Characteristics of Soil Media Where Subsurface Drip Systems Are Being Used to Distribute Residential Wastewater

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EXECUTIVE SUMMARY

This project evaluated the influence of the application of domestic effluent treated with septic tanks and constructed wetlands using a subsurface drip dispersal system on soil chemical and hydraulic properties. Four different residential systems, located in different climatic regions of Texas, were evaluated during this project. Soil samples were collected for chemical and hydraulic evaluation along two transects from a drip emitter, a transect along the drip lateral and a transect perpendicular to the drip lateral emitter. Samples for chemical analyses were disturbed soil cores and soil cores for hydraulic evaluation were undisturbed soil cores. Control samples were collected from an area adjacent to the drip drain field with similar soil characteristics.

The quantity and distribution of chemical constituents in the soil profile are influenced by soil properties, soil structure that affect water movement patterns, crop uptake, concentration of the chemical in applied effluent, concentration of the chemical in the original soil, and distance from the emitter. The most important concern was elevation of Na concentration in soil when Na was presented in large quantities in the applied effluent. It is known that increasing Na in soil could cause deterioration of soil physical properties, especially if the increase in soil Na occurred in conjunction with reduction in Ca and Mg concentration. Phosphorus concentrations were significantly increased near the emitter and close to soil surface where the drip line was installed at shallow depth. This could pose a hazard for surface water pollution by erosion and runoff. There were no drastic change in soil TN, Ca, Mg, K, EC, and TOC. Generally, there was slightly more build up of the chemical constituents in the cross section along the drip line than in the cross section perpendicular to the drip line. This difference in chemical distribution in both cross sections was more pronounced for chemicals with low crop uptake such as P (compared to nitrogen and potassium) and Na.

Application of treated effluent resulted in an increase in soil water retention, a decrease in the volume of pores with large radii, and a decrease in saturated hydraulic conductivity. These results were consistent with previous research findings (De Vries, 1972; Sigriest, 1978). The areal extent of influence of applied effluent on soil hydraulic properties depended on effluent quality, actual application rate, and soil type. At site 2 application of effluent had a more pronounced impact due to high Na content and a greater actual application rate. At this site, the impact of applied treated effluent on saturated soil hydraulic conductivity decreased with increasing distance from the emitter. More reduction in K_{sat} occurred along the drip line than perpendicular to the drip line. At both sites, the greatest impact of effluent application occurred in the area located beneath the emitter. The subsurface drip system did not exhibit a severely clogged layer like those observed within drain fields of conventional septic systems.

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INTRODUCTION

On-site wastewater treatment systems serve as the land based treatment method for residential systems utilizing a decentralized approach to wastewater management. In 1990, approximately 25 % of the population of the United States relied on individual on-site wastewater systems (Bureau of Census, 1993). However, the 1997 response to congress on Decentralized Management identified on-site systems servicing 37% of new construction. The most common type of on-site wastewater treatment system used in the United States was a septic tank with a conventional distribution system for final treatment and disposal. The conventional distribution system typically consists of a 4 in diameter perforated pipe placed in a trench of gravel located about 2 feet below the soil surface. The effluent flows by gravity from the septic tank to the perforated pipe. The combination of septic tank and conventional distribution system is referred to as a septic system in this study. An underlying assumption for the septic system is that effluent will receive initial treatment by anaerobic digestion in the septic tank and final treatment is accomplished during effluent movement through the soil matrix by the processes of adsorption, filtration, and microbiological decomposition (Bouma et al., 1972).

In some places, septic systems have functioned properly for decades; however, at many sites, systems have failed to provide adequate treatment and allowed partially treated effluent to reach the soil surface and/or groundwater. A major cause of septic system failure is that the 4 in diameter perforated pipe provides very poor distribution of effluent in the drainfield. Most of the effluent exits the pipe near the inlet, resulting in a localized overloading of effluent in a small area of the drainfield. This creates a continuous saturated condition resulting in rapid effluent movement and inadequate treatment by the soil. An alternative to the conventional distribution system is needed which will result in a uniform distribution of effluent in the drainfield. This will improve the performance of on-site wastewater treatment systems and reduce the risk of groundwater contamination and effluent surfacing.

Subsurface drip dispersal systems have been used in many areas of the United States as an alternative to the perforated pipe and conventional trench drainfield. Subsurface drip dispersal provides better control of the application rate and distributes effluent evenly throughout the land application area. Subsurface drip dispersal systems consist of a pretreatment device, pump chamber, a mechanical filter, small diameter tubing, and emission devices (emitters) which are placed at equal intervals along the tubing. Emitters are designed to dissipate fluid pressure and discharge at a rate that does not vary significantly because of minor differences in pressure along the drip lateral. If a large difference in pressure is expected along the drip lateral, pressure compensating emitters, which discharge water at a constant rate over a wide range of pressure, can be used. Thus, the design strategy for subsurface drip dispersal systems focuses on achieving high emission uniformity. Research with a subsurface drip irrigation system shows that a uniformity coefficient greater than 90% can be achieved (Phene at al., 1992 , Camp et al., 1993).

A major concern when using subsurface drip dispersal systems for effluent distribution is the potential for emitter clogging. A potential solution is providing secondary treatment (aerobic treatment unit, sand filter, constructed wetland) to improve effluent quality before entering the subsurface drip dispersal system. If the subsurface drip dispersal systems are designed properly, an equal distribution of effluent over the entire drainfield can be achieved, avoiding overloading of soil and associated adverse environmental impacts.

Criteria specifically developed for the design and operation of subsurface drip dispersal systems are not available because of a lack of information about changes in soil hydraulic properties around subsurface drip emitters. Soil hydraulic properties in the drainfield of an on-site disposal system exhibit great variability due to chemical, physical, and biological impacts of the applied effluent. Studies on drain fields of conventional septic systems showed that a clogged layer tended to develop at the interface between soil and gravel fill and extended into the upper few centimeters of soil (Thomas et al., 1966; Jones and Taylor, 1965; DeVries, 1972). As a result, soil hydraulic properties, such as saturated hydraulic conductivity, and soil water retention are altered in the upper few centimeters of the soil (Magdoff and Bouma, 1974). This impacts the soil moisture distribution within the drainfield. The alteration of soil hydraulic characteristics by effluent applications should be considered in the design of an effluent distribution system. Bouma (1975) suggested that the design application rate for a septic system should be based on the hydraulic characteristics of the clogged soil layer and the relationship between hydraulic conductivity and moisture content in the soil below the clogged layer.

Since subsurface drip dispersal provides a more uniform spatial distribution of effluent and flow from subsurface emitters is essentially three-dimensional, subsurface drip is expected to exhibit different soil clogging characteristics than conventional drain fields. Wastewater enters the soil at the emitter and moves through the soil away from the emitter. Wastewater is treated as it moves through the soil pores. Subsurface drip design loading rates are based an areal loading rate, which is the soil surface area, and the assumption of complete use of the soil matrix for wastewater treatment. Water movement in the soil follows mass flow through the matrix or preferential flow paths. Wastewater moving through the soil will follow the path of least resistance. One potential preferential flow path is along the drip lateral. Flow along the drip lateral improves wastewater distribution along the drip lateral but would have limited wastewater movement perpendicular to the drip lateral. Because drip systems in Texas require 12 inches of soil below the emitter, wastewater treatment must occur in this soil depth (TNRCC, 1997).

No previous study has documented the impact of effluent application on the alternation of soil hydraulic characteristics in the drainfield of a subsurface drip dispersal system. Such information is essential for the proper design and operation of a subsurface drip dispersal system. To understand what causes the change in soil hydraulic properties, soil chemical properties must be considered.

Objectives

The focus of this research was to characterize changes in soil hydraulic and chemical properties associated with the application of effluent by a subsurface drip dispersal system. The pretreatment devices consisted of septic tank followed by a subsurface flow constructed wetland. The specific research objectives were:

1) Evaluate changes in soil chemical properties caused by application of septic tank effluent through a subsurface drip dispersal systems, and

2) Evaluate changes in soil hydraulic properties caused by application of effluent through subsurface drip dispersal systems. This will include

- Evaluate water retention curves for soil around drip emitters,
- Evaluate pore size distribution around drip emitters, and
- Evaluate saturated hydraulic conductivity of the soil around drip emitters.

LITERATURE REVIEW

Nonuniformity of Conventional Distribution System

Several studies document the non-uniform distribution of effluent discharged from conventional distribution systems. Bouma et al. (1972) evaluated twenty septic systems in twelve major types of soil in Wisconsin. They indicated that most of the effluent is discharged from the 4 in diameter perforated pipe at a point close to the inlet. The soil near the pipe inlet receives a continuous trickle of effluent. This leads to soil crusting and consequent reduction of effluent movement into soil, and ponding of effluent at that point. The effluent then flows along the bottom of the trench until it encounters uncrusted soil. This movement progresses until the whole bottom area is crusted (Figure 1).

To verify the field findings of poor distribution, Converse et al. (1974) conducted a laboratory experiment to investigate effluent distribution from the 4 in diameter perforated pipe. They constructed a full-size gravel trench in which effluent flowed from the septic tank to the perforated pipe by gravity. The distribution of effluent was analyzed at 18 in intervals. They tried different configurations, sizes, and perforation spacing. The distribution of effluent discharge along the pipe was highly non-uniform in all studied situations.

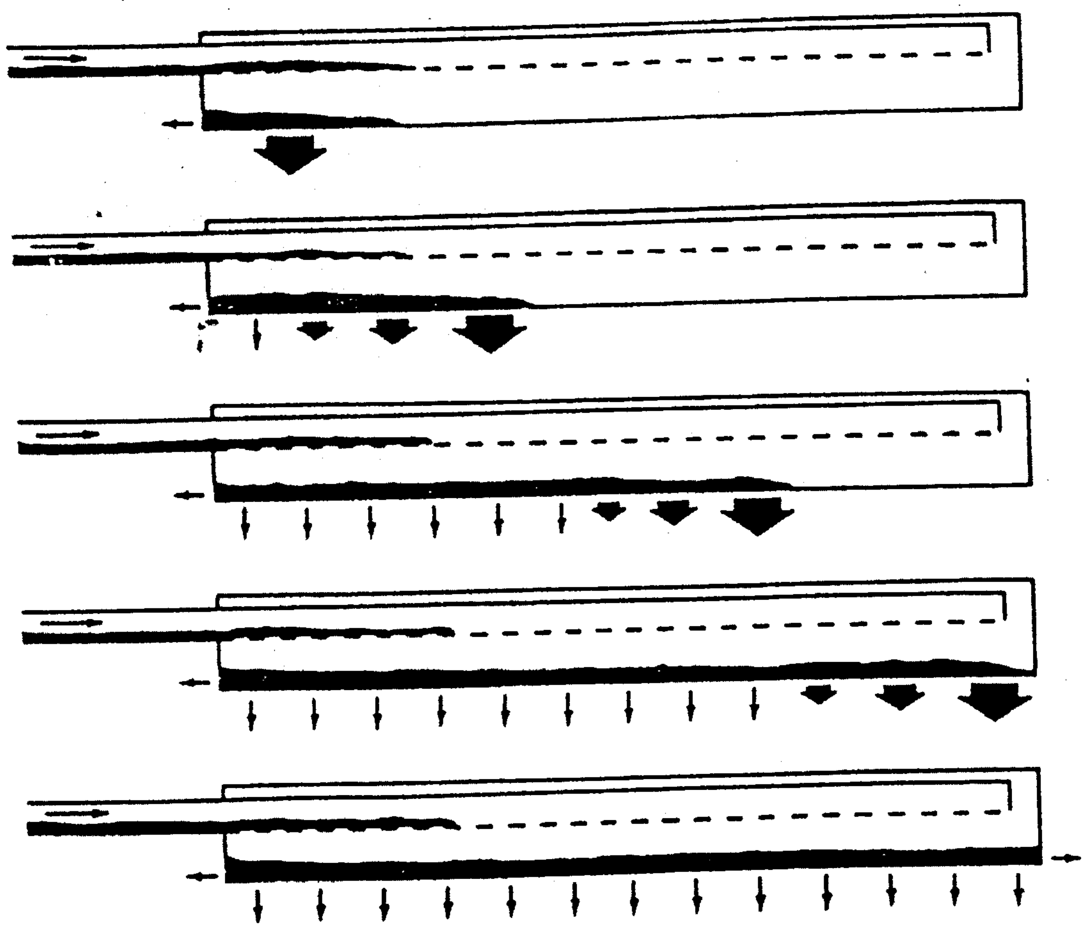

Figure 1-Progress of soil crusting below the perforated pipe used in the drainfield of conventional septic system (Bouma et al., 1972).

In another laboratory study, Machmeier and Anderson (1987) reported that, for a flow rate of 1 gpm, only two perforations discharged water. Similarly for a flow rate of 8 gpm, the majority of the liquid was discharged by the first four perforations. Ver Hey and Woessner (1987) examined groundwater quality below the drainfield of a septic system in a coarse texture soil. They reported that, even though all legal requirements were met, i.e. depth to the groundwater below the drainfield was greater than four feet and the percolation rate was greater than 1 min/inch, no significant decrease in phosphorous and nitrogen occurred before the effluent reached groundwater. Exploratory excavation in the site showed the effluent was entering the soil from the beginning of the perforated pipe only. They suggested that there was a need for a distribution system utilizing the entire drainfield to improve septic system performance.

Subsurface Drip Dispersal Systems

Research on subsurface drip dispersal systems has been limited to the evaluation of system performance in terms of hydraulic uniformity, system efficiency, and environmental consequences (Hoover and Amozegar, 1989; Stewart and Reneau, 1988; Rubin et al., 1994).

Stewart et al. (1983) used a subsurface drip system for distribution of septic tank effluent after it was treated by a sand filter and chlorination. The study period was only five months in 1982 and three months in 1983. They reported good performance of the system during this short period. Oron (1991) conducted four years of field experimentation to evaluate using a subsurface drip dispersal system for irrigation, utilizing domestic secondary-treated wastewater. He found that the system operated without any failure during the entire study period, and the effluent was evenly distributed in the irrigated soil. Rubin et al. (1994) monitored the concentration of nitrate nitrogen in shallow groundwater below a drip system in North Carolina. They reported that the effluent only marginally affected the groundwater.

Soil Clogging

Factors that result in soil clogging can be classified as chemical, biological, and physical (Rice, 1974). Chemical clogging is caused mainly by interaction between dissolved salts in the water and the soil, resulting in decreased pore diameter and, consequently, lower hydraulic conductivity. Chemical clogging occurs when the sodium (Na) content of water is high. High Na concentration may result in the deterioration of soil physical properties through clay particle swelling and dispersion. This in turn causes a reduction in soil porosity and hydraulic conductivity (Feigin et al., 1991). The adverse influences of Na are moderated by calcium (Ca) and magnesium (Mg). The potential hazards of Na is estimated using the Sodium Adsorption Ratio (SAR) (Ayers and Westcot, 1976):

$$SAR = \frac{[Na^{+}]}{\sqrt{[Ca^{+2}] + [Mg^{+2}]}} \qquad (1)$$

where $[Na^{+}]$, $[Ca^{+2}]$, and $[Mg^{+2}]$ are the concentration (mmol/l) of these ions in the applied effluent.

Biological clogging occurs when bacterial growth or its by-products reduce pore diameters. Biological clogging frequently is associated with anaerobic conditions. However, aerobic bacteria may also play an important role in soil clogging (Vandevivere and Baveye, 1992).

Physical clogging results from suspended solids blocking the pores when the soil pore size is smaller than the diameter of the solid. Vinton et al. (1983) labeled the suspended solid in sewage effluent to determine distribution of solids in the soil profile. He found the majority of solids remained in the upper 0.2 in of the soil profile.

Significant research has been conducted to understand the impacts of wastewater on the clogging of soils in an effort to design better delivery systems. Most of the research has been focused on surface application of waste. In a laboratory study, McGauhey and Winneberger (1964) constructed a 1 ft by 1 ft by 2 ft steel lysimeter and filled it with sandy soil. They applied primary-settled wastewater on the surface of soil within the lysimeter. After 338 hours of effluent application, a clogged surface layer developed which was less than 0.75 in thick. They found that both suspended solids and biological growth were major factors in soil clogging. Thomas et al. (1966) and DeVries (1972) applied septic tank effluent on a column filled with sand and gravel. They observed that a thin layer developed at the gravel/sand interface due to deposition of organic material.

Laak (1970) applied septic tank effluent to soil columns 6 in in diameter. Complete soil clogging occurred within 180 days of effluent application. The clogging zone was in the upper 0.2 in. The clogging material consisted of about 90 % bacteria cells. He found that there was a linear relationship between the sum of total suspended solids (TSS) and biochemical oxygen demand (BOD_5) load and the noncapillary porosity of the soil.

Rice (1974) investigated soil clogging in soil columns located in a greenhouse. He applied secondary wastewater effluent with different suspended solids concentrations onto six columns, 24.5 in long and 4 in in diameter. A clogged layer formed at the soil surface. Physical clogging caused by deposition of suspended solids on the soil surface was the major cause of infiltration reduction.

To confirm the laboratory results, Simons and Magdoff (1979) monitored soil moisture tension below the gravel/sand interface in the drainfield of a septic system. The pattern of measured soil moisture tension indicated development of a crust layer at the gravel/sand interface. They attributed the development of this crust layer to build-up of organic solids. Most recently, in a pilot-scale study, Siegrist (1987) applied septic effluent to 0.9 m (36 in) diameter cells installed in structured silty loam soil. They applied the effluent at three different rates: 0.5 in/day, 1 in/day, and 2 in/day. During 18 to 24 months of effluent application, the soil in the cells exhibited substantial clogging at all three loading rates. He observed that the infiltrative surface zones, where wastewater was applied, exhibited significant accumulation of organic materials within the first few millimeters of soil matrix.

Because using subsurface drip systems for wastewater distribution is relatively new, there have been no studies published on the development of a clogged layer in the receiving soil of such a system.

Application Rate

The primary factor affecting the design of a septic system drain field is the determination of the proper application rate. The most comprehensive study to determine application rates for conventional drainfields was provided by Bouma (1975). Based on clogged layer thickness, soil matric potential under the clogged layer, and the relationship between hydraulic conductivity and moisture content for the soil below the clogged layer, he determined a long-term application rate for four different types of soil (Table 1). Perkins (1989) introduced a procedure for determining hydraulic loading based on the infiltration capacity of the soil. Carlile and Sanjines (1996) suggested using a hydraulic rate less than 10% of the mean saturated hydraulic conductivity to allow for adequate treatment after rainfall events. In Texas, the maximum allowable hydraulic loading is defined based on textural classification of the most restrictive soil layer (Table 1) (TNRCC, 1997).

Design application rates for subsurface drip dispersal disposal systems have not been developed yet. In Texas, the same application rate developed for conventional septic systems is used for design of subsurface drip dispersal disposal systems (TEEX, 1998). Georgia's regulations for drip irrigation of domestic wastewater require a design loading rate of no more than 12% of the mean saturated hydraulic conductivity of the most restrictive soil horizon if the seasonal high water table is greater than 1.5 m (60 in), and no more than 10% of the mean saturated hydraulic conductivity otherwise. However, such application rates were developed based on the assumption that a clogged layer will develop at the application surface. Bouma et al. (1974) stated that "in any case, sizing criteria derived for the conventional type of subsurface bed do, of course not necessarily have to apply to innovative systems. New criteria may have to be developed. It would be necessary to based criteria on an analysis of the hydraulic properties of the soil."

Table 1-Application rates for septic system drainfields for four different soil types.

Soil type	Soil Texture	Application Rate	
		Bouma (1975)	TNRCC (1997)*
		g/day/ft^2	g/day/ft^2
Type I	Sand	1.65	0.38
Type II	Sandy loam, loam	0.27	0.25
Type III	Silt loam, some silty clay loam	0.19	0.20
Type IV	Clay, some silty clay loam	0.12	0.10

* Texas Natural Resource Conservation Commission.

Soil chemical characteristics

Since septic tank effluent is usually rich with nutrients and other chemical constituents, it is expected to alter the soil chemical properties in the application field. To date, several reports documented the impact of effluent application on soil chemical properties, but almost all dealt with flood irrigation (Waly et al., 1987, Liu et al., 1998), furrow irrigation (Hinrichs et al., 1974), or sprinkler application (King et al., 1990, Hayes et al., 1990, Mancino and Pepper, 1992). Since the use of subsurface drip dispersal systems for wastewater disposal is relatively new, little information is available on the impact of wastewater on the chemical properties of the soil surrounding the drip emitter. Oron et al. (1991) applied treated domestic effluent for five years using a subsurface drip dispersal system. However, they reported only limited information concerning distribution of chemical constituents around subsurface drip emitters. Papadopoulos and Stylianou (1991) evaluated the impact of application of secondary treated urban effluent using a subsurface drip irrigation system on soil chemical properties. However, fertilizer nitrogen (N), phosphorous (P), and potassium (K) were added to the applied effluent. Moreover, the examined soil chemical properties were limited to N, P, and electrical conductivity (EC).

MATERIALS AND METHODS

Sites Description

This project was conducted at four on-site residential wastewater treatment systems located throughout Texas. Each system consists of a septic tank for primary treatment, a constructed wetland for advanced treatment, and subsurface drip dispersal system for land application of the treated wastewater. The first system (site 1) is located in D'Hanis, Texas, and treats domestic wastewater from a three-bedroom residence. The wastewater flows from the home into a 1000 gallon septic tank and then into a subsurface flow constructed wetland. From the constructed wetland, the water flows into a 550 gallon pump tank and is then distributed to the drip dispersal system Appendix A, Figure A1). The entire treatment system is designed to treat and apply 350 gallons of wastewater per day. The drip dispersal system is comprised of a wastewater effluent filtration system and two subsurface drip application areas. Each 800 ft^2 application area is 16 ft x 50 ft. The east area (Field I) contains 1 gal/h emitter rate drip tubing on 2 ft centers with a 2 ft emitter spacing. The emitters in Field I are non-pressure compensating. The west area (Field II) contains 0.5 gal/h emitter rate drip tubing with the same emitter spacing as Field I. The emitters in Field II are pressure compensating. The drip dispersal system irrigates a small pasture plot of coastal bermudagrass. Operation of the system began in July 1994. Only Field I was used in this study and hence it will be referred to as site 1. The soil at this site is Castroville silty clay loam with weak medium subangular blocky structure and 14% sand, 38% silt, and 48% clay.

The second system (site 2) is located in Weslaco, Texas. The system treats domestic wastewater from a two-bedroom residence. The wastewater flows from the home into a 750 gallon septic tank and then into a subsurface flow constructed wetland. From the constructed wetland, the water flows into a 500 gallon pump tank and is then distributed to the subsurface drip dispersal system (Appendix A, Figure A2). The entire treatment system is designed to treat and apply 250 gallons of wastewater per day. The drip dispersal system is comprised of an effluent filtration system and two drip application areas. Each 1000 ft^2 application area is 20 ft by 50 ft. The west area (Field I) contains 0.5 gal/h emitter rate drip tubing on 2 ft centers with a 2 ft emitter spacing and an installation depth of 3 in. The emitters in Field I are non-pressure compensating. The east area (Field II) contains 0.9 gal/h emitter rate drip tubing with the same emitter spacing and installation depth as in Field I. The emitters in Field II are pressure compensating. The drip system irrigates common bermudagrass. System operation began in January 1994. Only Field II was used in this study and it will be referred to as site 2. The soil at this site is a Willacy fine sandy loam with weak fine granular structure and 71% sand 16% silt, and 13% clay.

The third system (site 3) is located in Stephenville, Texas. The system treats domestic wastewater from a three-bedroom residence, a recreational vehicle (RV) dump station, and a dog kennel. The wastewater flows from the home into a 1250 gallon septic tank, while wastewater from the RV dump station and the dog kennel flows into a

500 gallon septic tank and then into the 1250 gallon tank. From the 1250 gallon septic tank, the water flows into a subsurface flow constructed wetland. From the constructed wetland, the water flows into a 500 gallon pump tank and is then distributed to the subsurface drip dispersal system (Appendix A, Figure A3). The entire treatment system was designed to treat and apply 300 gallons of wastewater per day. The land application site is comprised of two areas of 920 ft^2 each. The south area (Field I) contains 1 gal/h emitter rate drip tubing on 2 ft centers with a 2ft emitter spacing. The emitters in Field I are non-pressure compensating. The north area (Field II) contains 0.5 gal/h emitter rate drip tubing with the same spacings as Field I. The emitters in Field II are pressure compensating. The subsurface drip dispersal system irrigates common bermudagrass, fescue, and several other types of landscape vegetation. Operation of the system began in July 1994. Only Field I was investigated in this study and it will be referred to as site 3. The soil at this site is Waurika fine sandy loam with weak fine granular structure and 48% sand, 24% silt, and 28% clay.

The fourth system (site 4) is located in College Station, Texas. The system treats domestic wastewater from a three-bedroom residence. The wastewater flows from the home into a 1000 gallon septic tank and then into a subsurface flow constructed wetland. From the constructed wetland, the water flows into a 500 gallon pump tank and is then distributed to the subsurface drip dispersal system (Appendix A, Figure A4). The land application site is comprised of two areas. The east area (Field I) which is 1200 ft^2 contains 0.5 gal/h emitter rate drip tubing on 2 ft centers with a 2 ft emitter spacing. The emitters in Field I are pressure compensating. The west area (Field II) contains 1 gal/h emitter rate drip tubing with the same spacings as Field I. The emitters in Field II are non-pressure compensating. The subsurface drip dispersal system irrigates common bermudagrass. Only Field II was investigated in this study and it will be referred to as site 4. Operation of the system began in July 1996. The soil is Lufkin fine clay loam with 30% sand, 19% silt, and, 51% clay. A summary of operational characteristics for the four sites is given in Table 2.

Table 2-Operational characteristics for four subsurface drip dispersal fields receiving domestic effluent in Texas.

Site	Location	Emitter Rate (gal/hr)	Average Application Rate (gal/day/ft^2)	Emitter Depth (inches)	System Operation (years)
1	D'Hanis	1	0.02	12	5
2	Weslaco	0.9	0.04	3	6
3	Stephenville	1	0.08	12	6
4	College Station	1	0.41	7	4

Soil Chemical Characteristics Data Collection and Analysis

Triplicate soil samples were collected in January 1999 from each drip field at four depths: at the emitter, 3 in above the emitter, 3 in below the emitter, and 12 in below the emitter. Due to the shallow installation depth of drip tubing at site 2, the soil samples were collected at 1 in above the emitter instead of 3 in. At site 4, no soil samples were collected at 12 in below the emitter. At each depth, the samples were taken at an emitter, 3 in, 6 in, 9 in, and 12 in horizontally away from the emitter. The soil samples were collected in two directions, one parallel and one perpendicular to the drip lateral. Additional soil samples were collected from a non-irrigated area of bermudagrass adjacent to the drip field. These samples were collected at similar depths to those collected within the drip field.

The collected soil samples were analyzed for phosphorus (P), total nitrogen (TN), sodium (Na), calcium (Ca), magnesium (Mg), soluble sulfate (SO_4), potassium (K), salt content (EC), and total organic carbon (TOC). Soil samples were air dried and sent to the Environmental Analytical Research Laboratory at Texas A&M University system Agricultural Research and Extension Center at El Paso, Texas. Ca, K, Mg, and Na were analyzed using 1:2 soil:water extract and atomic absorption spectrometry (Prince, 1982). P was analyzed using OLSEN extraction (0.5 M $NaHCO_3$) (Olsen and Sommers, 1982). TN and TOC were analyzed using the dynamic composition method. EC was determined by conductivity meter (YSI model 32) and 1:2 soil:water extract.

Soil Hydraulic Characteristics

Average of seven replicates of undisturbed soil cores, 3 in diameter and 3 in, long were obtained using an Uhland core sampler (Blake and Hartge, 1986) for each site. At site 1, the soil cores were obtained from four different depths: 4 in above the emitter level, at the emitter level, 6 in below the emitter, and 12 in below the emitter level. At site 2, the core samples were taken 1 in above the emitter level, 3 in below the emitter level, and 12 in below the emitter level. Sampling depths were not matched due to differences in installation depth of drip lateral (Table 2). At each depth, core samples were obtained at five locations: location A next to the emitter, location B 6 in from the drip emitter along the drip lateral, and location C midway between two emitters, location

D at 6 in from the emitter along a transect perpendicular to the drip lateral, and location E at the midpoint between two drip laterals (Figure 2). At sites 3 and 4, soil cores were collected at 4 in above the emitter, at the emitter level, and 6 in below the emitter. At each depth, core samples were obtained at three locations with respect to the drip lateral: location A, next to the emitter; location C, midway between two emitters along the drip lateral; and location E, midway between two drip laterals.

Control soil samples were obtained from a non-irrigated area of bermudagrass adjacent to the drip field (location O in Figure 2) where the soil had the same characteristics as within the drip fields but was not subjected to wastewater application. These core samples were collected at depths similar to those sampled within the drip field.

Saturated hydraulic conductivity and water retention values were determined for all undisturbed soil cores. Soil cores were saturated from the bottom by soaking in water for five days. Saturated hydraulic conductivity was determined using the constant head method (Klute and Dirksen, 1986). Water retention was determined successively at 1, 3, 7, 10, 14, 20, 27, 34, and 51 kpa, using a pressure cell extractor (Klute, 1986). The mean pore radius at a given matric potential was estimated from water retention data using the equation by Ghildyal and Tripathi (1978)

$$h = (2\sigma \cos\varphi)/rg\rho \qquad (2)$$

where h is the matric potential (m), σ is the water surface tension (mJ/m^2), φ is the contact angle between liquid and solid (assumed to be zero), g is acceleration due to gravity (m/sec^2), and ρ is the density of water (Mg/m^3). The calculated pore radius was partitioned into pore radius interval of > 22 μm, between 3 and 22 μm and < 3 μm and the relative pore volume for each pore size interval was determined. The relative pore volume is defined as the portion of the pore volume occurring within a given pore size interval divided by total soil volume.

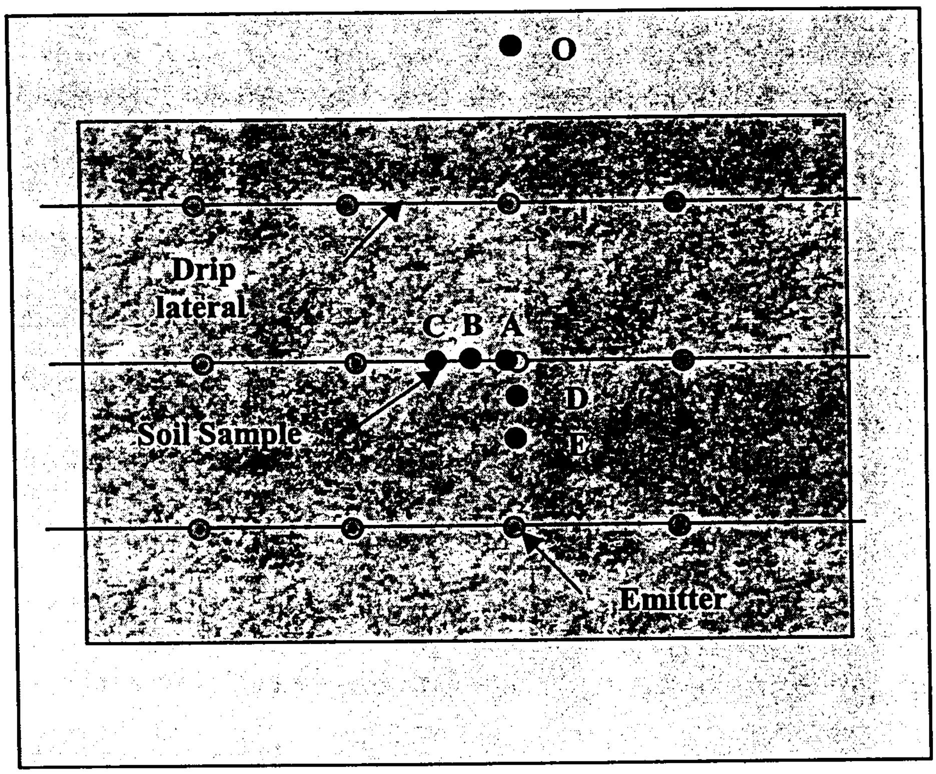

Figure 2- Location of soil core samples collected for hydraulic characteristics analysis

Effluent Quality

One-liter effluent grab samples were collected monthly from the pump tank of the drip dispersal system and immediately chilled below 4° C until analyzed to slow microbial activity. A portion of each sample was removed for direct analysis of BOD_5, which were initiated within 24 hrs after collection. The remainder of the sample was frozen and analyzed for Chemical Oxygen Demand (COD), ammonium (NH_4), total salts, and nutrients. Details of the analytical procedures were reported by Lesikar et al. (1998). Effluent quality data were determined only during the September 1, 1993, to June 1, 1998 time period. Samples numbers for Cl, HCO_3, and EC were low because these parameters were tested following experimentation. Fresh water supplies for residences at sites 1, 3, and 4 originated with ground water having relatively stable constituents. The fresh water supply for the residence at site 2 was surface water from the Rio Grande. Residents remained consistent during and after the experimentation, consequently the effluent quality for the parameters should have been relatively stable with the possible exception of EC for site 2. The average concentrations of constituents in the effluent are provided in Table 3.

Table 3-Chemical properties of the applied treated effluent for time period of September 1, 1993 to June 1, 1998.

Constituent	Site 1	Site 2	Site 3	Site 4
TN (ppm)	37	29	33	12*
P (ppm)	0.9	0.7	0.9	0.6
K (ppm)	22	29	26	10*
Ca (ppm)	96	113	104	41*
Mg (ppm)	22	32	27	10*
Na (ppm)	109	305	207	342*
SO_4 (ppm)	44	280	162	NA
Cl (ppm)†	120	199	NA	NA
HCO_3 (ppm)†	457	578	NA	NA
COD (ppm)‡	55	76	66	NA
NH_4 (ppm)	30	40	34	12
BOD_5 (ppm)	15	23	20	8
EC (ds/cm)†§	1.12	1.24	0.93	1.52*
TSS (ppm)	5	5	30	7
SAR χ	2.6	6.5	4.7	12.4*

*Data for two samples in July and August 2000
†Data for one sample in January 2000
‡ Chemical Oxygen Demand
§Electrical conductivity
χSodium Adsorption Ratio

Data Analysis

Change in soil chemical properties, saturated hydraulic conductivity, water retention, and pore size distribution due to wastewater application were evaluated using analysis of variance (ANOVA). Separation of the means was performed using Fisher's least significant difference at the 0.05 level of significance for chemical properties data and 0.05 and 0.10 level of significance for hydraulic properties data. Nielsen et al. (1973) and Freeze and Cherry (1979) found the hydraulic conductivity to be logarithmically distributed. Therefore, logarithms of saturated hydraulic conductivity values were used in the statistical analysis.

RESULTS AND DISCUSSION

The information gained through the evaluation of the subsurface drip dispersal drain fields was presented in terms of the chemical analysis data and the soil hydraulic information collected at each site.

Phosphorus (P)

Generally, at all four sites, P concentration in the vicinity of the emitter was significantly greater than that in the control area (Table 4, Figures 3-6) while there was no significant effect of applied effluent on soil P noted at 12 in below the emitter. This result was expected and agrees with other researcher's findings (Liu et al., 1998; Papadopoulos, 1991; King et al., 1990; and Reddy et al. 1980). Phosphate ions rapidly undergo precipitation and adsorption reaction in the soil, thus, the movement of P through the soil is restricted. Therefore, most of the phosphorous accumulation occurs in the vicinity of the emitter. However, movement of P for larger distance could occur when the soil adsorption capacity of P is reached. At site 2, P concentration in the area located above the emitter was significantly greater than that in the control area. The drip line at this site was installed only 3 in below the soil surface. Moreover, the saturated hydraulic conductivity of the soil layer immediately below the emitter was only 60 % of that at or above the emitter (Table 19). Therefore accumulation of P near the soil surface could be the result of upward and lateral movement of water by capillary flow and subsequent deposition of P as the water evaporates. At site 4, the high concentration of P in the irrigated area compared to the control area could be attributed to the high clay

Table 4- Average phosphorous concentrations (ppm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
						At site 1					
I†	1.8b‡	2.6ab	1.9b	1.9b	1.8b	1.8b	5.3a	1.7b	1.6b	1.8b	2.1b
II	6.1a	4.1ab	2.0b	1.7b	1.6b	6.1a	7.8a	1.8b	1.3b	1.4b	1.8b
III	17.5b	14.5b	7.2c	5.0c	2.9c	17.5b	31.9a	4.7c	3.2c	2.0c	1.7c
IV	1.5b	1.2b	1.3b	1.6ab	1.3b	1.5b	2.8a	1.5b	1.3b	1.3b	2.1ab
						At site 2					
I	29.5a	24.7a	25.9a	39.2a	26.6a	29.5a	32.9a	24.2a	31.1a	35.4a	1.6b
II	17.4ab	18.8ab	8.5ab	22.5b	19.0ab	17.4ab	17.2ab	6.4ab	12.0ab	22.7b	1.5a
III	12.7a	4.0a	7.4a	13.8a	12.5a	12.7a	14.6a	3.1a	6.0a	11.2a	1.5a
IV	6.2a	6.4a	7.9a	11.0a	7.1a	6.2a	7.2a	6.3a	6.1a	8.5a	6.1a
						At site 3					
I	1.5b	2.1b	3.0b	3.8b	4.0b	1.5b	14.8a	9.7ab	1.7b	2.0b	1.5b
II	24.9ab	25.1ab	13.9ab	13.4ab	13.0ab	24.9ab	34.2a	8.3b	2.2b	2.9b	1.5b
III	11.7b	8.0bc	7.5bc	2.6c	3.9c	11.7b	19.6a	1.8c	1.9c	1.5c	2.2c
IV	1.5a	1.5a	1.5a	1.5a	1.5a	1.5a	1.5a	1.5a	1.5a	1.5a	1.5a
						At site 4					
I	9.6ab	10.0ab	11.4ab	10.8ab	10.1ab	9.6ab	11.6ab	7.2bc	6.2bc	6.6bc	1.7c
II	9.2abc	11.2ab	9.6abc	8.4bc	7.3bcd	9.2abc	15.1a	7.0bcd	4.8dc	5.5bcd	1.5d
III	8.2ab	6.5bc	6.3bc	8.6ab	7.3ab	8.2ab	12.2a	6.1bc	5.9bc	6.2bc	1.5c

†I depth at 3 in above the emitter at sites 1, 3, and 4 and 1 in above the emitter at site 2, II depth at the emitter level, III depth at 3 in below the emitter, and IV depth at 12 in below the emitter.

‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

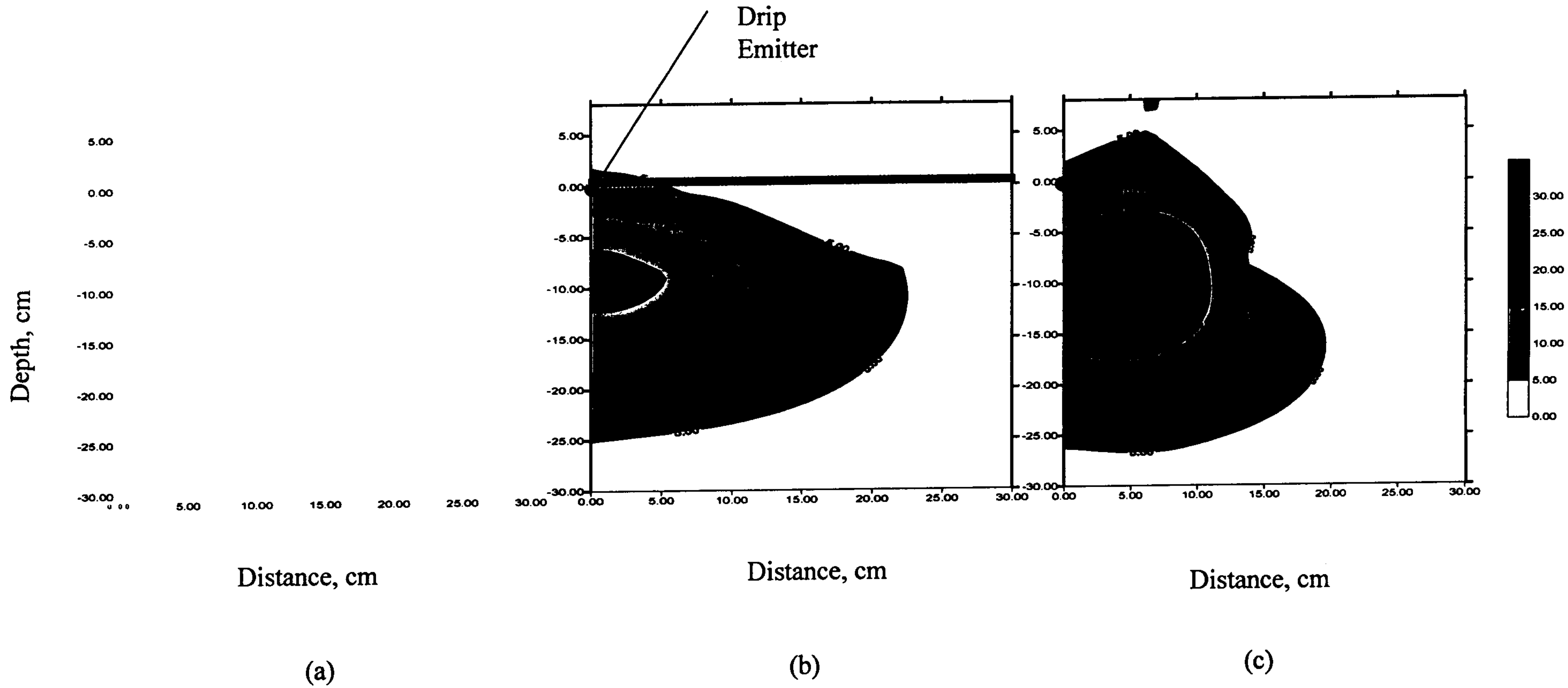

Figure 3-Phosphorous concentration distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

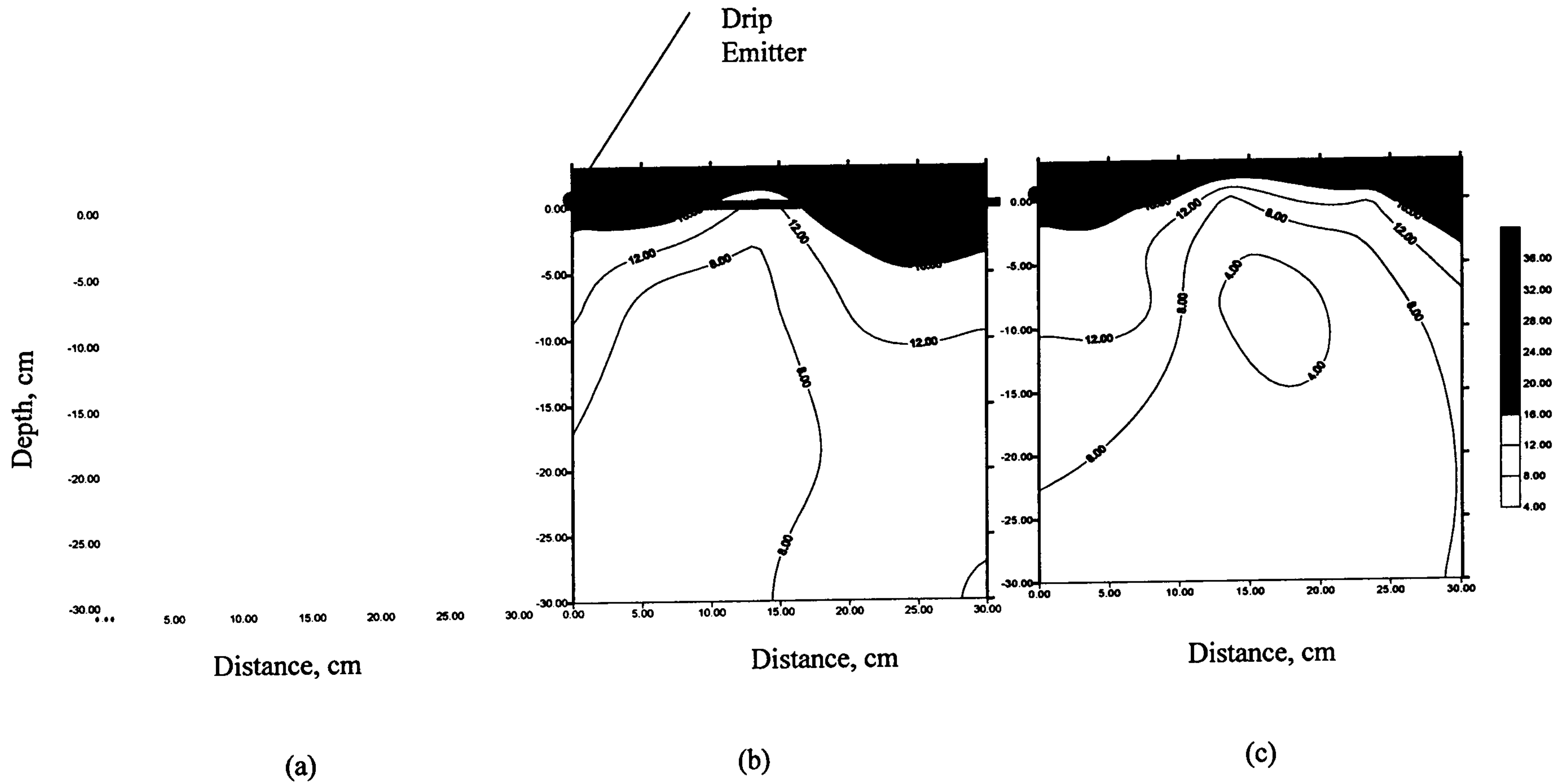

Figure 4-Phosphorous concentration distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

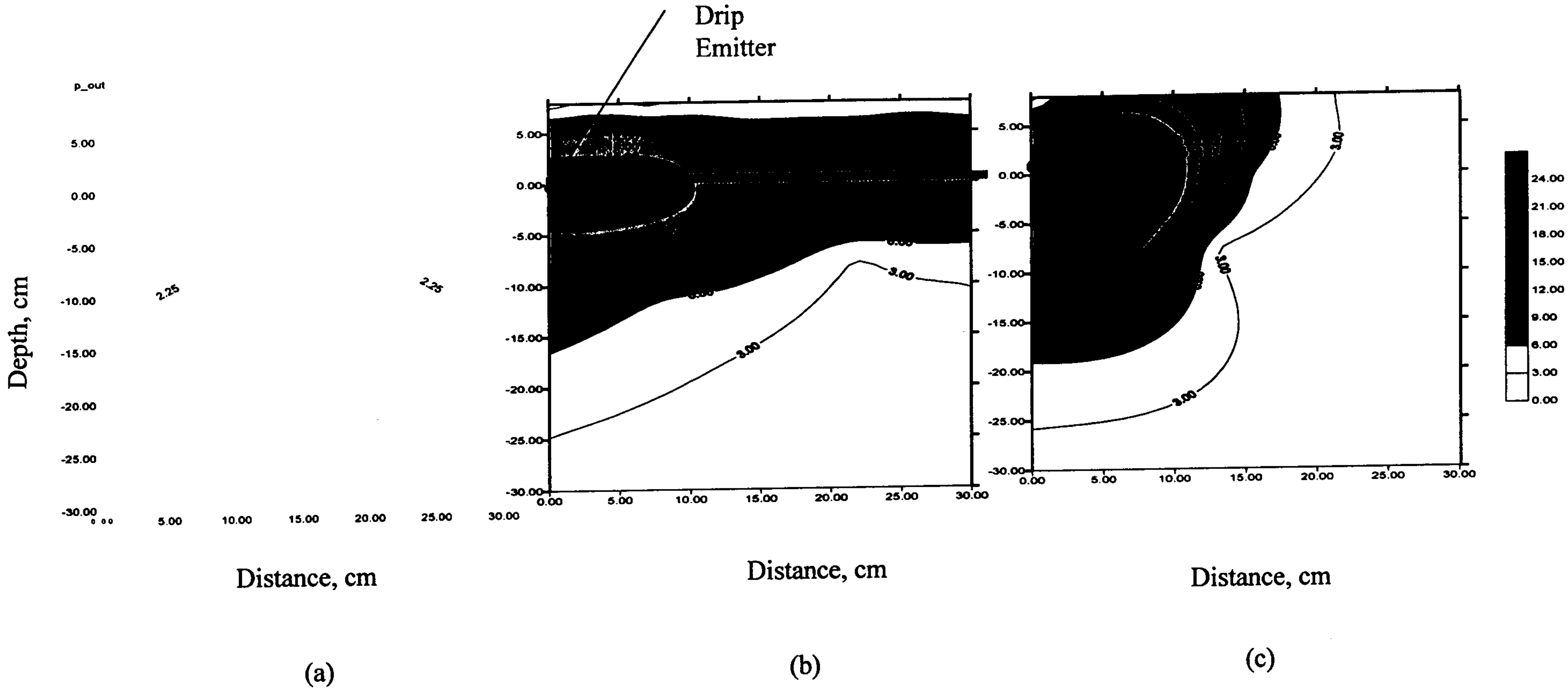

Figure 5-Phosphorous concentration distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

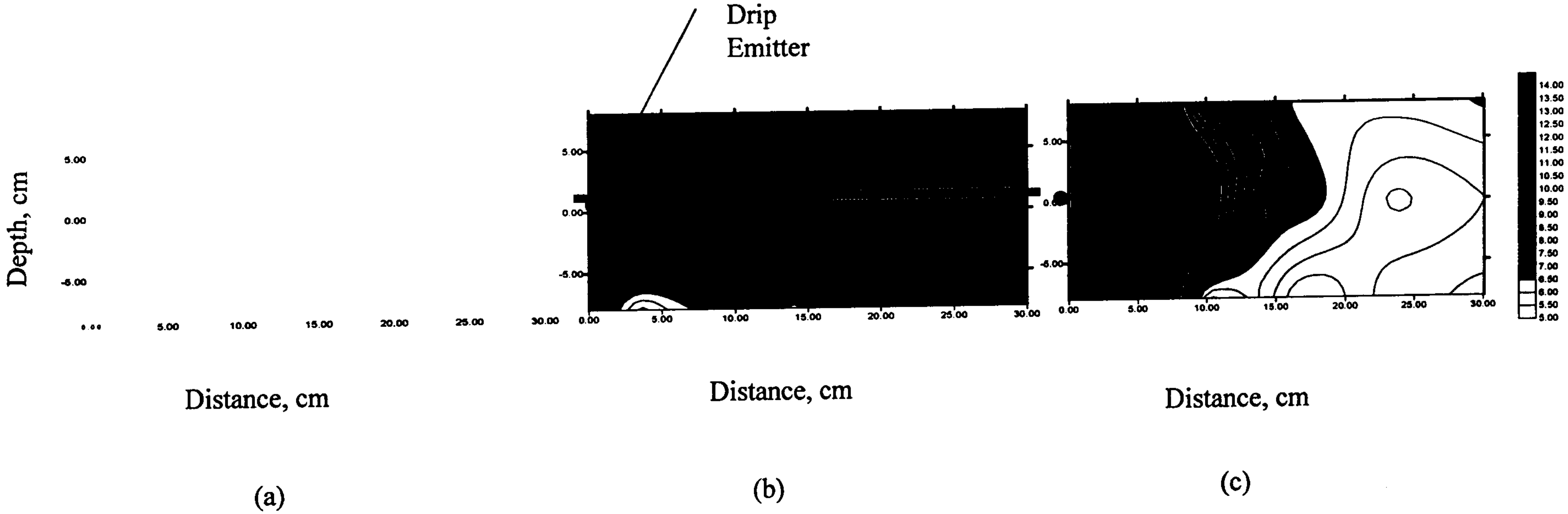

Figure 6-Phosphorous concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

content, and low saturated conductivity of soil at this site (Table 1). Moreover, the application rate at this site was considerably higher than those at the other three sites.

In general, there was more movement of P along the drip lateral than perpendicular to the drip lateral. Due to soil disruption during drip tubing installation using a trencher, the soil along the drip lateral would have a higher saturated hydraulic conductivity than in the direction perpendicular to the drip lateral. This, in turn, would lead to faster movement of water along the drip lateral.

Total Nitrogen (TN)

Most nitrogen in septic system effluent is in the form of ammonium (Feigin et al., 1991). However, when effluent reaches the soil, NH_4 is typically oxidized to NO_3. High NO_3 concentrations in drinking water are potentially hazardous and can cause methemoglobinemia in infants (Feigin et al., 1991). Being an anion, NO_3 is easily leached through the soil profile.

At sites 1, 3, and 4, the concentration of TN in the vicinity of the emitter (Table 5, Figures 7, 9 and 10) was slightly greater than in the control area. However, in the rest of the soil profile, TN concentrations were lower than in the control area. This lower soil TN could be caused by irrigation induced NO_3 leaching (Feigin et al., 1991). At site 2, similar to that noted for P (Table 5, Figure 8), the concentration of TN in the area above the emitter was appreciably greater than in the control area. Again, this was attributed to enhanced upward movement of soil water. There were no significant

Table 5 - Average total nitrogen concentrations (ppm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
At site 1											
I†	0.095 a‡	0.099a	0.096a	0.098a	0.104a	0.095a	0.101a	0.087a	0.093a	0.093a	0.114a
II	0.093ab	0.101ab	0.101ab	0.089ab	0.098ab	0.093ab	0.110a	0.082b	0.083b	0.089ab	0.108ab
III	0.101ab	0.095bc	0.089bcd	0.075ed	0.085ecd	0.101ba	0.112a	0.080ecd	0.071d	0.081ecd	0.093bc
IV	0.062ab	0.059b	0.057b	0.063b	0.059b	0.062ab	0.053b	0.054b	0.059b	0.059b	0.073a
At site 2											
I	0.085ab	0.091ab	0.081ab	0.111a	0.076ab	0.085ab	0.097ab	0.097ab	0.109a	0.091ab	0.044b
II	0.068a	0.061a	0.059a	0.066a	0.059a	0.068a	0.062a	0.059a	0.052a	0.058a	0.043a
III	0.046a	0.046a	0.052a	0.061a	0.043a	0.046a	0.044a	0.043a	0.046a	0.050a	0.037a
IV	0.043a	0.050a	0.048a	0.044a	0.039a	0.043a	0.041a	0.048a	0.050a	0.041a	0.055a
At site 3											
I	0.039a	0.047a	0.043a	0.052a	0.053a	0.039a	0.045a	0.049a	0.050a	0.046a	0.065a
II	0.059a	0.060a	0.056a	0.049a	0.059a	0.059a	0.059a	0.054a	0.058	0.064a	0.056a
III	0.054a	0.045a	0.052a	0.038a	0.033a	0.054a	0.059a	0.043a	0.061a	0.053a	0.056a
IV	0.020b	0.022b	0.021b	0.022b	0.022b	0.020b	0.021b	0.021b	0.023b	0.021b	0.051a
At site 4											
I	0.072abc	0.067abc	0.080a	0.074abc	0.070abc	0.072abc	0.075ab	0.068abc	0.049bc	0.047c	0.081a
II	0.073a	0.085a	0.075a	0.076a	0.068a	0.073a	0.080a	0.102a	0.065a	0.059a	0.075a
III	0.085a	0.054a	0.054a	0.039a	0.038a	0.085a	0.080a	0.056a	0.039a	0.038a	0.071a

†I depth at 3 in above the emitter at sites 1, 3, and 4 and 1 in above the emitter at site 2, II depth at the emitter level, III depth at 3 in below the emitter, and IV depth at 12 in below the emitter.

‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

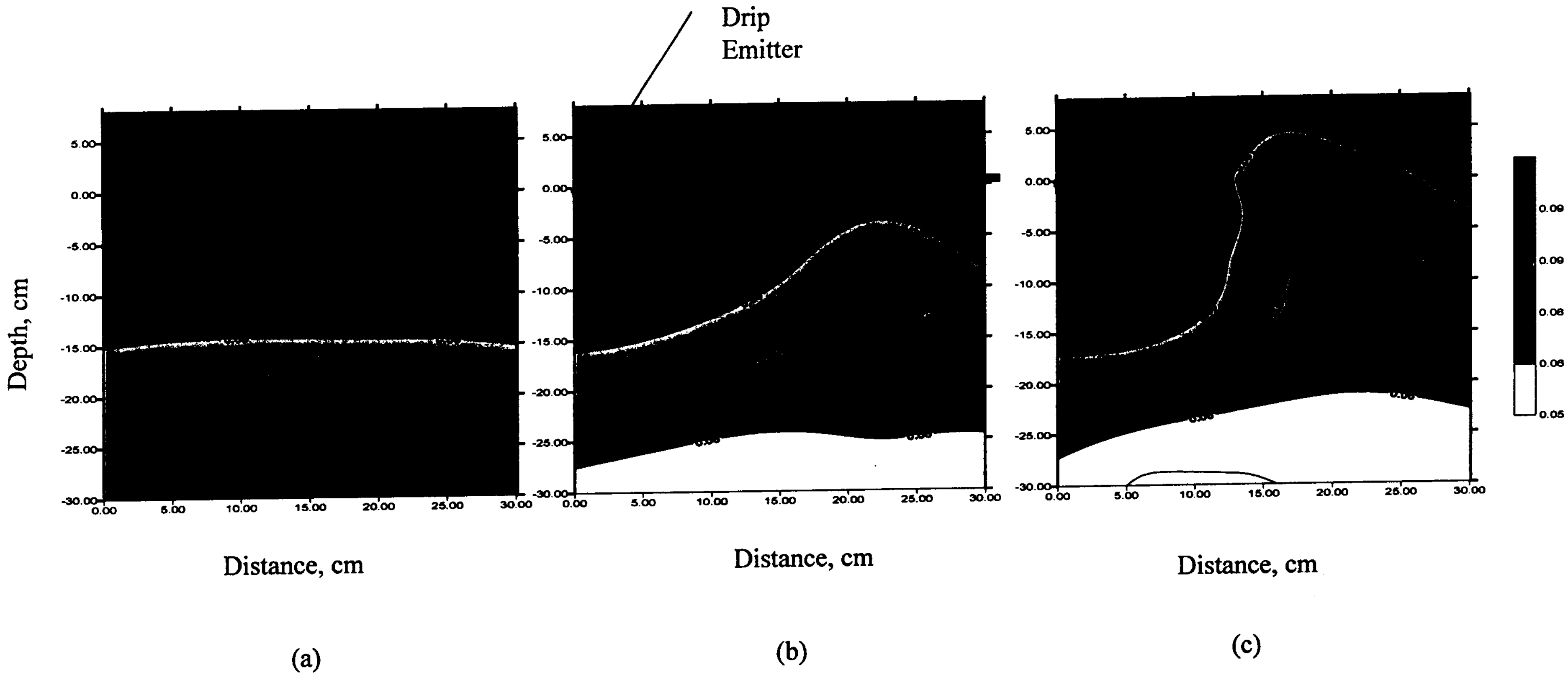

Figure 7-Total Nitrogen concentration distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

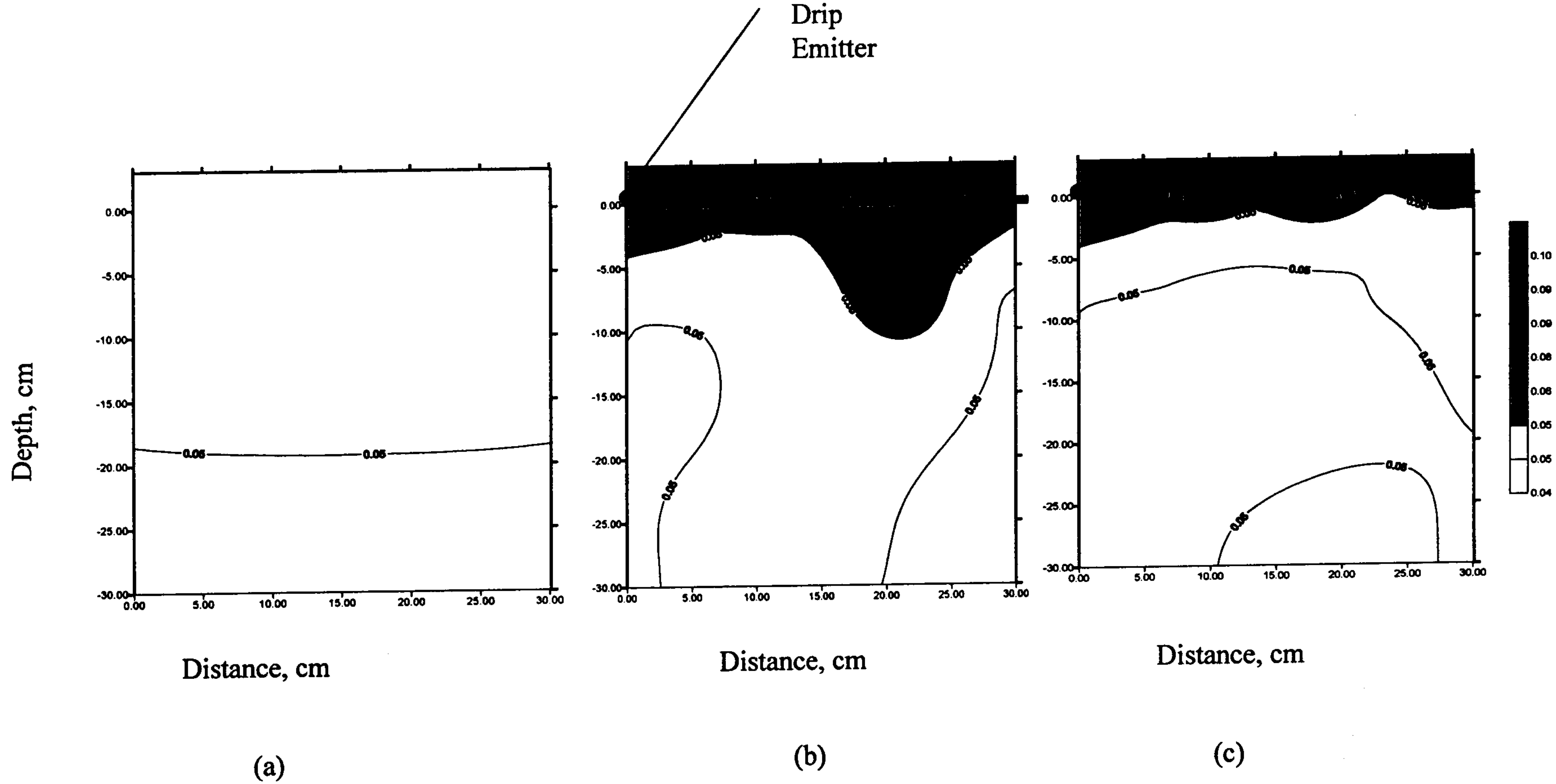

Figure 8-Total nitrogen concentration distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

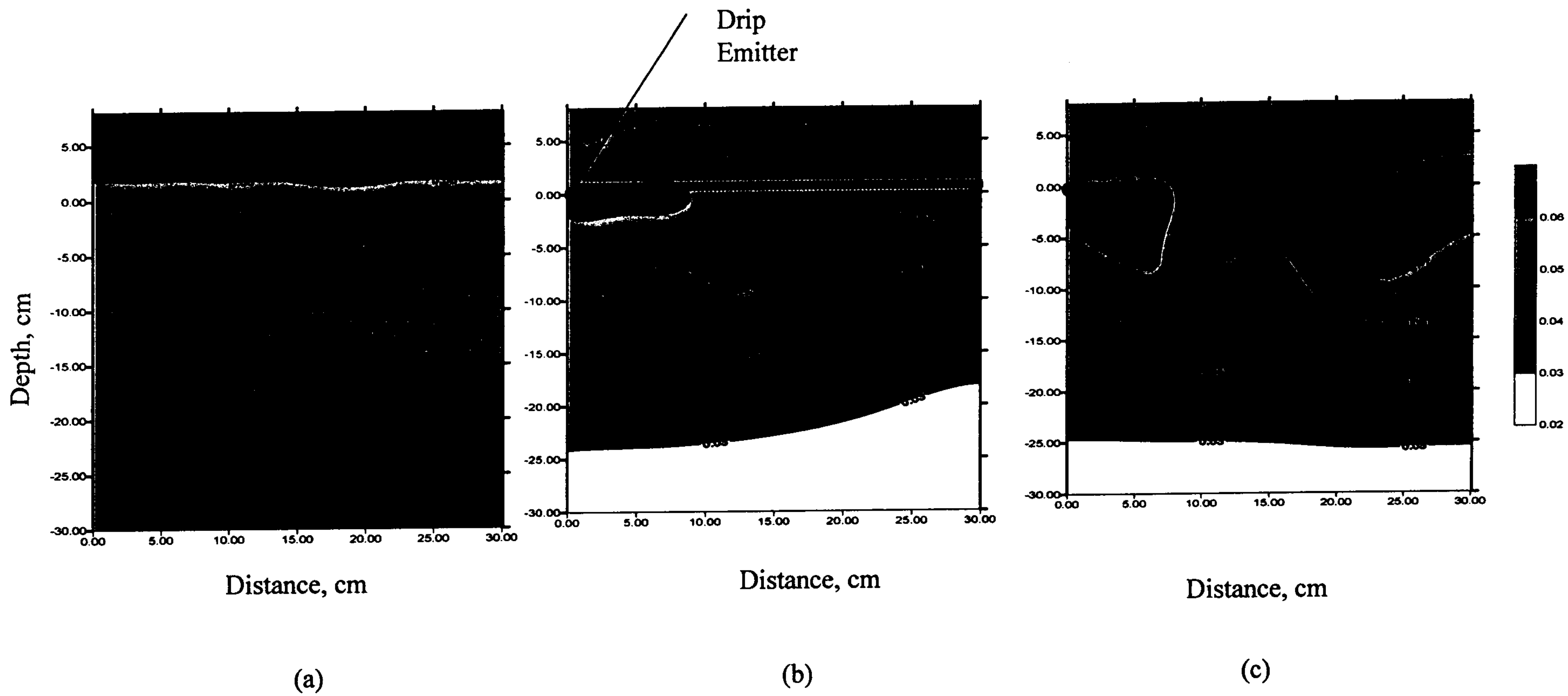

Figure 9-Total nitrogen concentration distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

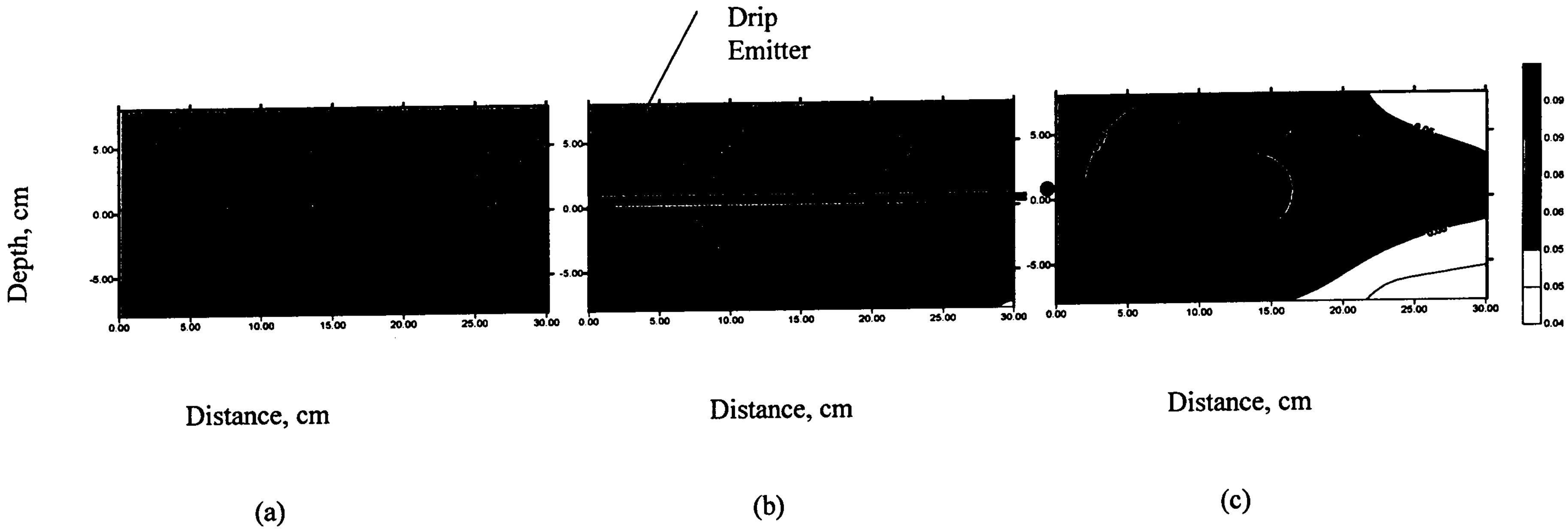

Figure 10-Total nitrogen concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

difference between TN distribution in the transect along the drip lateral and the one perpendicular to the drip lateral.

Sodium (Na)

High Na concentrations in soil may cause clay particle swelling and dispersion, resulting in the deterioration of soil physical condition. This, in turn, reduces soil porosity and hydraulic conductivity (Feigin et al., 1991).

At sites 1, 2, and 3, the difference in Na concentration in the irrigated area and control area were directly related to Na content in the applied effluent. At site 1, where the Na concentration in the applied effluent was relatively low (108 ppm), there were only a slight difference between Na concentration in the irrigated area and that in the control area (Table 6, Figure 11). However, at site 2, where Na concentration in the applied effluent (305 ppm) was high, Na concentrations in the irrigated area were significantly greater than in the control area (Table 6, Figure12). At this site there was considerably more lateral movement of Na along the drip lateral than perpendicular to the drip lateral. At site 3, Na concentration increased significantly above the emitter and at the emitter level (Table 6, Figure 13). At site 4, no significant difference was observed between soil Na concentration in the irrigated area and in the control area (Table 6, Figure14). This could be due to high initial soil Na concentration or the high application rate of effluent, which might cause leaching of Na deeper in the soil profile. Prior to effluent application at this site, the soil was irrigated with water that had a high Na concentration (250 ppm). Consequently, this could have elevated the Na

Table 6- Average sodium concentrations (ppm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
At site 1											
I†	5.7a‡	4.8a	8.0a	5.6a	6.4a	5.7a	5.2a	5.3a	5.3a	5.3a	6.9a
II	7.3abc	7.1abcd	6.4bcd	5.1dc	4.6dc	7.3abc	8.3ab	5.1dc	6.9abcd	4.3d	9.6a
III	9.5ab	13.0a	6.5b	6.2b	5.3b	9.5ab	11.1ab	7.7ab	6.5b	5.2b	10.3ab
IV	15.7b	24.1a	14.7b	13.7b	11.6b	15.7b	17.2ab	16.0ab	12.5b	10.1b	12.8b
At site 2											
I	29.9a	22.1ab	22.8ab	40.0a	29.0ab	29.9a	25.5a	16.4ab	10.0b	8.2b	8.6b
II	47.9a	33.2ab	22.8abc	43.7a	40.9ab	47.9a	27.3a	17.9abc	30.9abc	8.7bc	7.4c
III	43.7ab	30.1ab	39.8ab	45.7a	41.4ab	43.7ab	36.1ab	37.8ab	17.3abc	13.2bc	7.2c
IV	48.2a	62.9a	66.2a	50.9a	44.7a	48.2a	47.9a	53.7a	41.7a	29.3a	9.3b
At site 3											
I	24.1a	22.0a	20.4ab	23.1a	20.9ab	24.1a	21.5ab	21.5ab	21.3ab	25.4a	12.8b
II	27.5a	26.9a	21.9ab	23.3a	27.5a	27.5a	26.2a	26.6a	25.4a	22.8a	13.6b
III	24.5ab	21.0ab	25.6a	23.7ab	24.5ab	24.5ab	25.4a	26.1a	23.7ab	27.2a	15.8b
IV	24.7a	24.7a	30.1a	23.5a	26.4a	24.7a	23.4a	26.7a	35.2a	31.0a	21.9a
At site 4											
I	92.6a	57.5a	110.7a	54.9a	53.5a	92.6a	89.0a	72.9a	82.7a	136.2a	122.0a
II	92.2ab	86.7ab	67.4ab	76.5ab	63.3ab	92.2ab	97.0ab	82.8ab	55.3b	53.1b	85.1ab
III	84.2ab	92.0ab	84.6ab	59.8ab	58.0ab	84.2ab	113.5a	108.5ab	88.1ab	46.0b	73.9ab

†I depth at 3 in above the emitter at sites 1, 3, and 4 and 1 in above the emitter at site 2, II depth at the emitter level, III depth at 3 in below the emitter, and IV depth at 12 in below the emitter.

‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

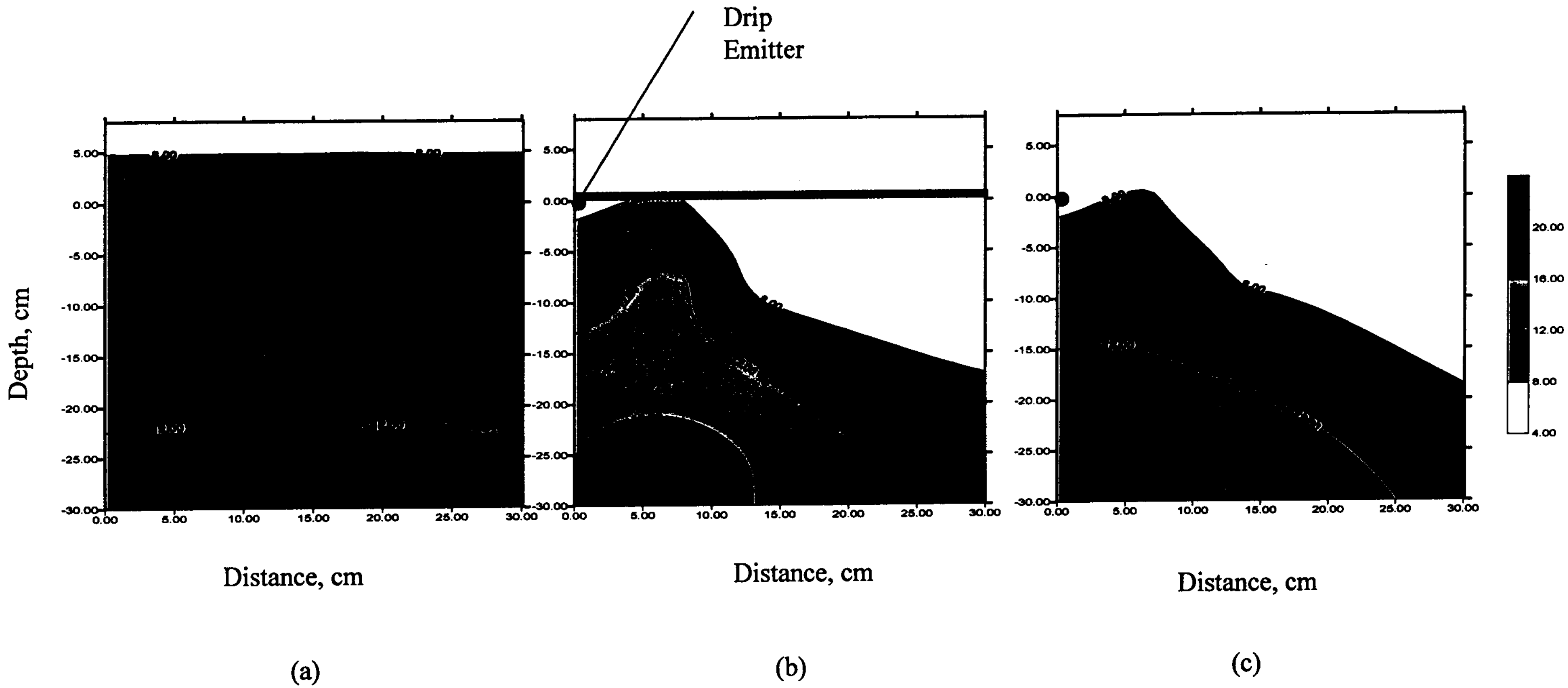

Figure 11-Sodium concentration distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

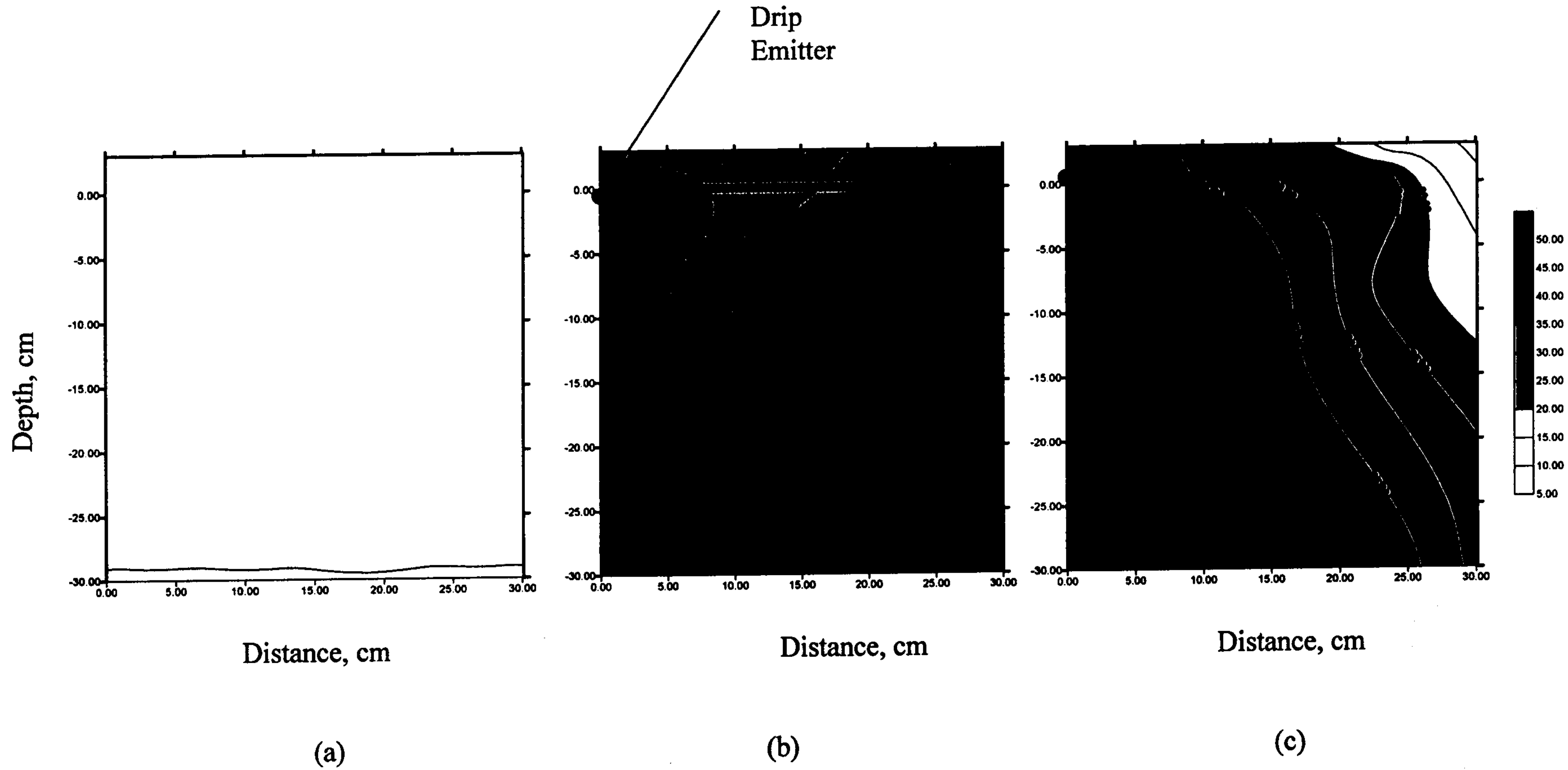

Figure 12- Sodium concentration distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

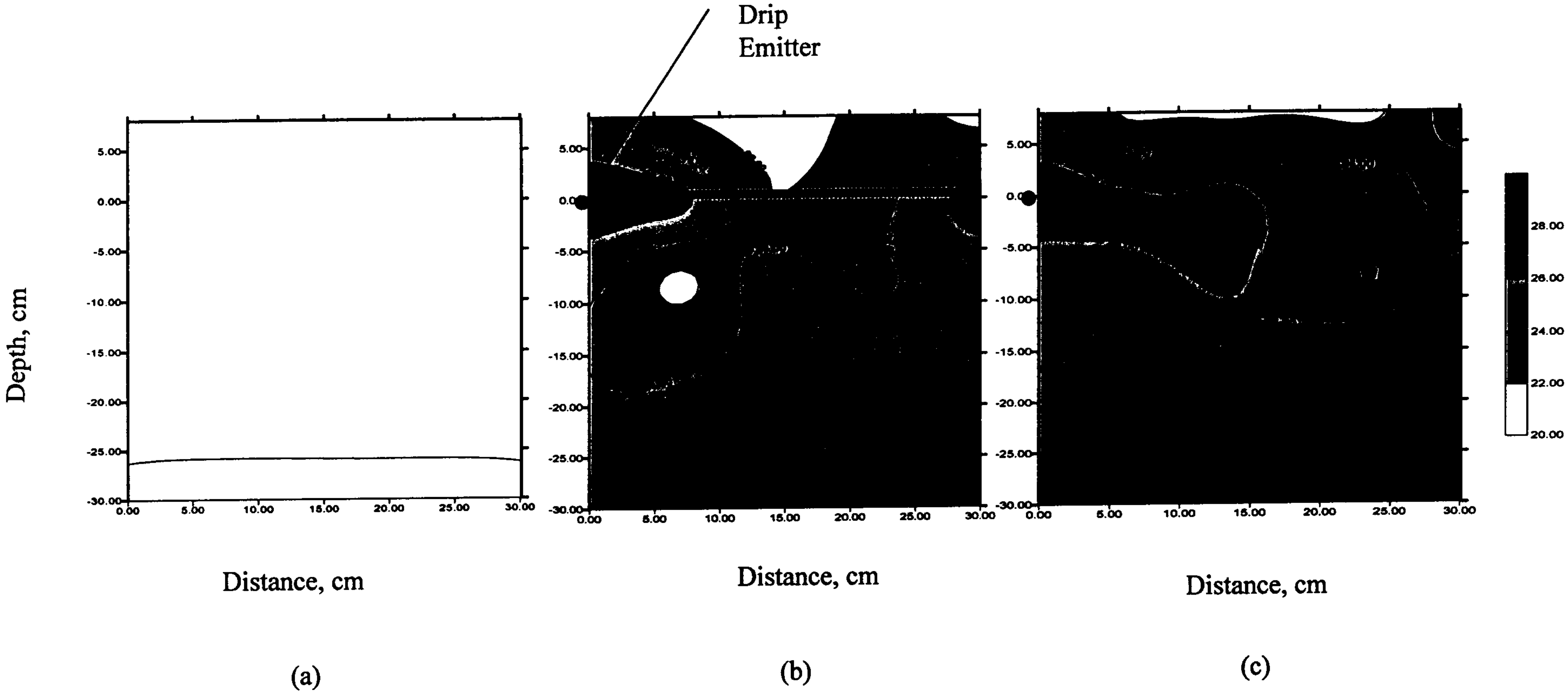

Figure 13-Sodium concentration distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

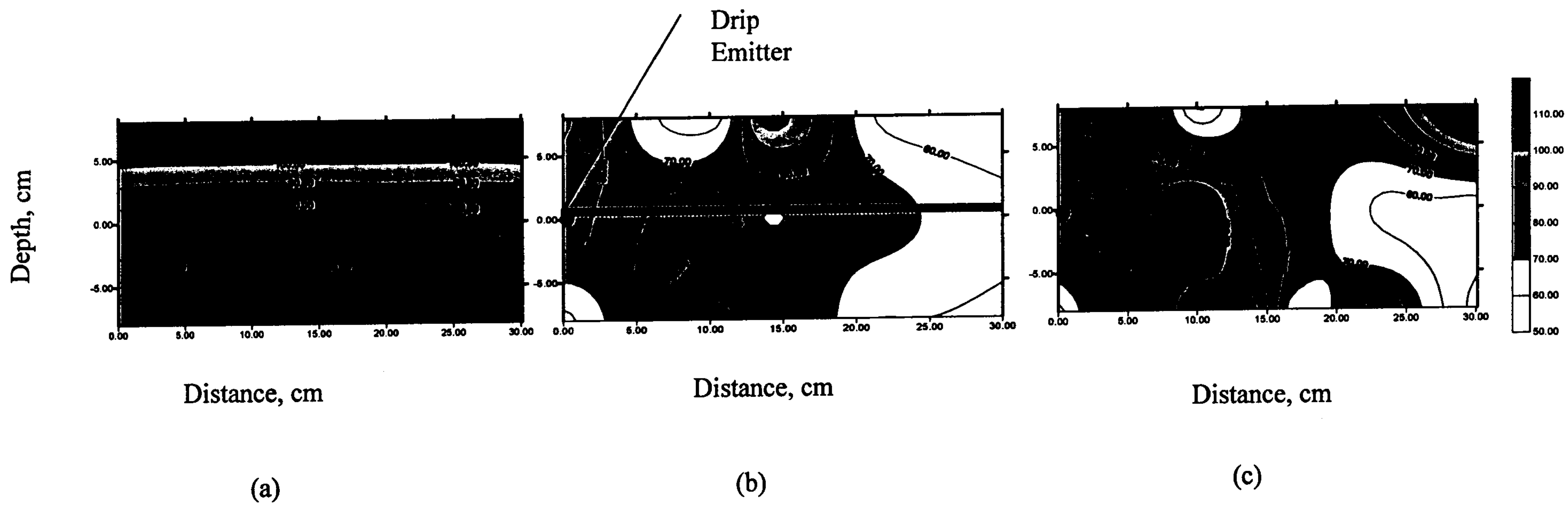

Figure 14-Sodium concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

concentration in the soil before applying wastewater. More Na moved along the drip lateral than perpendicular to the drip lateral at this site.

Calcium (Ca)

At site 1, where the soil is calcareous (ASCS, 1970), above the emitter, at the emitter, and at 3 in below the emitter, Ca concentration in the irrigated area was greater than in the control area (Table 7, Figure 15). However, this difference in Ca concentration was not statistically significant. At 12 in below the emitter, at all distances from the emitter, Ca concentration in irrigated area was less than in the control area. At site 2, in the majority of the soil profile, Ca concentration in the irrigated area was significantly less than in the control area (Table 7, Figure 16). A greater difference in Ca concentration between the irrigated and control area occurred at the lower depths of the soil profile. The reduction in soil Ca at this site could be due to reaction of Ca with carbonate and sulfate which were present in high concentrations in the applied effluent (Table 3), and precipitation. At site 3, Ca concentrations in the irrigated area were generally less than in the control area but, the difference was significant only at 12 in below the emitter (Table 7, Figure 17). At site 4, near the emitter and in the area above the emitter, soil Ca concentration in the irrigated area was greater than in the control area (Table 7, Figure 18). However, at 3 in below the emitter, Ca concentration in the irrigated area was significantly less than in the control area. The lower concentration of Ca observed in the lower soil profile at the four sites could be due to displacement of Ca with sodium. This explanation or concept is supported by the

Table 7- Average calcium concentrations (ppm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
At site 1											
I†	67.9ab‡	62.2ab	62.2ab	75.7ab	87.3a	67.9ab	68.7ab	58.7b	70.5ab	62.6ab	53.1b
II	66.7a	60.3a	55.2a	65.2a	57.5a	66.7a	56.7a	60.4a	59.4a	57.8a	58.2a
III	67.7a	73.7a	66.4a	65.0a	57.3a	67.7a	65.3a	58.6a	66.4a	58.5a	53.9a
IV	46.3a	41.5a	44.1a	59.4a	52.8a	46.3a	38.14a	48.4a	51.6a	58.1a	65.0a
At site 2											
I	26.7a	37.3a	24.7a	24.0a	31.3a	26.7a	38.1a	35.8a	33.7a	33.0a	26.1a
II	28.1ab	22.7ab	14.0a	25.6ab	14.4a	28.1ab	19.7ab	17.4ab	19.9ab	17.4a	36.7b
III	21.3ab	11.3b	16.2ab	17.2ab	13.4b	21.3ab	17.8ab	21.2ab	18.9ab	21.5ab	26.2a
IV	12.9	14.9b	18.8b	14.5b	10.1b	12.9b	10.0b	11.4b	13.4b	10.8b	32.6a
At site 3											
I	31.6a	32.1a	26.8a	31.5a	31.2a	31.6a	35.4a	29.3a	31.5a	30.8a	39.4a
II	32.5a	32.1a	25.9a	27.4a	31.7a	32.6a	36.1a	31.9a	24.6a	24.3a	33.9a
III	29.6a	25.3ab	27.2ab	25.2ab	27.0ab	29.5a	31.7a	27.3ab	17.7b	22.5ab	26.6ab
IV	25.3bc	27.1bc	29.7bc	27.5bc	31.3bc	25.3bc	25.7bc	23.2c	34.1ab	27.1bc	41.1a
At site 4											
I	19.8b	25.5ab	22.6b	46.4ab	52.1ab	19.8b	34.5ab	40.3ab	36.3ab	65.4a	19.6ab
II	59.8abc	79.0a	56.6abc	29.6bc	21.9c	59.8abc	62.4ab	29.3bc	25.3bc	36.7bc	31.3bc
III	37.4ab	23.6b	25.7b	27.2b	25.7b	37.4ab	36.1ab	32.7ab	39.4ab	34.6b	63.8a

†I depth at 3 in above the emitter at sites 1, 3, and 4 and 1 in above the emitter at site 2, II depth at the emitter level, III depth at 3 in below the emitter, and IV depth at 12 in below the emitter.

‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

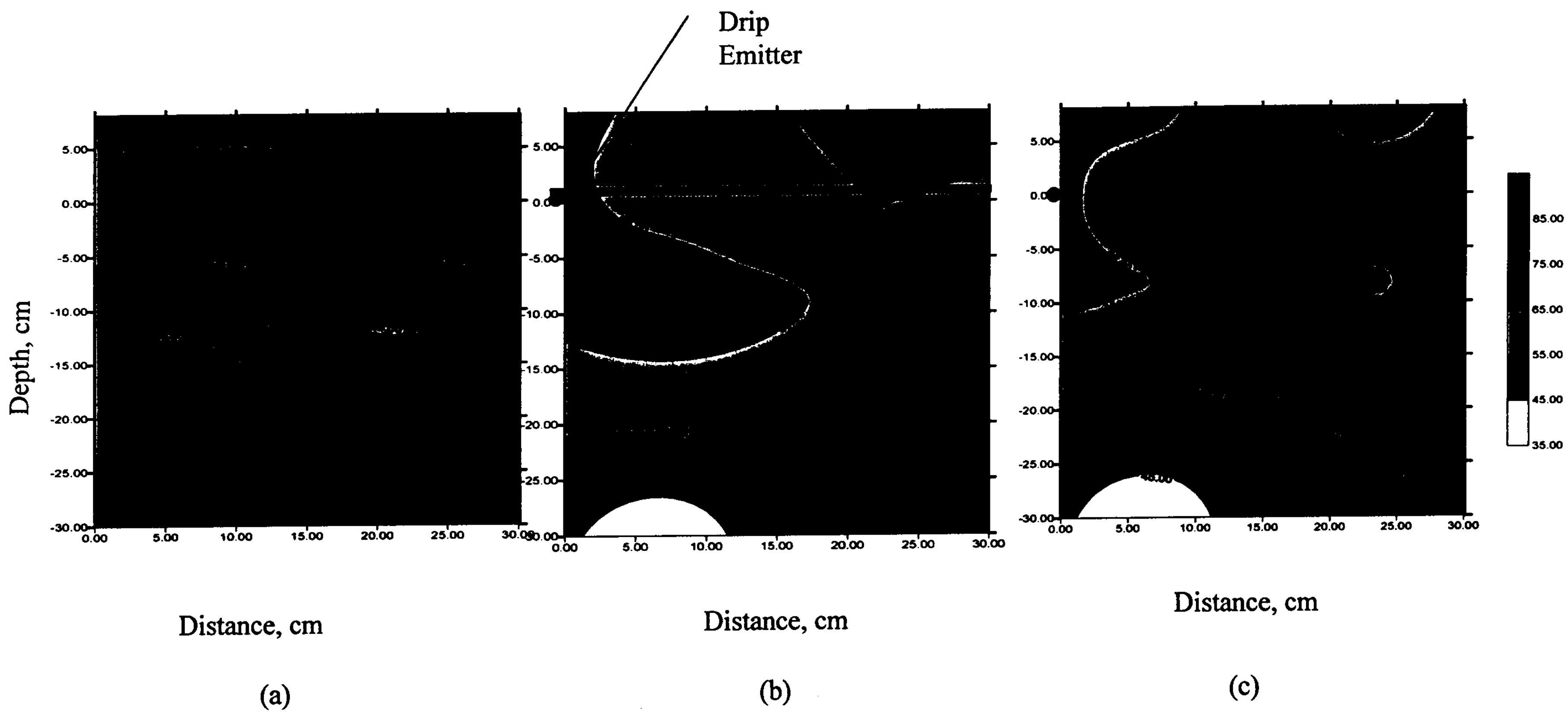

Figure 15-Calcium concentration distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

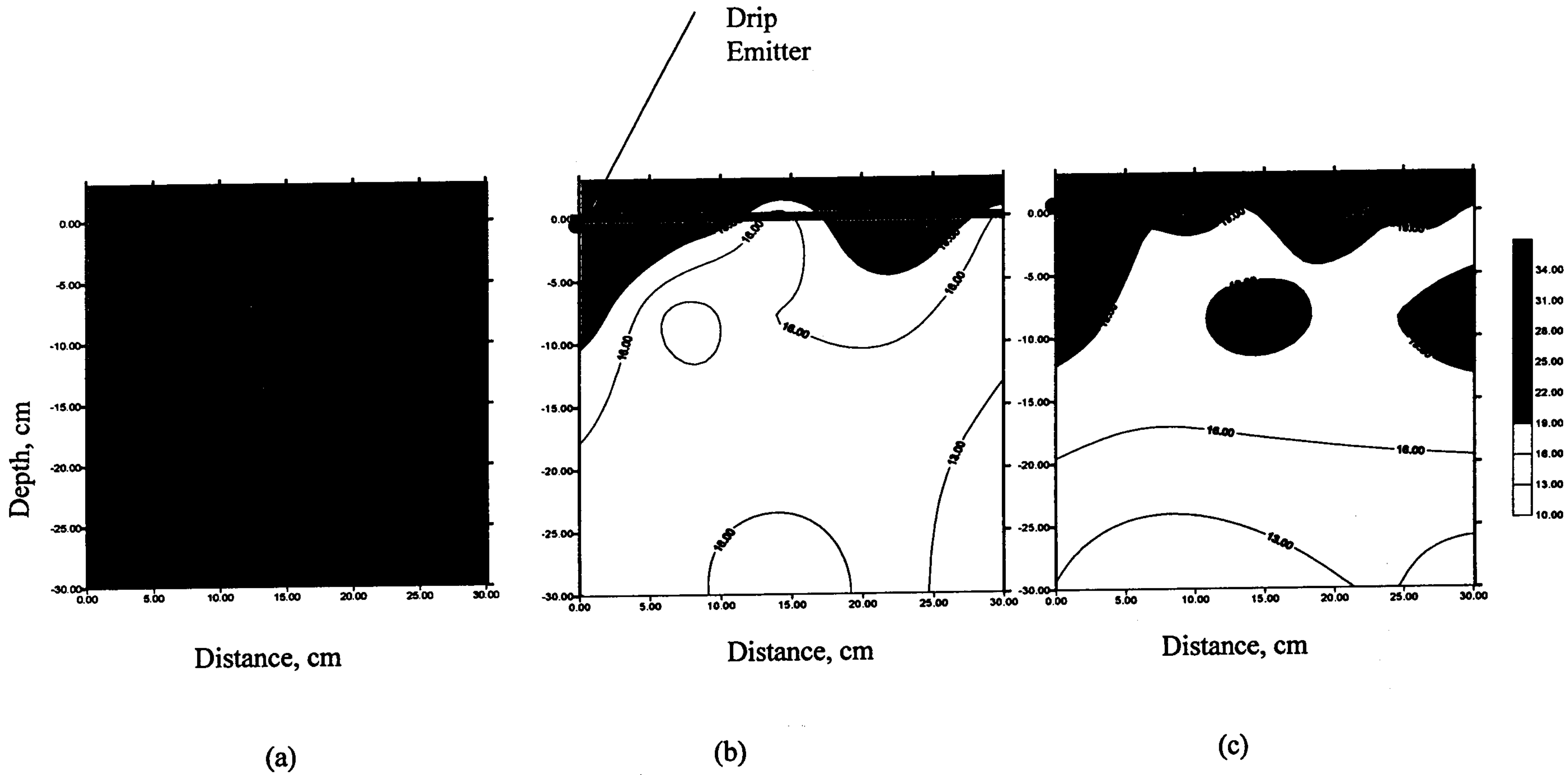

Figure 16-Calcium concentration distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

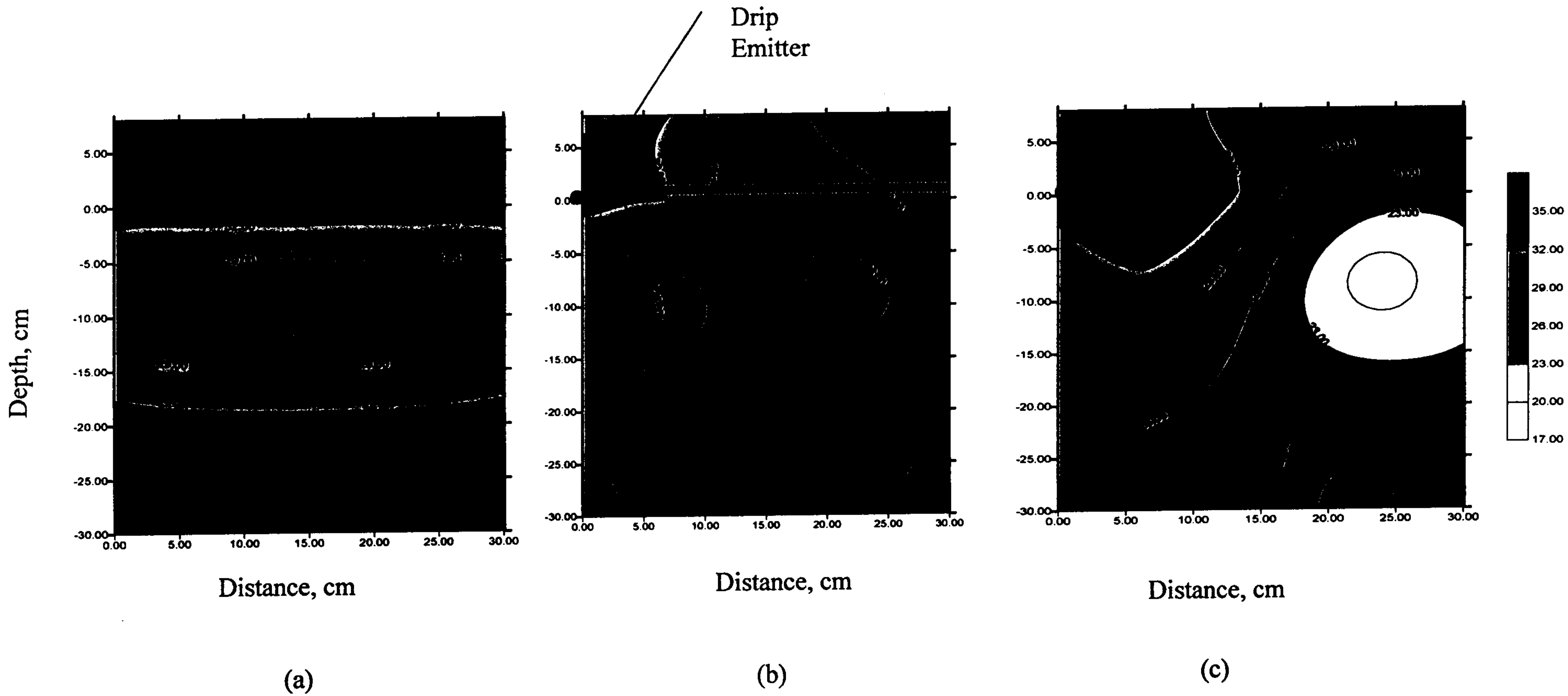

Figure 17-Calcium concentration distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

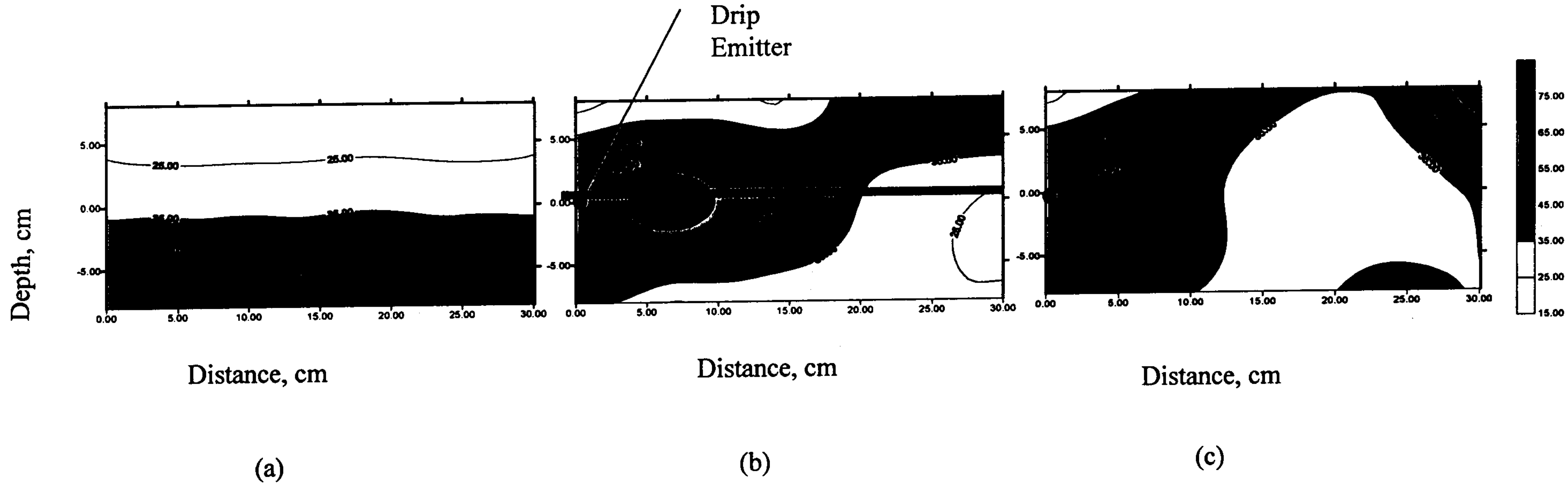

Figure 18-Calcium concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

observation that the greatest reduction in Ca occurred at lower depths in the soil profile, where a significant increase in Na concentration also occurred. Calcium is known to moderate the influence of Na on soil physical properties. Therefore, Ca removal from soil solution by precipitation, exchange, or crop uptake would lead to a potential increase in Na damage or influence on soil.

Magnesium (Mg)

At sites 1, 2, and 3, in most of the soil profile, Mg concentration in the irrigated area was greater than in the control area (Table 8 Figures 19-21). More accumulation in soil Mg was observed near the emitter. At site 4, the differences between Mg concentration in the irrigated area and in the control area were large (Table 8, Figure 22) but, due to wide variation among replications, this difference was not significant. As with calcium, Mg moderates the influence of Na on soil physical properties. Therefore, an increase of Mg concentration will reduce Na damage or influence on soil.

Sulfate (SO_4)

Because sulfate is a soluble ion and is readily leached from soil, sulfate concentration was lower compared to the control in most of the soil profile at sites 1, 3, and 4 (Table 9, Figures 23, 25, and 26). The soil SO_4 concentration was directly related to SO_4 content in the applied effluent. At site 1, where SO_4 concentration in the applied effluent was relatively low (43 ppm), soil SO_4 in the irrigated area was significantly below that in the non-irrigated soil. However, at site 3 where SO_4 concentration in the

Table 8- Average magnesium concentrations (ppm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
At site 1											
I†	1.8b‡	2.2ab	2.1ab	2.2ab	5.6a	1.8b	2.4ab	1.8b	1.4b	1.7b	1.4b
II	3.0ab	2.5abc	2.5abc	1.4c	1.5bc	3.0ab	3.3a	1.7bc	1.5bc	1.2c	1.2c
III	4.8a	3.6ab	3.3abc	1.6bc	1.4bc	4.8a	5.5a	3.4abc	1.3c	1.2c	1.4bc
IV	2.0a	1.5a	1.1a	1.8a	1.5a	2.0a	1.4a	0.8a	0.8a	0.8a	1.4a
At site 2											
I	6.2a	9.0a	5.8a	6.0a	8.9a	6.2a	9.2a	10.2a	11.1a	8.9a	3.1a
II	7.6a	4.8a	3.3a	8.1a	4.0a	7.6a	4.3a	4.0a	6.9a	6.6a	3.9a
III	5.4ab	3.0b	4.5ab	3.8ab	4.2ab	5.4ab	4.7ab	4.3ab	6.9ab	7.2a	3.4ab
IV	3.5a	11.2a	16.3a	11.1a	8.3a	3.5a	2.5a	6.5a	9.5a	3.1a	4.7a
At site 3											
I	9.8a	9.5a	7.7a	9.7a	8.4a	9.8a	9.6a	8.1a	9.2a	8.3a	11.1a
II	7.8a	8.1a	6.7ab	7.3ab	7.7ab	7.8a	8.2a	8.1a	5.8ab	5.7ab	4.3b
III	7.7a	6.6abc	6.7abc	6.5abc	7.1abc	7.9a	7.7a	7.4a	4.0c	5.5c	3.6c
IV	8.8a	8.8a	10.0a	9.2a	9.6a	8.7a	8.2a	8.6a	10.9a	10.5a	3.8b
At site 4											
I	48.5a	17.9a	12.8a	19.0a	35.7a	44.1a	69.2a	15.5a	38.2a	39.9a	19.2a
II	44.1a	74.5a	46.0a	12.3a	26.8a	78.7a	17.6a	10.4a	15.3a	25.5a	43.1a
III	78.7a	15.9a	14.7a	14.9a	5.8a	7.9a	7.7a	7.4a	4.0c	5.5c	63.3a

†I depth at 3 in above the emitter at sites 1, 3, and 4 and 1 in above the emitter at site 2, II depth at the emitter level, III depth at 3 in below the emitter, and IV depth at 12 in below the emitter.
‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

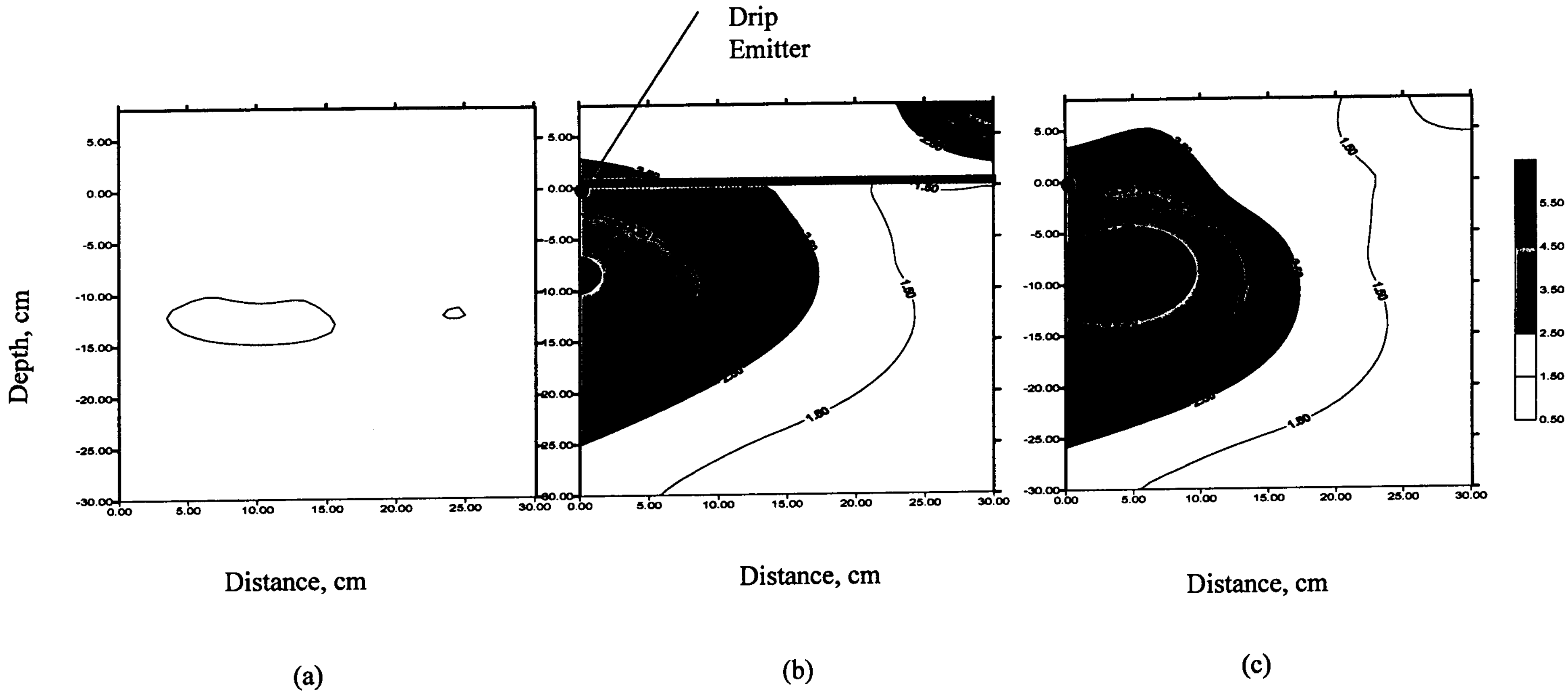

Figure 19-Magnesium concentration distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

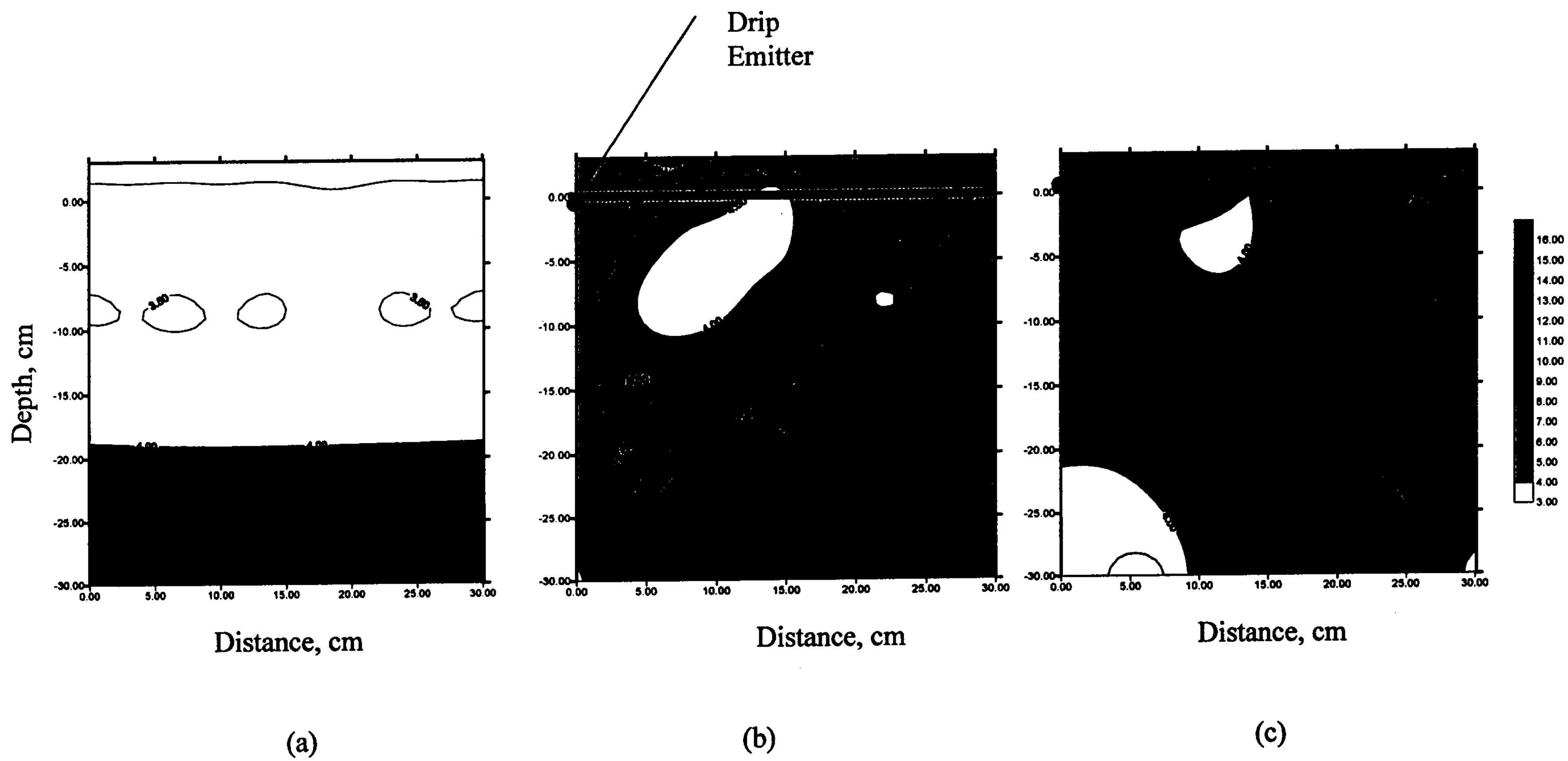

Figure 20-Magnesium concentration distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

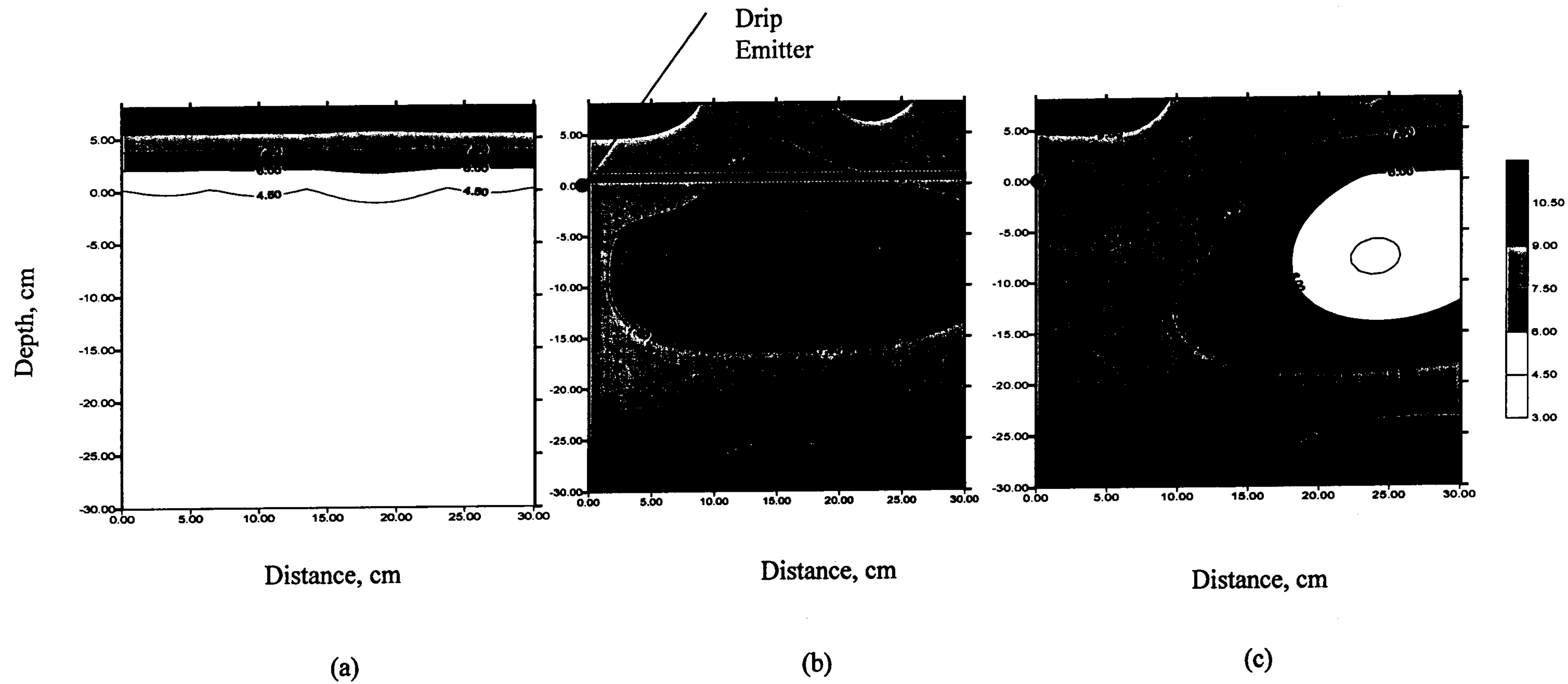

Figure 21-Magnesium concentration distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

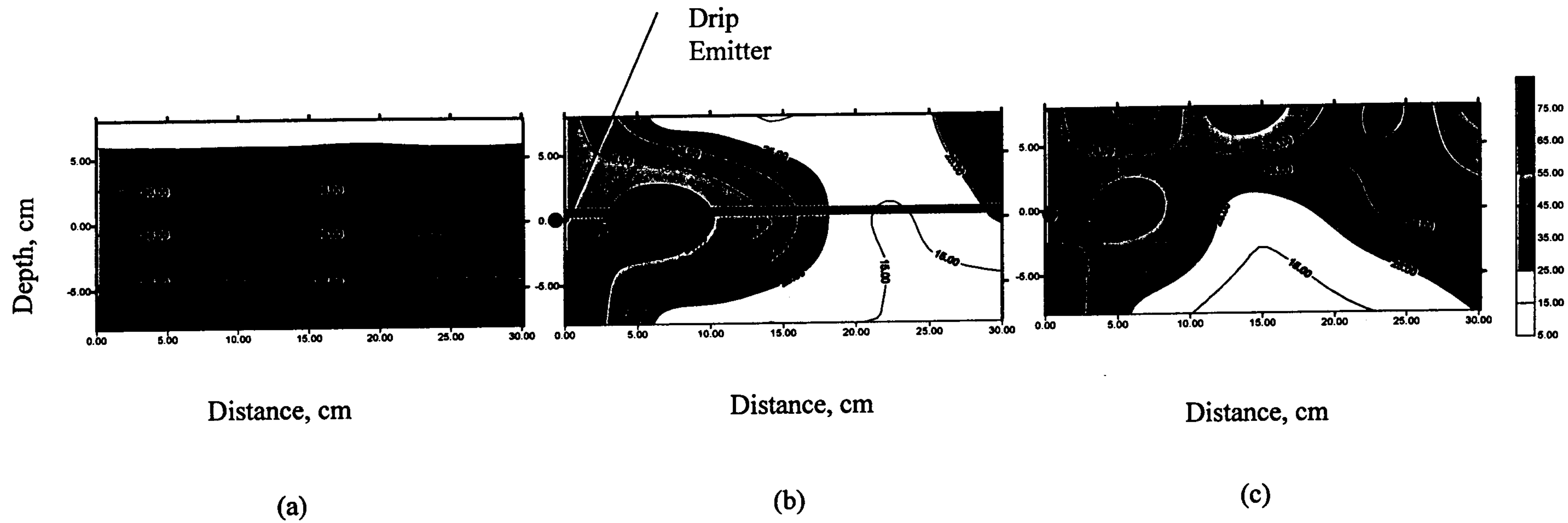

Figure 22-Magnesium concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

Table 9- Average sulfate concentrations (ppm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
						At site 1					
I†	10.1abc‡	10.3abc	13.2ab	9.1bc	10.4abc	10.1abc	6.8c	7.9c	9.3bc	11.0abc	13.8a
II	11.2bc	9.7bc	8.1c	12.7b	9.0bc	10.9bc	10.0bc	10.0bc	8.1c	7.9c	17.6a
III	10.9bc	10.0bc	10.0bc	8.1c	7.9c	10.9bc	12.3b	9.5bc	10.9bc	10.4bc	18.1a
IV	11.9b	12.8b	11.9b	10.0b	11.5b	11.9b	10.7b	11.3b	13.5b	12.9b	35.2a
						At site 2					
I	29.5ab	35.5ab	29.0ab	29.9ab	25.7ab	29.5ab	39.2a	34.1ab	19.7ab	17.5ab	12.3b
II	26.0abc	30.0ab	23.2abcd	32.7a	19.8bcd	26.0abc	27.6ab	19.5bcd	24.1abcd	16.8cd	14.8d
III	26.8ab	19.9b	25.5ab	24.8ab	23.8ab	26.8ab	24.1ab	35.9a	19.5b	18.6b	12.4b
IV	27.5ab	23.7abc	34.9a	22.4abc	24.2abc	27.5ab	28.0a	28.1a	22.4abc	14.9bc	13.6c
						At site 3					
I	13.0a	13.9a	12.3a	14.1a	12.9a	13.0a	11.9a	11.2a	14.6a	16.5a	12.4a
II	10.7abc	10.2abc	8.8c	10.5abc	11.7abc	10.7abc	9.8bc	12.2ab	13.0a	12.7ab	11.6abc
III	16.8a	9.9a	11.6a	11.6a	11.7a	16.8a	9.7a	12.9a	13.5a	15.4a	12.0a
IV	12.0c	12.3c	17.1abc	13.1c	14.7bc	12.0c	11.9c	14.0bc	20.7ab	17.3abc	22.2a
						At site 4					
I	25.5bc	20.1bc	14.3bc	11.8bc	19.5bc	25.5bc	32.6b	14.6bc	13.7bc	9.1c	57.9a
II	18.4ab	21.6ab	14.5ab	18.5ab	16.7ab	18.4ab	32.0a	31.0ab	17.8ab	9.8b	33.5a
III	20.2b	27.9b	18.6b	17.6b	21.4b	20.2b	17.5b	24.5b	23.4b	19.7b	58.3a

†I depth at 3 in above the emitter at sites 1, 3, and 4 and 1 in above the emitter at site 2, II depth at the emitter level, III depth at 3 in below the emitter, and IV depth at 12 in below the emitter.

‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

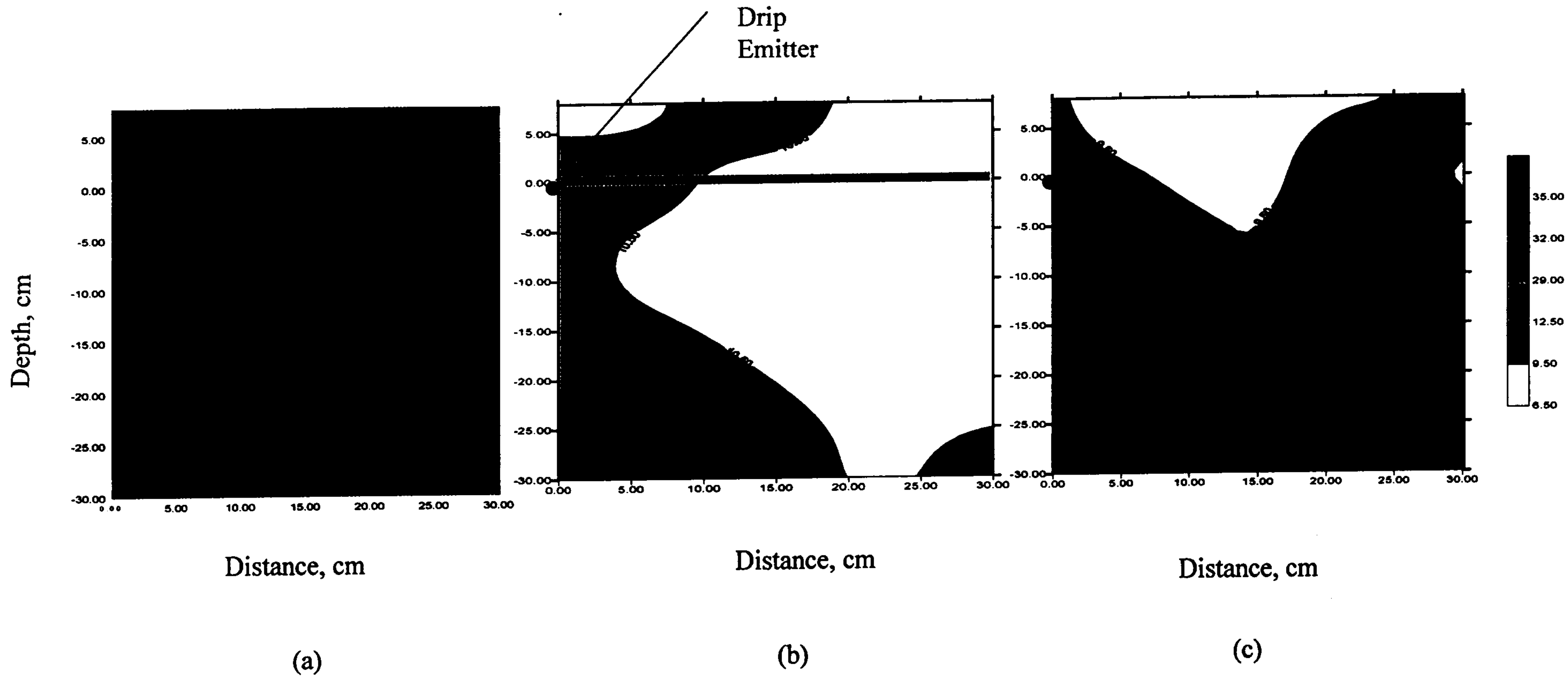

Figure 23-Sulfate concentration distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

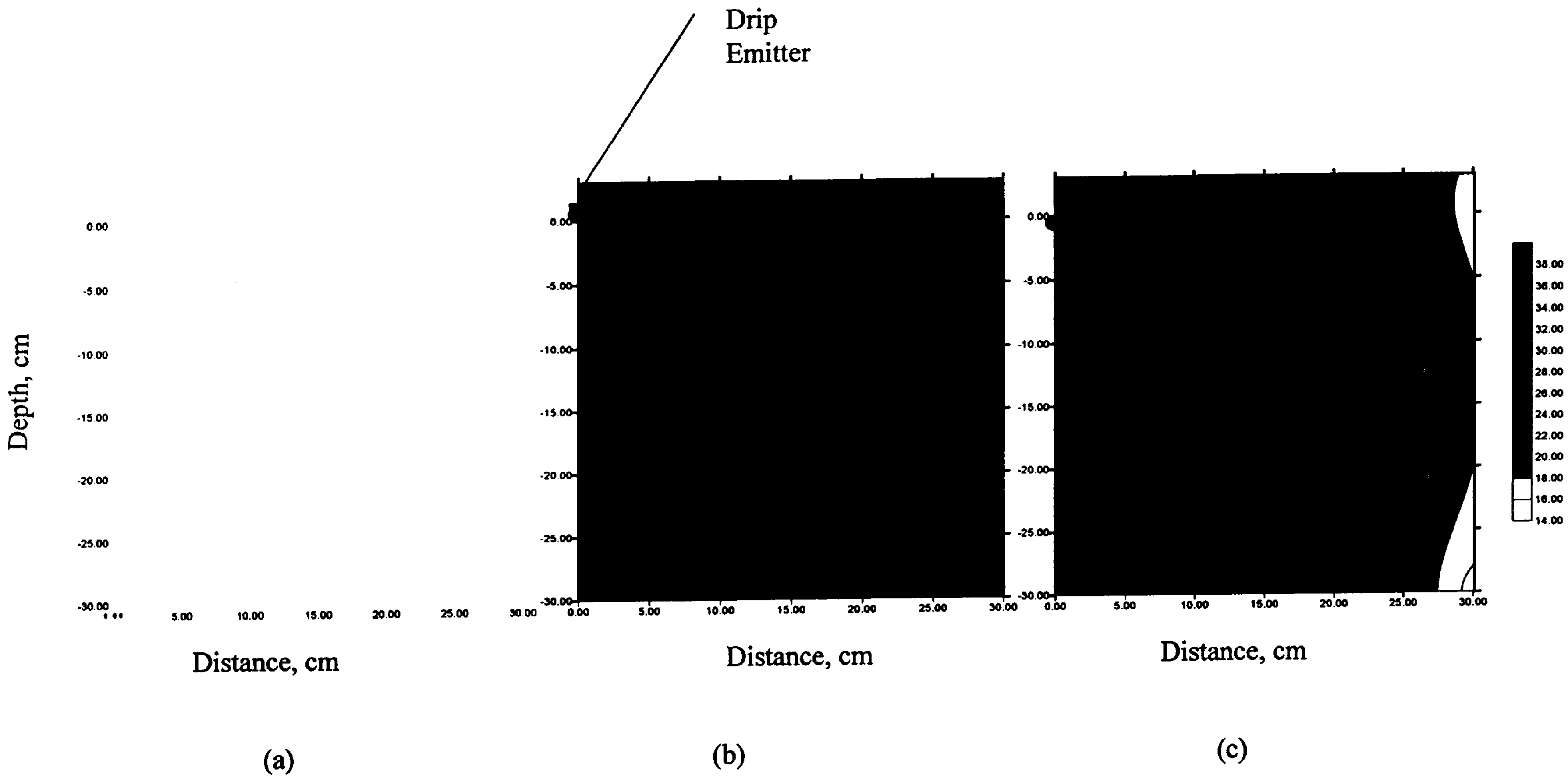

Figure 24-Sulfate concentration distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

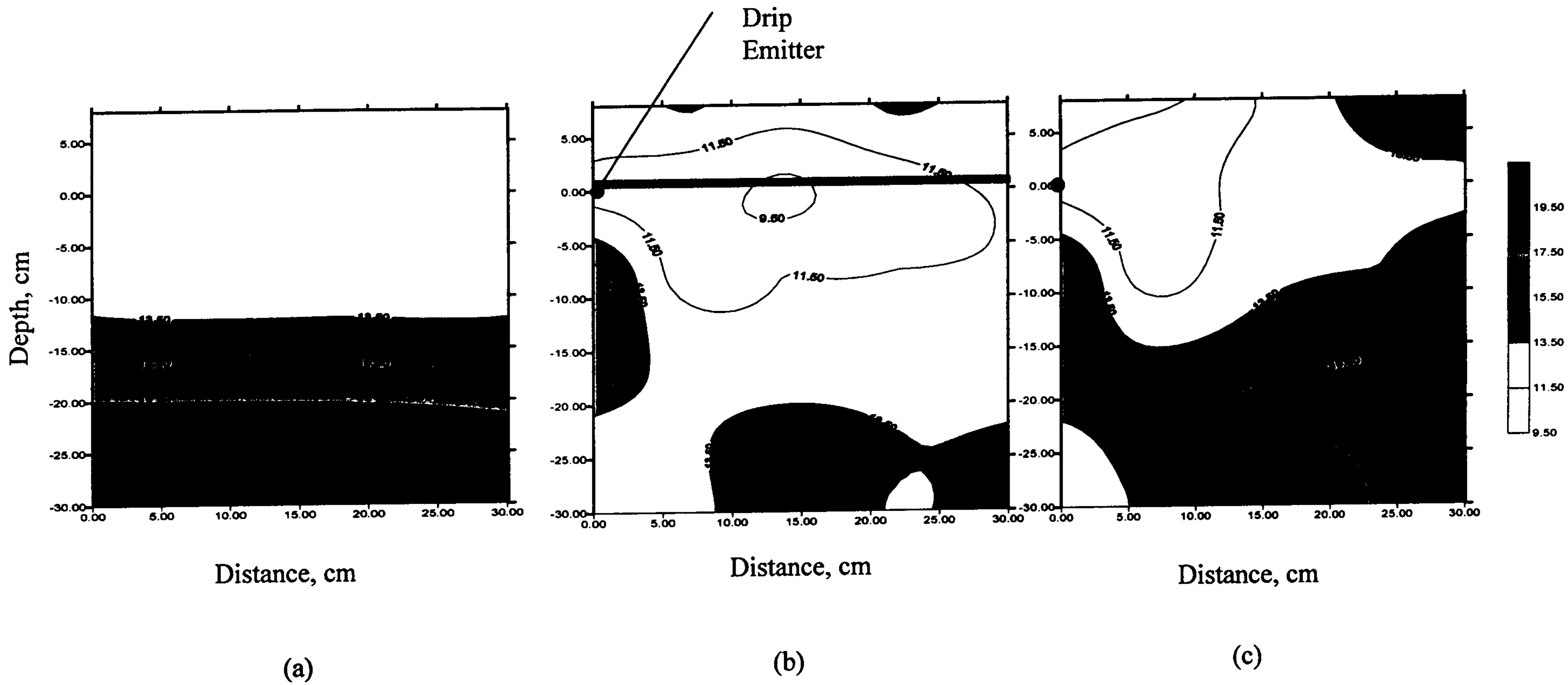

Figure 25-Sulfate concentration distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

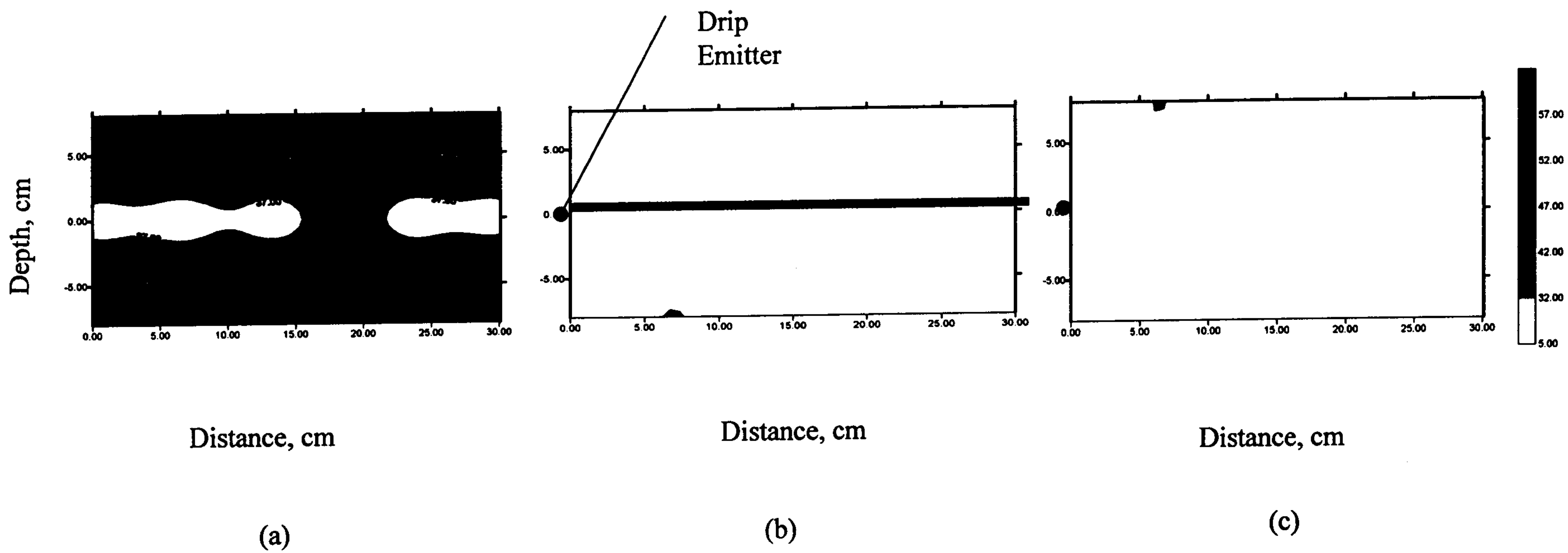

Figure 26-Sulfate concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

applied effluent was 162 ppm, the difference in soil SO_4 between the irrigated area and the control area was significantly lower only at 30 cm below the emitter. At site 2, in the majority of the soil profile, SO_4 concentration in the irrigated area was appreciably greater than in the non-irrigated area (Table 9, Figure 24). This was mainly due to the high content of SO_4 in the applied effluent at this site (280 ppm).

If SO_4 exists in high concentrations, it could result in calcium precipitation and formation of gypsum according to the following equation:

$$Ca^{2+} + SO^{4-} + 2H_2O \rightleftharpoons CaSO_4.2H_2O \qquad (2)$$

If the concentration products of Ca and SO_4 ions are greater than the solubility product constant, gypsum precipitation will occur. The solubility product constant for gypsum is $10^{-4.64}$. So, if the concentration products of Ca and SO_4 ions are greater than $10^{-4.64}$, gypsum precipitation will occur.

Potassium (K)

The differences between K concentrations in the irrigated area and that in the control area at the investigated sites were related directly to the K concentration in the control area and to the K content of the applied effluent. At site 1, and 3 where soil K averaged 4.2 and 6.3 ppm, respectively, soil K in the majority of the soil profile in the irrigated area was greater than in the control area (Table 10, Figures 27 and 29). A greater accumulation of K was noted in the vicinity of the emitter. At site 2 soil K was

Table 10-Average potassium concentrations (ppm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
At site 1											
I†	5.2a‡	6.5a	6.4a	6.0a	8.5a	5.2a	6.9a	4.9a	5.9a	6.3a	7.5a
II	5.5a	5.8a	6.0a	5.6a	6.4a	5.5a	7.0a	4.5a	4.9a	4.6a	3.3a
III	6.9ab	6.2ab	5.4ab	5.1ab	5.0ab	6.9ab	8.2a	5.3ab	4.3ab	4.3ab	3.0b
IV	4.2ab	4.3ab	7.5a	4.5ab	4.8ab	4.2ab	4.4ab	4.3ab	4.2ab	4.2ab	3.0b
At site 2											
I	26.8ab	28.8ab	24.8ab	25.3ab	30.8 ab	26.8 ab	33.3ab	36.4ab	42.7a	41.0a	15.2b
II	17.9bc	15.9c	14.5c	22.2abc	14.0c	17.9bc	15.3c	15.7c	24.9ab	30.3a	21.2bc
III	13.9bc	10.3c	12.9bc	13.2bc	12.8bc	13.9bc	12.3bc	12.8bc	19.3ab	25.7a	14.0bc
IV	8.6a	20.9a	26.2a	18.7a	15.6a	8.6a	8.1a	12.1a	15.6a	9.2a	12.3a
At site 3											
I	8.2ab	8.9ab	12.0a	8.2ab	7.4b	8.2ab	8.1ab	8.0ab	8.1ab	7.4b	7.1b
II	8.4abc	9.0abc	10.2ab	10.5a	7.7abc	8.4abc	7.9abc	8.4abc	6.7c	7.0c	6.1c
III	8.2a	7.9a	8.0a	7.2a	7.3a	8.2a	7.5a	8.8a	6.3a	8.9a	5.8a
IV	5.4a	5.5a	5.9a	6.5a	5.4a	5.4a	6.6a	5.7a	8.4a	6.0a	5.8a
At site 4											
I	25.7a	12.0a	5.4a	10.3a	14.1a	25.7a	20.1a	28.5a	12.9a	35.5a	25.4a
II	26.1ab	31.4a	23.9ab	5.4b	12.4ab	26.1ab	26.3ab	10.9ab	20.3ab	19.3ab	19.0ab
III	29.6ab	12.9ab	9.0b	8.6b	10.1b	29.6ab	11.7ab	8.7b	14.0ab	13.2ab	38.9a

†I depth at 3.14 in above the emitter at sites 1, 3, and 4 and 1.18 in above the emitter at site 2, II depth at the emitter level, III depth at 3.14 in below the emitter, and IV depth at 11.81 in below the emitter.

‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

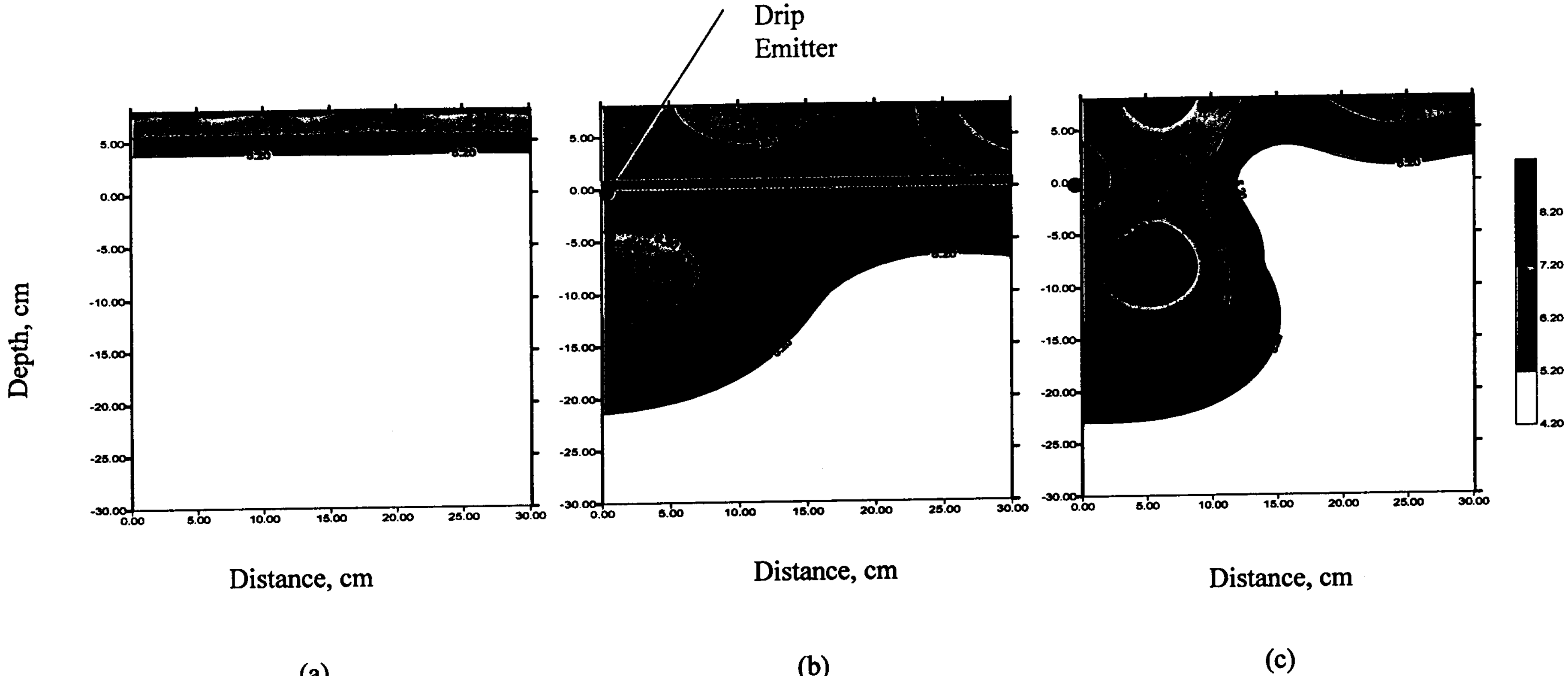

Figure 27-Potassium concentration distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

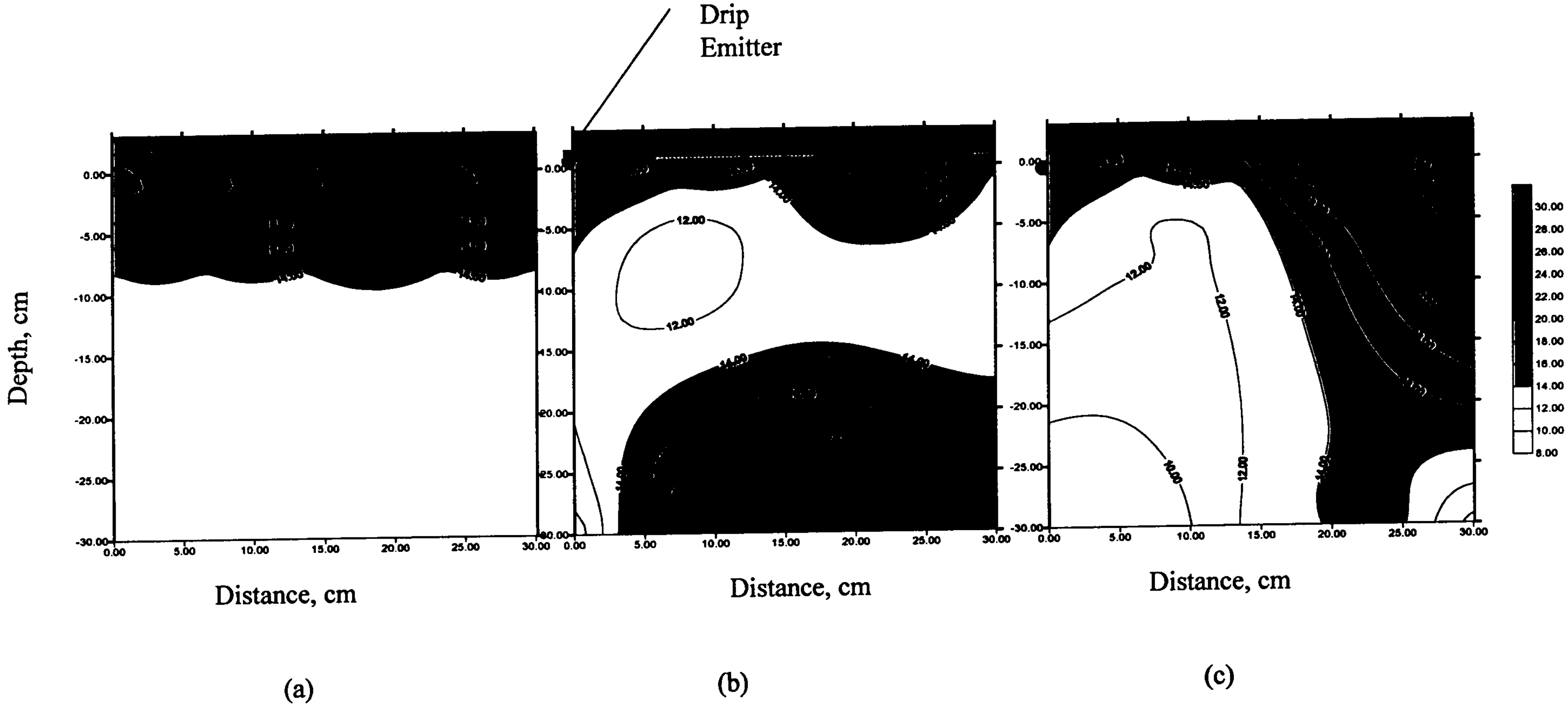

Figure 28-Potassium concentration distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

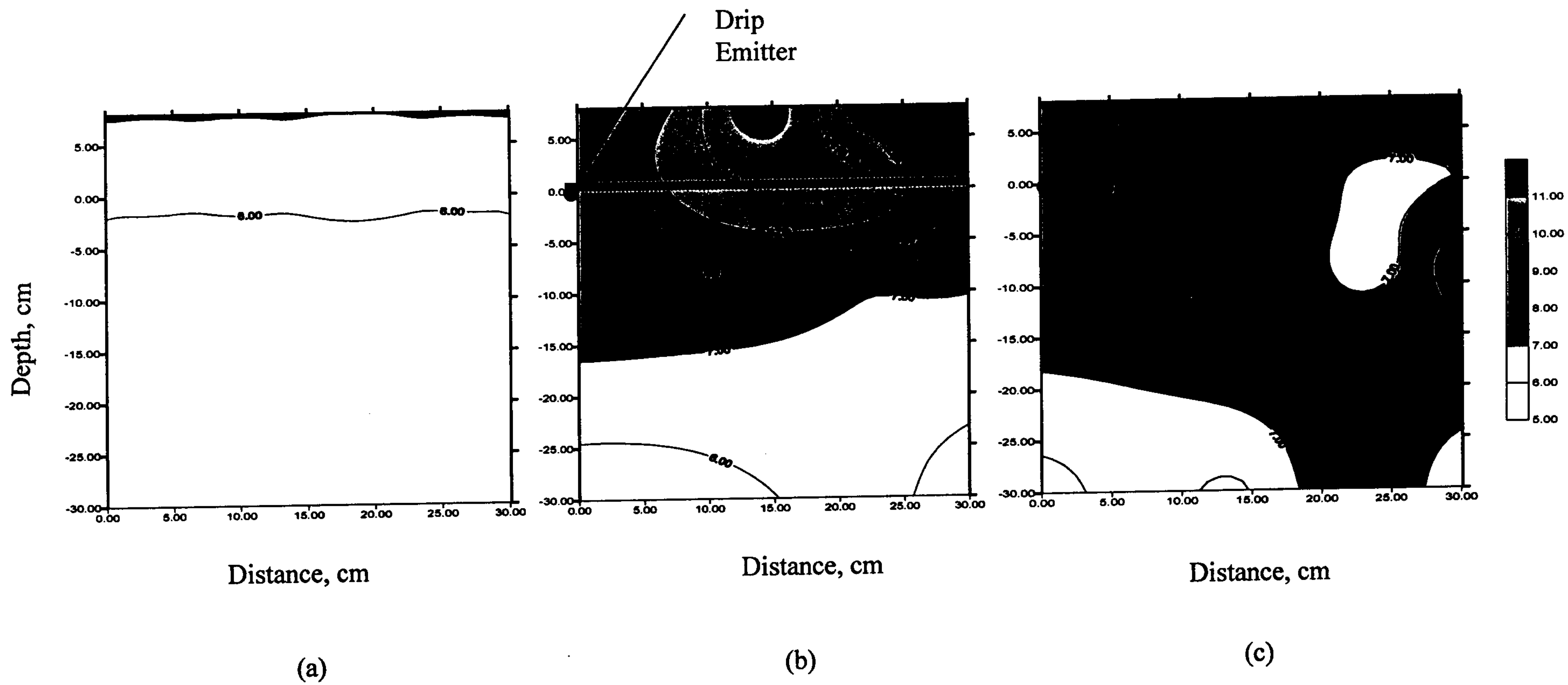

Figure 29-Potassium concentration distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

elevated in the area above the emitter and at all depth at the midpoint between the two drip lines and reduces in most of the rest of the soil profile (Table 10, Figure 28). At site 4 which had relatively high K concentration in the control area (average 27.9 ppm) and low concentration of K in the applied effluent (Table 2), soil K concentration was elevated near the emitter and reduced in the rest of the soil profile (Table 10, Figure30). The difference in K concentration in the irrigated soil and the control area was not statistically significant at any of the four sites.

Electrical Conductivity (EC)

Soil EC is typically used to indicate soluble salt concentrations in soil. Because crops only remove small quantities of salt, salt movement and distribution in soil is directly related to water movement (Nakayamn and Bucks, 1986).

At all four sites, in the majority of the soil profile EC values in the irrigated area were greater than in the control area. The difference in soil EC between the irrigated area and the control area was directly related to the EC value of the applied effluent. At site 1, where the applied effluent had an EC value of 1.12 ds/cm, the increase in soil EC was significant only in the area located beneath the emitter (Table 11, Figure 31). At site 2 which received effluent with an EC value of 1.24 ds/cm, EC values at all distances from the emitter in the area above and below the emitter were significantly greater than in the control area (Table11, Figure 32). As mentioned earlier, there was probably more water movement in the area above the emitter at this site due to differences in soil hydraulic conductivity of soil layers and enhanced upward movement of water by

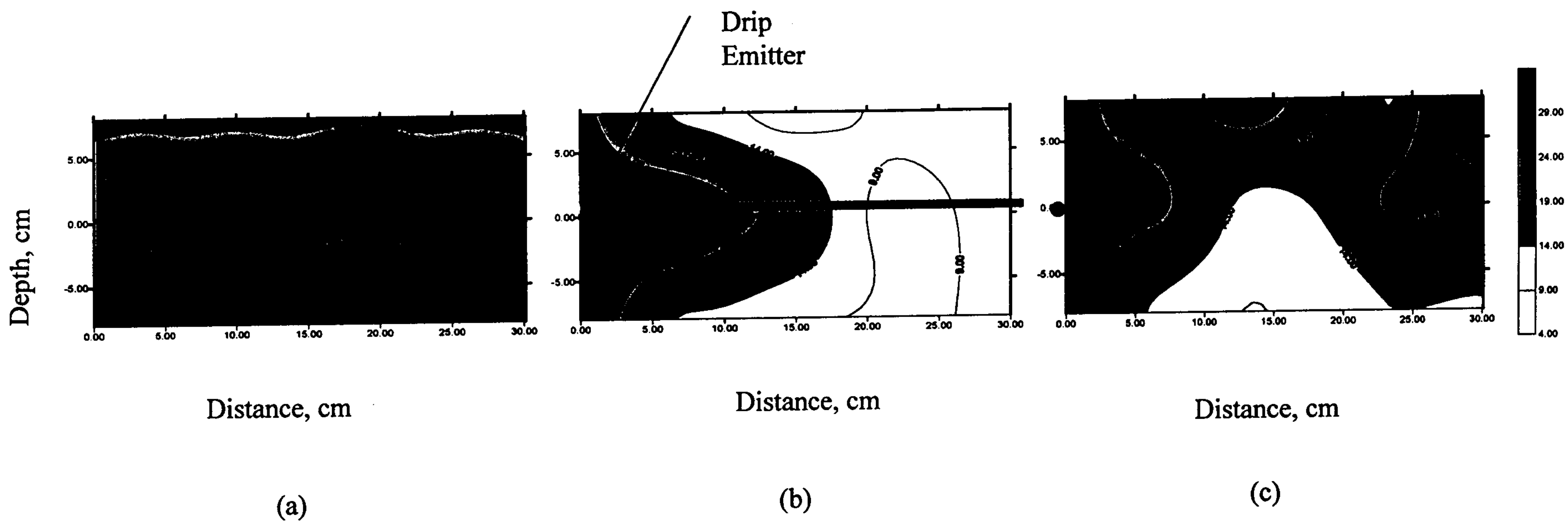

Figure 30-Potassium concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

Table 11- Average electrical conductivity values(ds/cm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
						At site 1					
I†	0.23a‡	0.20a	0.20a	0.20a	0.27a	0.23a	0.23a	0.18a	0.21a	0.21a	0.17a
II	0.20a	0.18a	0.17a	0.19a	0.16a	0.20a	0.21a	0.17a	0.16a	0.15a	0.18a
III	0.23ab	0.20abc	0.19bc	0.17c	0.18c	0.23ab	0.25a	0.18bc	0.17c	0.18bc	0.17c
IV	0.16a	0.18a	0.19a	0.19a	0.18a	0.16a	0.16a	0.16a	0.16a	0.17a	0.21a
						At site 2					
I	0.200a	0.234a	0.166ab	0.188ab	0.210a	0.200a	0.266a	0.241a	0.207a	0.168ab	0.074b
II	0.208a	0.187a	0.127a	0.202a	0.139a	0.208a	0.177a	0.158a	0.150a	0.124a	0.175a
III	0.182a	0.125ab	0.151ab	0.144ab	0.128ab	0.182a	0.163ab	0.153ab	0.142ab	0.146ab	0.109b
IV	0.134a	0.154a	0.160a	0.138a	0.133a	0.134a	0.148a	0.135a	0.103a	0.103a	0.111a
						At site 3					
I	0.161a	0.136a	0.153a	0.181a	0.159a	0.161a	0.184a	0.145a	0.152a	0.155a	0.181a
II	0.176a	0.169a	0.130a	0.159a	0.156a	0.176a	0.177a	0.179a	0.146a	0.115a	0.154a
III	0.185a	0.139ab	0.166ab	0.142ab	0.122ab	0.185a	0.173ab	0.169ab	0.112b	0.127ab	0.116ab
IV	0.175a	0.151a	0.167a	0.164a	0.205a	0.175a	0.155a	0.169a	0.169a	0.183a	0.198a
						At site 4					
I	0.41a	0.31a	0.47a	0.30a	0.29a	0.41a	0.49a	0.29a	0.33a	0.54a	0.33a
II	0.39ab	0.39ab	0.32abc	0.32bc	0.26c	0.39ab	0.41ab	0.46a	0.26bc	0.22cb	0.19c
III	0.37b	0.44b	0.38b	0.30cb	0.33b	0.37b	0.44b	0.40b	0.40b	0.29cb	0.16c

†I depth at 3 in above the emitter at sites 1, 3, and 4 and 1 in above the emitter at site 2, II depth at the emitter level, III depth at 3 in below the emitter, and IV depth at 12 in below the emitter.

‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

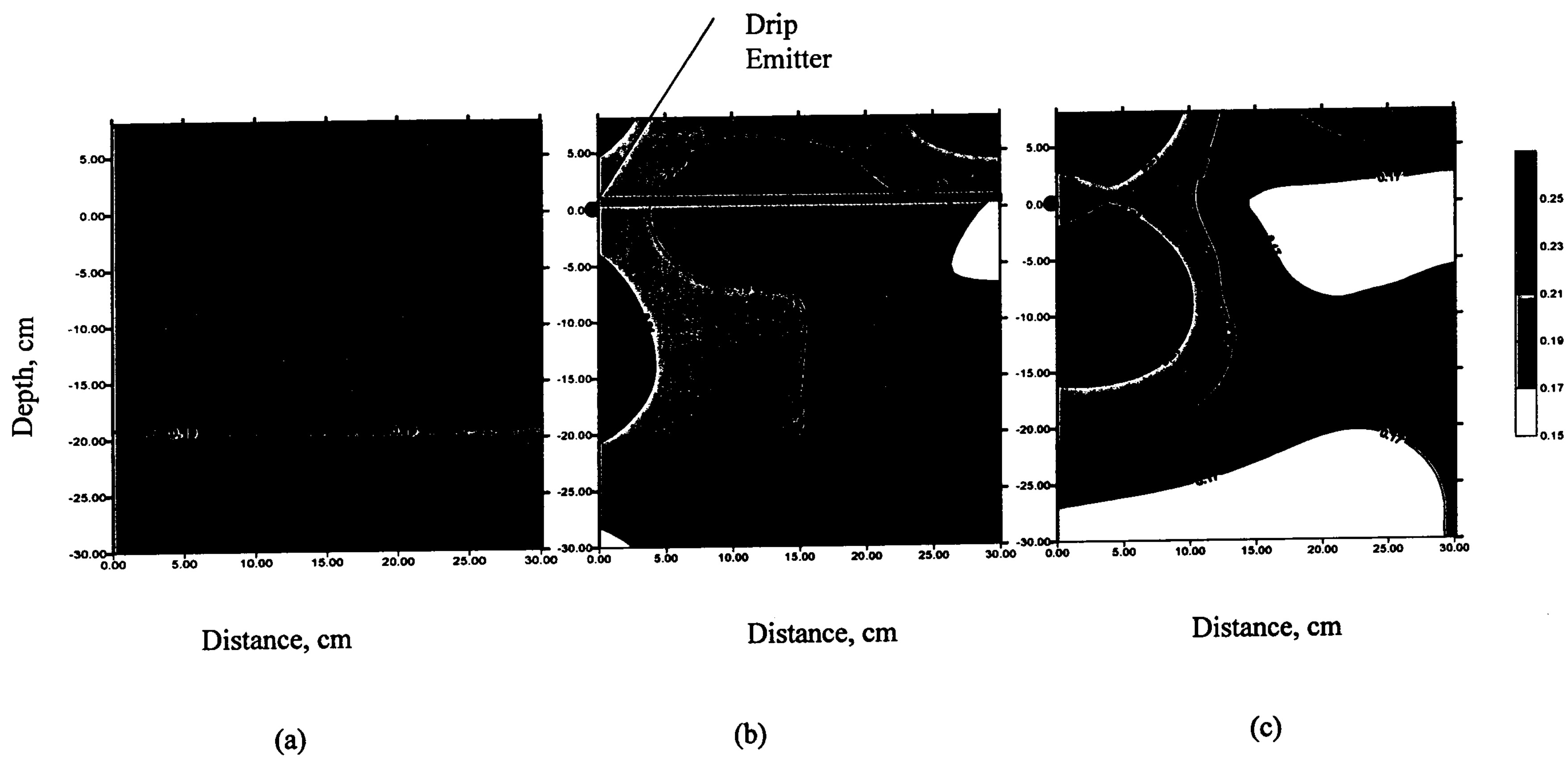

Figure 31-Electrical conductivity distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

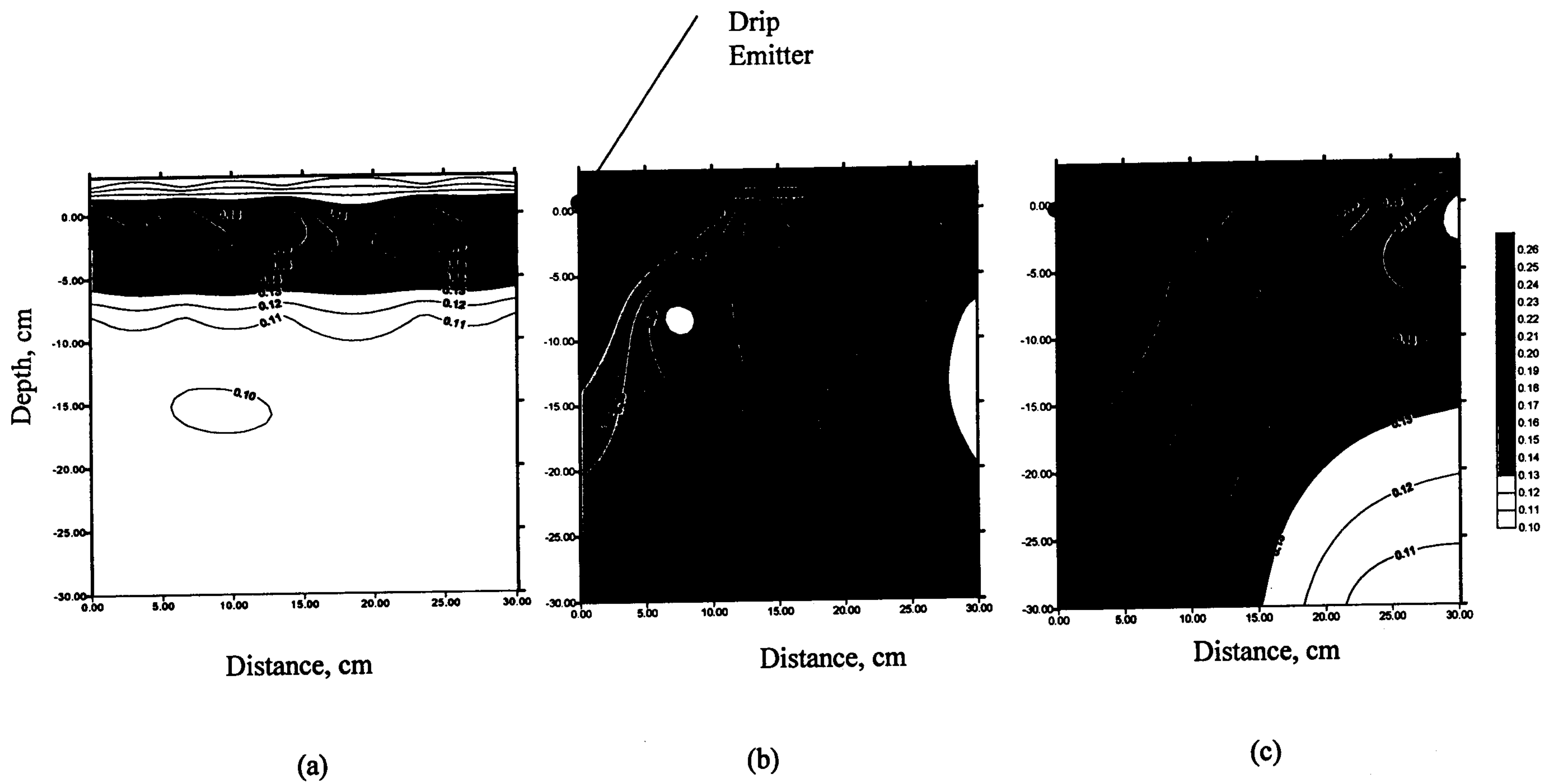

Figure 32-Electrical conductivity distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

evaporation. At site 3, which received effluent with an EC value of 0.93 ds/cm, the difference between EC values in the irrigated area and control area was not significant at any distance from the emitter (Table 11, Figure 33). The applied effluent at site 4 had a relatively high EC value (1.52 ds/cm). This resulted in appreciable greater soil EC through the entire soil profile when compared to EC values in the control area (Table 11, Figure 34).

The influence of Na on soil particle swelling and dispersion depends on the total electrolyte concentration in the soil solution (Feigin et al., 1991). Therefore, increased salinity reduces the potential of soil dispersion due to increased soil sodicity.

Total Organic Carbon (TOC)

At sites 1, 2, and 4, TOC concentration in the entire soil profile in the irrigated area was less than in the control area (Table 12 Figures 35, 36, and 38). At site 3, TOC concentration in the irrigated area was greater than in the control area (Table 12, Figure 37), but this difference was not statistically significant.

Application of septic tank effluent with high BOD_5 concentration could result in significant accumulation of TOC in the soil profile. However, at the investigated sites the septic tank effluent was treated with a constructed wetland prior to application in the subsurface drip dispersal field. Therefore, BOD_5 concentrations for the applied effluents were relatively low (Table 3), and so was the TOC concentration in the soil profile. The reduction in TOC concentration could also be due to microbial activity in the soil profile.

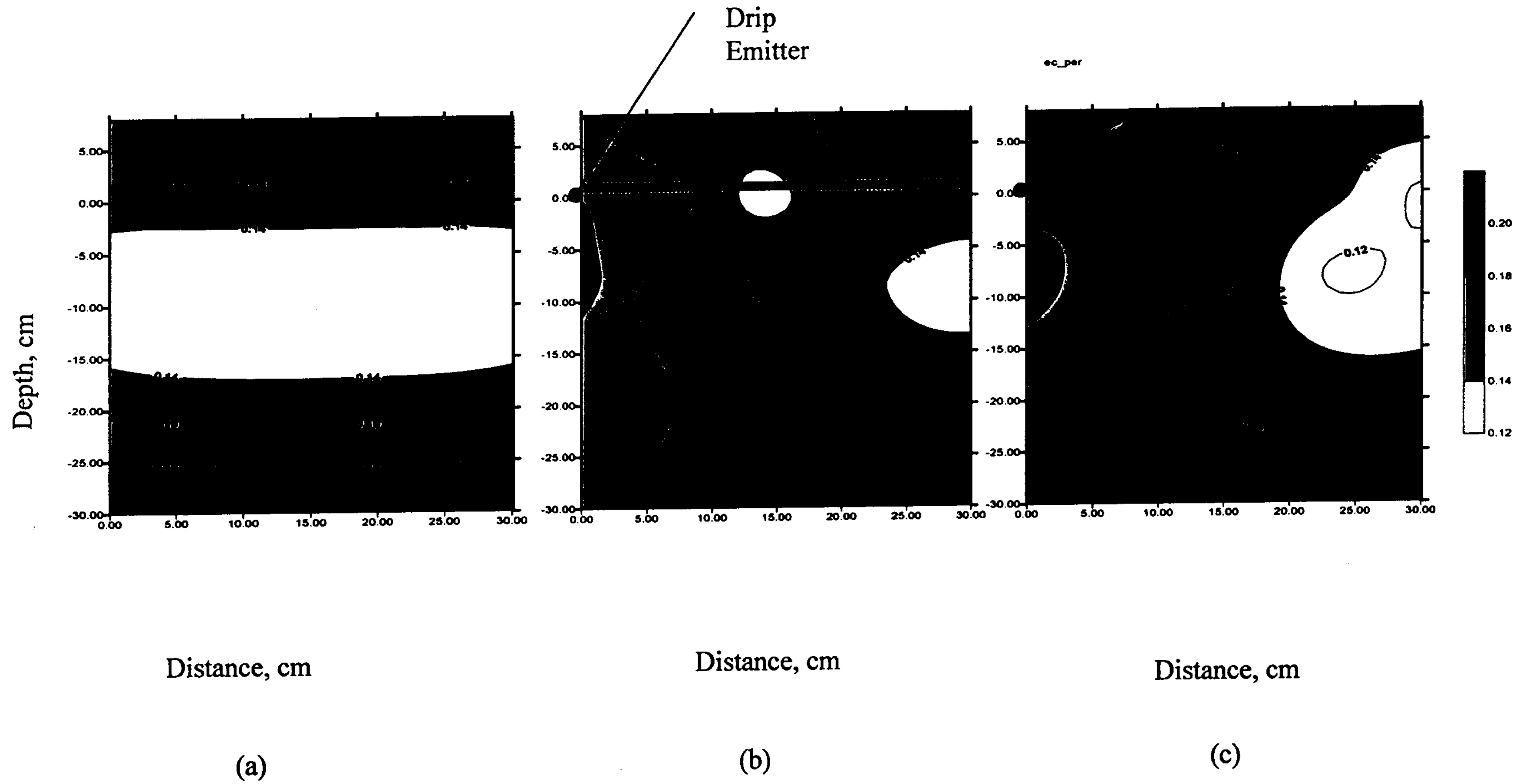

Figure 33-Electrical conductivity distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

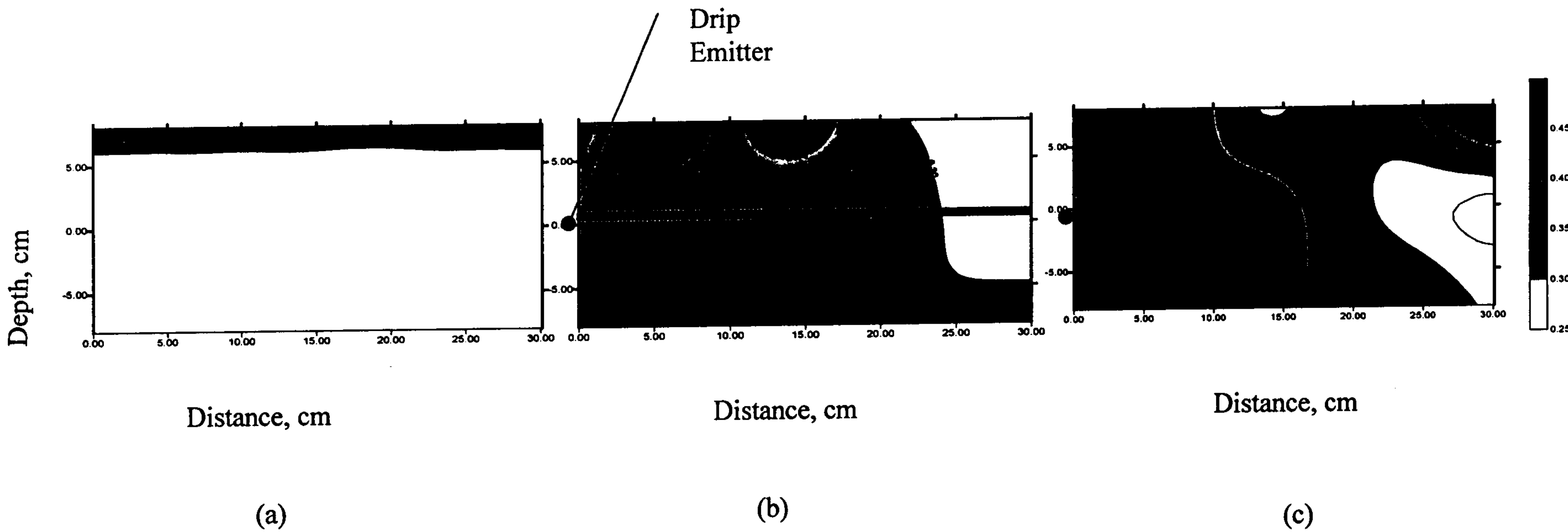

Figure 34-Electrical conductivity concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

Table 12- Average total organic carbon concentrations (ppm) at various distances and depths from the emitter in a transect along the drip lateral and perpendicular to the drip lateral.

Depth	Along the drip lateral					Perpendicular to the drip lateral					Control area
	Distance from the emitter (in)					Distance from the emitter (in)					
	0	3	6	9	12	0	3	6	9	12	
At site 1											
I†	1.810a‡	1.321a	1.387a	1.769a	1.888a	1.810a	1.362a	1.430a	1.360a	1.633a	3.080a
II	1.521a	1.640a	1.399a	1.739a	1.647a	1.521a	1.726a	1.600a	1.556a	1.749a	2.667a
III	1.556ab	1.466b	1.829ab	1.385b	1.253b	1.556ab	1.645ab	1.866ab	1.714ab	1.591ab	3.242a
IV	1.686a	1.469a	1.619a	1.490a	1.661a	1.686a	1.535a	1.442a	1.997a	1.947a	3.308a
At site 2											
I	0.535a	0.667a	0.515a	0.540a	0.514a	0.535a	0.315a	0.552a	0.643a	0.709a	0.499a
II	0.326b	0.312b	0.283b	0.338ab	0.414ab	0.326b	0.406ab	0.321b	0.378ab	0.339ab	0.431a
III	0.366ab	0.304ab	0.370ab	0.245ab	0.313ab	0.366ab	0.384ab	0.278ab	0.355ab	0.305ab	0.39a
IV	0.409b	0.427b	0.389b	0.375b	0.413b	0.328	0.249b	0.294b	0.294b	0.220b	0.73a
At site 3											
I	0.454a	0.511a	0.488a	0.454a	0.480a	0.454a	0.463a	0.427a	0.467a	0.461a	0.488a
II	0.491ab	0.578ab	0.529ab	0.556ab	0.871a	0.491ab	0.524ab	0.540ab	0.488ab	0.570ab	0.336b
III	0.548a	0.368a	0.398a	0.420a	0.369a	0.548a	0.431a	0.406a	0.476a	0.513a	0.349a
IV	0.191b	0.183b	0.260ab	0.375ab	0.213b	0.191b	0.189b	0.253ab	0.207b	0.514a	0.375ab
At site 4											
I	0.676ab	0.368bc	0.580abc	0.608abc	0.420abc	0.676ab	0.505abc	0.337bc	0.415abc	0.351bc	0.745a
II	0.468ab	0.460ab	0.306b	0.296b	0.333b	0.468ab	0.470ab	0.371b	0.355b	0.324b	0.679a
III	0.270cd	0.437abc	0.523ab	0.416abc	0.364abc	0.270cd	0.495ab	0.123d	0.218cd	0.227cd	0.592a

†I depth at 3 in above the emitter at sites 1, 3, and 4 and 1 in above the emitter at site 2, II depth at the emitter level, III depth at 3 in below the emitter, and IV depth at 12 in below the emitter.

‡ Values in any given row followed by the same letter do not differ at the 0.05 significance level.

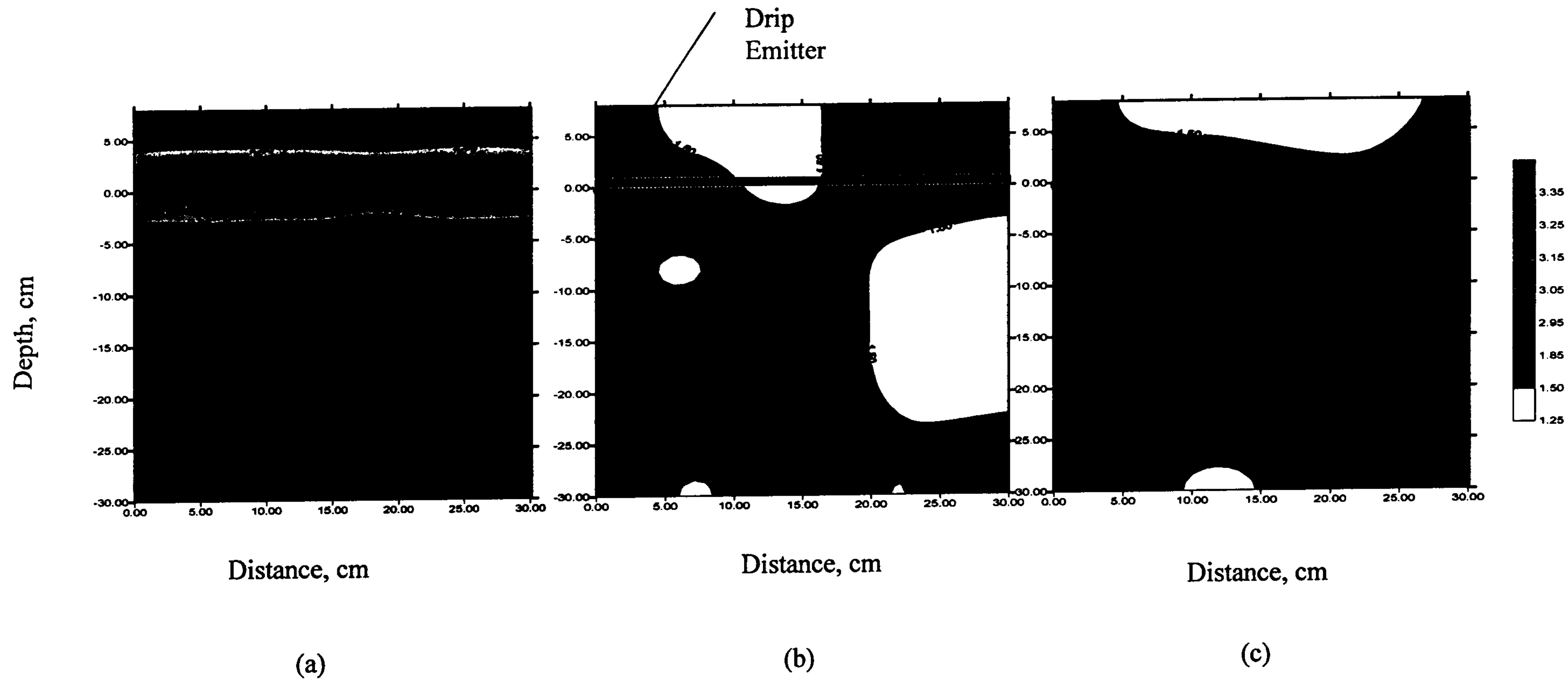

Figure 35-Total organic carbon concentration distribution at site 1: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

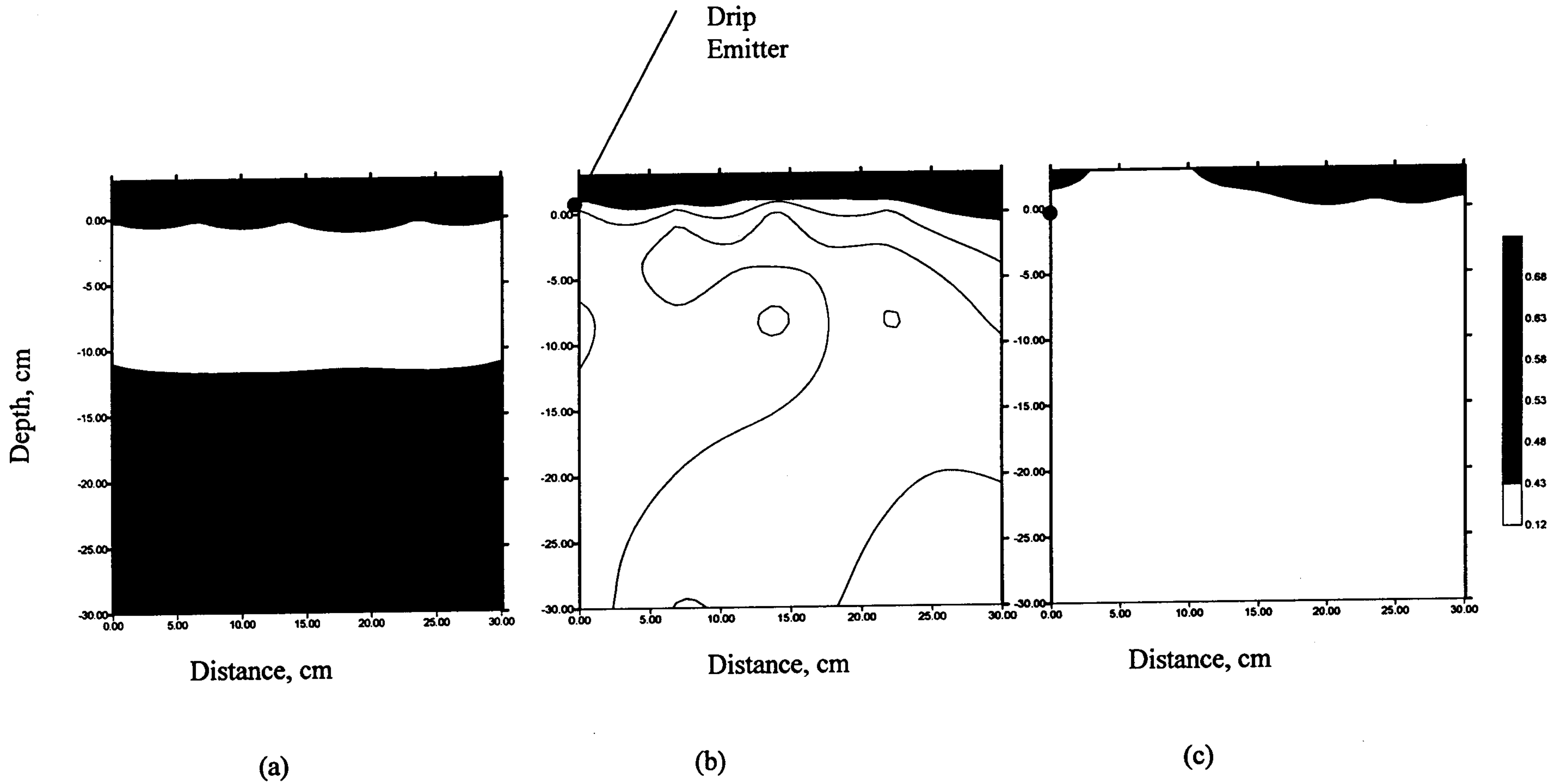

Figure 36-Total organic carbon distribution at site 2: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

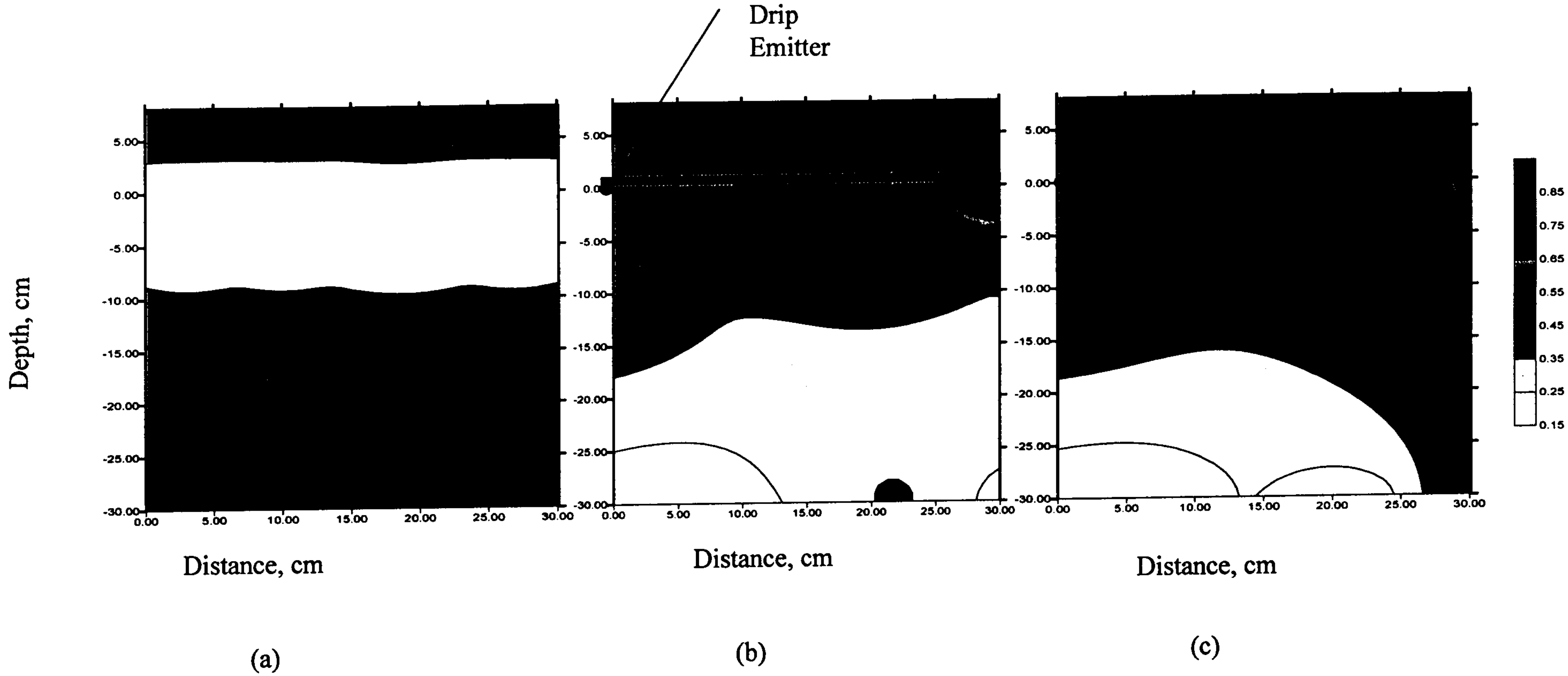

Figure 37-Total organic carbon concentration distribution at site 3: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

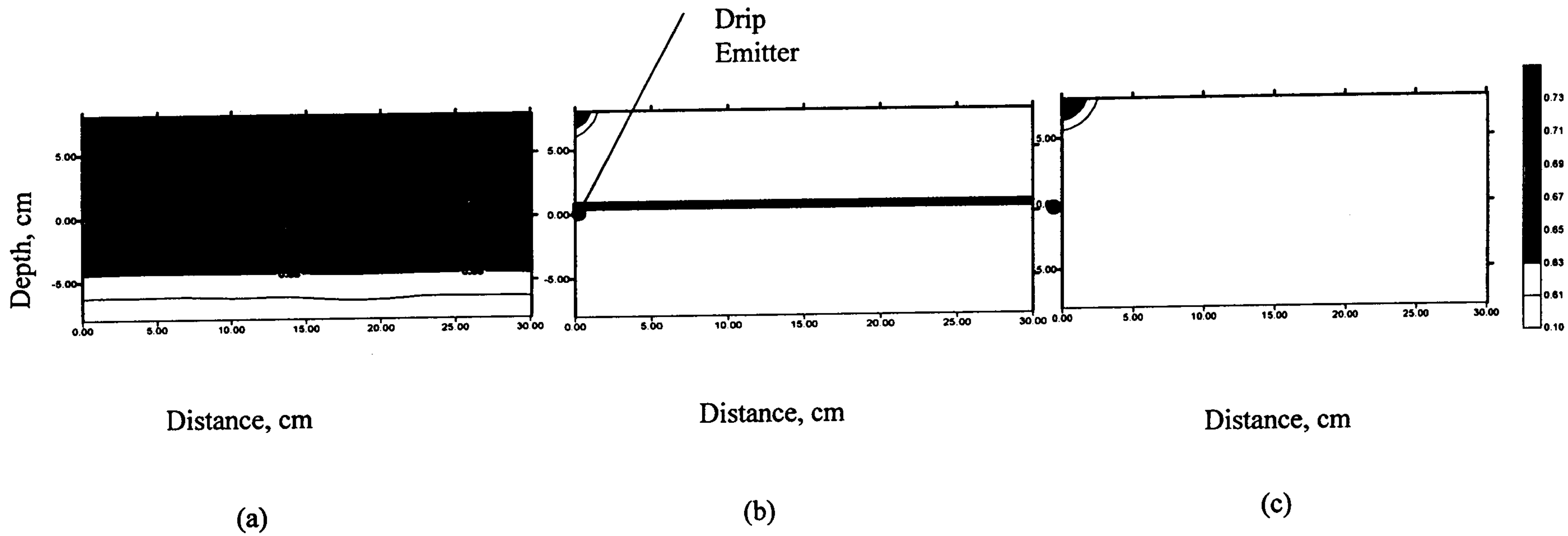

Figure 38-Total organic carbon concentration distribution at site 4: a) in the control area, b) along the drip line, and c) perpendicular to the drip line.

Water Retention and Pore Size Distribution

At site 1, application of treated effluent did not significantly effect pore size distribution (Table 13) or soil water retention (Figure 39) above or at the emitter level. At 6 in below the emitter, there was significantly less relative volume of pores with radii > 22 μm at location A than in the control area, while the relative volume of pores with smaller radii was significantly greater at location A than in the control area. This, in turn, resulted in greater soil water retention at location A than in the control area for all matric potentials greater than 0 kpa, but this difference was not statistically significant. At 12 in below the emitter, application of effluent caused an appreciable effect on pore size distribution at location A and B only. The relative volume of pores with radii > 22 μm at these two locations was less than in the control area, while the relative volume of pores with radii between 3 and 22 μm was greater than in the control area. This shift in pore size distribution resulted only in a slightly greater water retention at these two locations compared to values in the control area for all matric potentials greater than 0 kpa.

At site 2, there was no significant difference in pore size distribution (Table 14) or soil water retention (Figure 40) between the irrigated area and the control area at 1 in above the emitter. At a depth of 3 in below the emitter, there was significantly less relative volume of pores with radii > 3 μm over the majority of the irrigated area than in the control area. This, in turn, resulted in greater water retention in the irrigated area than in the control area for all matric potentials greater than 10 kpa (Figure 40). At a depth of 12 in below the emitter, there was significantly less relative volume of pores with radii >

Table 13-Comparison of relative pore volumes occurring within selected size classes (ft^3/ft^3) at site 1.

Sample depth	Pore radii, µm	Location† A	B	C	D	E	O
1 in above emitter	>22	0.147	0.143	0.126	0.161	0.128	0.130
	3-22	0.061	0.055	0.058	0.101	0.089	0.062
	<3	0.289	0.308	0.304	0.060	0.060	0.307
At the emitter	>22	0.172	0.139	0.173	0.162	0.155	0.152
	3-22	0.056	0.068	0.055	0.066	0.053	0.051
	<3	0.290	0.292	0.274	0.272	0.276	0.280
6 in below emitter	>22	0.116*	0.147	0.139	0.170	0.123	0.147
	3-22	0.068	0.057	0.054	0.046	0.057	0.062
	<3	0.287	0.265	0.275	0.270	0.275	0.271
12 in below emitter	>22	0.134	0.119*	0.156	0.155	0.177	0.156
	3-22	0.055	0.056	0.049	0.046	0.055	0.047
	<3	0.261	0.260	0.254	0.246	0.252	0.258

*,** Relative pore volume at selected location is significantly different from the pore volume at location O at 0.05 and 0.10 level, respectively.

† Locations A- next to the emitter, B- 6 in from the emitter along the drip lateral, C- at the midpoint between two emitters, D- 6 in from the emitter perpendicular to the drip lateral, E- 12 in from the emitter perpendicular to the drip lateral, and O-outside the drip field.

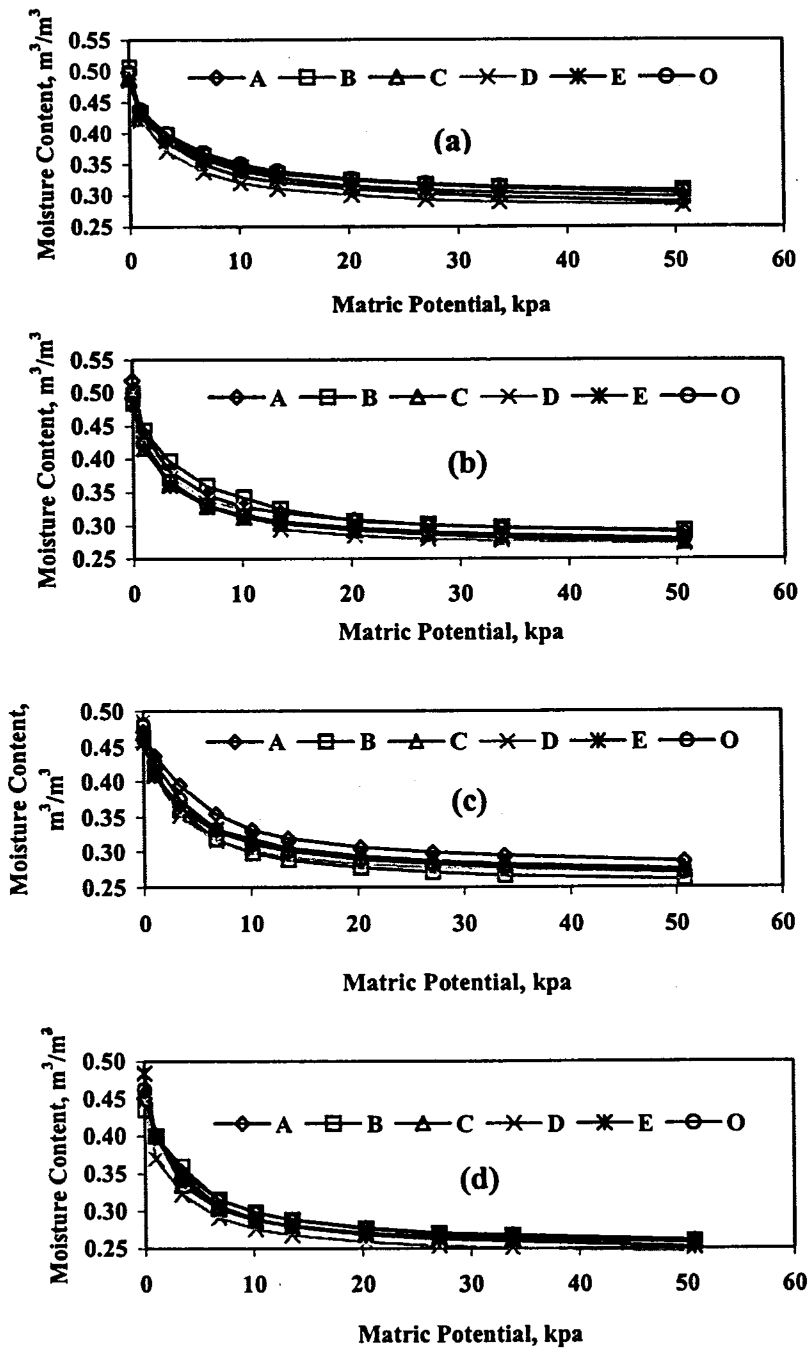

Figure 39 -Water retention curves at site 1 at four depths: a) at 4 in above the emitter, b) at the emitter, c) at 6 in below the emitter, and d) at 12 in below the emitter for six locations A- next to the emitter, B-6 in from the emitter along the drip lateral, C-at the midpoint between two emitters, D- 6 in from the emitter along a transect perpendicular to the drip lateral, E- 12 in from the emitter along a transect perpendicular to the drip lateral, and O-outside the drip field.

Table 14-Comparison of relative pore volumes occurring within selected size classes (ft^3/ft^3) at site 2.

Sample depth	Pore radii, µm	Location					
		A	B	C	D	E	O
	>22	0.124	0.125	0.157	0.156	0.152	0.141
1 in above emitter	3-22	0.096	0.089	0.097	0.113	0.091	0.091
	<3	0.182	0.192	0.182	0.192	0.174	0.177
	>22	0.094**	0.096**	0.091**	0.123	0.093**	0.136
At the emitter	3-22	0.083**	0.084**	0.082**	0.098	0.093**	0.104
	<3	0.198	0.194	0.192	0.181	0.185	0.190
	>22	0.089**	0.084**	0.107	0.106	0.078**	0.128
6 in below emitter	3-22	0.072	0.071	0.068	0.082	0.064	0.077
	<3	0.237*	0.242*	0.231*	0.213	0.244*	0.199
12 in below emitter							

*,** Relative pore volume at selected location is significantly different from the pore volume at location O at 0.05 and 0.10 level, respectively.

† Locations A- next to the emitter, B- 6 in from the emitter along the drip lateral, C- at the midpoint between two emitters, D- 6 in from the emitter perpendicular to the drip lateral, E- 12 in from the emitter perpendicular to the drip lateral, and O-outside the drip field.

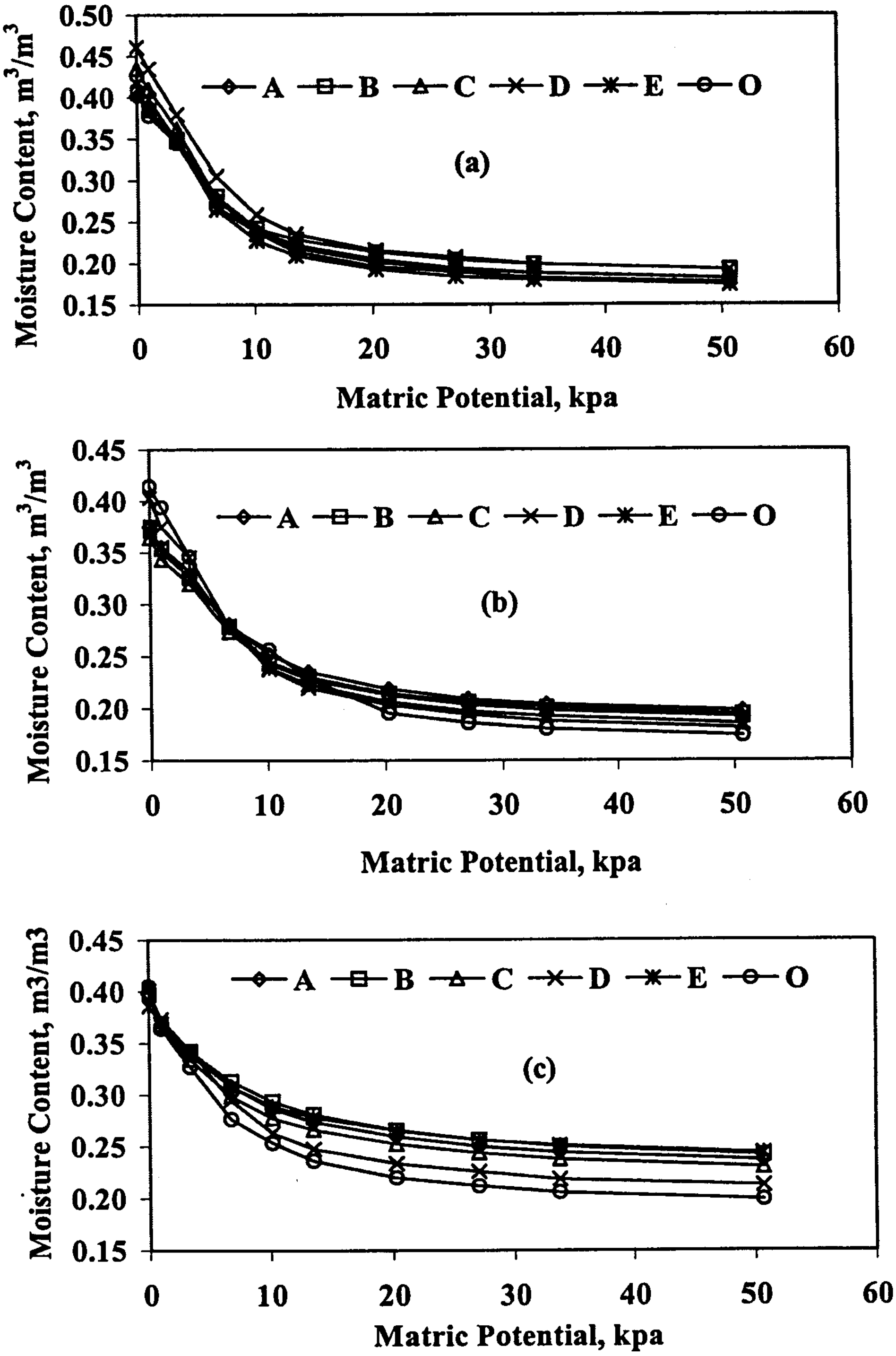

Figure 40-Water retention curves at site 2 at three depths: a) at 1 in above the emitter, b) at 3 in below the emitter, and c) at 12 in below the emitter for four for six locations A- next to the emitter, B- 6 in from the emitter along the drip lateral, C-at the midpoint between two emitters, D- 6 in from the emitter along a transect perpendicular to the drip line, E- 12 in from the emitter along a transect perpendicular to the drip line, and O-outside the drip field.

22 μm at locations A, B, and E than in the control area while the relative volume of pores with radii < 3 μm was significantly greater at locations A, B, C, and E than in the control area. This shift of soil pore volume resulted in significantly greater water retention at locations A, B, C, and E compared to values in the control area for all matric potentials greater than 10 kpa (Figure 40). The greater impact of the applied effluent at location E compared to location D, which is closer to the emitter, could have been influenced by the high variability in pore volume values for selected size classes at this location.

Equation 1 shows that there is an inverse relationship between soil matric potential and pore size, which means smaller pores require greater tension to drain compared to larger pores. Therefore, increasing the number of small pores will increase the volume of water held at greater matric potentials. Previous research shows application of wastewater to soil may reduce the size of soil pores due to 1) accumulation of suspended solids and biological growth (Bouma, 1975), 2) deposition of organic matter on the surface of the soil pores (Siergrist, 1987), and 3) increase in Na concentration in the soil and associated clay particle dispersion (Patteson, 1997; Amoozegar et al., 1998).

Soil chemical analyses at site 1, presented in detail in Jnad et al. (2001) and summarized in Table 15, did not reveal significant increases in TOC or Na contents in the soil profile. Therefore, reduction in the volume of soil pore at this site could be due to microbial activity. Eliot (1975) and Johnson (1957) indicated that decomposition of

Table 15-Change in the concentration of selected chemicals in the irrigated area compared to that in the control area (%) at site 1.

Constituents	Location†				
	A	B	C	D	E
			At 4 in above the emitter		
Na	-17	16	-7	-23	-23
Ca	17	7	50	1	8
Mg	29	50	300	29	21
TOC	-41	-55	-39	-54	-47
EC	35	18	59	6	24
			At the emitter		
Na	-24	-33	-52	-47	-55
Ca	15	-5	-1	4	-1
Mg	150	108	25	42	0
TOC	-43	-48	-38	-40	-34
EC	11	-6	-11	-6	-17
			At 6 in below the emitter		
Na	-8	-37	-49	-25	-50
Ca	16	14	-90	4	-1
Mg	243	136	0	143	-14
TOC	-52	-44	-61	-42	-51
EC	35	12	6	6	6
			At 12 in below the emitter		
Na	23	15	-9	25	-21
Ca	-29	-32	-19	-26	-11
Mg	35	-26	1	-46	-46
TOC	-49	-51	-50	-56	-41
EC	-24	-10	-14	-24	-19

†Locations A- next to the emitter, B- 6 in from the emitter along the drip lateral, C- at the midpoint between two emitters, D- 6 in from the emitter perpendicular to the drip lateral, and E- 6 in from the emitter perpendicular to the drip lateral.

organic matter by microbial activity could result in clogging of soil pores because of gases and solid that would result from decomposition.

At site 2, soil chemical analyses (Table 16) showed significantly greater Na concentrations in the soil profile. These increases in Na concentrations were associated with decreases in Ca concentrations at depths of 3 in and 12 in below the emitter. An increase in Na concentration associated with reduction in Ca concentration will increase the hazard of clay particle swelling and dispersion. This, in turn, could lead to a reduction in soil pore size and, consequently, an increase in soil water retention. Since there was nó significant increase in TOC concentration in the soil profile (Table 16), an increase in organic matter most likely was not a factor in reduction of pore size at this site. However, decomposition of organic matter could cause clogging of pores because of gases or solids from the decomposition products.

Saturated Hydraulic Conductivity (K_{sat})

Application of effluent through the subsurface drip dispersal system at site 1 did not have a significant effect on hydraulic conductivity values over the majority of the soil profile (Table 17). At 3 in above the emitter, the saturated hydraulic conductivity all distances from the emitter were greater than in the control area. However this difference in K_{sat} values was not statistically significant. This increase in K_{sat} at this depth could be caused by an increase in Ca and Mg concentration in conjunction with a reduction in Na concentration (Table 15). At the emitter level, there was no significant difference in K_{sat} between the irrigated area and the control area. At 6 in below the emitter, at all distances

Table 16-Change in the concentration of selected chemicals in the irrigated area compared to that in the control area (%) at site 2.

	Location†				
Constituents	A	B	C	D	E
			At 1 in above the emitter		
Na	247	165	237	91	-5
Ca	2	-5	2	37	26
Mg	97	87	187	229	187
TOC	7	3	3	11	42
EC	170	124	184	226	127
			At 3 in below the emitter		
Na	500	450	475	425	83
Ca	-19	-38	-49	-19	-18
Mg	59	32	23	26	112
TOC	-6	-5	-20	-29	-22
EC	67	39	17	40	34
			At 12 in below the emitter		
Na	418	600	380	477	215
Ca	-60	-42	-70	-65	-67
Mg	-25	246	76	-89	-34
TOC	-85	-47	-43	-60	-69
EC	21	44	20	22	-5

† Locations A- next to the emitter, B- 6 in from the emitter, and C- at the midpoint between two emitters, D- 6 in from the emitter perpendicular to the drip lateral, and E- 12 in from the emitter perpendicular to the drip lateral.

Table 17-Comparison of average saturated hydraulic conductivity (K_{sat}) [cm/day] (gal/ft^2-day) at site 1.

Location	Number of sample	Average K_{sat} [cm/day]	Average K_{sat} (gal/ft^2-day)	Standard deviation [cm/day]	Standard deviation (gal/ft^2-day)	Coefficient of variability (%)
			At 4 in above the emitter			
A	4	593	22.3	91	22.3	15
B	9	757	185.7	800	196.3	106
C	3	666	163.4	275	67.4	41
D	4	1059	259.9	611	149.9	58
E	7	848	208.1	839	205.9	99
O	9	593	145.5	491	120.5	83
			At the emitter			
A	5	577	141.6	185	45.4	32
B	9	325	79.7	273	67.0	84
C	5	546	134.0	274	67.2	50
D	4	345	84.6	139	34.1	40
E	5	360	88.35	152	37.3	42
O	9	414	101.6	318	78.0	77
			At 6 in below the emitter			
A	8	143*	35.0	128	31.4	89
B	10	331	81.2	138	33.87	42
C	9	316	77.5	364	89.3	115
D	4	247	60.62	82	20.1	33
E	6	293	71.9	307	75.3	105
O	11	376	92.2	223	54.7	59
			At 12 in below the emitter			
A	5	214	52.5	111	27.2	52
B	7	220	53.9	124	30.4	57
C	6	178	43.6	57	13.9	32
D	4	262	64.3	100	24.54	38
E	3	214	52.5	117	28.71	54
O	10	377	92.5	250	61.35	66

*,**value of the saturated hydraulic conductivity at selected location is significantly different from the saturated hydraulic conductivity at location O at 0.05 and 0.10 level, respectively.

from the emitter, the K_{sat} values were less than in the control area. However, the difference between K_{sat} in the irrigated area and that in the control area was significant only in the area located directly below the emitter. Concentrations of Na and TOC at this depth were not significantly different from those in the control area (Table 15). Therefore, the reduction in K_{sat} was most likely due to microbial activity. Water moves beneath the emitter via gravitational and capillary forces. Thus, this area was expected to have consistently high moisture content, which stimulated the bacterial activity. At 12 in below the emitter, the K_{sat} value throughout the irrigated area was not significantly different from the control area.

The minimal impact of effluent application on the saturated hydraulic conductivity at this site could be attributed to several factors: 1) low application rate (Table 1), 2) low Na and BOD_5 concentration in the applied effluent (Table 2), and 3) calcareous soils (ASCS, 1970).

At site 2, application of treated effluent through a subsurface drip dispersal system resulted in K_{sat} values throughout much of the soil profile less than in the control area (Table 18). The reduction in K_{sat} values varied spatially as well as with depth. A greater reduction in K_{sat} occurred close to the emitter. At 1 in above the emitter, the difference between K_{sat} value in the irrigated area and in the control area was only significant at location A. However, at a depth of 3 in below the emitter, the K_{sat} value, at all three locations located along the drip lateral were significantly less than in the control area. At a depth of 12 in below the emitter, the K_{sat} values at locations A and B were significantly less than in the control area.

Table 18-Comparison of average saturated hydraulic conductivity (K_{sat}) (cm/day) at site 2.

Location	Number of sample	Average K_{sat} [cm/day]	Average K_{sat} (gal/ft^2-day)	Standard deviation [cm/day]	Standard deviation (gal/ft^2-day)	Coefficient of variability (%)
			At 1 in above the emitter			
A	7	91**	22.3	68	16.6	75
B	7	129	31.6	99	24.2	76
C	7	199	48.8	166	40.7	83
D	3	165	40.4	67	16.4	40
E	6	216	53.0	218	53.5	101
O	10	159	39.0	55	13.4	35
			At 3 in below the emitter			
A	5	14*	3.4	20	4.9	146
B	10	47*	11.5	65	15.9	137
C	6	53*	13.0	61	14.9	115
D	3	74	18.1	34	8.3	46
E	6	93	22.8	74	18.1	84
O	9	93	22.8	41	10.0	44
			At 12 in below the emitter			
A	7	56*	13.7	67	16.4	121
B	10	67**	16.4	66	16.1	99
C	6	69	16.9	90	22.0	131
D	3	100	24.5	78	19.1	78
E	7	75	18.4	89	21.8	118
O	9	104	25.5	58	14.2	56

*,**value of the saturated hydraulic conductivity at selected location is significantly different from the saturated hydraulic conductivity at location O at 0.05 and 0.10 level, respectively.

The reduction in saturated hydraulic conductivity at this site could be due to microbial activity and Na-induced clay dispersion. As mentioned earlier, microbial activity stimulated by the nutrients and persistent moisture provided with wastewater can result in decreased K_{sat} either by producing gases or organic materials or by decomposing the binding agents responsible for stabilizing soil structure (Otis, 1985). The Sodium Adsorption Ratio (SAR) is used to predict sodium hazard. Ayers and Westcot (1976) reported that when SAR values are above 6, irrigation water can reduce hydraulic conductivity. In the case of irrigation with septic tank effluent, the effect of Na on soil physical properties is aggravated by the presence of carbonate, bicarbonate, and sulfate (Feigin et al., 1991). These components cause precipitation of Ca and consequently increase SAR values. Patterson (1997) reported that effluent with SAR values of 3 could significantly reduce soil hydraulic conductivity. Therefore, effluent with a SAR value of 6.5, as in this study (Table 3), can be expected to reduce hydraulic conductivity. Accumulation of TOC could also be a factor in K_{sat} reduction; however, soil chemical analyses at this site did not show such accumulation. Variation in K_{sat} values among replications was high but was with the normal range (Warrick and Nielsen, 1980)

At sites 3 and 4, undisturbed soil samples were collected. However, due to the low K_{sat} only a few samples would accept water to become fully saturated in order to conduct the K_{sat} test. Tables 19 and 20 present the value of the measured K_{sat} at sites 3 and 4, respectively.

Table 19-Measured saturated hydraulic conductivity at site 3 (K_{sat}) [cm/day] gal/ft^2-day)*.

Location	Sample Set1		Sample Set2		Sample Set3	
			At 4 in above the emitter			
A	16	3.9	27	6.6	86	21.0
C	227	55.6	26	6.37	NA	NA
E	1486	364.0	NA	NA	30	7.3
O	25	6.1	233	57.0	689	168.8
			At the emitter level			
A	2	0.49	NA	NA	NA	NA
C	NA	NA	NA	NA	NA	NA
E	NA	NA	NA	NA	NA	NA
O	77	18.8	186	45.5	183	44.8
			At 6 in below the emitter			
A	NA	NA	NA	NA	NA	NA
C	1	0.24	2	0.49	NA	NA
E	NA	NA	2	0.49	NA	NA
O	8	1.9	25	6.1	36	8.8

* Due to the low saturated hydraulic conductivity of the soil at this site, the hydraulic conductivity of several samples was below the measurement capability of the testing method.

Table 20-Measured saturated hydraulic conductivity at site 4 (K_{sat}) [cm/day] (gal/ft^2-day)*.

Location	Sample Set1		Sample Set 2		Sample Set 3	
			At 4 in above the emitter			
A	1.6	0.39	NA	NA	NA	NA
C	4	0.98	7.06	1.7	NA	NA
E	NA	NA	NA	NA	NA	NA
O	2.6	0.63	2.8	0.68	NA	NA
			At the emitter level			
A	0.6	0.14	NA	NA	NA	NA
C	0.2	0.04	NA	NA	NA	NA
E	NA	NA	NA	NA	NA	NA
O	0.57	0.13	NA	NA	NA	NA
			At 6 in below the emitter			
A	11.2	2.7	NA	NA	NA	NA
C	10.9	2.6	NA	NA	NA	NA
E	NA	NA	NA	NA	NA	NA
O	0.61	0.14	3.4	0.83	NA	NA

* Due to the low saturated hydraulic conductivity of the soil at this site, the hydraulic conductivity of several samples was below the measurement capability of the testing method.

Comparison with Conventional Septic Systems

Several researchers (Bouma et al. 1972; Bouma et al. 1975; Simons and Magdoff, 1979) reported development of a severely clogged layer along the absorptive surface of the trench in conventional septic systems. Data presented by Bouma et al. (1975) (Table 21) show that the K_{sat} value of native soil in the drainfield of a septic system was four orders of magnitude higher than K_{sat} in the clogged layer.

In the subsurface drip dispersal systems investigated in this study, all of the measured values of K_{sat} were within the same order of magnitude as in the control area (Tables 17 and 18). Moreover, excluding the area located directly below the emitter at site 2, all the measured hydraulic conductivities were greater than 50% of values in the control area. This indicates that the subsurface drip dispersal field did not exhibit a severely clogged layer such as that associated with conventional septic systems. Use of a constructed wetland to improve effluent quality and uniform application of effluent via a subsurface drip dispersal system were probably the main factors that prevented development of a clogging layer.

Table 21-Data used in calculating saturated hydraulic conductivity of the clogged layer developed in the two septic systems presented by Bouma et al. (1975).

System	Age (year)	H_o* (in)	h† (in)	q‡ (in/day)	K_{sat1}§ (in/day)	K_{sat2} (in/day)
1	1.5	13.4	0.8	0.23	0.007	16
2	3	8	0.8	0.40	0.013	16

* H_o is depth of ponded water above the clogged layer.
† h is matric potential below the clogged layer.
‡q is the flow rate through the clogged layer.
§ K_{sat1} is the calculated saturated hydraulic conductivity of the clogged layer using Darcy's law.
K_{sat2} is the saturated hydraulic conductivity of the original soil.

SUMMARY AND CONCLUSIONS

This project evaluated the influence of the application of effluent treated with septic tanks and constructed wetlands using a subsurface drip dispersal system on soil chemical and hydraulic properties. The quantity and distribution of chemical constituents in the soil profile are influenced by soil properties, soil structure that affect water movement patterns, crop uptake, concentration of the chemical in applied effluent, concentration of the chemical in the original soil, and distance from the emitter. The most important concern was elevation of Na concentration in soil when Na was presented in large quantities in the applied effluent. It is known that increasing Na in soil could cause deterioration of soil physical properties, especially if the increase in soil Na occurred in conjunction with reduction in Ca and Mg concentration. Phosphorus concentrations were significantly increased near the emitter and close to soil surface where the drip line was installed at shallow depth. This could pose a hazard for surface water pollution by erosion and runoff. There were no drastic change in soil TN, Ca, Mg, K, EC, and TOC. Generally, there was slightly more build up of the chemical constituents in the cross section along the drip lateral than in the cross section perpendicular to the drip lateral. This difference in chemical distribution in both cross sections was more pronounced for chemicals with low crop uptake such as P (compared to nitrogen and potassium) and Na.

Application of treated effluent resulted in an increase in soil water retention, a decrease in the volume of pores with large radii, and a decrease in saturated hydraulic conductivity. These results were consistent with previous research findings (De Vries, 1972; Sigriest, 1978). The areal extent of influence of applied effluent on soil hydraulic properties depended on effluent quality, actual application rate, and soil type. At site 2, application of effluent had a more pronounced impact due to high Na content and a greater actual application rate. At this site, the impact of applied treated effluent on saturated soil hydraulic conductivity decreased with increasing distance from the emitter. More reduction in K_{sat} occurred along the drip lateral than perpendicular to the drip lateral. At both sites, the greatest impact of effluent application occurred in the area located beneath the emitter. The subsurface drip dispersal system did not exhibit a severely clogged layer like those observed within drain fields of conventional septic systems.

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APPENDIX A

Drawings for the sites were provided as a general description of the layout for the on-site wastewater treatment systems. These drawings cover both the treatment and land application systems. Each site has two subsurface drip drain fields. Soil samples were collected from within the subsurface drip drain field having the greater flow rate emitters.

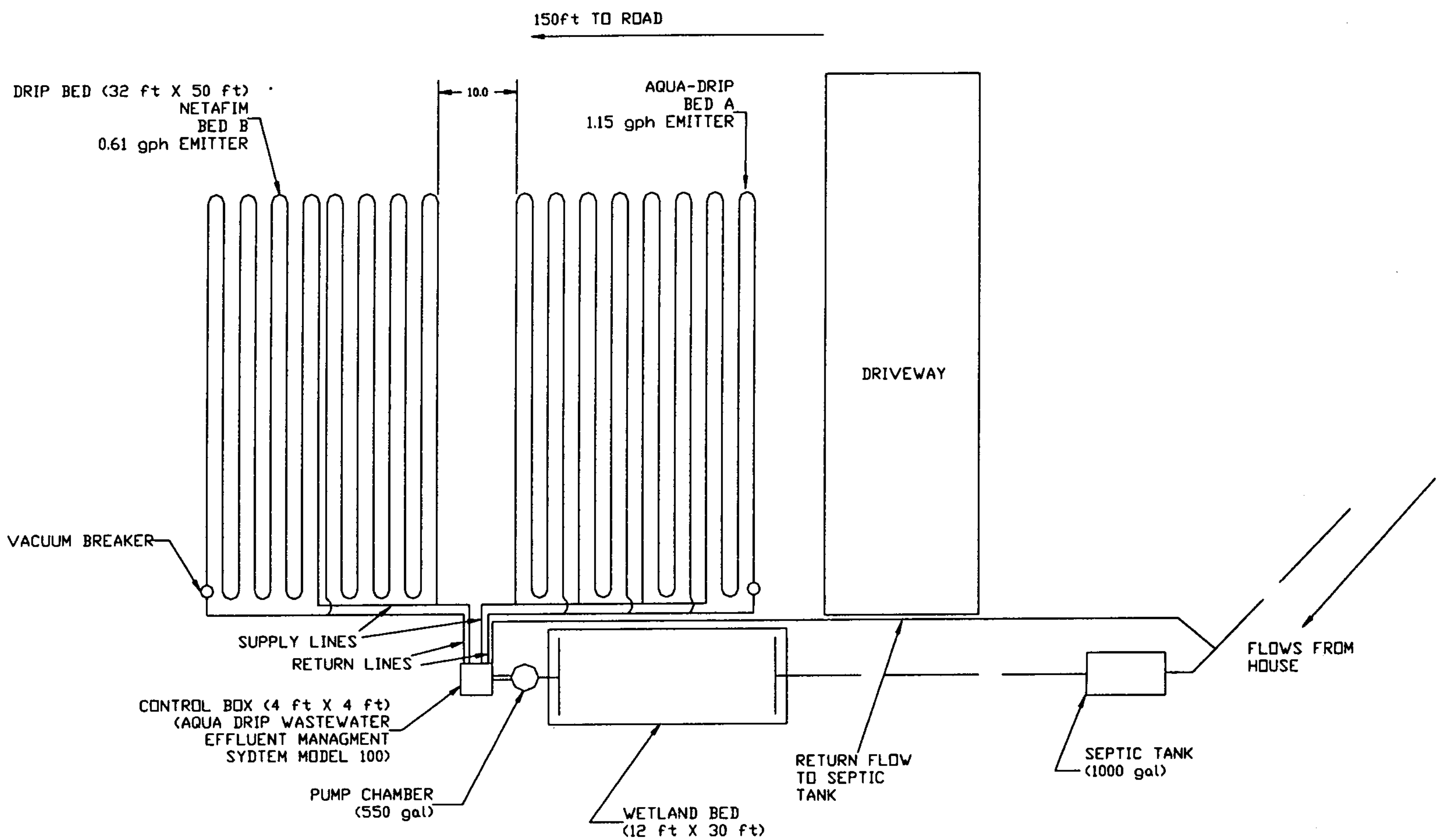

Figure A1- Drawing for site 1 on-site system located in D'Hanis, Texas.

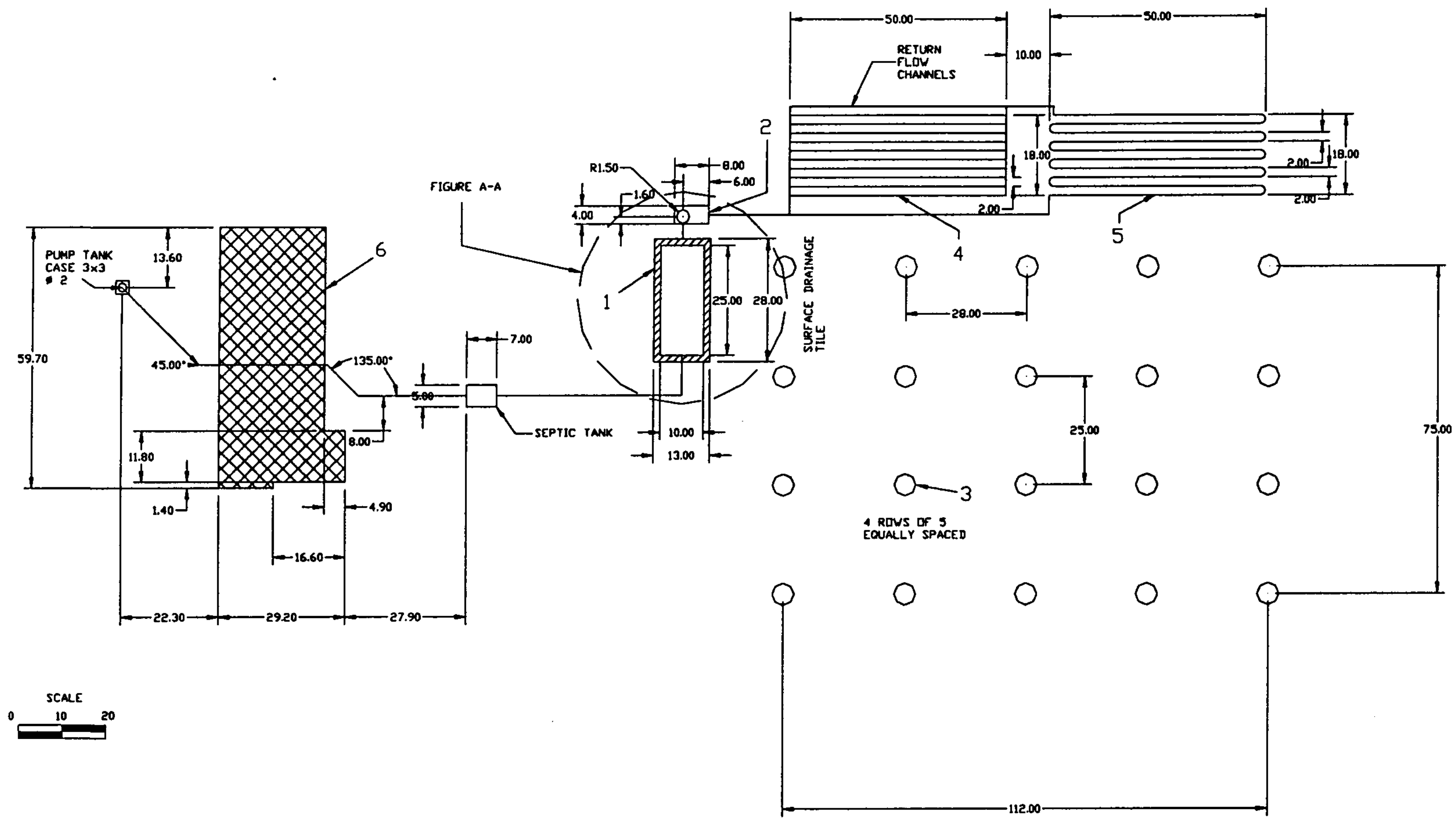

Figure A2- Drawing for site 2 on-site system located in Weslaco, Texas.

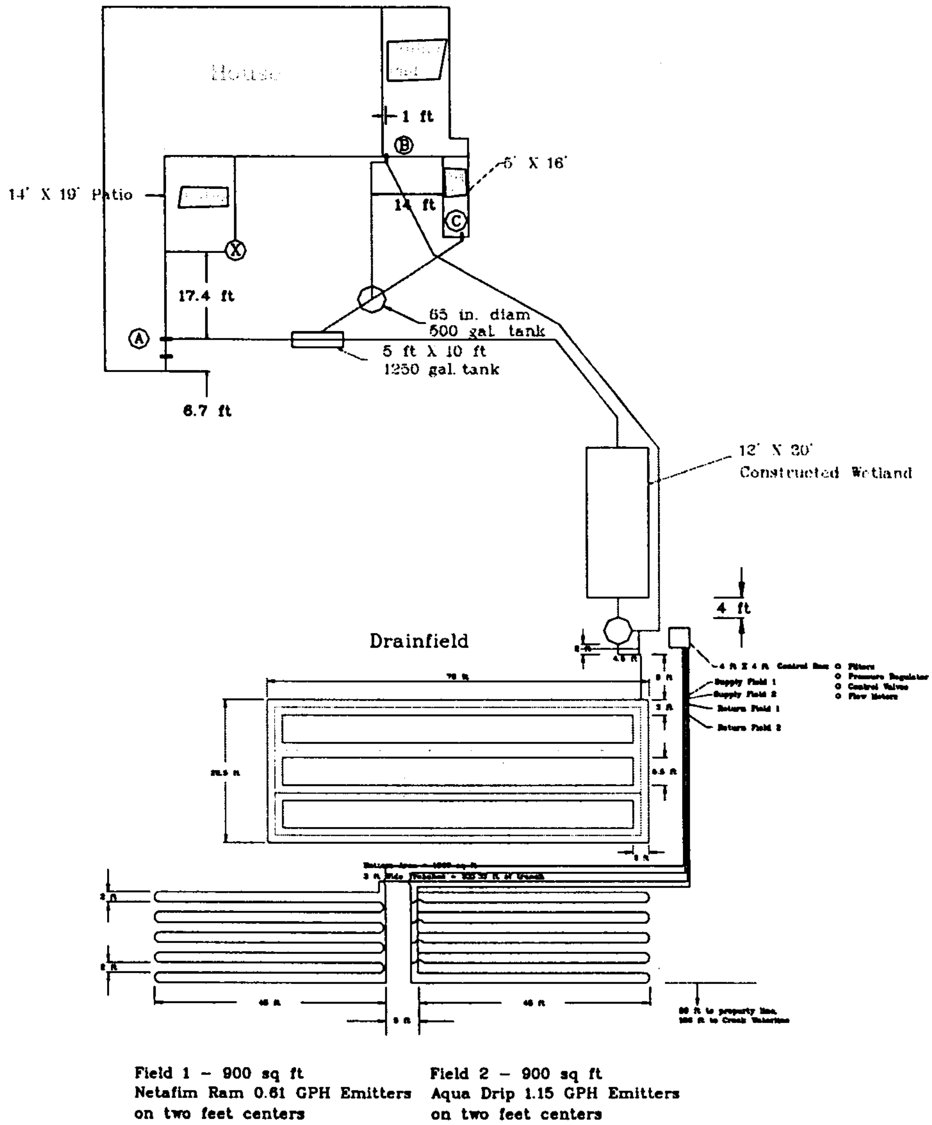

Figure A3- Drawing for site 3 on-site system located in Stephenville, Texas.

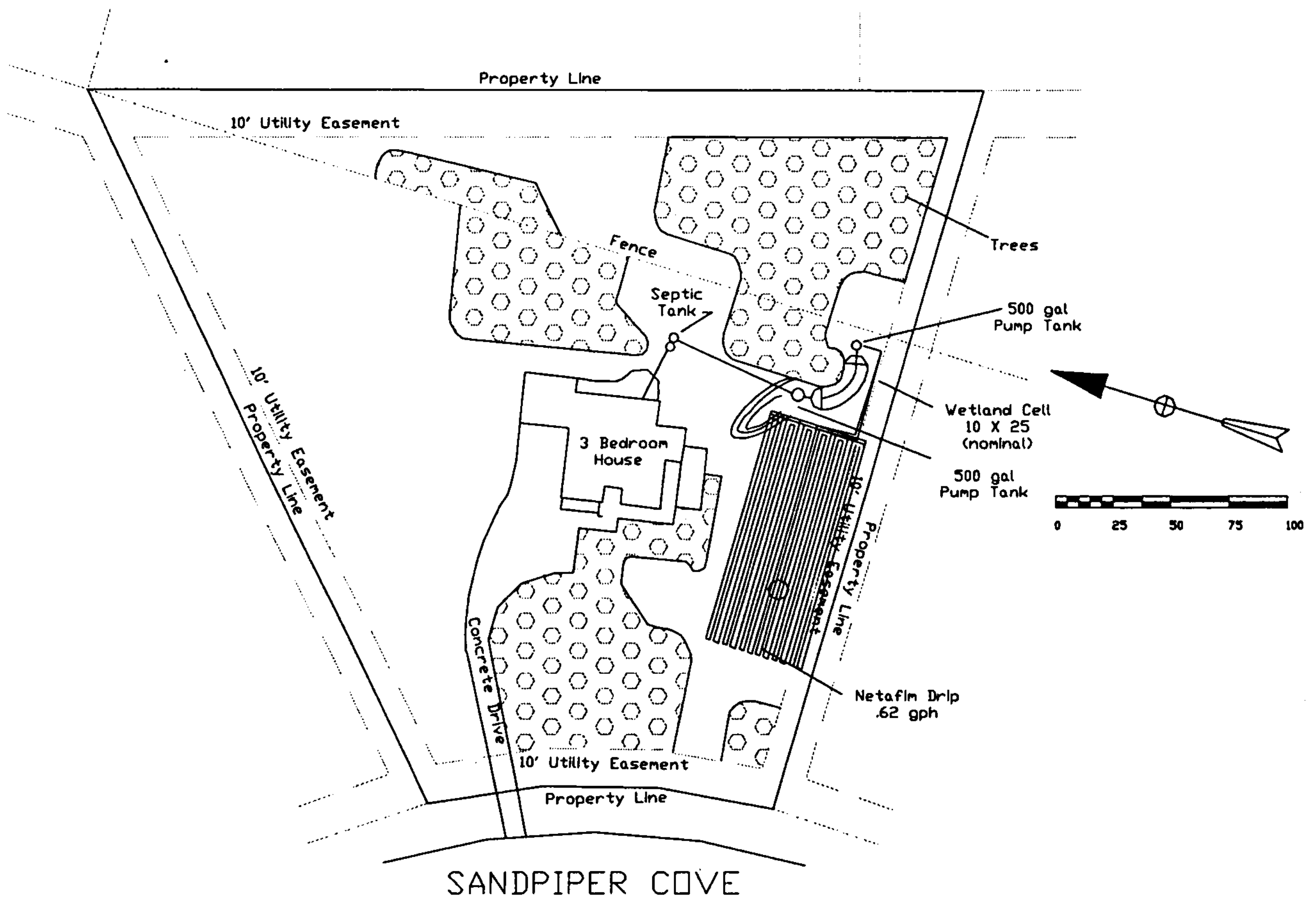

Figure A4- Drawing for site 4 on-site system located in College Station, Texas.