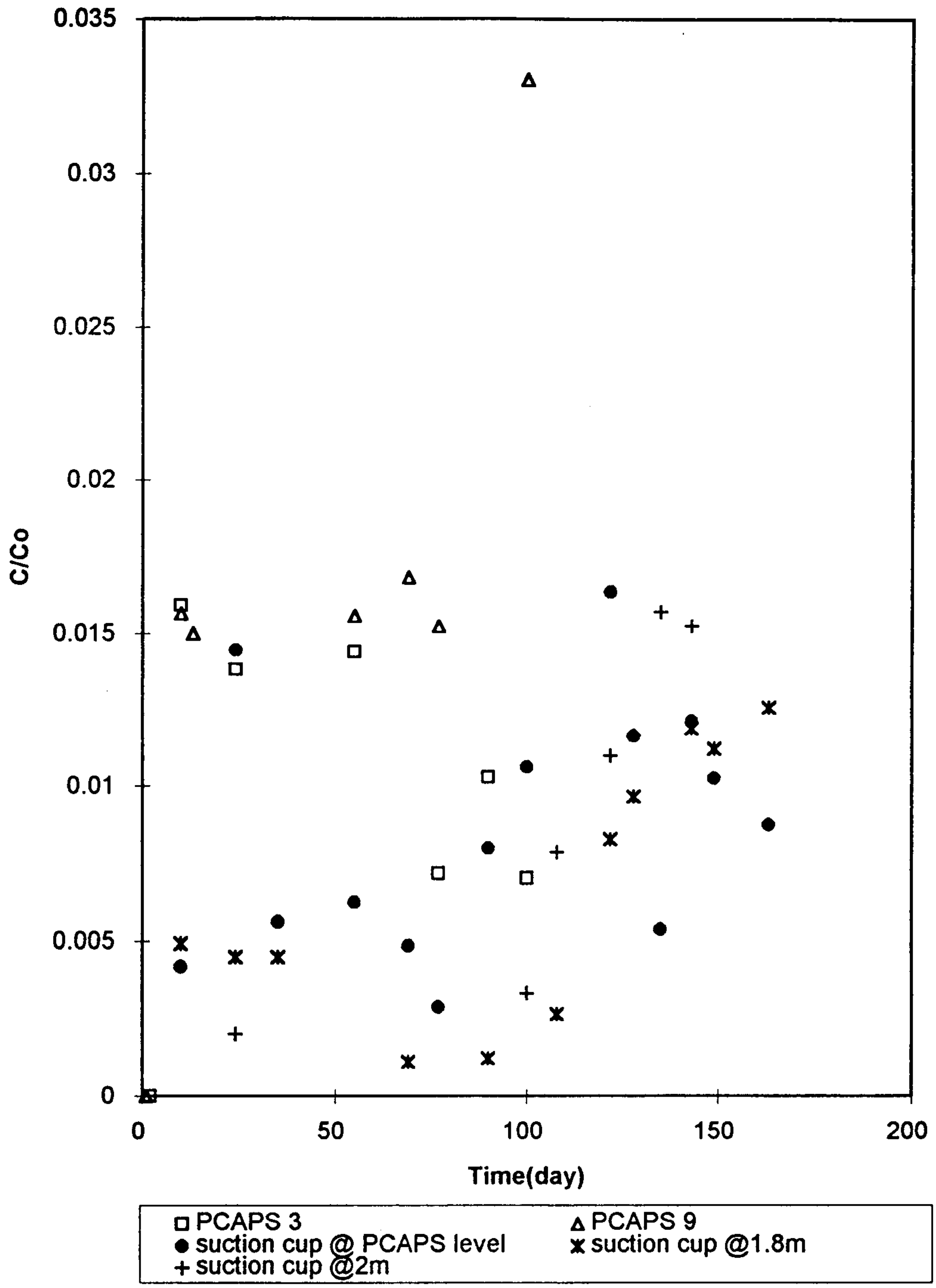

Figure 39. Blue dye concentration vs. time at B2 West.

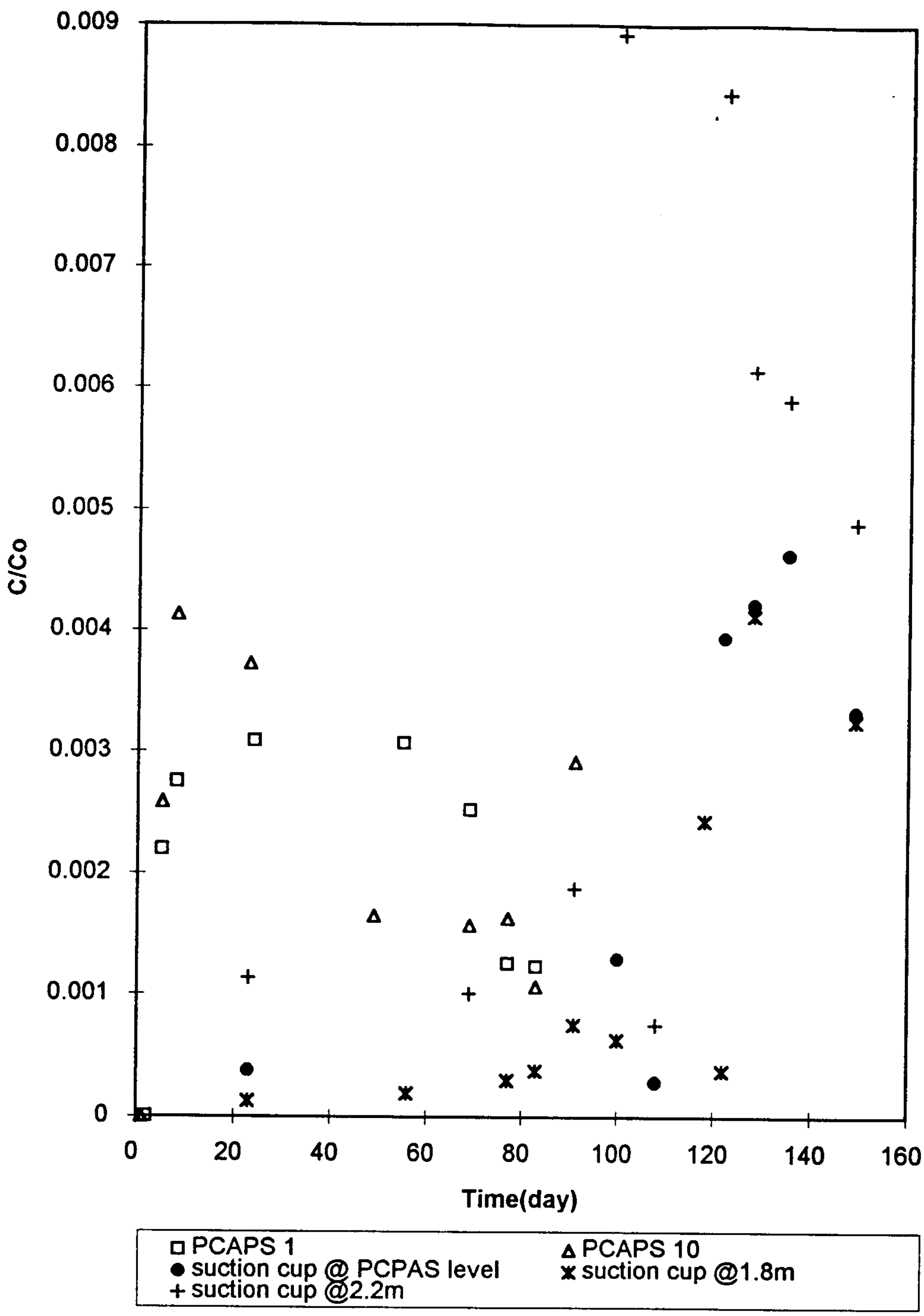

Figure 40. Blue dye concentration vs. time at B4 East.

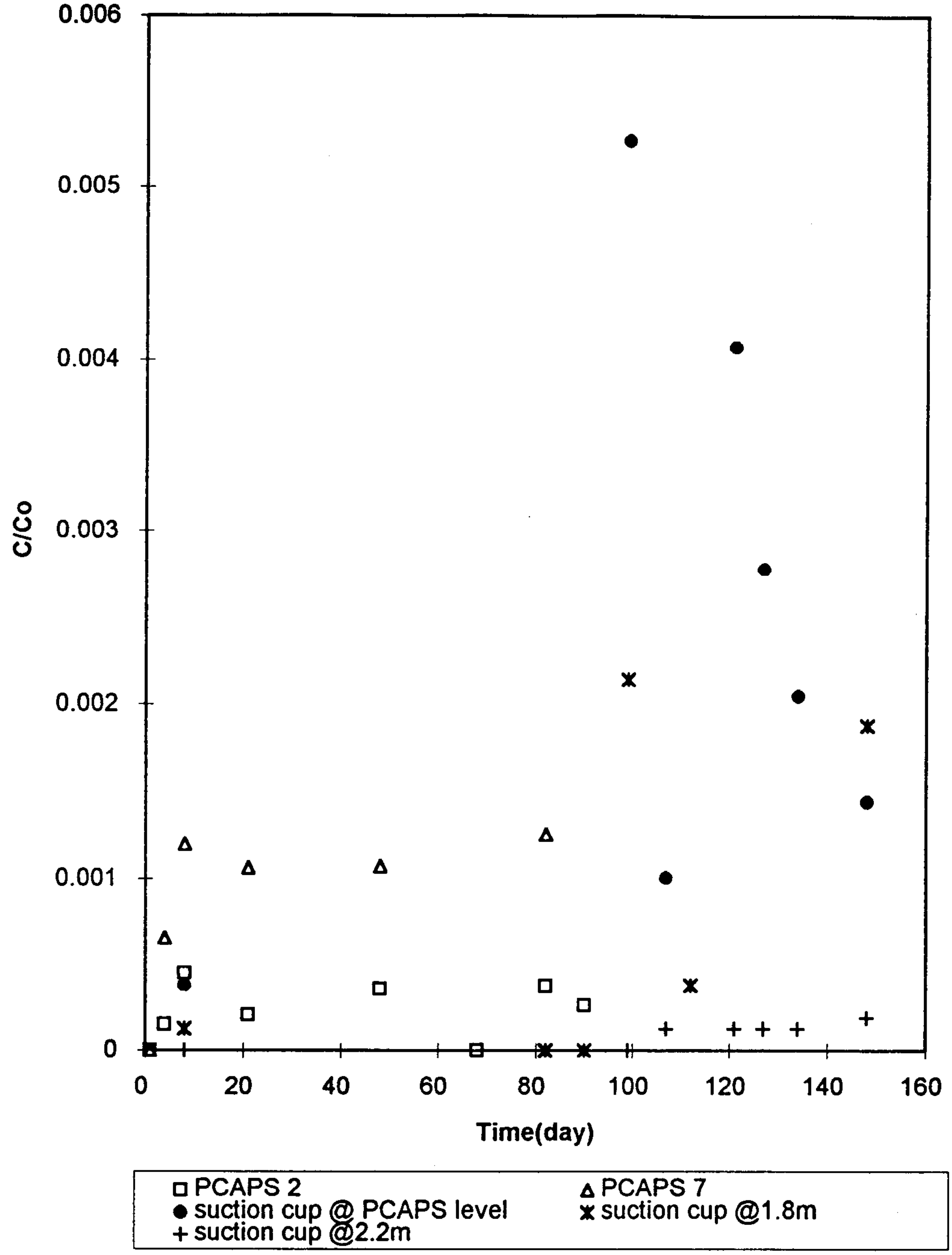

Figure 41. Blue dye concentration vs. time at B4 West.

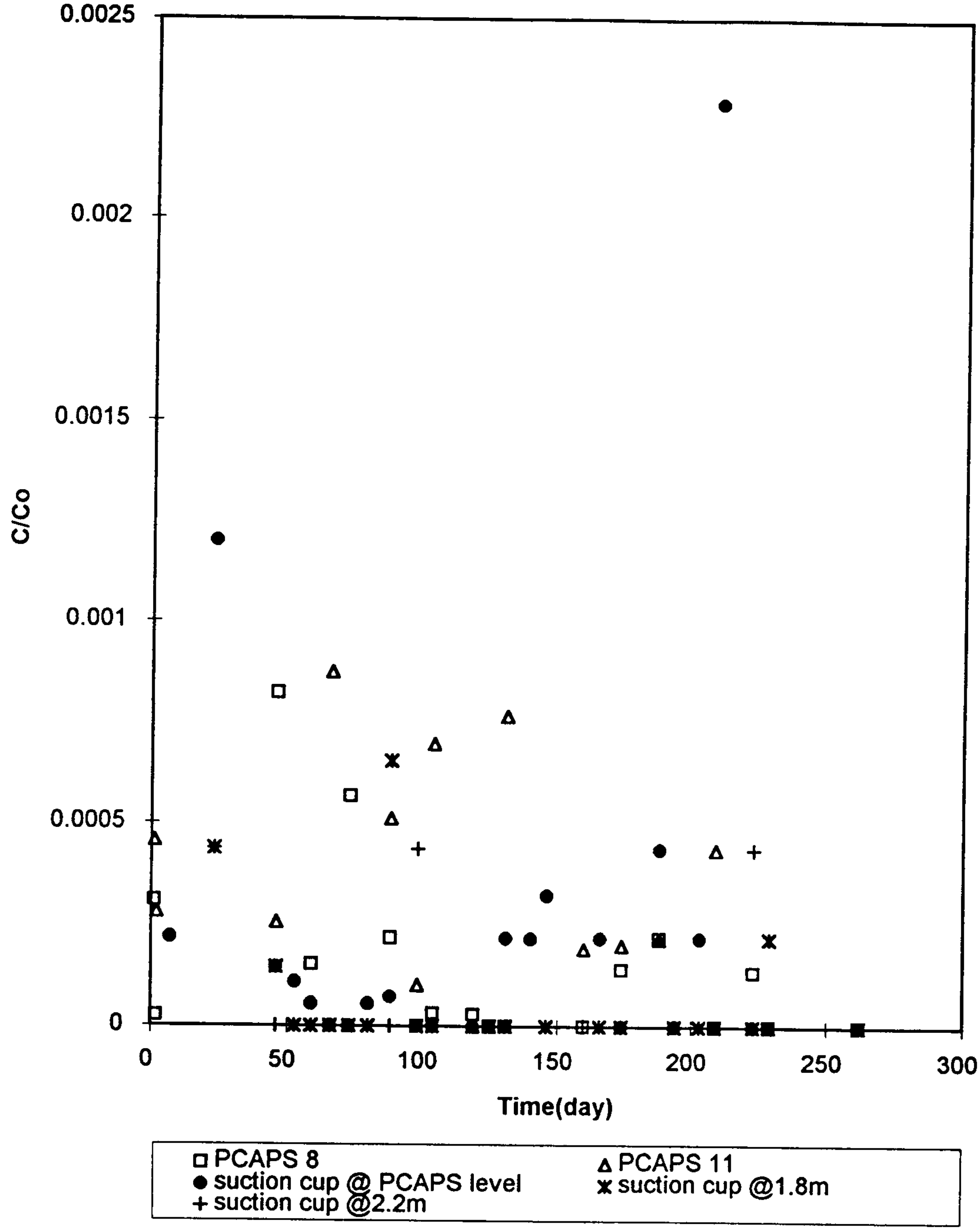

Figure 42. Blue dye concentration vs. time at Hanley East.

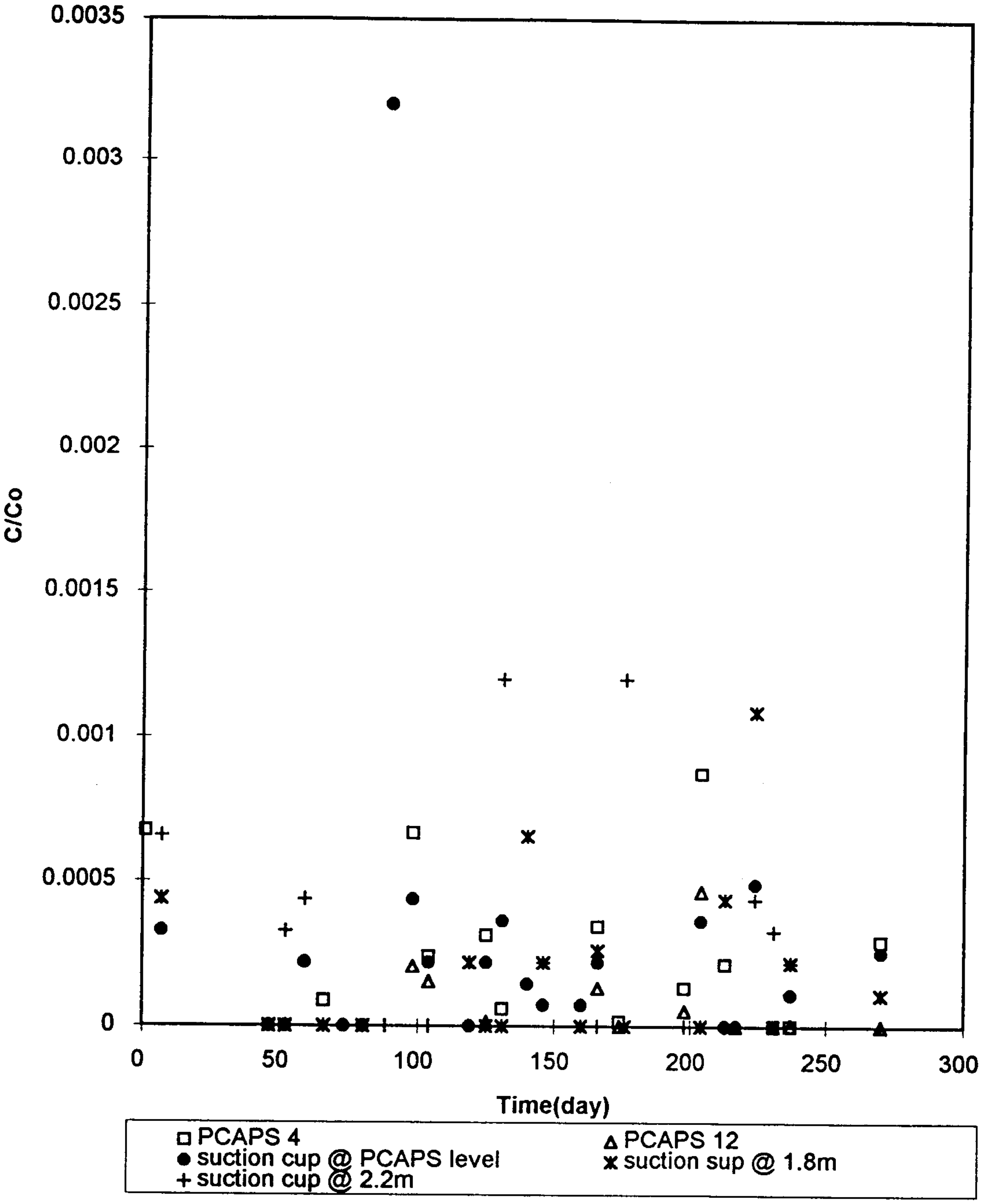

Figure 43. Blue dye concentration vs. time at Hanley West.

Rhodamine Transport

Rhodamine WT was used to study the leaching behavior of interactive solutes such as insecticides, herbicide, and many other organic pollutants which are adsorbed by soil particles. Rhodamine transport through the vadose zone declined in the same order as blue dye order: B2 > B4 > Hanley (Figures 44 to 49). Rhodamine concentration under flood (at B2) is about 2-3 times higher than that under micro-sprinkler (at B4). Comparing breakthrough curve at 2.2-m depth with 1.8-m depth in B2 West, peak concentration was reached at 2.2-m depth earlier than at 1.8-m depth. Rhodamine concentration at 2.2-m depth was higher than at 1.8-m depth in Hanley East for all seasons while this observation was not seen in B4 West or Hanley West. We also found that there was a concentration jump in early fall at each plot. These phenomena could only be explained by a preferential flow mechanism. Rhodamine concentrations at each plot showed overall instability and low mass recovery. This could be explained by the following guesses: 1) rhodamine has high retardation coefficients and strong adsorption by soil particles (Singh et al., 1989). Because clay soil has high adsorption to the organic compound, rhodamine migration to groundwater would be low; 2) some other compound was fluorescent at this excitation emission pair.

Because blue dye has similar properties as some adsorbed pesticides such as atrazine and rhodamine WT has similar properties as some insecticides and other organic pollutants, we expect that pesticide would be transported in decreasing order : flood (at B2) > micro-sprinkler (at B4) > over-head sprinkler (at Hanley). From the above illustration, it appeared that irrigation methods and soil structure have great impact on the nitrate-nitrogen and pesticide migration to groundwater.

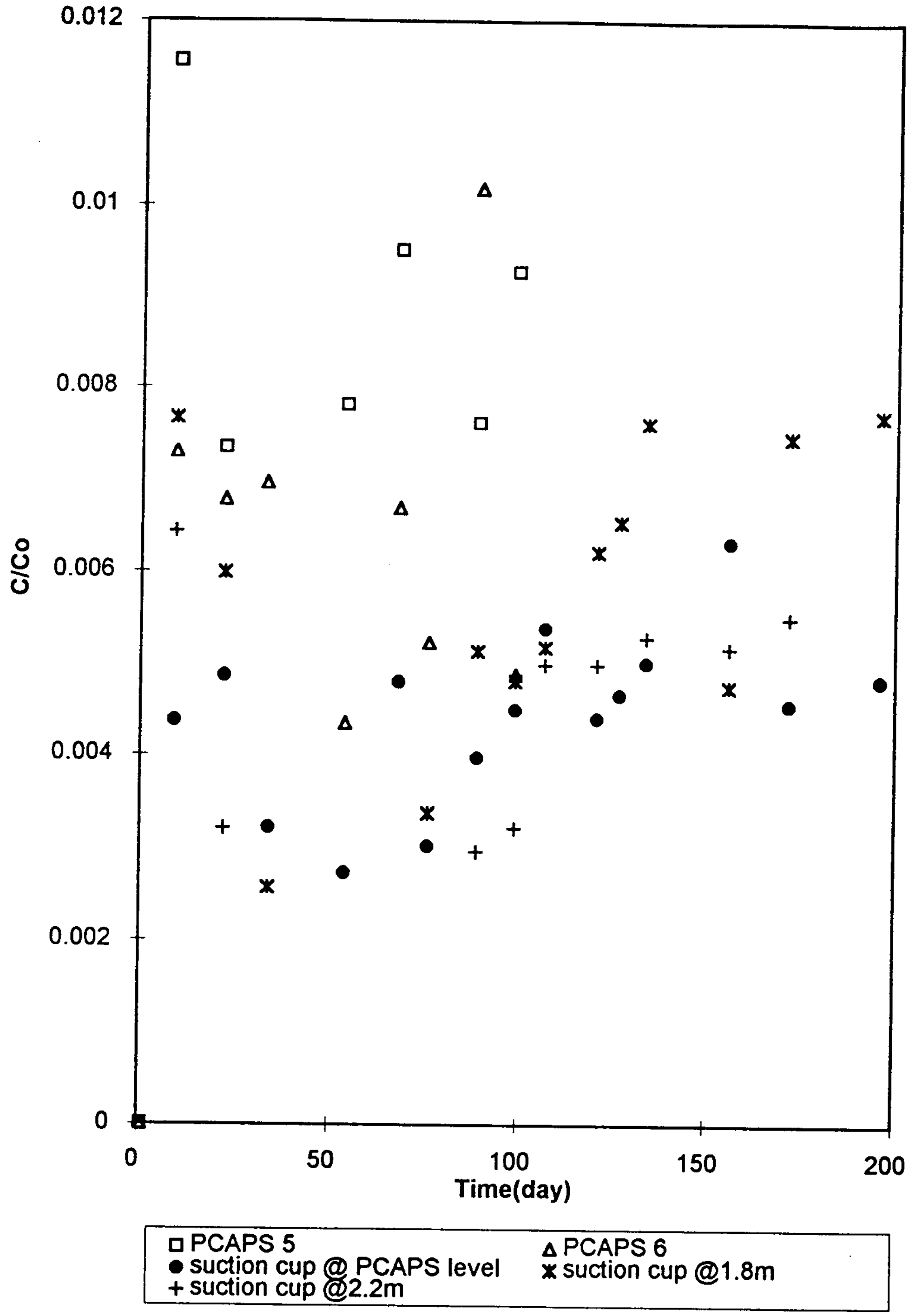

Figure 44. Rhodamine concentration vs. time at B2 East.

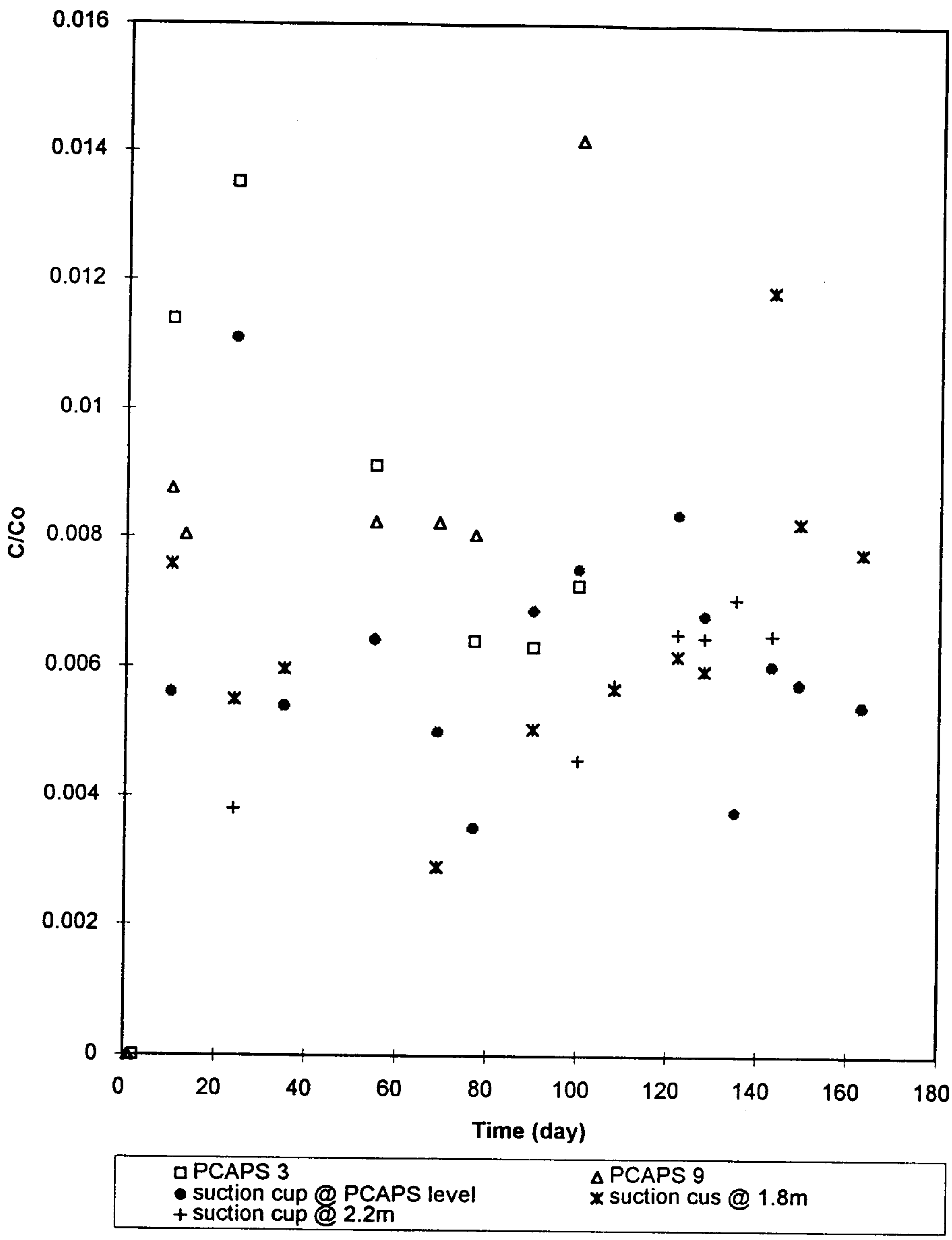

Figure 45. Rhodamine concentration vs. time at B2 West.

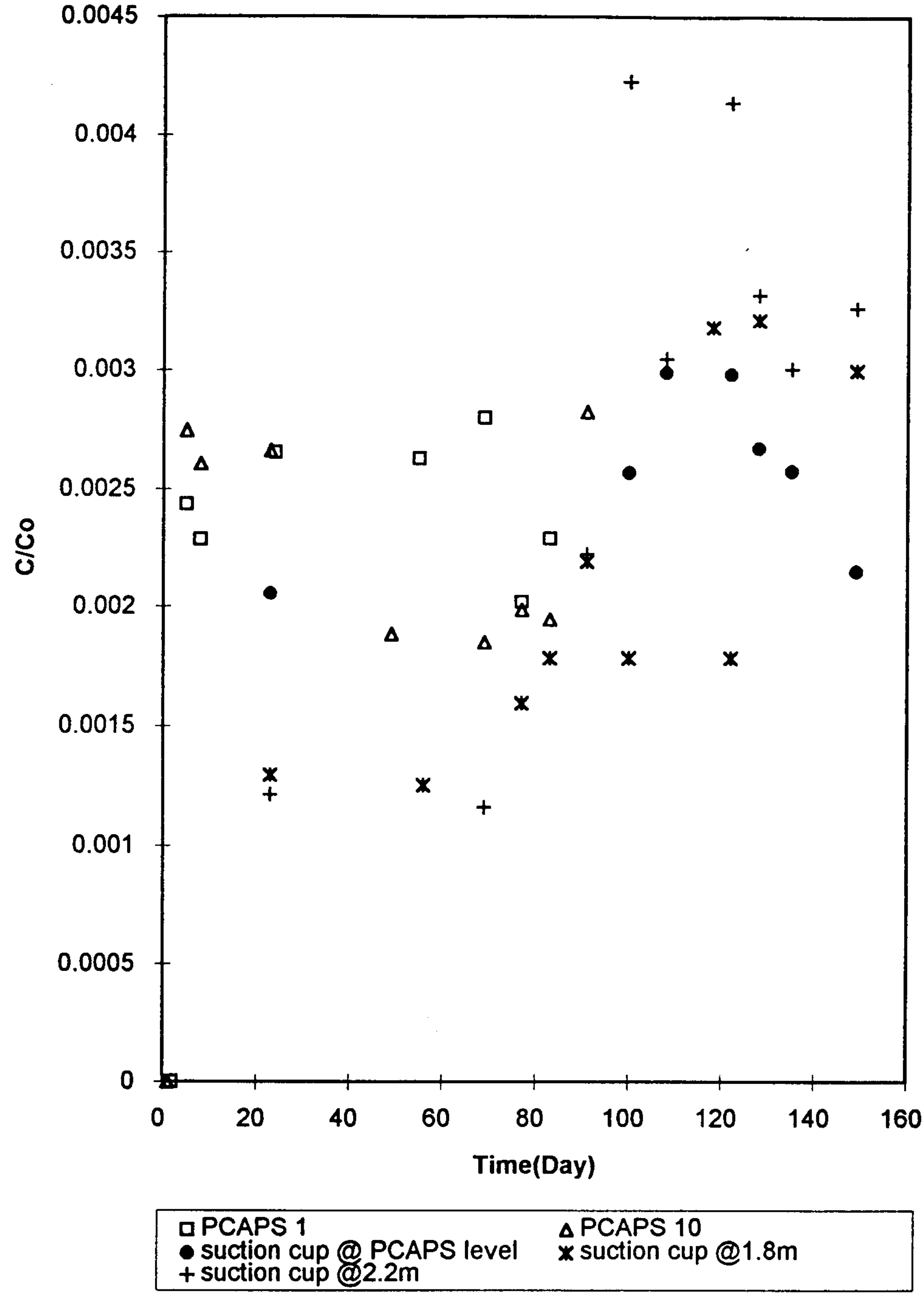

Figure 46. Rhodamine concentration vs. time at B4 East.

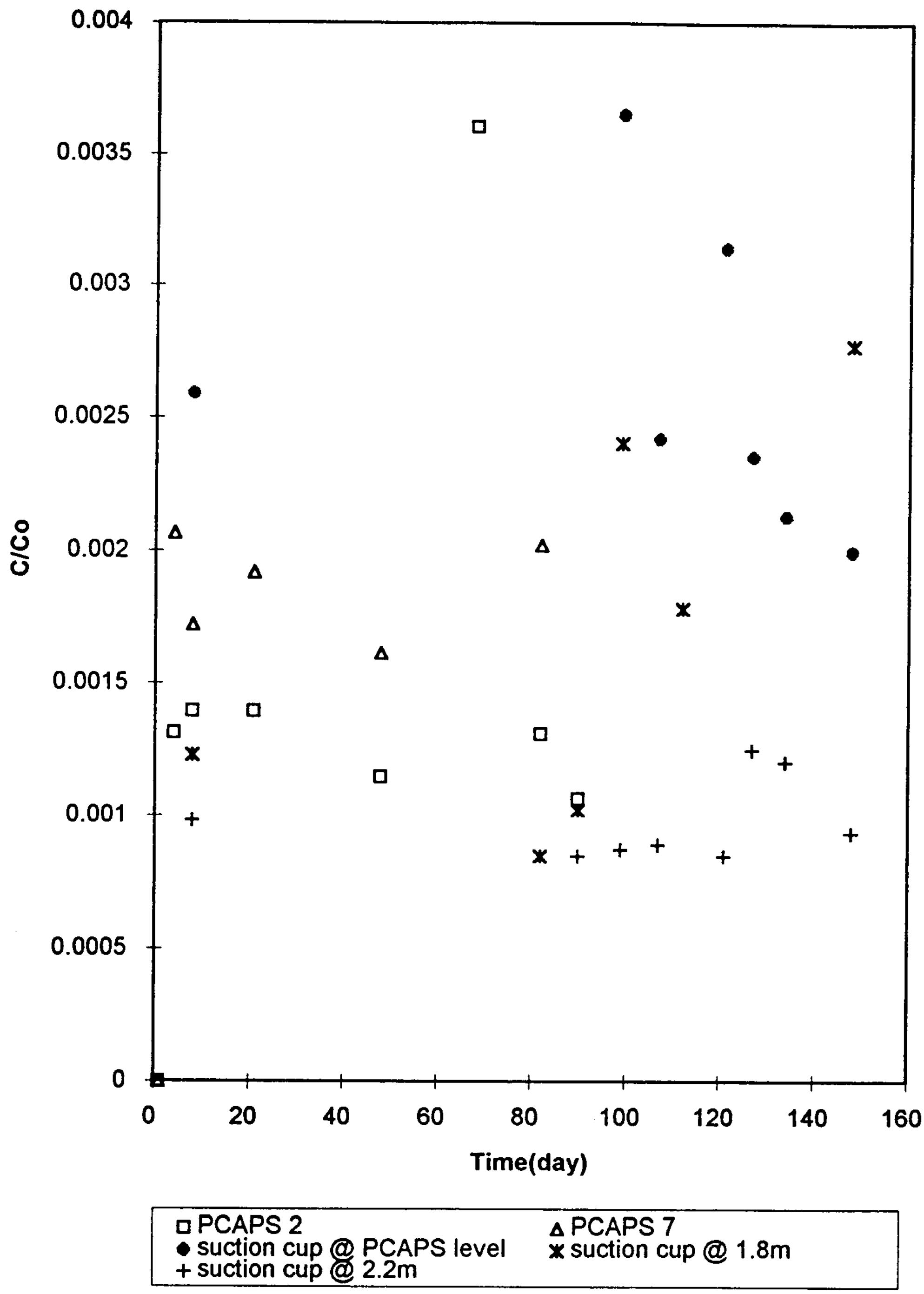

Figure 47. Rhodamine concentration vs. time at B4 West.

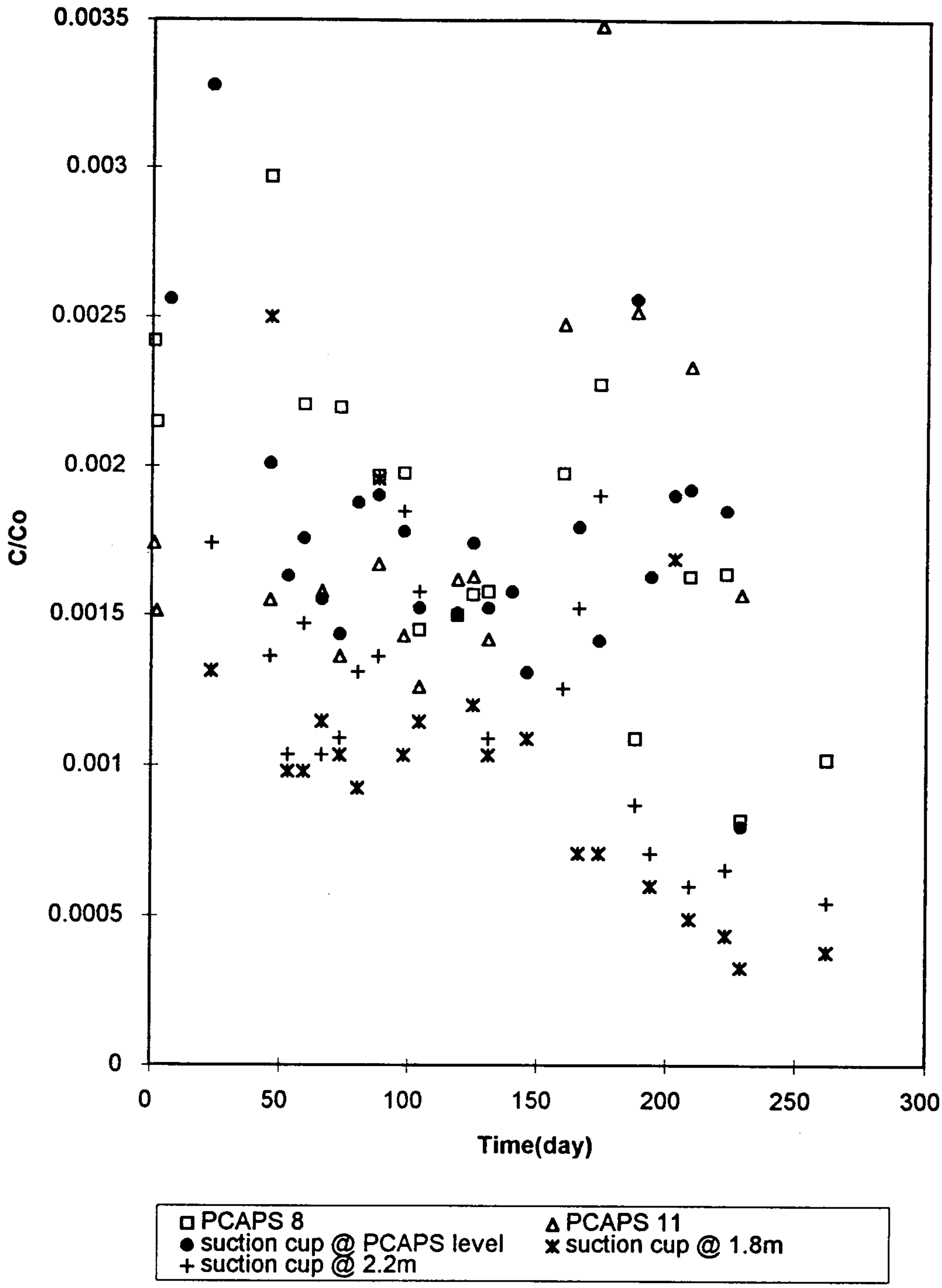

Figure 48. Rhodamine concentration vs. time at Hanley East.

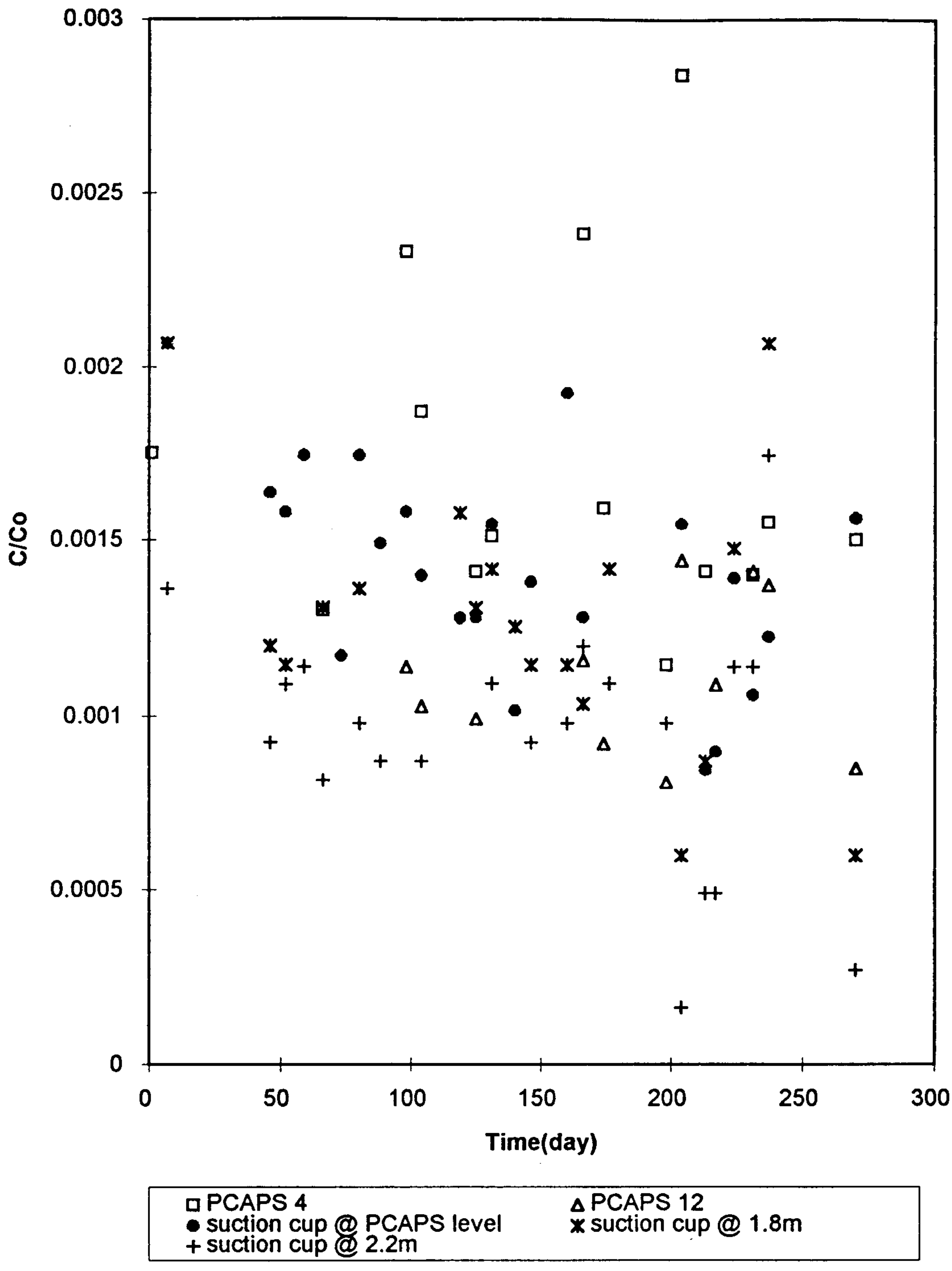

Figure 49. Rhodamine concentration vs. time at Hanley West.

DISCUSSION

Leaching Analysis

Large quantities of leaching water were collected in cracking clay soils. This high leaching rate most likely resulted from extensive macropore flow through cracks. This suggests that a significant amount of the applied water may have moved to significant depths without wetting the soil matrix of the upper layer in the root zone. Intensive channels and fissures may be responsible for high leaching volume at the early stages. Topographical land conditions may have changed the water flow patterns, increasing the non-uniformity. PCAPS at Hanley West trench collected 127% more leachate than the Hanley east trench. Greater lateral flow in the Hanley West trench could also contribute to the higher leaching. Agricultural activities created a very shallow ditch near the top of PCAPS in the West trench where some runoff water may have accumulated. Thus, a ponding condition was easily formed which lasts longer at West trench and results in high leaching rate. The combined funneling and fingered flow mechanisms that sometimes occur in sandy soil was another factor which may have impacted the leaching behavior, although neither was specifically identified on these sites. Of course, irrigation non-uniformity and variability in soil structures could also contribute to high leaching and spatial variability.

Impacts of agricultural activities on water leaching are also likely to be responsible for the observed variability in leaching. Through agricultural practices such as fertilization and pesticide spraying, agricultural vehicles compressed the PCAPS installation trench to create a shallow ditch. We observed prolonged local ponding in the vicinity of the excavation area in Block 4. This may explain the high leachate in Block 4 even under the micro-sprinkler irrigation. Sampling cells within the PCAPS closest to the trench exhibited lower flux in comparison to the cells farthest away from the trench (Figures 7 to 17). This same trench effect was true for all rectangular PCAPS (No. 1 to 8) which have larger catchment area. It seems that the preferential flow-path system was disturbed or destroyed within the nearby, refilled trench. Thus, macropore flow near the trench may have been eliminated. Another reason could be that cells near the trench had better sealing than cellls away from the trench. Injected liquid foam in the PCAPS near the trench had better contact with sample bottles than those away from the trench because of the foam expansion properties and the method of injection.

Even though the square PCAPS had smaller interception area than rectangular PCAPS, the square PCAPS collected greater volume than the rectangular PCAPS. This could be explained by following guesses: 1) square PCAPS had less impact from the refilled trench. Thus, partial cutoff of preferential flow-path was less influential for the square PCAPS; 2) smaller square PCAPS had better contact with the soil. 3) sampling bottle may be too small for rectangular PCAPS under heavy rainfall of irrigation (square PCAPS have smaller area but same size sampling bottles).

High leaching rates can have great impact on water quality. For nutrients and pesticides, high leachate and rapid movement below the biologically active root zone may mean less degradation or uptake, and thus a greater risk of groundwater contamination. This situation becomes even worse when the water table is shallow, as it takes less time for the contaminant to travel to the groundwater. Even though the nitrate-nitrogen concentration was observed to be higher in the sandy soil than in the clay soil, the threat of groundwater contamination in the cracking clay soil may be even higher because the water table in clay soil was extremely high (see Figures 50 through 54). The shallow water table greatly shortened the traveling time of pollutants to the groundwater.

Impact of High Water Table

During our field study, we found that the water table in the clay soil was quite high. In the winter, the water table was within 60 cm of the soil surface almost continually from December to June (Figures 50 to 54). The current agricultural practices are to apply fertilizer in the fall following harvest. If heavy rainfall and snow occur, these compounds would be carried to the groundwater quickly. The rising water table in the winter could harm groundwater quality by carrying pollutants such as nitrate and pesticides to the groundwater when the water table goes down in the spring. Due to such potential pollution, current agricultural practices should be improved. However, determination of the specific impact of high water table on water quality is beyond our current study scope.

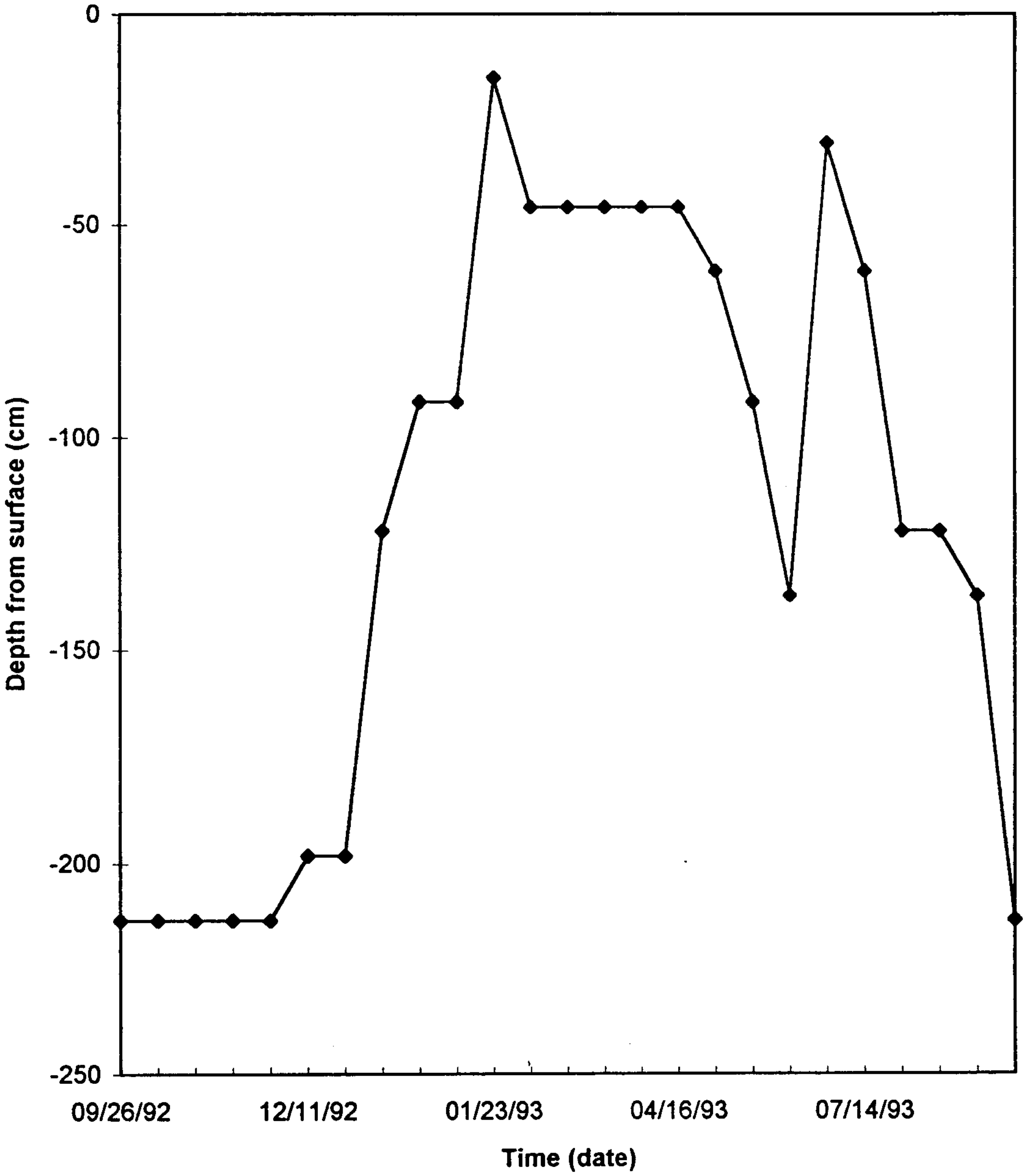

Figure 50. Water table vs. time at B2.

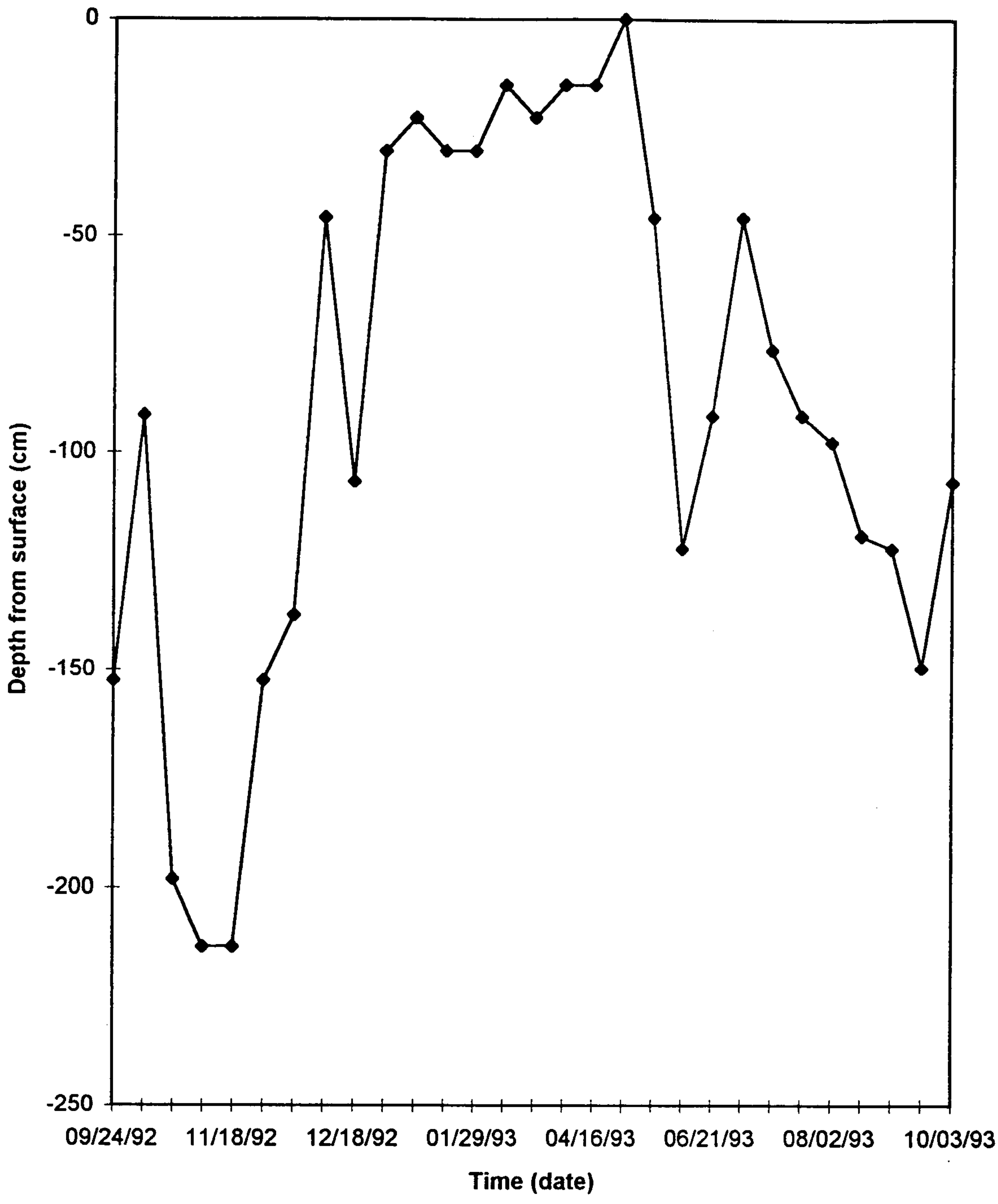

Figure 51. Water table vs. time at B4 East.

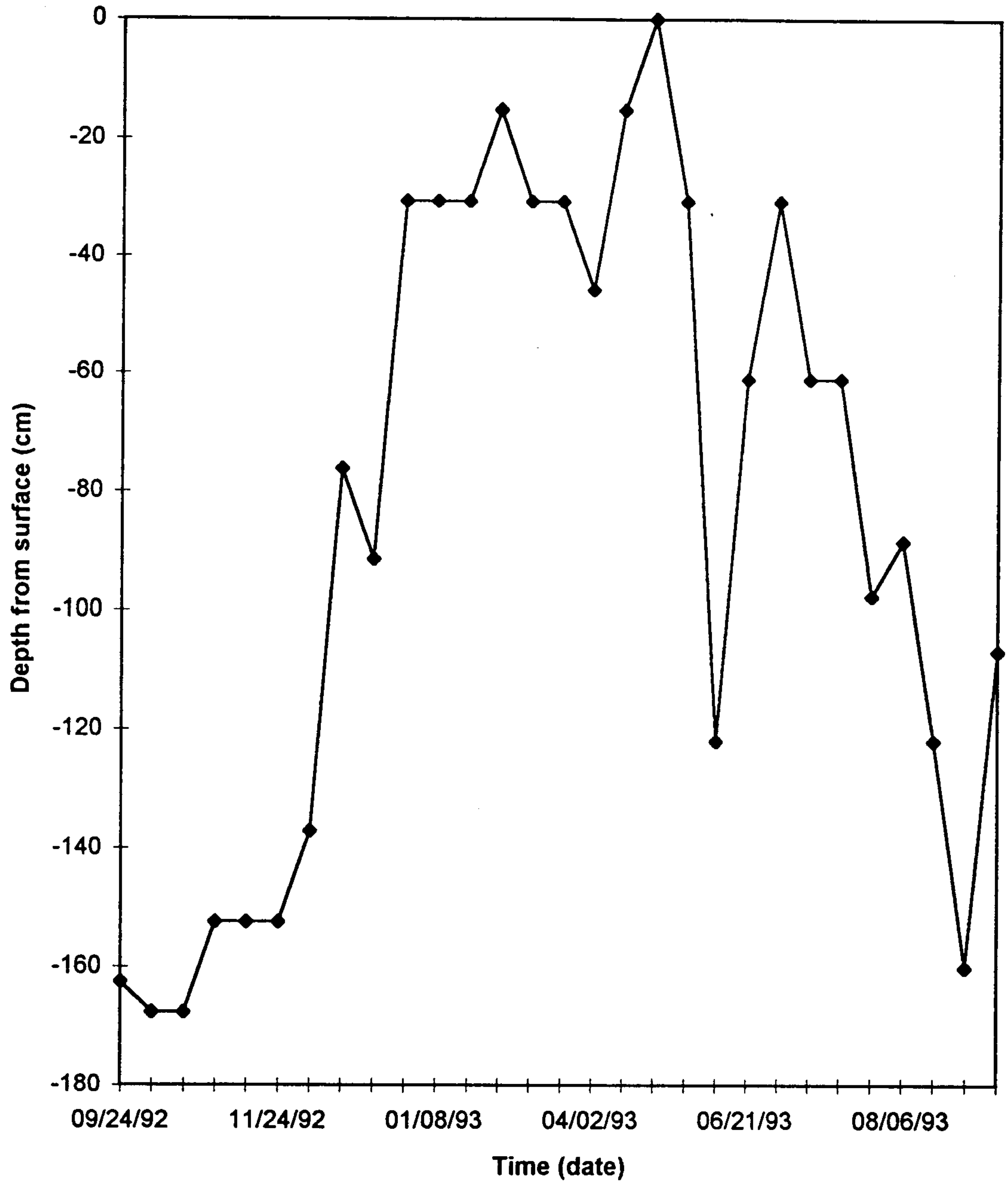

Figure 52. Water table vs. time at B4 West.

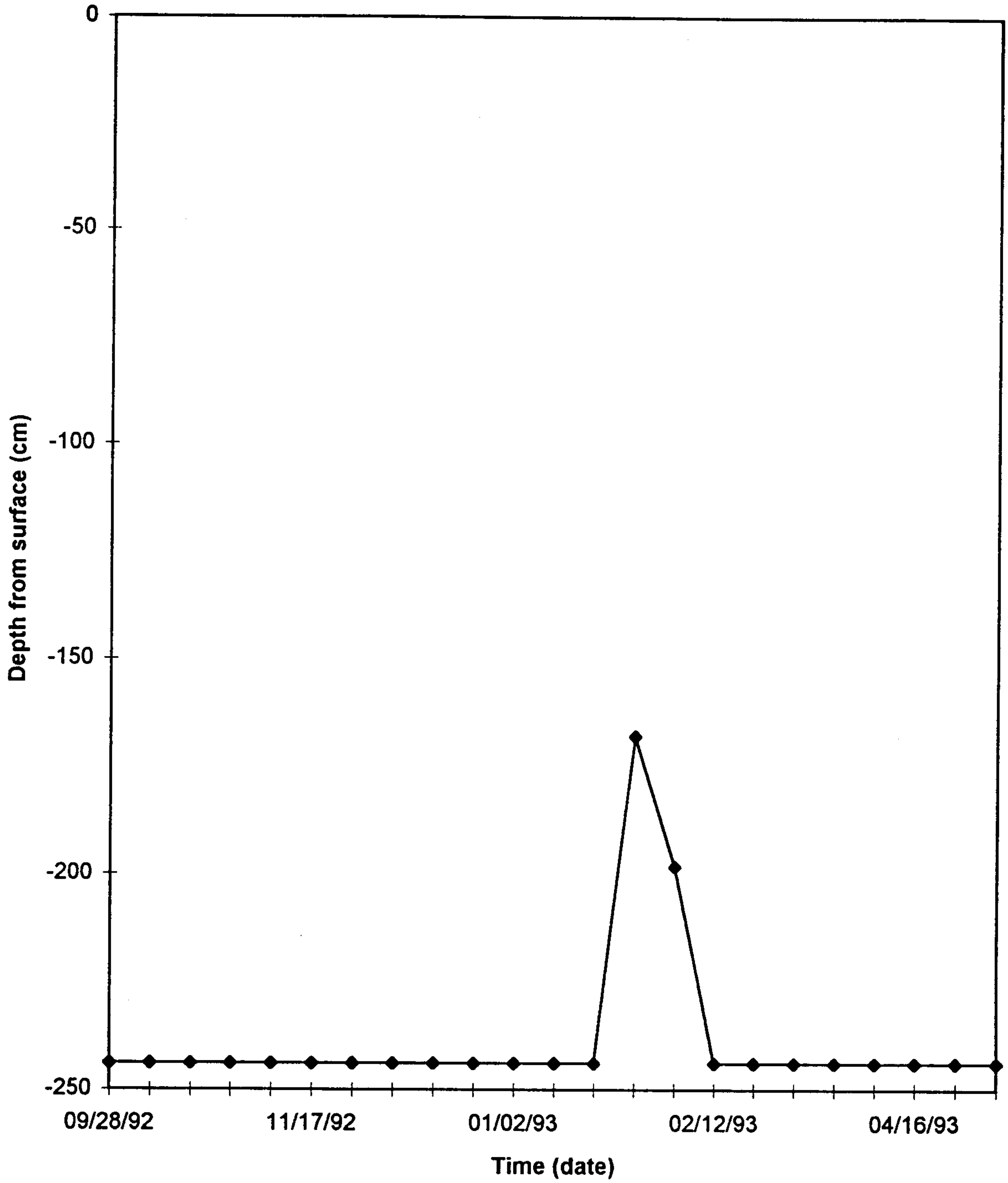

Figure 53. Water table vs. time at Hanley East.

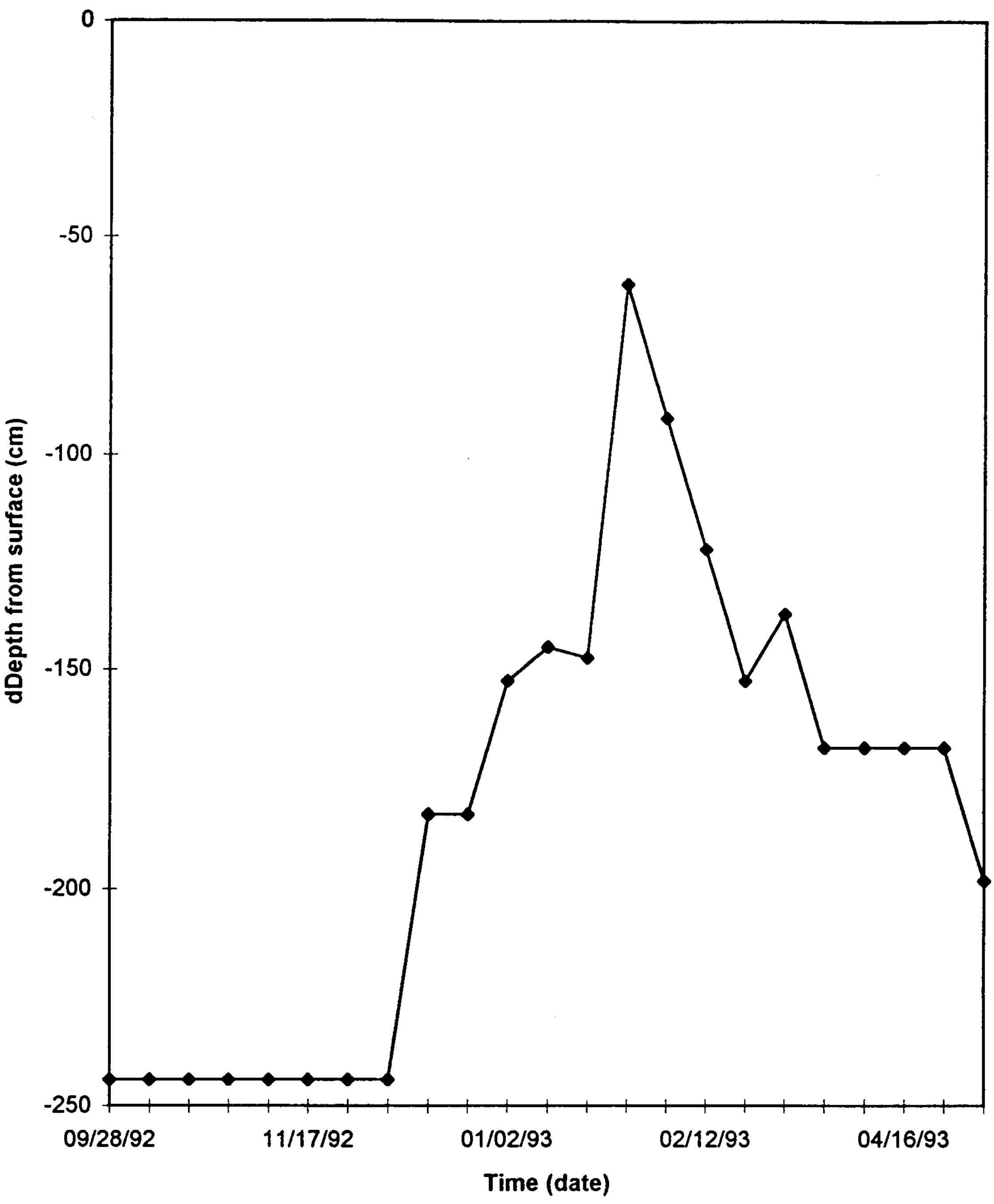

Figure 54. Water table vs. time at Hanley West.

Preferential Flow Effects

Flury et al. (1994) found that the occurrence of preferential flow is the rule rather than the exception. This is supported by our findings. Considering either the total leaching volume or the mass of solutes collected, the evidence of preferential flow was obvious. Rapid and voluminous leaching observed in the clay soils probably resulted from macropore flow via the extensive system of cracks. Because water movement in clay soil matrix is relatively slow, there must have been some macropores in clay soil to carry enormous amount of water at velocities that greatly exceeded those in the surrounding matrix (Beven and Germann, 1982). Deeper movement of tracers in most plots also demonstrated the effect of preferential flow. Preferential flow contributed more to bromide and nitrate-nitrogen mass transport than to blue dye and rhodamine because blue dye and rhodamine have higher tendency of adsorption and high degradation rates. The preferential flow had more pronounced effect on nitrate-nitrogen migration than on tracers. High nitrate-nitrogen transport below the root zone reduces the availability of nitrogen to the plant and nutrient application efficiency. It has potential to contaminate the groundwater. High leaching due to preferential flow also diminishes the availability of total water to the plant and increases the non-uniformity of flow. These effects would increase the cost of sustainable agricultural production and influence the groundwater quality.

CONCLUSIONS

The magnitude of leaching differed between irrigation methods and soil structures and decreased in the order: flooding in clay soil > micro-sprinkler in clay soil > over-head sprinkler in sandy soil. Leaching was spatially varied. Soil types had higher Impact on deep percolation than the irrigation methods. High leaching has potential to reduce the water availability to plants and water uniformity within the root zone.

Mass recovery and concentration of all tracers including bromide, blue dye, and rhodamine had the same decreasing order: flooding in clay soil > micro-sprinkler in clay soil > over-head sprinkler in sandy soil. Since blue dye and rhodamine have adsorption properties similar to some pesticides, such pesticide leaching in three sites would be expected to follow the same order. Even though recovery of adsorbed tracers under all irrigation methods was limited, resulting from their high adsorption and degradation, irrigation methods impacted the adsorbed tracer transport. In other words, irrigation methods had an effect on pesticide movement even with same soil structures. This conclusion is different from Ghodrati and Jury's [1992] who found that the irrigation method had no effect on the movement of pesticide.

Pesticide migration in clay soil was more pronounced for flooding than microsprinkler, similar to Troiano et al.'s [1993].

The concentration of nitrate-nitrogen differed between irrigation methods and soil structures and decreased in the following order: over-head sprinkler in sandy soil >flooding in clay soil > micro-sprinkler in clay soils. The annual average nitrate-nitrogen concentration under over-head sprinkler in sandy loam was 14.50 mg/l which exceeds the maximum allowed concentration level by the EPA while seasonal nitrate-nitrogen concentration was low in clay soil under both flooding and micro-sprinkler irrigation.

We observed strong evidence of the occurrence of the preferential flow. Such preferential flow may contributes to high water leaching, nitrate-nitrogen, and pesticide migration.

Pairs of PCAPS were highly correlated in terms of leaching volumes. PCAPS at each plot had similar leaching response at most times.

Several improvements in PCAPS are needed to obtain representative samples under intermittently flooding conditions.

CHAPTER 4 UTILIZATION OF ULTRA-LOW RATE APPLICATION DEVICES TO ELIMINATE MACROPORE FLOW DURING IRRIGATION

INTRODUCTION

There is increasing concern about groundwater pollution resulting from agricultural activities. Some pollutants such as nutrients and pesticides can migrate from the vadose zone to the groundwater during irrigation. The physical and chemical nature of the soil at any given location strongly influences this movement. One of the most widely implicated mechanisms for contaminant transport under agricultural production is preferential flow along macropores driven by high intensity irrigation. Preferential flow refers to any transport process through which water and solutes obtain enhanced movement. Soils which contain cracks and root channels (macropores) may result in water and solute movement that is quite different from similar soils without such preferential flow pathways (Beven and Germann, 1982; White, 1985; Dick et al., 1989). As shown in the preceding chapters, the maximum nitrate-nitrogen concentration under flood, micro-sprinkler, and overhead-sprinkler irrigation surpassed 10 mg/l, the maximum drinking water level defined by the federal government. Preferential flow contributes significantly to such solute transport. Preferential flow may carry significant amounts of toxic substances (Steenhuis et al., 1989), in comparison to the relatively benign bulk matrix flow. The quality and quantity of water and solute transported through the vadose zone are strongly affect by the contribution of these two flow components. This is especially true for cracking clay soils that shrink and swell with changes in water content, resulting in infiltration rates that can vary by several orders of magnitude (Bouma and Wosten, 1979; McIntyre et al., 1982). When rain or irrigation water flows into continuous vertical cracks, the results are loss of water for crops and redistribution of soil material and plant nutrients (Van Stiphout et al., 1987). Preferential flow has been observed in field studies using conservative tracers (Bowman And Rice, 1986; Rice et al., 1986). Everts and Kanwar (1990) observed in their subsurface drain with tracer that: preferential flow was found to contribute 24% of the bromide and 20% of the nitrate transport on a mass basis during sprinkler irrigation. Soil macropores are an important factor in determining the rate and depth of movement of water and solutes. Jabro et al. (1991) carried out a field study of macropore flow using a bromide tracer and found the movement of water via macropores may have accounted for up to 50% of the groundwater recharge over the winter and early spring. Because NO_3-N moves similarly to the bromide in soils, NO_3-N contained in irrigation water or fertilizer solutions could be transported by preferential flow from the root zone to groundwater under saturated conditions.

The characteristics of conventional irrigation are high application rates for short duration, separated by relatively long intervals without irrigation. This approach has traditionally been selected to minimize management and equipment maintenance costs. Unfortunately, with high application rates water often ponds on the soil surface when the supply rate begins to exceed the capability of the soil to absorb water, leading to macropore transport and deep movement of solutes and sometimes runoff. Long intervals without irrigation also lead to the development of cracks and fissures which enhance the macropore flow, especially in swelling soils. Bouma et al. (1978) demonstrated that the movement of water into cracks occurred only when rainfall intensity exceeded the infiltration rate into and through the soil peds. In contrast, if water is applied sufficiency slowly to the soil, movement along preferential pathways can be completely eliminated. Conceptually, this can be understood by noting that with sufficiently low infiltration rates the matrix potential of the soil will remain sufficiently negative to keep all water out of the largest soil pores. Laplace equation clearly explains this concept. Laplace equation can be written as:

$$p = 2\sigma\cos\gamma/r$$

where:

p - soil metric potential (Pa)

σ - surface tension of water (0.0728 Pa m at 20°C)

γ - contact angle of water on solid surfaces (usually $\alpha = 0$)

r - pore radius (m)

If the matrix potential is kept sufficiently negative, water only occupies very small pores. In other words, large pores are vacant during irrigation, thus avoiding the macropore flow and reducing the loading of contaminant to the groundwater. In addition to eliminating macropore flow, the low irrigation rate eliminates runoff, which serves to improve the application efficiency as well as to protect surface water quality. As long as the rate of water supply to the surface is smaller than the soil infiltration capacity, water infiltrates at the supply rate. This study aimed to supply the very rate of water that allowed the occurrence of infiltration in the small pores, avoiding macropore flow. The question arises: can this scheme be practically implemented?

Several features of present drip irrigation technology render it unable to practically achieve the above ultra-low application goal. First, they often create locally saturated conditions in the immediate vicinity of the emitters, potentially producing macropore flow. Jaynes and Rice (1993) have also proven this point by finding occurrence of preferential flow under drip irrigation during their field study. Second, they are not well suited to cracking clay soils, where capillary conduction away from the emitters can be disturbed by cracks. Finally, there are prohibitively expensive to install and maintain for many crops. With drip irrigation being shown to be a less than optimal strategy, then what are the alternatives?

Recently, a wide-distribution surface irrigation method was marketed by a US manufacturer (Wade Mfg. Co.). This irrigation method, referred to as the pulsator method, can apply as little as 0.24 mm/hr to the soil surface on a continuous basis. The pulsator operates by accumulating a small volume of water in a pressurized collection chamber which is then discharged in a short burst spreading it over a 5 m by 5 m area. Presently the pulsator design appears to be the lowest application-rate device available. It is anticipated that other ultra-low rate applicators will become available as the advantages of this approach are illuminated.

Conclusive determination of the impact of ultra-low rate irrigation on macropore flow and contaminant migration through vadose zone can only be made through a field evaluation, which is the subject of this study.

The primary objective of this study was to determine the impact of ultra-low rate pulsator irrigation on eliminating the macropore flow and loading of nitrate and adsorbed agrochemical to groundwater in the field. The second objective was to provide preliminary data for future study.

RESULTS AND DISCUSSION

Our preliminary data demonstrates no macropore flow occurred under ultra-low rate irrigation even in cracking clay soil that has shown a great deal of preferential flow under conventional irrigation methods. For example, on November 17, 1993, PCAPS under the pulsator irrigation did not collect any water at all, while samplers under flood irrigation collected significant amounts (Figures 55 to 57). Since we maintained a balance between applied water and the evaportranspiration rate, No net leaching resulted during the study. The infiltration rate was controlled by the water application rate. In this case, no deep percolation occurred. As mentioned earlier, deep leaching was observed under flood. This recharge could carry nutrient and agrochemical from the root zone to the groundwater, leading to groundwater pollution. Figures 5, 8, 9, 14, and 17 showed water leaching patterns under micro-sprinkler treatment during the irrigation season. They all indicated that a great deal of percolation occurred. Clearly micro-sprinkler irrigation did not reduce the percolation and macropore flow since the water application rate was several times greater than K_s. This leaching decreased the water availability to the plant and increased the potential of pollutants' loading to the groundwater.

A limited deep percolation was observed by PCAPS 3 in clay soil in both 1993 and 1994 (Figure 58 and 59) because water supply rate (irrigation and precipitation) was a little higher than the ET. The reason why higher net irrigation rate was applied was that we tried to find if ultra-low rate pulsator had ability to allow water to penetrate to root zone. It may suggest that pear should not suffer water deficit under ultra-low rate pulsator irrigation. Figure 58 and 59 also demonstrated the good water application uniformity under pulsator irrigation. Table 10 showed that ultra-low rate application device improved the spatial uniformity of application by avoiding the flux concentrating effects which are created when preferential flow is the dominant infiltration process. Jaynes and Rice (1993) demonstrated that flood irrigation results in greater variability of tracer velocity and increased dispersion and dispersivity than drip irrigation. Comparing drip irrigation and pulsator system, pulsator avoids locally saturated soil. Thus, pulsator has a high tendency to achieve high uniformity.

Ultra-low rate irrigation demonstrate that pollutant loading to the groundwater can be dramatically lowered by maintaining irrigation rates significantly below the maximum infiltration capacity of a soil. This is a result of the longer traveling time in vertical transport, and the greater uniformity of infiltration. In addition, under ultra-low rate irrigation, plants experience shorter deficit periods, no runoff, and low overall water consumption, all of which have positive repercussions from the farmer's perspective.

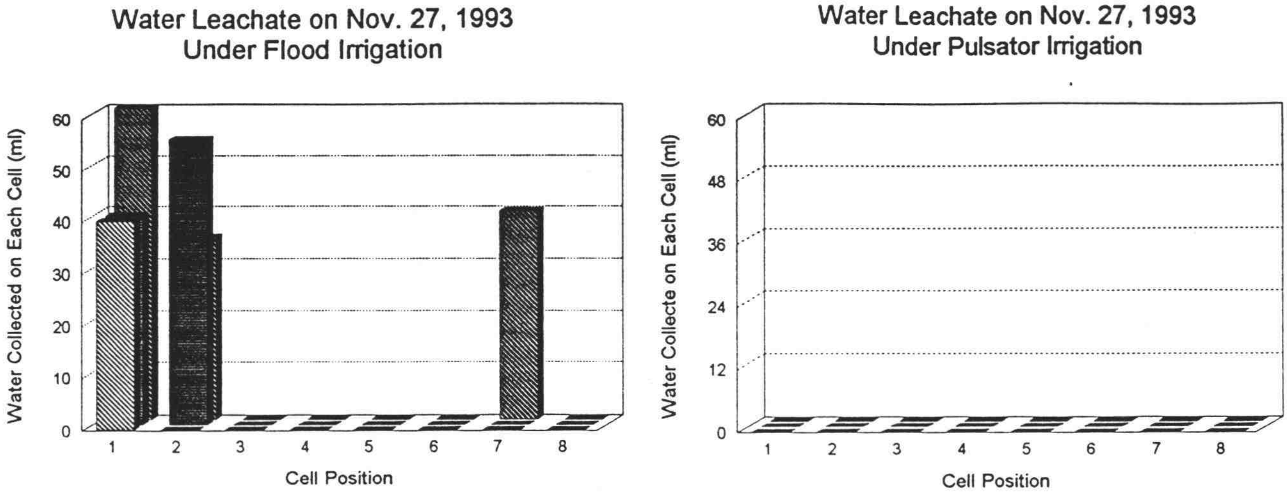

Figure 55. Leachate collected on November 27, 1993 under flood and pulsator irrigation in clay soil.

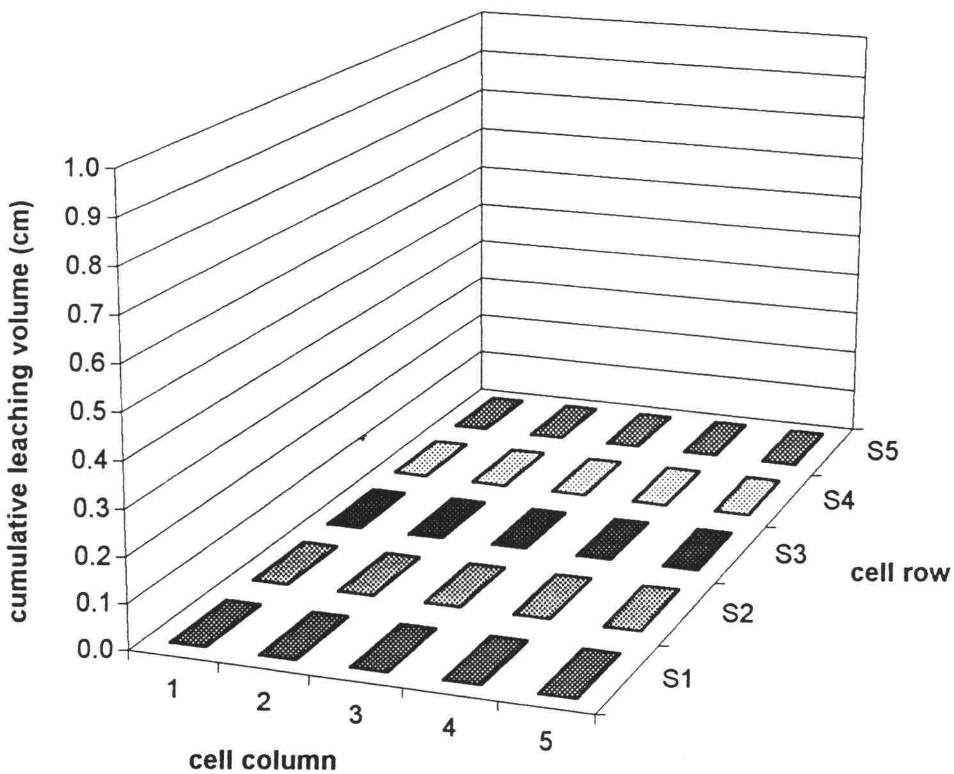

Figure 56. Cumulative deep percolation observed by PCAPS 9 in each cell under pulsator irrigation in clay soil from Oct. to Dec. 1993.

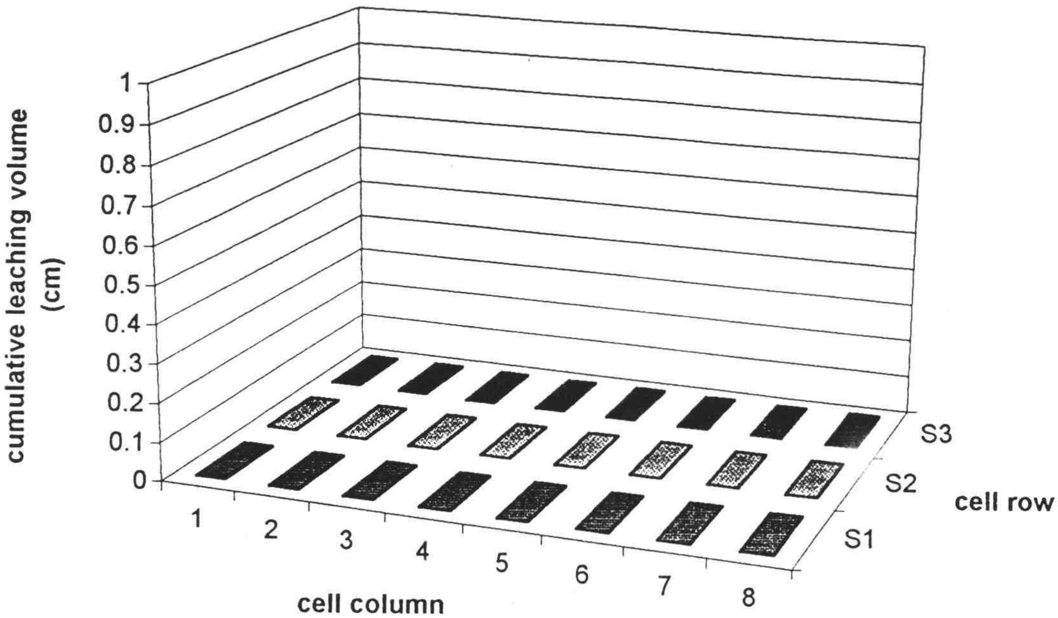

Figure 57. Cumulative deep percolation observed by PCAPS 4 in each cell under pulsator irrigation in sandy soil from Sept. to Oct.

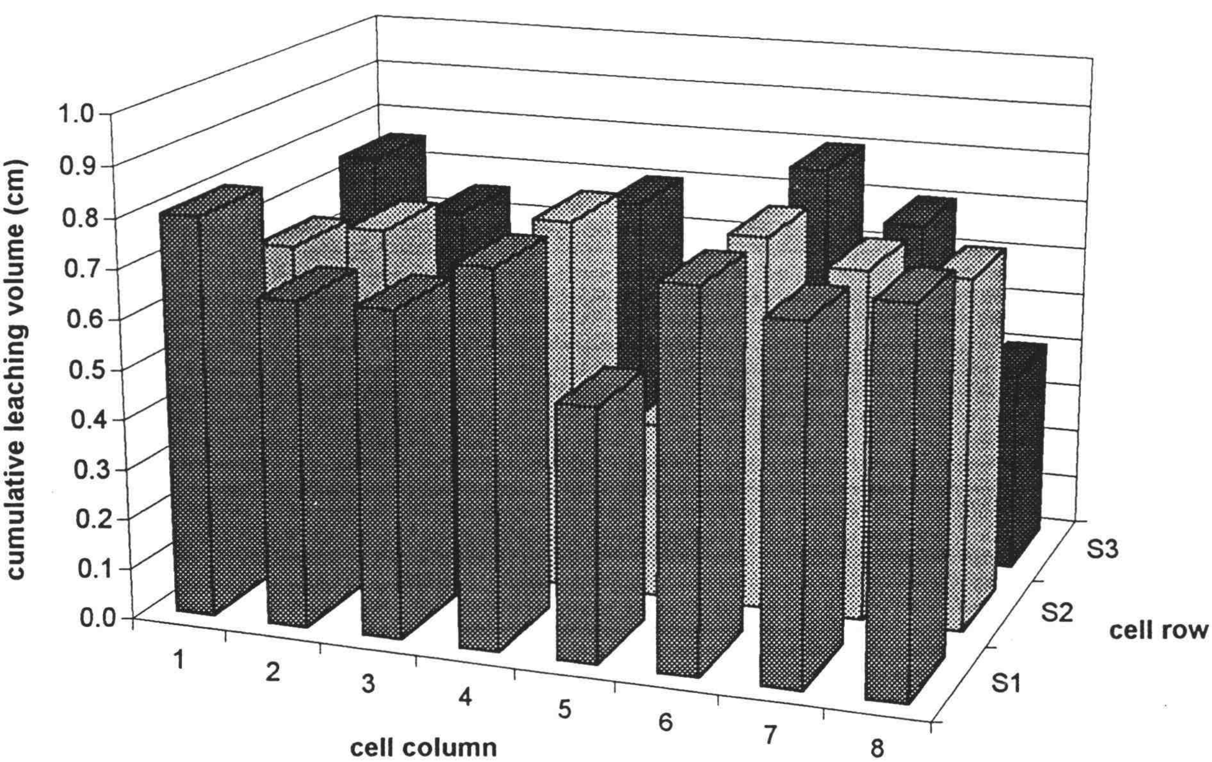

Figure 58. Cumulative deep percolation observed by PCAPS 3 in each cell under pulsator irrigation in clay soil in Oct. 1994.

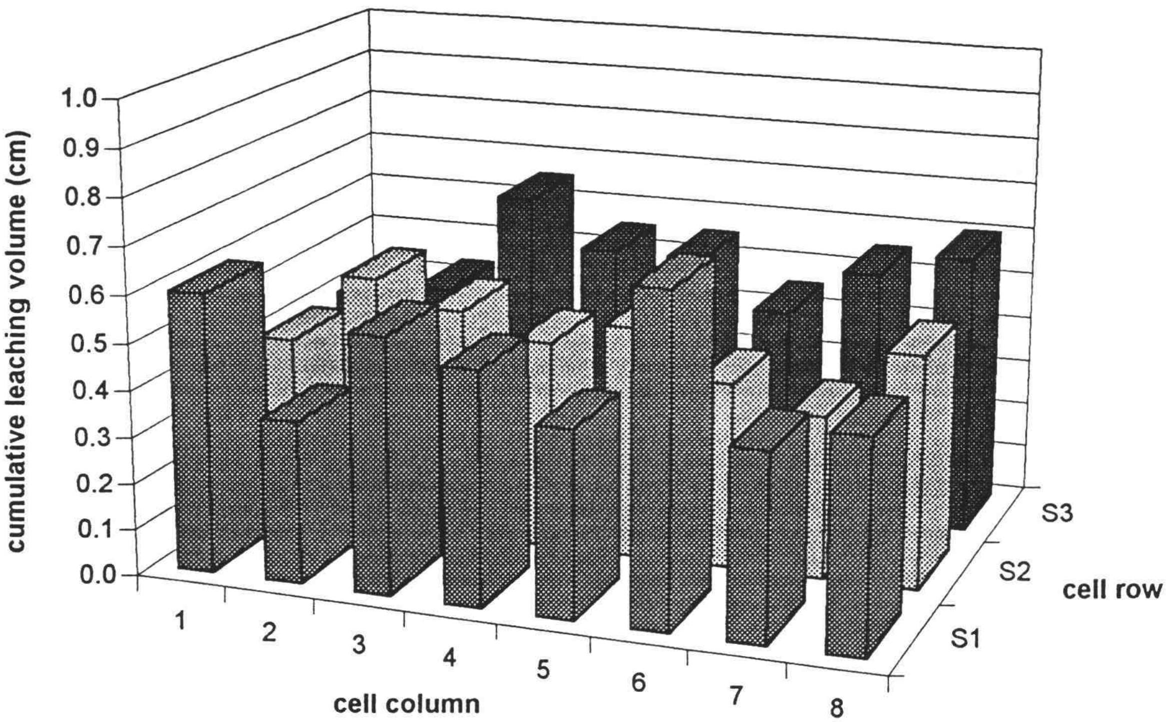

Figure 59. Cumulative deep percolation observed by PCAPS 3 in each cell under pulsator irrigation in clay soil from Oct. to Dec. 1993.

Table 10. Uniformity coefficient (UC) of collection under pulsator irrigation

PCAPS No	UC	Soil Type	Year
3	0.84	clay	1993
3	0.84	clay	1994
9	0.72	clay	1994
12	0.7	sandy loam	1994

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