MOVEMENT OF BROMIDE AND IODIDE THROUGH AN ASHPORT SOIL PEDON AND IMPACT ON A SHALLOW UNCONFINED AQUIFER

By

MARK ALEXANDER EVERETT

Bachelor of Science

University of Tulsa

Tulsa, Oklahoma

1993

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1996

MOVEMENT OF BROMIDE AND IODIDE THROUGH AN ASHPORT SOIL PEDON AND IMPACT ON A SHALLOW UNCONFINED AQUIFER

Thesis Approved:

Brian J. Carter

Thesis Adviser

Nicholas T. Basta

Jeffory A. Hattey

Thomas C. Collins

Dean of the Graduate College

ACKNOWLEDGMENTS

I would like to express my thanks to my major advisor, Dr. Brian Carter for his guidance, suggestions, and encouragement. Dr. Carter has been an enormous help to me throughout my Master's program, and has been a very fun person to be around. I would also like to thank the other members of my committee, Dr. Nick Basta, and Dr. Jeff Hattey, for their guidance and assistance in improving this project. Much thanks also goes to Phil Ward, for his many hours of help with various aspects of this study.

I would also like to thank Steve Alspach and Patti Zietlow for their efforts in starting this project in 1991. Without their preliminary work, this study would not be possible. Thanks also to Tyrelle Thompson, who worked many hours on the laboratory analysis portion of the study. For her tireless help with the figures, I am indebted to Vickie Brake. In addition, I would like to thank Eric Hanke and Debbie Porter for help with the final copy of this thesis.

Finally, I would like to thank my entire family, and especially my mother, Frances Everett. Their support and encouragement during my Master's program, and especially during the final preparation of this thesis, has been invaluable.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

Figure Page

Table

INTRODUCTION

Soil properties exert a profound influence on ground-water quality. As soil is the "filter" through which water often travels prior to entering an aquifer, local soil properties such as texture and structure can influence the rate and quality of ground-water recharge. Shallow ground-water systems can be more vulnerable to spills and ill-advised surface chemical applications compared to deeper ground-water systems as less soil overlies them to help buffer potential problems. Shallow aquifers are easily accessible sources of water, they serve as sources of recharge to deeper aquifers, and they can maintain streamflows in times of drought (Fetter, 1994). Materials that are applied to the soil surface or are buried in the soil can move through the vadose zone to shallow and surficial aquifers by saturated and unsaturated water flow (Fetter, 1994). Field experiments are needed to understand the role of soil in regard to rate and quality of ground-water recharge.

The rapid movement of soil water through macropores does not follow piston-flow theory and can carry water-soluble compounds (Bouma, 1983). Some of these compounds can degrade water quality upon entering a shallow aquifer. Matrix or piston-flow can also move solutes into the saturated zone over a longer period of time. If preferential macropore flow occurs in a shallow soil and ground-water system, aquifers can be impacted in a short period of time. In addition, if piston-flow also occurs, aquifers can be impacted over the long-term.

The objectives of this research are: 1) to determine rate and type of movement of surface applied solutes through soil to a shallow aquifer, 2) to assess the impact of a subsequent recharge event on tracer remaining in the soil, and 3) to determine changes in ground-water quality after recharge from surface applied water containing bromide and iodide.

LITERATURE REVIEW

Previous Site Research

The site is located in a residential area of Stillwater, OK. Twenty-seven ground-water monitoring wells, 8 soil-moisture suction lysimeters, and 4 neutron probe access tubes are present at the site (Ross, 1988). Initial investigations by Hagen (1986) and Hoyle (1987) revealed spatial and temporal changes in ground-water quality (electrical conductivity) and water table elevation. These variations were beleived to be caused by rapid preferential flow through soil macropores.

Macropore flow was also documented at the site by Ross (1988) and Acre (1989). Ross (1988) found fluctuations in soil-water quality over short periods of time, and attributed them to fertilization and macropore flow. Acre (1989) documented fluctuations in soil-moisture content and also determined that preferential flow through macropores was the cause.

Froneberger (1989) utilized surface-applied bromide and chloride tracers to study soil-water movement through the unsaturated zone. Within a short period of time, large slugs of the tracers were found in the lysimeters, and this was credited to preferential macropore flow.

Macropores

Lawes et al. (1882) were some of the first researchers to document the effects of macropores on soil-water behavior. They observed that soil macropores moved water quickly to a sizeable depth with only small changes in chemical composition.

Brewer (1964) described macropores as pores that are at least 100 μm in diameter. Luxmoore (1981) detailed three classes of soil pores: micro, meso, and macropores. Size classification of soil pores was also furthered by Skopp's (1981) response to Luxmoore (1981) to incorporate the processes occurring within the pore in the definitions of soil porosity terms. Zietlow (1992) states that techniques for measuring macropore size include timing and measuring water flow through soil cores, tracing visible voids, staining with methylene blue, and scanning soil photographs with an image analyzer (Smettem, 1987; Louren et al., 1988; Radulovich et al., 1989; Edwards et al., 1988).

Pore space in soils typically ranges from 33% to 67% of the total soil volume (Soil Survey Staff, 1981). The Soil Survey Staff (1981) developed a system for classifying soil pores in which pores are classified according to size, quantity and shape. Pores less than 0.075 mm are classified as micropores.

Beven and Germann (1982) classified macropores according to their type. This included cracks and fissures along ped faces of shrinking soils, and cracks caused by worm, insect, and plant-root activity. Chan and Mead (1989) found that a 25 year-old pasture had a higher density of water-transmitting macropores when compared to both a 9-year old pasture and a field under cultivation. Heard et al. (1988) studied the effects of long-term conservation tillage on soil macroporosity. They found that while not increasing the number of channels, conservation tillage plots had the greatest number of continuous channels or macropores (Heard et al. 1988).

To describe vertical saturated flow through macropores in unsaturated soils, Bouma and Dekker (1978) coined the phrase "short circuiting". Rogowski and Simmons (1988) confirmed that soil macropores produce field measured hydraulic conductivities greater than laboratory calculated conductivities due to preferential flow. In a laboratory study using undisturbed soil cores, Germann and Beven (1981) illustrated that with a continuous water supply and subsequent macropore flow, the hydraulic conductivity of the soil increases due to rapid flow through macropores.

Many researchers have shown that macropores can enhance solute movement through the unsaturated zone. Black et al. (1973) found that tritium applied to a clay soil with shrinkage cracks moved to a depth of 80 cm within one hour after being applied. Black et. al. (1973) also found that soil coatings on the outer surface of the peds in this soil had higher tritium concentrations than soil material from the inner portions of the peds, and attributed this to tritium moving down the cracks and then being absorbed into the outer surface of the peds. Quisenberry and Phillips (1976) noted that water and chloride moved through a silt-loam aquifer with only small changes in composition. They attributed the phenomenon to preferential macropore flow. Priebe and Blackmer (1989) also found macropores to cause ^{18}O labeled water and ^{15}N labeled urea to have little change in composition after moving preferentially through soil.

Ehlers (1975) found that almost all earthworm channels that reached the surface of an untilled soil formed from loess were capable of transmitting water deep into the soil profile. Edwards et al. (1988) found that continuous worm burrows were important factors for rapid infiltration into a non-tilled silt loam soil during intense rainstorms.

Bromide and Macropores

Bromide tracers have been used to evaluate the influence of macropores on infiltration, solute movement, and ground-water quality. Tennyson and Settergren (1980) quantified bromide movement through a soil profile in order to evaluate water and ion movement at a proposed sewage effluent irrigation site. Results showed that macropores cause field measured values of hydraulic conductivity to be greater than those measured in the laboratory. Zachmann et al. (1987) used bromide to trace water movement into soils in which worm populations had been added and found that these soils showed evidence of macropore flow through worm burrows. Germann et al. (1984) utilized bromide to document that water infiltrates to a greater depth in soils with macropores. Bromide tracer recovery below 0.5 m, one day after being applied in a 3 cm rainfall, ranged from 32% to 42% on a non-tilled silt loam soil column and was attributed to movement through macropores (Germann et al., 1984). Chan and Mead (1989) studied the movement of bromide into soil and verified that macropores significantly decreased runoff. Starr and Glotfelty (1990) studied the pattern of bromide movement through a field soil as affected by plow and conservation tillage under severe leaching conditions. Two different processes of bromide movement were described: one-dimensional movement through the soil matrix and rapid downward movement through macropores, by-passing most of the soil matrix (Starr and Glotfelty, 1990).

Bromide as a Tracer

Bromide can be used in field experiments at low but detectable concentrations, posing no health or pollution problem (Schmotzer et al., 1973). Bromide is not considered to be toxic to plants (Martin, 1966). Davis et al. (1980) concluded that bromide is a good tracer in ground-water studies because it occurs in concentrations less than 0.01 mM bromide in natural waters and has low toxicity. LeBlanc and Garabedian (1986) utilized bromide to examine the process of solute dispersion in ground-water. D'Lugsoz (1976) used bromide present in brines as an indicator of salt-water contamination in aquifers.

Afyuni et al. (1994) evaluated lateral and vertical transport of bromide as a function of landscape position. When comparing footslope, linear slope, and interfluve landscape positions, they found vertical and lateral bromide transport to be greatest at the footslope position. They concluded that variability in bromide transport is related to soil profile characteristics and hydrology at different landscape positions. Sharma and Taniguchi (1991) investigated the effect of the mode of water application (steady state vs. intermittent) on the leaching of a pulse of bromide. Results showed that the movement of the solute peak was much faster under the steady state than the intermittent application. Levy and Chambers (1987) tested the assumption that potassium bromide is a conservative tracer for soil-water studies. Their results showed no significant sorption of bromide to soils and therefore indicated that bromide is a conservative tracer under the conditions examined. Owens and Edwards (1992) studied the impact on ground-water quality of a one-time application of bromide. Results indicated seasonal variations in bromide concentrations in the ground-water. The highest concentration (9.2 mg/L) occurred within three years following the initial application. Bromide concentration in the ground-water was slightly above baseline levels ten years after application (Owens and Edwards, 1992). Bruce et al. (1985) measured the redistribution of bromide applied to the surface of a sandy loam soil in relation to rainfall and pedon characteristics. Rainfall was found to be more effective in transporting bromide through drainageway soil pedons than those on the slopes.

Iodide has also been used as a tracer in soil and ground-water systems. As iodide behaves similarly to bromide, the two ions can be used in the same experimental system in order to substantiate impact of one tracer application period on another. However, bromide and iodide are not identical. The iodide ion is larger, with a radius of 0.219 nm, while the bromide ion is smaller, with a radius of 0.196 nm (Brown and LeMay, 1981). Because the iodide ion is larger than bromide, it may move more slowly through the soil system (Zietlow 1992). Davis et al. (1985) and Leap and Sun (1978) noted that iodide may also be adsorbed to a larger degree than bromide, lowering its concentration in groundwater.

Muramatsu et al. (1990) documented that iodide is not highly adsorbed to quartz sand or clay minerals. Bradbury and Green (1985) analyzed diffusion rates through crystalline rock matrices with iodide to study the feasibility of radioactive waste disposal in crystalline rocks such as granite. Results indicated weathered fracture surfaces increase diffusion and rock holding capacity. Leap and Sun (1978) used iodide in carbonate rock tracer studies and found that iodide can be detected at lower concentrations than bromide. Rowe et al. (1965) analyzed underground water circulation in hot springs and geysers of Yellowstone National Park with sodium iodide. Results indicated that sodium iodide was a suitable tracer which aided in the identification of subterranean reservoirs and interconnections linking certain hot springs and geysers.

Bromide and Nitrate

Some researchers (Onken et al., 1977; Smith and Davis, 1974) have shown that bromide can be used to mimic nitrate movement in soils, however, differences exist between the ions that can create problems. Nitrogen is an essential element required in large amounts for plant growth, while bromide is not. In addition, nitrogen circulates through the environment via the nitrogen cycle, while bromide does not.

Onken et al. (1977) used bromide concentrations in soil water ranging from 0.06 mM to 0.50 mM and concluded that nitrate and bromide move similarly in soil under field conditions. Breakthrough curves for nitrate and bromide movement in subsoil columns illustrated that bromide simulates the movement of nitrate (Smith and Davis, 1974). Bromide can potentially mimic the movement of nitrate in soils because both are: 1) monovalent anions, 2) similar in ionic radii, and 3) taken up by plants (Kung 1990). The ionic radius of bromide is 0.196 nm compared to 0.189 nm for a nitrate ion (Sidgwick, 1950).

Owens et al. (1985) observed that the amount of applied bromide taken up by plants in a pasture research plot was similar to nitrate uptake. Five weeks after being applied, 32% of the 168 kg Br^-/ha applied had been taken up by plants (Owens et al., 1985). Kung (1990) examined the influence of plant uptake on the performance of bromide tracer in potatoes. Results showed that at least 53% of applied bromide mass was absorbed by potato plants. Approximately 44% of the absorbed bromide was later made available to the soil after portions of the potato plants decayed. Kung (1990) argued that leaching potential of some chemicals can be grossly overestimated by using bromide breakthrough curves in situations where plants will absorb much of the chemical, and be underestimated in situations where plants absorb little of the chemical. Brown et al. (1979) studied plant uptake of bromide following methyl bromide soil fumigation. Results showed that methyl bromide remaining in the soil was hydrolyzed or decomposed by microorganisms, releasing bromine as inorganic bromide. In addition, a linear relationship was found between soil bromide and plant uptake in one plot, while not in other plots (Brown et al., 1979). Kempton and Maw (1972b) studied tomato plants grown in soil fumigated with methyl bromide, and found that inorganic bromide was accumulated in the foliage. The bromide concentration in the tomatoes depended on application rate and the duration of interval between fumigation and planting. Kempton and Maw (1972a) also studied lettuce plants grown in soil supplemented with 0-5000 mg inorganic Br^-/kg soil. Concentrations in the plants ranged up to 100,000 mg/kg of dry tissue. Bromide was also found to be located mainly in the outer leaves (Kempton and Maw, 1972a).

Jabro et al. (1991) characterized the movement of water and solutes in soils with dual pore systems (macro and micropores) using bromide as a tracer under saturated conditions. Jabro found that the distribution of the bromide tracer in the soil profiles was highly variable. Results indicated that NO^-_3-N contained in irrigation water or fertilizer solutions added to soils could result in preferential movement of NO^-_3-N from the root zone to ground-water under saturated conditions.

It is clear that under certain conditions, bromide behaves similarly to nitrate. Also clear, however, are the many pathways of the nitrogen cycle which make nitrogen movement through the environment much more complex than that of bromide. Due to these complexities, researchers must use caution when evaluating the effectiveness of bromide as a nitrate tracer.

Piston-Flow

A commonly held concept of soil-water movement is that of piston or displacement flow. The piston flow concept states as water enters the soil it completely displaces the water that is already present in soil pores. Darcy's Law is commonly used to characterize this type of flow in saturated soils (Darcy, 1856; Hubbert, 1956). Richards (1931) extended Darcy's Law to encompass the flow of water in unsaturated soils. Bodman and Colman (1943) noted a wetting "front" when applying water to dry soil, and concluded that the maximum water content attained in the soil was approximately field capacity.

Izadi et al. (1993) used three piston-flow models based on Darcy's law, field capacity, and the Transfer Function Model (Jury, 1982) to predict movement of bromide through soil. The final measured position of bromide was significantly greater than predicted by the piston-flow models, and Izadi (1993) concluded that preferential flow must have occurred in the soil. Rice et al. (1991) also found that preferential flow phenomena in soils resulted in solute and herbicide velocities of 1.6 to 2.5 times faster than calculated by traditional water balance methods and a piston-flow model.

Preferential Flow Without Macropores

Ghodrati and Jury (1990) used dyes to track the pathway of water into a loamy sand soil and showed that three-dimensional preferential-flow channels occurred in the almost structureless loamy sand. These flow channels were likely present due to the channeling of water through matrix regions with higher than average permeability (Simpson and Cunningham, 1982) or a fluid instability induced by crusting or subsurface layering (Ghodrati and Jury, 1990). Based on research performed on a clay loam soil, Bowman and Rice (1986) also concluded that significant preferential flow can occur even in soils with weak structure.

MATERIALS AND METHODS

Site Description

The site lies within the northeast 1/4 of section 11, T 19 N, R 2 E in the city limits of Stillwater, Oklahoma. The uppermost soil profile at the site (0 - 1.22 m) has been mapped as the Ashport silt loam soil series (Henley et al., 1987). The Ashport soil series is classified as a Fine-silty, mixed, thermic Fluventic Haplustoll that occurs on floodplains along streams in Payne county (Henley et al., 1987). Ross (1988) provides a description of the complete soil profile at the site (Table 1). Ross (1988) described two buried soil profiles beneath the overlying Ashport soil profile. The first of these extends from 1.22 - 8.40 m below surface and has been radiocarbon dated at 1,300 +/- 70 years before present (Ross, 1988). The second buried profile occurs from 8.40 - 10.80 m and has been dated at 10,600 +/- 170 years before present (Ross, 1988). Below this second buried profile is a layer of gravel grading upward into alluvial sand (10.80 - 13.10 m), followed by the underlying Doyle shale (Table 1) (Ross, 1988). The aquifer is contained within these buried alluvial soils and the water table fluctuates between approximately 1.25 and 3.50 m below land surface (as observed from 1986-1996).

Typical soil moisture contents at the site range from 0.11 - 0.35 cc/cc (Ross, 1988; Froneberger, 1989). When the water table is high, moisture levels are fairly uniform with depth, however, when low, moisture levels are more variable (Zietlow, 1992).

Naturally occurring macroporosity is present at the site. Zietlow (1992) states that dessication crack macropores with surface openings as much as 1.27 cm wide often form at the site during prolonged dry periods. Hagen (1986) and Ross (1988) noticed cracks between ped faces during their examinations of the site. Zietlow (1992) noted abundant root macropores at the site, with the soil being characterized by deep root zones. Ross (1988) noted many roots and root casts in the upper soil profile. Zietlow (1992) also noticed tunneling earthworms in soil cores from the site. These characteristics are typical of the Ashport soil series (Soil Conservation Service, 1987).

Field Methods

Plot design

Field plots were designed to place bromide or iodide laden water in areas surrounding a cluster of ground-water monitoring wells (D1 through D5) (Figures 2a and 2b). The main plot had an area of 5.5 m^2 and two smaller plots each covered 1.5 m^2. As soil cores were taken to a depth of 2.4 m, the main plot volume was 13.2 m^3. Surface applied bromide and iodide laden water was contained within the plot area with plastic landscaping border partially buried to a depth of 2.5 cm. Loose soil was packed on the outward facing side of the landscape border to help stabilize it.

To prevent lateral movement of the tracer once it had entered the soil, a boundary area was established (Figure 2a) that received the same amount of rainfall as the research plots. Equal amounts of water were applied to both the treatment and boundary areas. Water was applied to the boundary area with biwall drip-irrigation tubing. The irrigation tubing was installed in three 152.5 m sections with a 15 cm spacing between each loop. Each section was connected to a residential water supply and each had an in-line pressure regulator to regulate the amount of water applied to each boundary section.

Timing of tracer application

Two separate tests were completed at the research site. The first test was made on March 1, 1991 using a bromide tracer. Both soil and ground-water samples were taken and analyzed during the first test. On April 29, 1991 a second test was made using an iodide tracer. This second test was made to assess the impact of another recharge event on bromide remaining in the soil and to determine the impact of the application of trace amounts of iodide on ground-water quality. The initial soil moisture content average during the iodide test (0.25 cc/cc) was higher than that for the bromide test (0.20 cc/cc) (Zietlow, 1992). For the iodide test, only ground-water samples were taken and analyzed.

Tracer application

The application of the bromide and iodide tracers to the treatment areas involved applying 7.5 cm of water to each plot over a three hour period. Storage containers with a capacity of 150 liters were filled with deionized distilled water and then KBr and KI were added to produce a 6.3 mM bromide (480 mg/L) and 0.05 mM (6.7 mg/L) iodide concentration. The bromide concentration was chosen to represent a typical soil amendment rate and the iodide concentration represented an application of trace amounts. Because iodide was added in trace amounts, detectable levels (via saturated paste and ion chromatograph) were not expected and were not found in the soil. The 5.5 m^2 plot received 412.5 L of tracer-laden water. Each of the smaller 1.5 m^2 plots received 112.5 L of water. Given this volume of water and the chosen tracer concentrations, 1.98×10^5 mg of bromide and 2.76×10^3 mg of iodide were added to the largest plot. To apply the water to the surface of the plots, several hoses running from the storage containers to the soil surface were used. The flow from each hose was regulated with clamps so that each plot received 2.5 cm of simulated rainfall per hour. The hoses were moved on a regular basis to equally cover the plots with bromide and iodide laden water.

Sampling in the field

Sampling in the field involved taking soil cores that were evaluated to monitor bromide movement in the soil, and ground-water sampling used to monitor bromide and iodide tracer amounts in the wells. A separate coring was also performed after tracer testing to determine bulk densities in 10 cm increments. Ground-water samples were taken every 5 minutes for the first 5 hours of the experiment, dropping to every 10 to 15 minutes for the remainder of the collection period (Zietlow, 1992). Water levels taken before testing verified ground-water flow from the tracer application area toward the D well cluster (Figure 2b) (Zietlow, 1992). A pressure transducer in the well continuously measured depth to water during the experiment.

Soil cores were taken prior to testing and after complete application of bromide. At timed intervals (background, 4.0 hrs after start, 5.7 hrs, 10.4 hrs, 23.1 hrs, 57.6 hrs, 151.0 hrs, 2.0 months, and 3.4 years), soil within the largest plot was cored to a maximum depth of 2.4 m using a soil probe machine (Giddings Machine Co., Inc. model HD-GSRP-S, Fort Collins, Colorado). Three continuous cores, 5 cm in diameter were taken at each time interval. Each core was retrieved in two parts with each part having a length of 1.2 m. After each core was removed, the hole was quickly filled with sand and bentonite to prevent water movement. The sand and bentonite were placed in approximately 30 cm layers and each layer was compacted using a metal rod. Immediately after being retrieved, each core was removed from the metal coring tube and cut into 10 cm segments. Each segment was then placed into a labelled plastic ziploc bag for storage.

Laboratory Methods

Each soil sample collected in the field was taken to a laboratory for analysis. One core was utilized to determine bulk densities in 10 cm increments. Soon after coring, gravimetric water contents were determined for each soil sample. To determine the bromide content in the soil samples, saturated paste extracts were made from each sample according to the method described by Rhoades (1982). The only variation from Rhoades (1982) was the extraction of soils using a Baroid press rather than a vacuum filter funnel. Extracted soil solution was filtered using a 0.2 μm membrane filter. After filtering, a 1:10 dilution of extract and distilled water was made, and 1 ml of this dilution was analyzed on an ion chromatograph (Dionex Corporation model 2000i, Houston, Texas) for determination of bromide concentration. Three bromide and iodide standards were used to calibrate the ion chromatograph. The separator column used was a Dionex corporation model HPIC AS4A, with an eluent of 1.8 mM Na_2CO_3/1.7 mM $NaHCO_3$ flowing at a rate of 2 ml/min. The column was regenerated with 0.0125 M H_2SO_4. Ground-water samples were also analyzed for bromide and iodide using the ion chromatograph.

RESULTS AND DISCUSSION

Soil-Water Content

Volumetric water content (θ_v) of the upper 240 cm of soil (Figure 3) increased from background levels after starting the bromide tracer test. Mean θ_v for the entire sampling depth prior to testing (background) was 0.25 cc/cc.

Background data also revealed a relatively dry zone (θ_v=0.16 cc/cc) in the soil profile from 90-100 cm (Figure 3). At 4 hours after starting tracer application, θ_v increased from background levels at all sampling depths. Mean θ_v at 4 hours for the upper 240 cm was 0.29 cc/cc. The 4 hour data also revealed a relatively dry zone (θ_v=0.23 cc/cc) from 90-100 cm compared to the rest of the sampling depths. For the remaining sampling times (5.7-151.0 hours) at which water content was determined, θ_v was similar throughout the entire sampling depth (Figure 3). Mean θ_v for 5.7, 10.4, 23.1, and 57.6 hours in the upper 240 cm was 0.30 cc/cc, and was 0.31 cc/cc for 151 hours.

The volumetric water content vs. soil depth curves in Figure 3 represent a typical recharge event of a relatively dry soil profile. Central Oklahoma's mean annual precipitation is 86.4 cm (Pettyjohn et al. 1983), with the wettest seasons being spring and fall. Oklahoma has relatively dry winters, and soil profiles tend to gradually dry out after the fall recharge period. The majority of data is within the 0.11-0.35 cc/cc averages for the site calculated by Ross (1988) and Froneberger (1989). The drier portions of the background and 4 hour curves at approximately 100 cm (Figure 3) is due to a sandier soil texture at that depth (Figure 1 and Table 1) which tends to hold less water than soil textures containing more silt and clay.

Soil-Bromide Content

Soil cores were taken before and after application of the bromide tracer solution and were analyzed for bromide content. Bromide concentration within the three cores was averaged for each sampling time. Nine sampling times were examined: background, 4.0 hrs after start, 5.7 hrs, 10.4 hrs, 23.1 hrs, 57.6 hrs, 151.0 hrs, 2.0 months, and 3. 4 years (Figures 4a-i). The background soil-bromide content for the entire sampling depth (0-240 cm) averaged 0.15 mg Br^-/kg soil (Figure 4a). The total background bromide content within the main plot volume (13.2 m^3) was 2.53×10^3 mg. A possible source for this background bromide concentration is leakage from septic and sewer lines in the area. Bromide is often used in cleaning agents and could therefore be present in septic and sewer lines.

At 4 hours after starting the bromide application (Figure 4b), the upper 60 cm of the plot had a significant increase from background in mean bromide concentration (3.12-30.68 mg Br^-/kg soil). Also at 4 hours, the 70-130 cm depth contained bromide discontinuously above background levels (0.85-3.32 mg Br^-/kg soil). Below 130 cm, mean bromide concentrations were below 1 mg Br^-/kg soil. Total bromide content in the plot volume at 4 hours was 6.19×10^4 mg (31% of total applied).

At 5.7 hours after beginning tracer application (Figure 4c), the 0-130 cm soil depth contained mean bromide concentrations significantly above background levels (4.35-27.22 mg Br^-/kg soil). Two "peaks" of bromide were present at 5.7 hours, the first at the surface (0-10 cm) (27.22 mg Br^-/kg soil) and the second at 100-110 cm (14.83 mg Br^-/kg soil). Below 130 cm, mean bromide concentration was below 1 mg Br^-/kg soil. Total bromide within the plot volume at 5.7 hours was 1.01×10^5 mg (51.2% of total applied).

The bromide data for 10.4 hours after tracer application appears quite similar to bromide data at 5.7 hours (Figure 4d). At 10.4 hours, the 0-140 cm soil depth contained mean bromide concentrations above 1 mg Br^-/kg soil. Two distinct peaks were also present at this sampling time. The first was found at the surface (0-10 cm) (22.36 mg Br^-/kg soil), and the second at 90-110 cm (11.57-11.68 mg Br^-/kg soil). Below 140 cm, mean bromide concentrations were below 1 mg Br^-/kg soil. Total bromide content within the plot volume at 10.4 hours was $9.26x10^4$ mg (46.8 % of total applied).

Two mean bromide concentration peaks also appeared at the 23.1 hour sampling time (Figure 4e). The first peak was located at the surface (0-10 cm) (22.06 mg Br^-/kg soil), and the second was located at 90-100 cm (18.74 mg Br^-/kg soil). Below 130 cm, mean bromide concentrations were below 1 mg Br^-/kg soil. Total bromide within the plot volume at 23.1 hours was $1.05x10^5$ mg (52.8% of total applied).

At the 57.6 hour sampling time (Figure 4f), the highest mean bromide concentration was at the surface (0-10 cm) (19.97 mg Br^-/kg soil). Bromide was then found discontinuously above 1 mg Br^-/kg soil from the surface to the 100 cm depth. Below 100 cm, mean bromide concentrations were below 1 mg Br^-/kg soil. Total bromide content within the plot volume at 57.6 hours was $5.08x10^4$ mg (25.7% of total applied).

One hundred fifty-one hours after beginning tracer application (Figure 4g), the highest mean bromide concentration of 18.29 mg Br^-/kg soil remained at the surface (0-10 cm). From 20 to 90 cm, mean bromide concentrations were within the 2.62-5.43 mg Br$^-$/kg soil range. A peak of 9.32 mg Br$^-$/kg soil was found at the 90-100 cm depth. Below 130 cm, mean bromide concentrations were below 1 mg Br$^-$/kg soil. Total bromide content within the plot volume at 151 hours was 6.25x10^4 mg (31.6% of total applied).

Two months after tracer application, bromide levels near the surface were lower than at 151 hours (Figure 4h). The maximum mean concentration found near the surface was 11.59 mg Br$^-$/kg soil. A peak of 6.53-6.78 mg Br$^-$/kg soil was found at the 90-110 cm depth. Below 120 cm, mean bromide concentrations were below 1 mg Br$^-$/kg soil. Total bromide content in the plot volume at 2 months was 5.35x10^4 mg (27.0% of total applied).

At 3.4 years after tracer application, mean bromide concentrations were below 1 mg Br$^-$/kg soil from the surface to a depth of 120 cm (Figure 4i). At 130-140 cm, a peak of 10.11 mg Br$^-$/kg soil was found. This peak then gradually declined to below 1 mg Br$^-$/kg soil between 200 and 220 cm. Total bromide content in the plot volume at 3.4 years was 2.63x10^4 mg (13.3% of total applied).

Many similarities exist between the soil-bromide data for the nine sampling times. Except for 3.4 years, the highest bromide concentrations for each sampling time were found at the 0-10 cm depth (Figure 4a-i). This occurs for two reasons. First, bromide was applied at the surface, and was retained within the matrix of the surface soil horizons via adsorption by water. Secondly, bromide concentration was increasingly diluted by resident soil-water with depth. All of the sampling times except 3.4 years also have their second highest bromide concentration corresponding to a discontinuity in the soil profile. Due to the rapid development with which this second peak appeared, the peak is likely due to macropore flow.

The C horizon of the uppermost soil profile represents a textural and structural soil discontinuity and is located from 97-127 cm (Figure 1 and Table 1). The C horizon is a fine-sandy loam with silt loam textures above and below. Ross (1988) describes its structure as finely laminated stratified sand and the horizons above and below as subangular blocky (Table 1). All of the sampling times (except background and 3.4 years) have a bromide peak just above or within this C horizon. Changes in soil texture and structure such as this Ashport soil C horizon tend to impede the downward movement of macropore flow of water and solutes through soil (Brady, 1990). The larger pores in the fine-sandy loam of the C horizon provide less matric potential for water than the finer pores of the silt loam above. Only when the moisture and the matric potential gradient is raised sufficiently will the water move into the sandier layer (Brady, 1990).

The upper 130 cm of soil was rapidly (within 4 hours) and continuously (up to 2 months) influenced by the surface-applied water and bromide (Figure 4b-h). The highest mean concentration found was 30.68 mg Br^-/kg soil (0-10 cm) at 4 hours after application began. The majority of the mean bromide concentration data from 4 hours through 151 hours are within the 4-20 mg Br^-/kg soil range. By two months, mean concentrations decreased to the 0-10 mg Br^-/kg soil range. As bromide was applied to the surface at a rate of 480 mg/L, the majority of bromide found in the soil-water was 4.8 to 24 times lower than surface applied concentrations. This lowering of bromide concentration was due to dilution with soil-water already present in the profile, and lateral flow of tracer away from the plot area after the effectiveness of the boundary area was diminished. The boundary area would not prevent lateral diffusion of bromide after drying, and this could be a source of lost bromide for the later sampling times. In addition, the saturated paste method could have underestimated bromide concentrations due to dilution.

The data (Figure 4a-i) indicates that much of the bromide moved downward through the soil via preferential macropore flow and piston-flow. The bromide spikes (Figure 4b-f: 4 hrs.- 57.6 hrs.) that occurred with depth soon after tracer application are likely due to macropore flow because of the rapid speed with which they appeared. This is supported by Rogowski and Simmons' (1988) claim that macropores cause field hydraulic conductivities to be greater than would be anticipated, and by Froneberger's (1989) findings of macropore flow at the site. The bromide curves (Figure 4a-i) also reveal that piston-flow and macropore flow of the tracer solution was influenced by textural and structural changes within the soil profile.

Total bromide levels found within the main plot volume (13.2 m^3) ranged from 13.3% (3.4 years) to 52.8% (23.1 hours) of total (1.98×10^5 mg) surface-applied bromide. Total bromide recovery rose to a maximum at 23.1 hours, and then declined to a minimum at 3.4 years. Some of the variation can be explained by the sometimes substantial variation between soil cores within the same sampling time (depicted as standard deviation in Figure 4a-i). Macropore flow is a likely cause of some of the variation between cores because due to their circuitous pathways, macropores can impact one soil core while not affecting another core nearby. As the cores were used to estimate total bromide content, macropore flow could cause some of the variation in the total bromide content between cores. In addition, the manner in which bromide was applied to the plot area could cause variation in total bromide content between cores. Bromide was applied with tubing that was manually moved across the plot area. This method may have resulted in a somewhat unequal distribution of bromide to the plot surface.

As the wells were periodically checked and no large amounts of bromide were found, some of the bromide moved laterally through the soil away from the main plot area by diffusion and this could account for some of the difference between total bromide applied and bromide found in the soil. Another potential loss pathway of bromide could have been uptake by grass, followed by grass removal after mowing at the site. Owens et al. (1985) reported that 32% of 168 kg Br^-/ha was taken up by grass in a pasture. Grass uptake could account for a portion of the bromide unaccounted for by soil extracts in the main plot, but amount of grass and bromide removal from the site was not monitored.

At 3.4 years after surface application, mean bromide data indicates a peak of 10.11 mg Br^-/kg soil below the Ashport soil C horizon (97-127 cm) (Figure 4i). Above this peak, mean bromide concentrations were below 1.5 mg Br^-/kg soil. By 3.4 years the peak at 2 months within the top of the C horizon had moved through the discontinuity and will likely continue to proceed downward via piston flow with time. If this "front" continues downward, it will eventually reach the aquifer. In addition, if this "front" moves at the same rate (41 cm/yr), it would reach 2.5 m and the water table at 6.1 years after surface application.

Bromide Content in Wells

The surface of the shallow aquifer at the site was 2.5 m below ground surface on the day of the bromide tracer test. Initial soil moisture content during the bromide test averaged 0.20 cc/cc. Background bromide concentration for the D wells was 0.33 mg/L. Well D1 did not contain water during the experiment. Wells D2 and D3 were monitored and were found to contain bromide after tracer application to the soil surface (Figure 5). Bromide above background levels was not detected within wells D4 and D5.

At approximately 3 and 6 hrs. after the start of surface water and bromide application, wells D2 and D3 contained bromide above background levels, respectively (Figure 5). After rising above background levels, bromide concentration in well D2 remained above 0.4 mg/L for the remainder of the test. Bromide in well D2 had a 5-hour peak above 0.5 mg/L, with a top concentration of 0.8 mg/L (2.4 times higher than background) at 6.17 hours. Bromide concentration in well D3 began to rise above background concentrations at approximately 6 hours and remained above background until 12 hours after surface application (Figure 5). A peak above 0.4 mg/L was present in well D3 from approximately 6.3 to 8.9 hours. The highest concentration found in well D3 was 0.49 mg/L (1.5 times higher than background) at 8 hours after surface bromide application.

Bromide did not appear in well D1 because it was screened above the water table (2.5 m). A possible explanation for bromide not appearing in wells D4 or D5 is dilution. Well D4 is screened from 4.1 - 4.2 m and any bromide reaching it was likely diluted to background levels by the aquifer volume. Any bromide in well D5 was also diluted to background levels because while D5 is screened over a large interval (2.1 - 4.3 m), ground-water samples were taken from the bottom of the well (4.3 m). Another possible explanation for lack of bromide in wells D4 and D5 is lateral ground-water flow moving bromide away from the wells before bromide could reach the lower depths in the aquifer at which these wells were sampled.

Bromide applied to the soil surface was detected first and for longer duration in well D2 compared to well D3 (Figure 5) because well D2 was monitoring the surface of the shallow aquifer (it is screened from 2.7 to 2.8 m). Well D3 detected bromide at lower concentrations, at a later time, and for a shorter period of time compared to well D2 because it was screened below D2 and the aquifer surface (3.0 - 3.2 m). Both dilution and lateral movement of bromide via ground-water are possible explanations for these results.

Bromide began appearing above background levels in well D2 approximately 3 hours after beginning surface application. As the top of well D2's screened interval is 2.7 m, bromide moved through the soil and aquifer at a rate of 90 cm/hr or 1.5 cm/min. Bromide arrived at well D3 (3 m) 6 hours after application began, which would indicate a movement rate of 50 cm/hr or 0.83

cm/min. These rates are much higher than the 2.1×10^{-3} - 5.4×10^{-3} cm/hr saturated hydraulic conductivities measured in the lab for the site (Melby, 1989).

Compared to the surface-applied bromide concentration of 480 mg/L, the maximum concentration found in the wells of 0.8 mg/L is small. This is due to dilution of the tracer solution by soil-water and aquifer water.

Bromide reached a shallow aquifer 2.5 m below surface before the overlying soil was fully impacted by the tracer solution as indicated by soil-bromide content (Figure 4a-i). While dilution of the bromide concentration took place, the speed with which some bromide reached the aquifer indicates preferential flow through macropores. As stated in the site description, the Ashport soil profile was relatively dry (9.3% saturation) and macropores of various types were present (dessication cracks, cracks between ped faces, roots and root casts, and earthworm-caused macropores).

As the wells were periodically checked up to March 1996 and no significant amounts of bromide were detected, most of the bromide was either not detected as it entered the aquifer, diffused away from the study area, or was taken up by plants. Only 13.3% of total bromide added was found in the main plot volume at 3.4 years, therefore much of the bromide could have remained in the adjacent soil or entered the aquifer outside the plot area.

Iodide Content in Soil and Wells

Background levels for iodide in the D wells was below the detection limit of the ion chromatograph (< 10 ug/L) (Zietlow, 1992). Initial depth to water on the day of the iodide test was 2.4 m. Initial soil moisture content (0.25 cc/cc average) was higher than that of the bromide test. Iodide above background levels was found only in wells D1 and D2 (Figure 6). Iodide concentration reached 3.0-3.5 mg/L 5.5 hrs after surface application of water and iodide and only 1 hr after initial detection of iodide in well D2. Iodide concentration 10.4 hrs after surface application was 0.86 mg/L in well D2. Iodide first appeared in well D1 at 5.8 hours (0.25 mg/L), then remained around 0.4 mg/L for the next 3 hours (Figure 6). Iodide in well D1 then rose to 1.0 mg/L at 10.2 hours after starting.

No iodide was found in the soil cores due to dilution with soil water, dilution within the saturated paste, and the low concentration applied (6.7 mg/L). Much of the iodide applied was not held in the soil because of the relatively high soil moisture content, and therefore the iodide travelled to the aquifer and then away from the study site via lateral ground-water flow. In addition, iodide was not found in wells D3, D4, and D5. As with bromide, iodide was diluted by soil water and aquifer water, and moved away via lateral ground-water flow.

Wells D1 and D2 received iodide because they were screened near the top of the aquifer. Well D2 received iodide sooner and in higher concentrations than well D1 (even though D1 is screened closer to the aquifer surface) due to preferential macropore flow (Figure 6). Macropores influencing well D2 were larger and less circuitous, thereby enabling iodide to reach well D2 sooner and in higher concentrations.

Iodide first appeared in well D2 (2.7 m) (1.3 mg/L) at 4.7 hours after surface application. Therefore, iodide travelled at a rate of 57.4 cm/hr or 0.96

cm/min. Iodide first arrived in well D1 (2.4 m) at 5.8 hours after starting tracer application at a concentration of 0.2 mg/L. This results in an iodide movement rate of 41 cm/hr or 0.68 cm/min. As with bromide, these rates are much higher than the 2.1 x 10^{-3} - 5.4 x 10^{-3} cm/hr saturated hydraulic conductivities measured in the lab for the site (Melby, 1989).

As opposed to the bromide test, iodide concentrations found in the wells were relatively close to surface applied concentrations. Iodide was applied to the surface at a rate of 6.7 mg/L, and iodide was found in well D2 up to 3.2 mg/L. Some dilution did occur, however much less than in the bromide test. Due to the relatively wet soil moisture conditions during the iodide test, little tracer was held in the soil and higher concentrations arrived at the aquifer. As no iodide was found in the soil, or in the wells (after the initial slugs), it is assumed that most of the iodide entered the aquifer and moved away via lateral ground-water flow or was diluted below detection limits.

Iodide moved rapidly and preferentially through macropores to the shallow aquifer. However, iodide took 1-1.5 hours longer than bromide to appear in the wells. Iodide is a slightly larger ion than bromide, which could account for the delay. In addition, dessication crack macropores were likely smaller during the iodide test due to higher initial soil moisture. The shrinking of these macropores would cause a slower rate of movement.

Bromide Content in Wells After Iodide Test

Well samples were also analyzed for bromide during the iodide test. Bromide above background levels (0.33 mg/L) was found only in well D2 (Figure 7). Bromide in Well D2 remained just above background levels until approximately six hours after starting the iodide application. A small peak in bromide of 0.4 to 0.463 mg/L was present from 6 to 7.5 hours after testing began. Bromide then began to gradually decrease to background levels.

Bromide did not appear in wells D3, D4, or D5 after the iodide test because they were either screened or sampled lower in the aquifer than well D2, and dilution or lateral ground-water flow prevented bromide from reaching them. Two potential explanations exist for the lack of bromide in well D1. First, D1 is screened from 244-250 cm and the water table the day of the iodide test was at 240 cm. Well D1 was therefore close to not being fully developed, which could potentially impede entry of water and solutes into the well. Secondly, the bromide remaining in the soil two months after the bromide test may have been in locations unavailable to the macropores that partially "feed" well D1. Well D2 was the only well that received bromide after the iodide test because D2 was monitoring the top of the shallow aquifer and was fully developed.

Bromide remaining in the soil two months after the bromide test was flushed to the aquifer via preferential macropore flow after the iodide recharge event. The 2-month soil-bromide data (Figure 4) reveals that some bromide does exist in the soil profile and can serve as a source of bromide to the aquifer following recharge events.

The bromide peak seen in well D2 arrived at the same time as the iodide peak (approx. 6 hrs.). Given the initial soil moisture conditions and the state of macropores on the day of the iodide test, 6 hours was the time required for solutes moving from the surface and solutes remaining in the soil to reach the aquifer via preferential macropore flow. The bromide peak after the iodide test took longer to arrive at well D2 than the bromide peak following the bromide test because of increased soil moisture reducing the size of macropores. The bromide peak after the iodide test (0.46 mg/L) was also of lower concentration than the bromide peak following the bromide test because bromide concentrations remaining in the soil after two months were much lower than bromide concentrations in the soil immediately and soon after the bromide test.

CONCLUSIONS

Shallow unconfined aquifers are easily accessible sources of water that are at higher risk for contamination than deeper aquifers due to their close proximity to the land surface. The soil and ground-water system studied in this investigation is typical of the Ashport soil series, as shallow aquifers are often found below Ashport soils.

Tracers were found to move through the Ashport soil profile to the aquifer at rates much higher than saturated hydraulic conductivities measured in the lab. Bromide was found to move at a maximum rate of 90 cm/hr, iodide at a maximum rate of 57.4 cm/hr, while lab saturated hydraulic conductivities were found to be 2.1×10^{-3} - 5.4×10^{-3} cm/hr (Melby, 1989). The tracers moved through the Ashport soil at such high rates due to preferential flow through macropores.

Results also indicate that some of the bromide tracer remained in the soil matrix and gradually travelled downward as a "front" via piston-flow. This "front" of bromide appears to be travelling at a rate of 5.0×10^{-3} cm/hr. At this rate, the bromide "front" will reach 2.5 m (the elevation of the water table on the day of the test) in the summer of 1997. This represents a second way in which surface-applied bromide will potentially impact the aquifer.

In addition to immediate macropore flow and piston-flow, the aquifer appears to be impacted by the tracers a third way: macropore flow after a recharge event. Following a recharge event, tracer remaining in the soil was transported within 6 or 7 hours to the aquifer via macropores.

Initial soil moisture content appears to have an impact on macropore flow at the site. When soil conditions were drier, tracers arrived at the aquifer sooner, yet in lower concentrations compared to moist soil conditions, when tracers took longer to arrive in the wells, yet arrived in higher concentrations. This was due to macropore size and continuity, and matric potential of the soil.

While three pathways of tracer entry into the aquifer have been identified, water-quality degradation only occurs if high concentrations arrive in the ground-water over extended periods. Tracers arrived in bursts that were less than 5 hours in duration. The concentrations of these bursts were low for bromide and high for iodide compared to surface-applied concentrations. Bromide never exceeded 2 mg/L and iodide never exceeded 3.5 mg/L.

The tracers were not seen in the aquifer at levels that would constitute a health hazard. However, iodide appeared briefly in well D2 at roughly half the surface-applied concentration. This is somewhat disconcerting because if more than trace amounts were applied, would a spike of half the concentration hit the aquifer? If yes, it could pose a health hazard. Initial soil-moisture levels appear to play a large role in the concentration of solutes flowing preferentially through soil macropores.

While some bromide may still impact the aquifer, much of the bromide is unaccounted for. Bromide has been leaving the site via lateral ground-water flow and lateral movement through the soil. The boundary area was designed to prevent lateral flow of tracer through soil on the day of the test. During the days following the test, however, a portion of the bromide moved laterally and therefore away from the sampling area. In addition, the saturated paste method likely underestimates solute concentrations, and an unknown quantity of bromide could have been removed from the site via grass removal during mowing.

This investigation represents a worst-case scenario for a pollutant that is an anion. This study is a potentially good model for similar halogens such as chloride, and its movement after a salt-water spill at an oil site, for example. Finally, this investigation is specific to the Ashport soil series containing buried soils and any correlation to other soil types should be done with caution.

REFERENCES CITED

Acre, T.J., 1989. The Influence of Macropores on Water Movement in the Unsaturated Zone. Unpublished M.S. Thesis, Oklahoma State University, 84 p.

Afyuni, M.M., Cassel, D.K., and Robarge, W.P. Lateral and vertical bromide ion transport in a Piedmont landscape. Soil Science Society of America Journal, v. 58 (3), pp. 967-974.

Beven, K., and Germann, P., 1982. Macropores and water flow in soil. Water Resources Research, v. 18, pp. 1311-1325.

Black, G., Schlichting, E., and Zimmerman, V., 1973. Water recharge in a soil with shrinkage cracks. Soil Science Society of America Proceedings. N. 37, pp. 669-672.

Bodman, G.B., and Colman, E.A., 1943. Moisture and energy conditions during downward entry of water into soils. Soil Science Society of America Proceedings, 8:116-122.

Bouma, J., 1983. Hydrology and soil genesis of soils with aquic moisture regimes. Pedogenesis and Soil Taxonomy, L.P. Wilding, N.E. Smeck, and G.H. Hall, eds. Elseiver, New York.

Bouma, J., and Dekker, C.W., 1978. A case study on infiltration into dry clay soil. I. Morphological observations. Geoderma, 20:27-40.

Bowman, R.S., and Rice, R.C., 1986. Transport of conservative tracers in the field under intermittent flood irrigation. Water Resources Research, 22:1531-1536.

Bradbury, M.H., and Green, A., 1985. Measurement of important parameters determining aqueous diffusion rates through crystalline rock matrices. Journal of Hydrology, v. 82, pp. 39-55.

Brady, N.C. 1990. The nature and properties of soils. 10th ed. Macmillan, New York.

Brewer, R., 1964. Fabric and Mineral Analysis of Soils. John Wiley and Sons Inc., New York, 470 p.

Brown, A.L., Burau, R.G., Meyer, R.D., Raski, D.J., Wilhelm, S., and Quick, J. 1979. Plant uptake of bromide following soil fumigation with methyl bromide. California Agriculture, v. 33(4), p. 11-13.

Brown, T.B. and H.E. LeMay. 1981. Chemistry - the central science. 2nd ed. Prentice-Hall, Englewood Cliffs, NJ.

Bruce, R.R., Leonard, R.A., Thomas, A.W., and Jackson, W.A. 1985. Redistribution of bromide by rainfall infiltration into a Cecil sandy loam landscape. Journal of Environmental Quality, v. 14 (3), pp. 439-445.

Chan, K.Y., and Mead, J.A., 1989. Water movement and macroporosity of an Australian alfisol under different tillage and pasture conditions. Soil Tillage and Research, v. 14, pp. 301-310.

Darcy, H., 1856. Les Fontaines Publiue de la Ville de Dijon. Dalmont, Paris, France.

Davis, S.N., Thompson, G.M., Bentley, H.W., and Stiles, G., 1980. Ground-water tracers - a short review. Ground-water, 18:14-23.

Davis, S.N., D.J. Campbell, H.W. Bentley, and T.J. Flynn. 1985. An introduction to ground-water tracers. U.S. Environmental Protection Agency, EPA/600/2- 85/022, 201 p.

D'Lugsoz, J.J., 1976. Degradation of water quality by salt water infiltration in east-central Oklahoma. Geological Society of America Abstracts of Programs, v. 8, pp. 837-838.

Edwards, W.M., Norton, L.D., and Redmond, C.E., 1988. Characterizing macropores that affect infiltration into nontilled soil. Soil Science Society of America Journal, v. 52, pp. 483-487.

Ehlers, W., 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Science, 119:242-249.

Fetter, C.W. 1994. Applied hydrogeology. 3rd ed. Macmillan, New York.

Froneberger, D.F., 1989. Influence of Prevailing Hydrologic Conditions on Variation in Shallow Ground-water Quality. Unpublished M.S. Thesis, Oklahoma State University, 153 p.

Germann, P., and Beven, K., 1981. Water flow in soil macropores I. An experimental approach. Journal of Soil Science, 32:1-13.

Germann, P.F., Edwards, W.M., and Owens, L.B., 1984. Profiles of bromide and increased soil moisture after infiltration into soils with macropores. Soil Science Society of America Journal, v. 48, pp. 237-244.

Ghodrati, M., and Jury, W.A., 1990. A field study using dyes to characterize preferential flow of water. Soil Science Society of America Journal, 54:1558-1563.

Hagen, D.J., 1986. Spatial and Temporal Variability of Ground-water Quality in a Shallow Aquifer in North-central Oklahoma. Unpublished M.S. Thesis, Oklahoma State University, 191 p.

Heard, J.R., Kladivko, E.J., and Mannering, J.V., 1988. Soil macroporosity, hydraulic conductivity and air permeability of silty soils under long term conservation tillage in Indiana. Soil Tillage and Research, v. 11, pp. 1-18.

Henley, J., Gelnar, R.D., and Mayhugh, R.E., 1987. Soil Survey of Payne County, Oklahoma. U.S. Department of Agriculture, 268 p.

Hoyle, B.L., 1987. Suburban Hydrogeology and Ground-water Geochemistry of the Ashport Silt Loam, Payne County, Oklahoma. Unpublished M.S. Thesis, Oklahoma State University, 277 p.

Hubbert, M.K., 1956. Darcy's law and the field equations of the flow of underground fluids. Am. Inst. Min. Met. Petl. Eng. Trans., 207:222-239.

Izadi, B., King, B., Westermann, D., and McCann, I. 1993. Field scale transport of bromide under variable conditions observed in a furrow-irrigated field. Transactions-ASAE. 36:1679-1685.

Jabro, J.D., Lotse, E.G., Simmons, K.E., and Baker, D.E., 1991. A field study of macropore flow under saturated conditions using a bromide tracer. Journal of Soil and Water Conservation, 46:376-380.

Jury, W.A. 1982. Simulation of solute transport using a transfer function model. Water Resources Research, 18:363-368.

Kempton, R.J. and Maw, G.A. 1972a. Soil fumigation with methyl bromide: bromide accumulation by lettuce plants. Annals of Applied Biology, v. 72, p. 71-79.

Kempton, R.J. and Maw, G.A. 1972b. Soil fumigation with methyl bromide: the uptake and distribution of inorganic bromide in tomato plants. Annals of Applied Biology, v. 74, p. 91-98.

Kung, K.-J.S. 1990. Influence of plant uptake on the performance of bromide tracer. Soil Sci. Soc. Am. J. 54:975-979.

Lawes, J.B., Gilbert, J.H., and Warington, R., 1882. On the Amount and Composition of the Rain and Drainage Water Collected at Rothamsted. Williams, Clowes and Sons Ltd., London.

Leap, D.I., and Sun, R.J. 1978. Iodide and bromide tracer studies in carbonate rock. U.S. Geological Survey Professional Paper 1100, p. 223.

LeBlanc, D.R., and Garabedian, S.P., 1986. Preliminary results of a natural gradient aquifer test in a sand and gravel aquifer, Cape Cod, Massachusetts. EOS, v. 67, p. 286.

Levy, B.S. and Chambers, R.M. 1987. Bromide as a conservative tracer for soil-water studies. Hydrological Processes, v. 1, p. 385-389.

Louren, J.G., Wagenet, R.J., Bouma, J., and Wosten, J.M., 1988. Variability of saturated hydraulic conductivity in a glossaquic hapludalf with macropores. Soil Science, v. 145, pp. 20-28.

Luxmoore, R.J., 1981. Micro-, meso-, and macroporosity of soil. Soil Science Society of America Journal, v. 45, pp. 671-672.

Martin, J.P., 1966. Bromine. P. 62-64. In H.D. Chapman (ed.) Diagnostic criteria for plants and soils. University of California Press, Berkeley, CA.

Melby, J.T. 1989. A comparative study of hydraulic conductivity determinations for a fine grained alluvium aquifer. Unpublished M.S. Thesis, Oklahoma State University, 79 p.

Muramatsu, Y., Uchida, S., Sriyotha, P., and Sriyotha, K. 1990. Some considerations on the sorption and desorption phenomena of iodide and iodate on soil. Water, Air, and Soil Pollution, v. 49, pp. 125-138.

Onken, A.B., Wendt, C.W., Hargrove, R.S., and Wilke, O.C., 1977. Relative movement of bromide and nitrate in soils under three irrigation systems. Soil Science Society of America Journal, v. 41, pp. 50-52.

Owens, L.B., Van Keuren, R.W., and Edwards, W.M., 1985. Ground-water quality changes resulting from a surface bromide application to a pasture. Journal of Environmental Quality. 14:543-548.

Owens, L.B., and Edwards, W.M. 1992. Long-term ground-water quality changes from a one-time surface bromide application. Journal of Environmental Quality. 21:406-410.

Pettyjohn, W.A., White, H., and Dunn, S. 1983. Water atlas of Oklahoma. University Center for Water Research, Oklahoma State University, Stillwater, 72 p.

Priebe, D.L., and Blackmer, A.M., 1989. Preferential movement of oxygen-18-labeled water and nitrogen-15-labeled urea through macropores in a Nicollet soil. Journal of Environmental Quality, v. 18, pp. 66-71.

Quisenberry, V.L., and Phillips, R.E., 1976. percolation of surface applied water in the field. Soil Science Society of America Journal., v. 40, pp. 484-489.

Radulovich, R., Soloranzo, E., and Sollins, P., 1989. Soil macropore size distribution from water breakthrough curves. Soil Science Society of America Journal, v. 53, pp. 556-559.

Rhoades, J.D., 1982. Soluble salts. In Methods of soil Analysis, ASA Inc. and SSSA Inc., Madison, WI, p. 169.

Rice, R.C., Jaynes, D.B., and Bowman, R.S. 1991. Preferential flow of solutes and herbicide under irrigated fields. Transactions-ASAE. 34:914-918.

Richards, L.A., 1931. Capillary conduction of liquids in porous mediums. Physics, 1:318-333.

Rogowski, A.S., and Simmons, D.E., 1988. Geostatistical analysis of field hydraulic conductivity in compacted clay. Mathematical Geology, v. 20, pp. 423-445.

Ross, R.R., 1988. Temporal and Vertical Variability of the Soil and Ground-water Geochemistry of the Ashport Silt Loam, Payne County, Oklahoma. Unpublished M.S. Thesis, Oklahoma State University, 116 p.

Rowe, J.J., Fournier, R.O., and Morey, G.W. 1965. Use of sodium iodide to trace underground water circulation in hot springs and geysers of the Daisy Geyser Group, Yellowstone National Park. U.S. Geological Survey Professional Paper 525-B, p. B184-B186.

Schmotzer, J.K., Jester, W.A., and Parizek, R.R., 1973. Ground-water tracing with post sampling activation analysis. Journal of Hydrology, 20:217-236.

Sharma, M.L., and Taniguchi, M. 1991. Movement of a non-reactive solute tracer during steady and intermittent leaching. Journal of Hydrology, v. 128 (1/4), p. 323-334.

Sidgwick, N.V., 1950. The Chemical Elements and Their Compounds. Oxford University Press, London, England, 1170 p.

Simpson, T., and Cunningham, R.L. 1982. The occurrence of flow channels in soils. Journal of Environmental Quality, 11:29-30.

Skopp, J., 1981. Comment on micro-, meso-, and macroporosity of soil. Soil Science Society of America Journal, v. 45, p. 1246.

Smettem, K.R.J., 1987. Characterization of water entry into a soil with contrasting textural class: spatial variability of infiltration parameters and influence of macroporosity. Soil Science, v. 144, pp. 167-174.

Smith, S.J., and Davis, R.J., 1974. Relative movement of bromide and nitrate through soils. Journal of Environmental Quality, v. 3, pp. 152-155.

Soil Conservation Service. 1987. Soil Survey of Payne County, Oklahoma. U.S. Department of Agriculture, 268 p.

Soil Survey Staff, 1981. Examination and Description of Soils in the Field. Chap. 4 in Soil Survey USDA Handbook 18. U.S. Government Printing Office, Washington, D.C.

Starr, J.L., and Glotfelty, D.E. 1990. Atrazine and bromide movement through a silt loam soil. Journal of Environmental Quality, v. 19 (3), p. 552-558.

Tennyson, L.C., and Settergren, C.D., 1980. Percolate water and bromide movement in the rood zone of effluent irrigation sites. Water Resources Bulletin, v. 16. pp. 433-437.

Zachmann, J.E., Linden, D.R., and Clapp, C.E., 1987. Macroporous infiltration and redistribution as affected by earthworms, tillage and residue. Soil Sci. Soc. Am. J., v. 51, pp. 1580-1586.

Zietlow, P.L. 1992. Influence of macropores and soil moisture content on the rapid movement of bromide and iodide to the saturated zone. Unpublished M.S. Thesis, Oklahoma State University, 189 p.

Table 1

Soil Profile Description of Ashport Soil Series and Underlying Buried Soils in the Study

From Ross (1989)

Horizon	Depth (m)	Description
Ap	0.00 - 0.48	Reddish Brown (2.5YR 4/4, dry) to dusky red (2.5YR 3/2 moist) silt loam; moderate medium subangular blocky, parting to weak medium platy structure; friable; common roots and fine, continuous root casts; gradual boundary.
A	0.48 - 0.66	Dark reddish brown (2.5YR 3/4, dry) to dark red (2.5YR 3/6) silt loam; weak, coarse, prismatic structure; friable; common, fine, continuous root casts in peds; gradual boundary.
Bw	0.66 - 0.97	Red (2.5YR 4/6, dry) to dark reddish brown (2.5YR 3/4, moist) silt loam; weak coarse, subangular structure; friable; common, fine, continuous root casts; gradual boundary.
C	0.97 - 1.27	Reddish brown (5YR 4/4, dry) to dark reddish brown (2.5YR 3/4, moist) fine sandy loam; finely laminated, stratified sands; friable; few, fine root casts; clear boundary.
2Ab	1.27- 1.63	Dark reddish gray (5YR 4/2, dry) to dark reddish brown (5YR 3/3, moist) silt loam; moderate, fine, subangular blocky structure; firm; roots; clear boundary.
2AB	1.63 - 1.73	Reddish brown (5YR 4/4, dry) to dark reddish brown (2.5YR 3/4, moist) silt loam; few, fine, faint, yellowish red (5YR 5/6) mottles; medium, fine, subangular blocky, parting to moderate, medium, prismatic structure; firm; common, fine, round, black (n 2/0) manganese nodules; few, fine, root casts; gradual boundary.

Table 1 (continued)

Horizon	Depth (m)	Description
2Bw1	1.73-1.98	Reddish brown (5YR 4/4, dry) loam; few, fine, faint, yellowish red (5YR 5/6) mottles; moderate, medium to fine, subangular blocky, parting to moderate, medium, prismatic, with moderate, coarse platy structure; firm; common, fine to medium, black (n 2/0) manganese nodules; few fine root casts; gradual boundary.
2Bw2	1.98 - 2.75	Reddish brown (5YR 4/4, dry) to dark red (2.5YR 3/6) silt loam; few, medium, faint, yellowish red (5YR 5/6) and reddish brown (5YR 5/3) mottles; moderate, medium to fine, subangular blocky, parting to moderate, medium, prismatic structure; firm; common, medium, black (n 2/0) manganese nodules; few, fine carbonate threads and fine concretions; few, fine root casts; gradual boundary.
2Bw3	2.75 - 3.15	Yellowish red (5YR 5/6, dry) silt loam; pinkish gray (5YR 7/2) mottles; moderate, to coarse to medium prismatic, parting to moderate medium prismatic structure; firm; few fine to medium black (n 2/0) manganese nodules; few, fine to medium carbonate concretions; few fine root casts, surrounded by intense yellowish red (5YR 5/6) mottling; clear boundary.
2Bw4	3.15 - 3.51	Yellowish red (5YR 4/6, dry) silty clay loam; few, medium, faint reddish gray (5YR 5/2) mottles; moderate, medium, prismatic, parting to moderate, medium, subangular blocky structure; firm; few, fine, irregular, black (n 2/0) manganese nodules; few, fine root casts; gradual boundary.
2Bw5	3.51 - 3.66	Yellowish red (5YR 4/6, dry) loam; few, fine, faint, reddish gray (5YR 5/2) mottles; moderate to weak, medium, subangular blocky, parting to moderate to weak, medium, prismatic structure; firm; few, fine, black (n 2/0) manganese nodules; few to common root casts; diffuse boundary.

Table 1 (continued)

Horizon	Depth (m)	Description
2BC1	3.66 - 3.97	Reddish brown (5YR 4/4, dry) clay loam; weak, medium, prismatic, paring to moderate, medium, subangular blocky structure; few, medium, black (N 2/0) manganese nodules; few, fine root casts; diffuse boundary.
2BC2	3.97 - 4.27	Reddish brown (5YR 4/4, dry) silty clay loam; weak, medium prismatic, parting to weak, medium, subangular blocky structure; few, fine to medium, black (n 2/0) manganese nodules; few, fine roots casts; diffuse boundary.
2BC3	4.27 - 4.88	Reddish brown (5YR 4/4, dry) silt loam; weak, medium, prismatic, parting to weak, medium, subangular blocky structure; firm; few, fine, irregular, with patches of many fine, round, black (n 2/0) manganese nodules; few, fine root casts; clear boundary.
2BC4	4.88 - 5.03	Yellowish red (5YR 4/6, dry) silt loam; massive, breaking to weak, medium, subangular blocky structure; firm; few medium, irregular, black (n 2/0) manganese nodules; very few, fine root casts; diffuse boundary.
2BC5	5.03 - 6.10	Reddish brown (5YR 4/4, dry) silty clay loam; weak, medium, prismatic, parting to weak, medium, moderate, platy structure; firm; few, medium, irregular, black (n 2/0) manganese nodules; few fine root casts; diffuse boundary.
2BC6	6.10 - 6.48	Reddish brown (5YR 4/4, dry) silty clay loam; few, very faint, yellowish red (5YR 4/6) mottles; weak, medium prismatic, parting to weak medium subangular blocky structure; friable; many continuous root casts and pores in peds; few, medium, irregular black (n 2/0) manganese nodules; diffuse boundary.

Table 1 (continued)

Horizon	Depth (m)	Description
2BC7	6.48 - 6.71	Reddish brown (5YR 4/4, dry) silt loam; few, medium, faint, yellowish red (5YR 4/6) mottles; weak, medium, prismatic, parting to weak, medium, subangular blocky structure; firm; few, medium, irregular black (n 2/0) manganese nodules; diffuse boundary.
2BC8	6.71 - 7.17	Yellowish red (5YR 4/6, dry) silt loam; few, medium, distinct, grayish brown (5YR 5/6) and yellowish brown (5YR 5/2) mottles; weak, medium, prismatic, parting to weak, medium, subangular blocky structure; firm; few, irregular, medium, black (n2/0) manganese nodules; diffuse boundary.
2BC9	7.17 - 7.78	Yellowish red (5YR 4/6, dry) silty clay loam; few, medium, faint, pinkish gray (5YR 6/2) mottles; weak, medium, subangular blocky structure; firm; few to common, continuous root casts; few, medium, round, black (n 2/0) manganese nodules; diffuse boundary.
2BC/A	7.78 - 8.39	Dark reddish brown (5YR 3/4, dry) and yellowish red (5YR 4/6, dry) clay loam; few, fine, faint pinkish gray (5YR 6/2) mottles; weak, medium, subangular blocky structure; few, fine black (n 2/0) organic matter fragments (charcoal); firm; few, fine root casts; diffuse boundary.
3Ab	8.39 - 9.00	Dark reddish brown (5YR 3/3, dry) silt loam; few, fine, faint, reddish gray (5YR 5/2) mottles; moderate, medium, subangular blocky structure, paring to weak, medium, platy structure; common, fine, continuous root casts; few, fine, black (n 2/0) organic matter fragments; clear boundary.
3AB1	9.00 - 9.30	Reddish brown (5YR 4/4, dry) silty clay loam; few, fine, faint, yellowish red (5YR 5/6) and reddish gray (5YR 5/2) mottles; moderate to weak, medium, subangular blocky, parting to moderate to weak, medium prismatic structure; gradual boundary.

Table 1 (continued)

Horizon	Depth (m)	Description
3AB2	9.30 - 9.91	Reddish brown (5YR 4/3, dry) silty clay; common, fine, distinct yellowish red (5YR 5/6), reddish gray (5YR 5/2) mottles; weak to moderate, medium, subangular blocky, parting to moderate to weak, medium prismatic structure; firm; common, medium, distinct gray (5YR 5/1) mottles surrounding common, medium root casts; gradual boundary.
3Bw	9.91 - 10.83	Reddish brown (5YR 4/6, dry) silty clay; common, fine, distinct gray (5YR 5/1) mottles; weak to moderate, medium, subangular blocky, parting to weak to moderate, medium prismatic structure; firm; common, medium, root casts; gradual boundary.
3C1	10.83 - 11.59	Reddish brown (5YR 4/6, dry) silt loam; few, fine, distinct, strong brown (7.5YR 5/8) and pinkish gray (5YR 6/2) mottles; stratified , massive structure; friable; gradual boundary.
3D1	11.59 - 11.90	Reddish brown (5YR 4/6, dry) sandy loam; stratified, massive structure; friable; gradual boundary.
3D2	11.90 - 13.12	Reddish brown (5YR 4/3, dry) gravelly sandy loam; massive; friable; abrupt boundary.
3R	13.12 - 13.73	Upper Pennsylvanian Doyle shale.

Figure 1. Soil Profile of Ashport Soil Series at the Study Site in Stillwater, Oklahoma

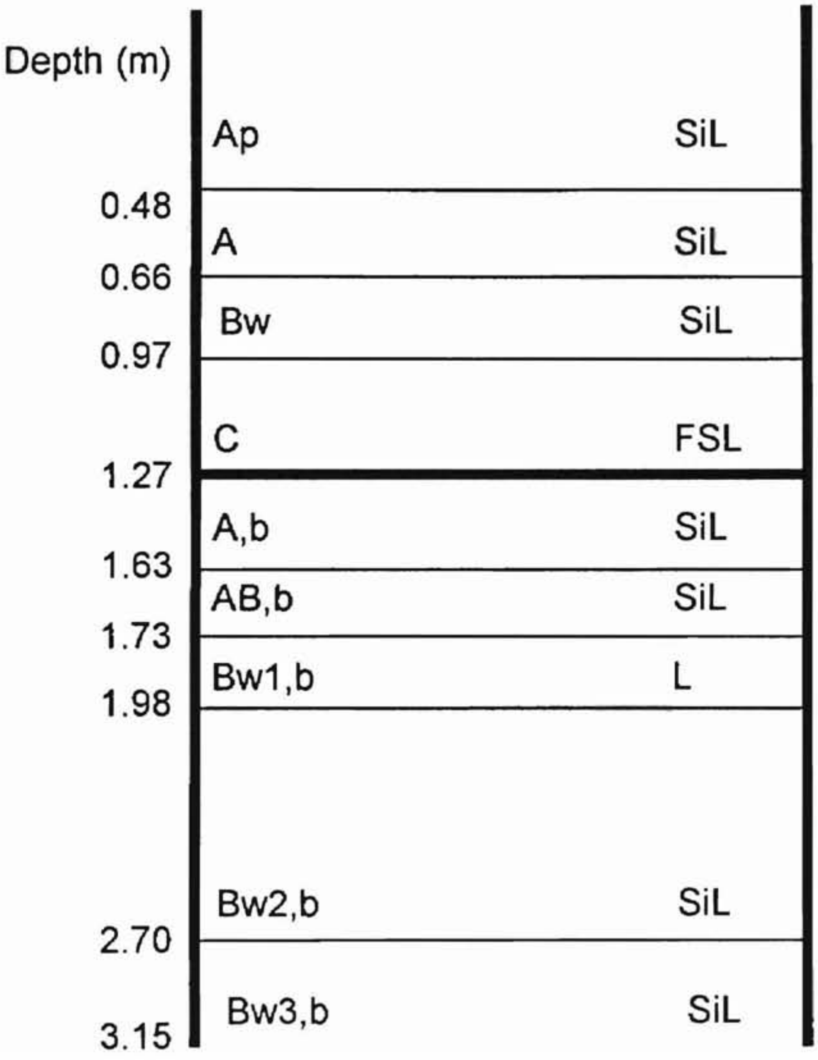
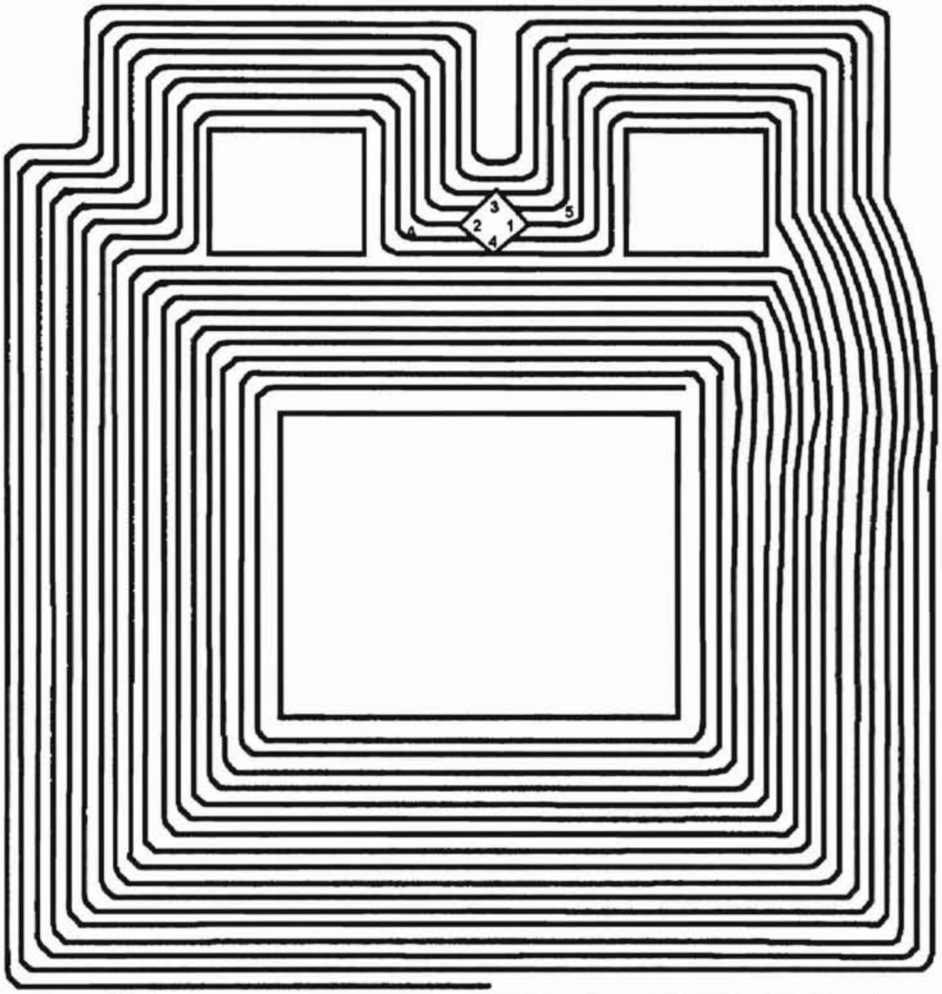


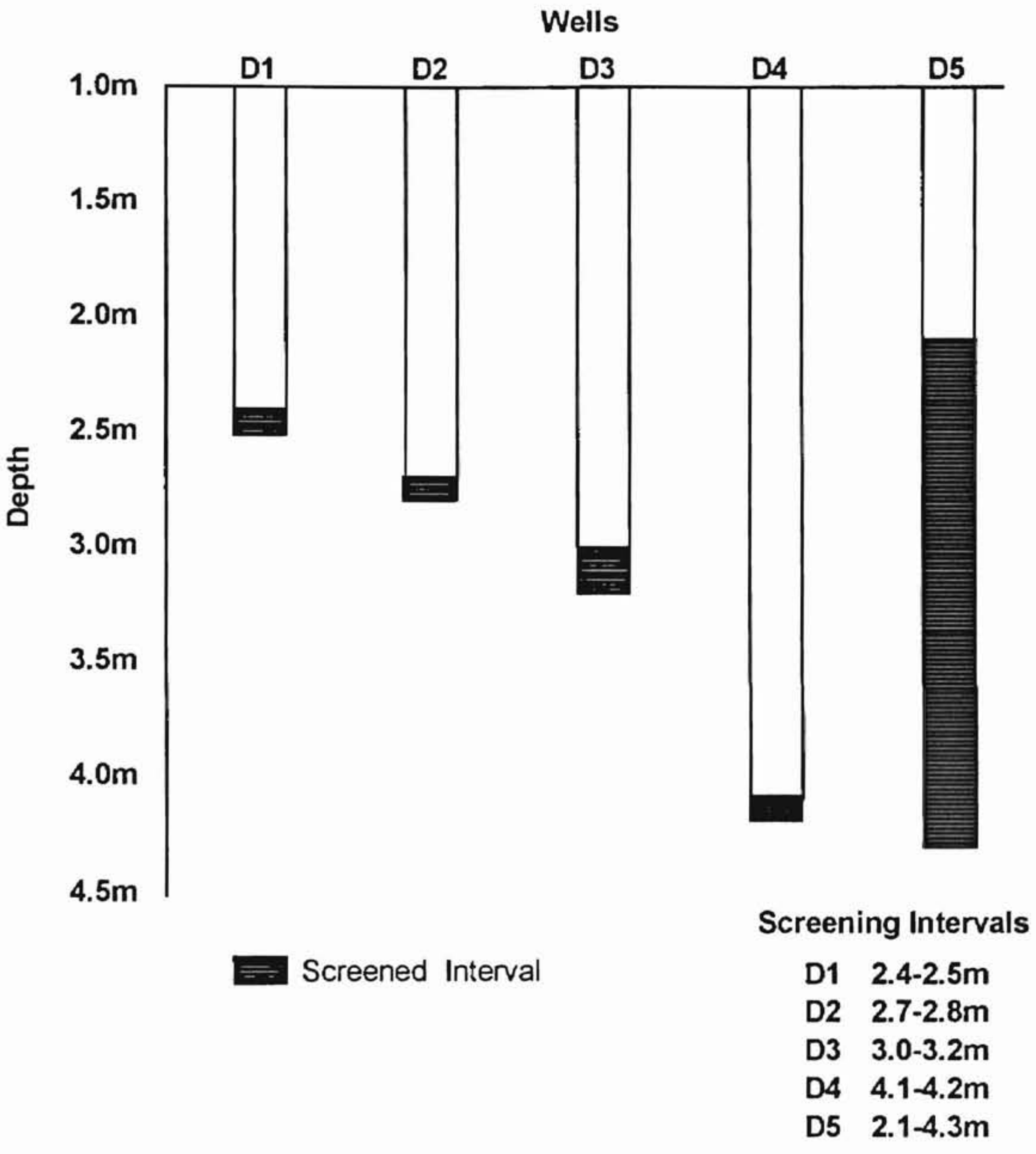
Figure 2a
Field-Plot Design for Bromide and Iodide Tracer Tests at the Study Site in Stillwater, Oklahoma
From Zietlow (1992)



Key

Scale - 6.35mm = 0.305m
◇ Concrete Pad
☐ Tracer Application Plots
A Soil Moisture Neutron Probe Access Tube
1,2...5 D Wells
—— Irrigation Tubing (boundary area)

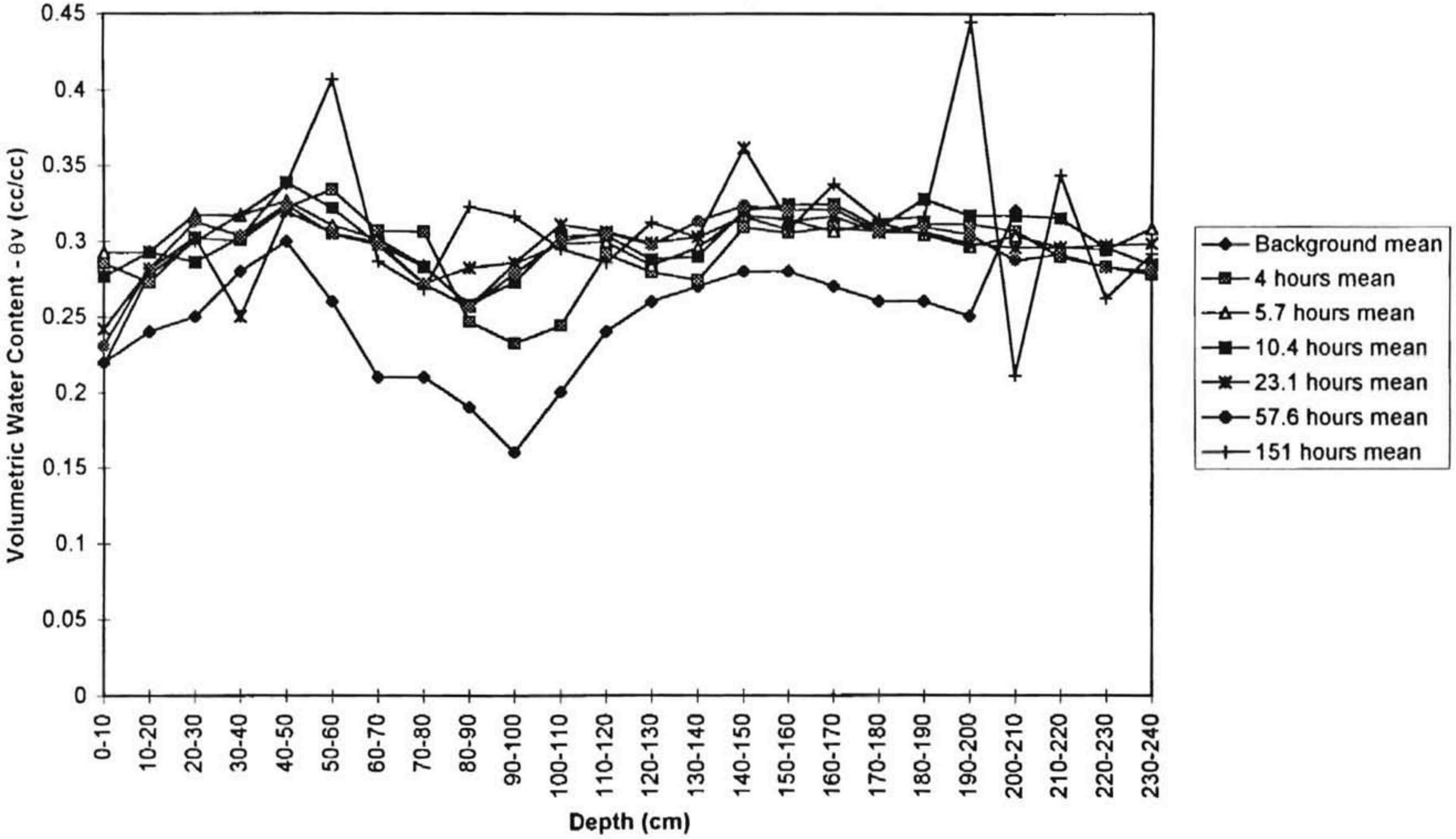
Figure 2b - Well Cluster Diagram of Groundwater Monitoring Wells at the Study Site in Stillwater, Oklahoma



Screening Intervals

D1	2.4-2.5m
D2	2.7-2.8m
D3	3.0-3.2m
D4	4.1-4.2m
D5	2.1-4.3m

Figure 3. Volumetric Water Content - Bromide Tracer Test



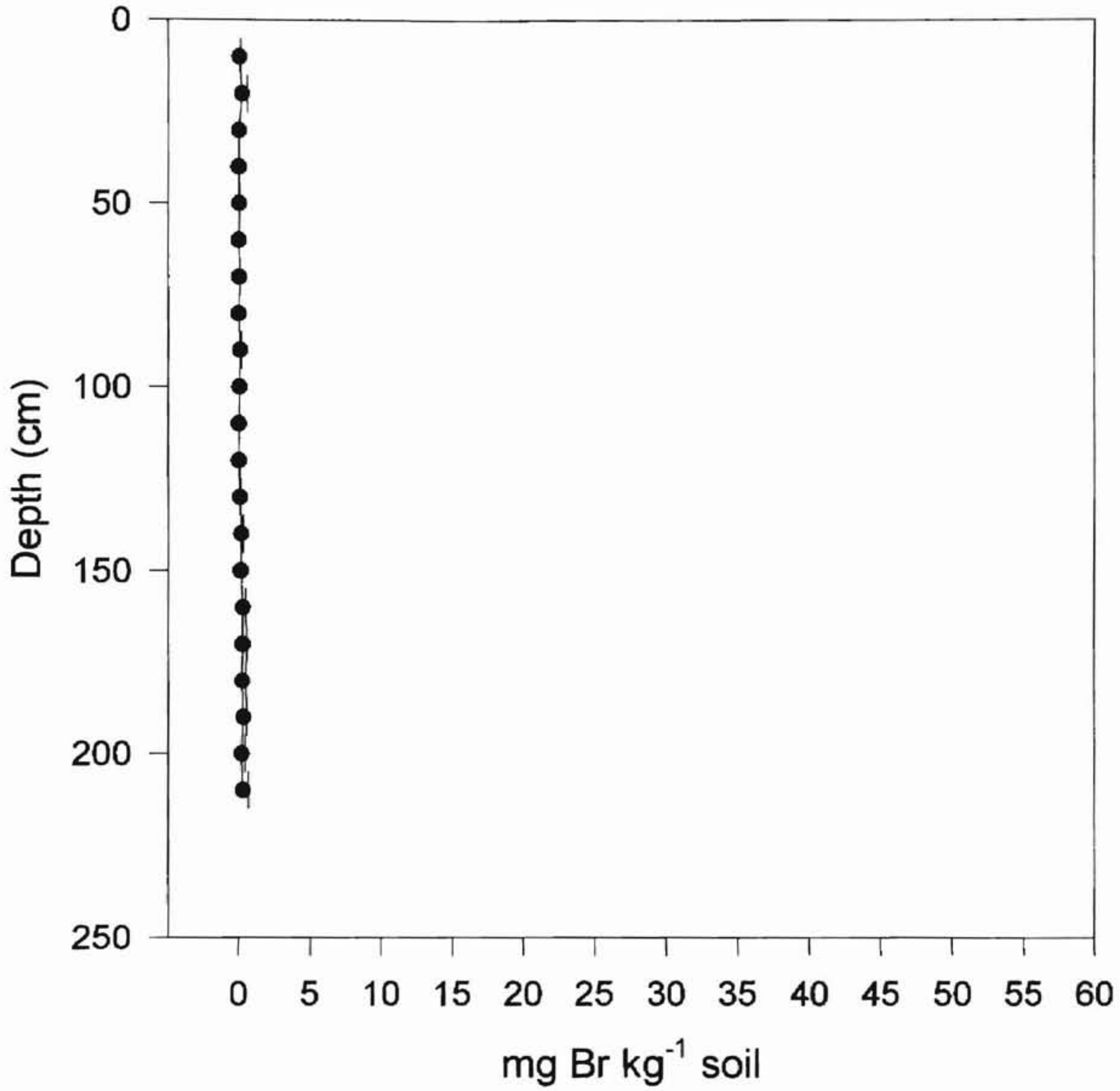


Figure 4(a). Changes in Br$^-$ concentration with depth before application. Bars represent positive component of standard deviation.

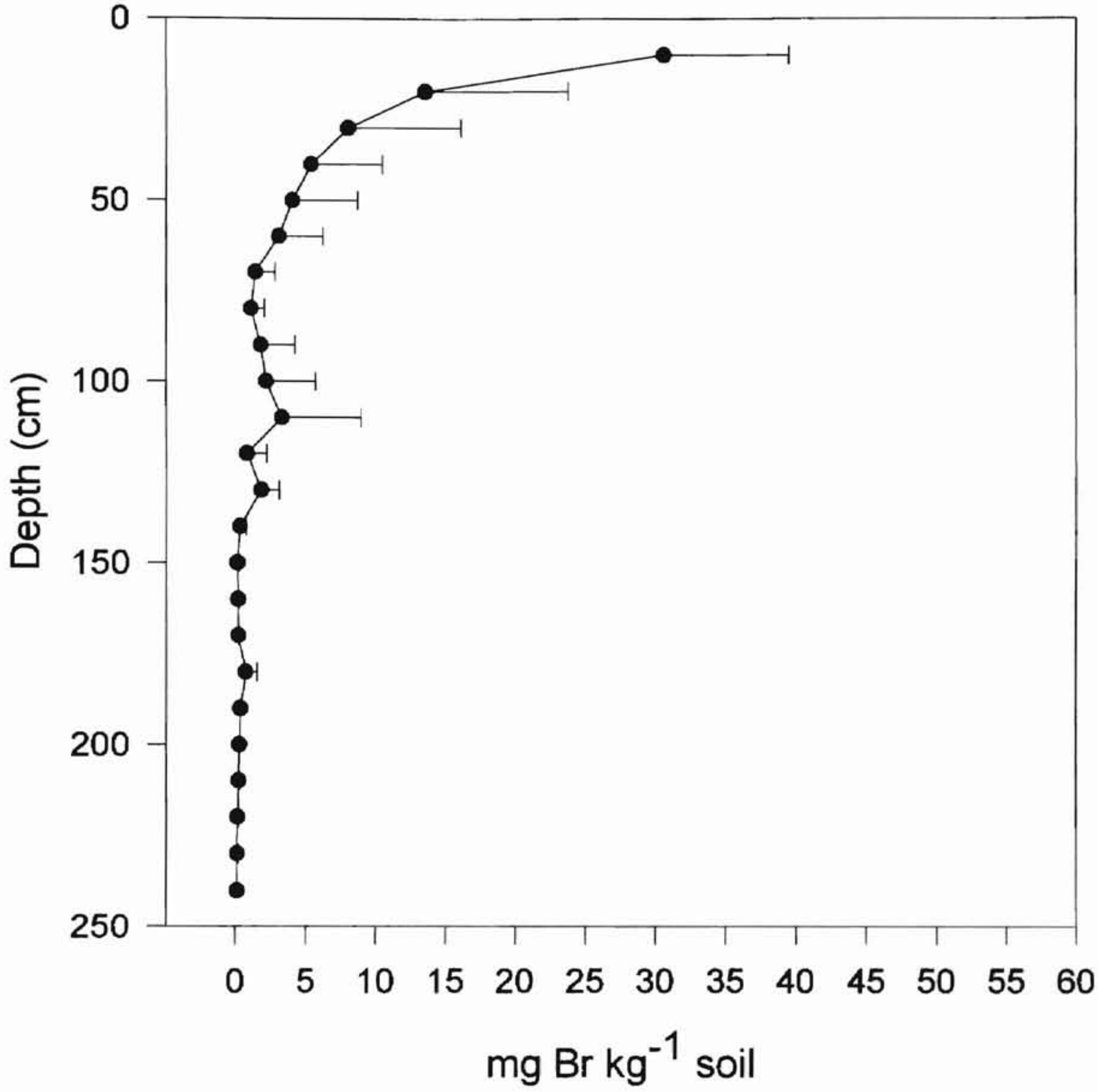


Figure 4(b). Changes in Br$^-$ concentration with depth at 4 hours after application. Bars represent positive component of standard deviation.

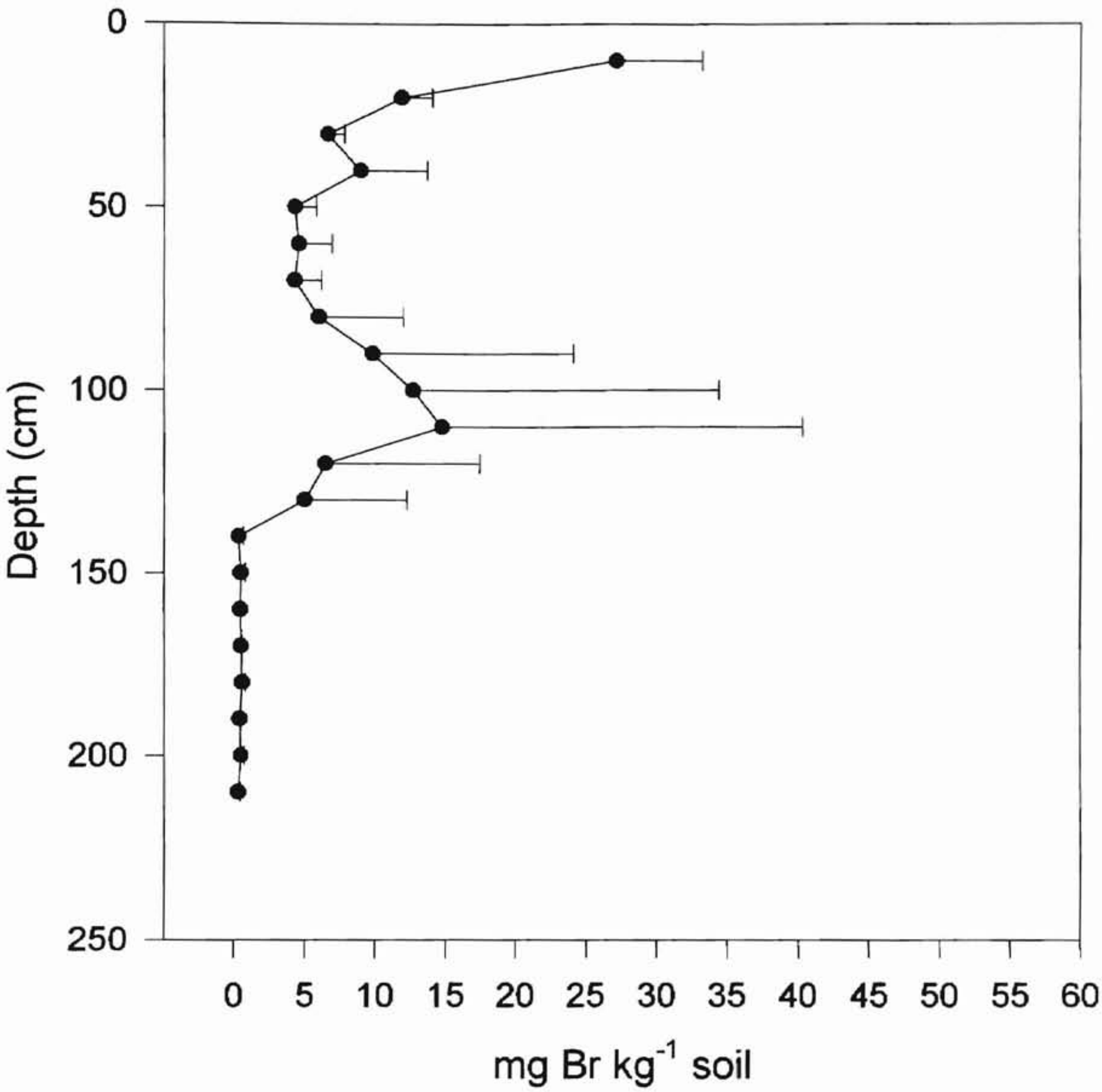


Figure 4(c). Changes in Br$^-$ concentration with depth at 5.7 hours after application. Bars represent positive component of standard deviation.

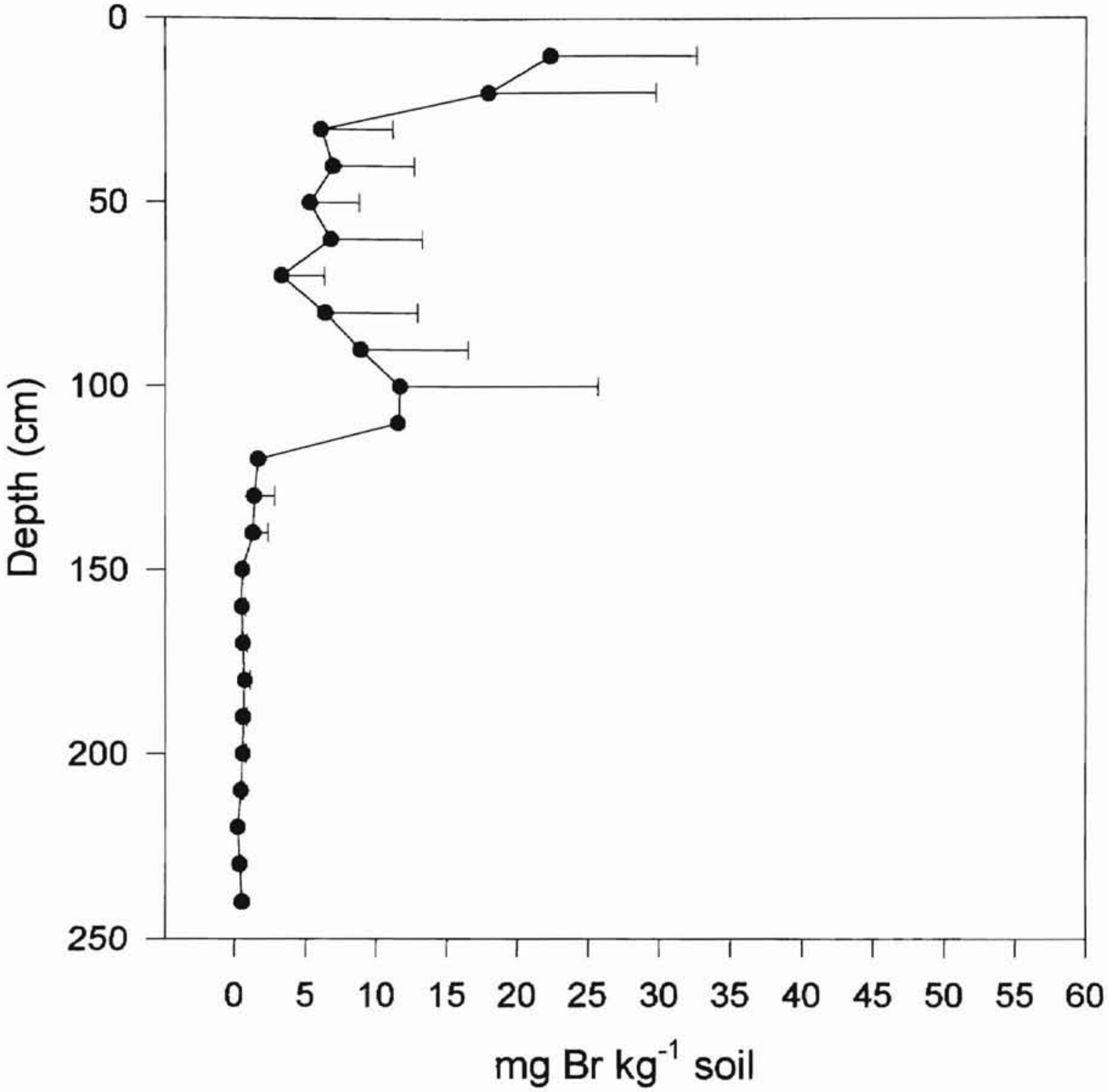


Figure 4(d). Changes in Br$^-$ concentration with depth at 10.4 hours after application. Bars represent positive component of standard deviation.

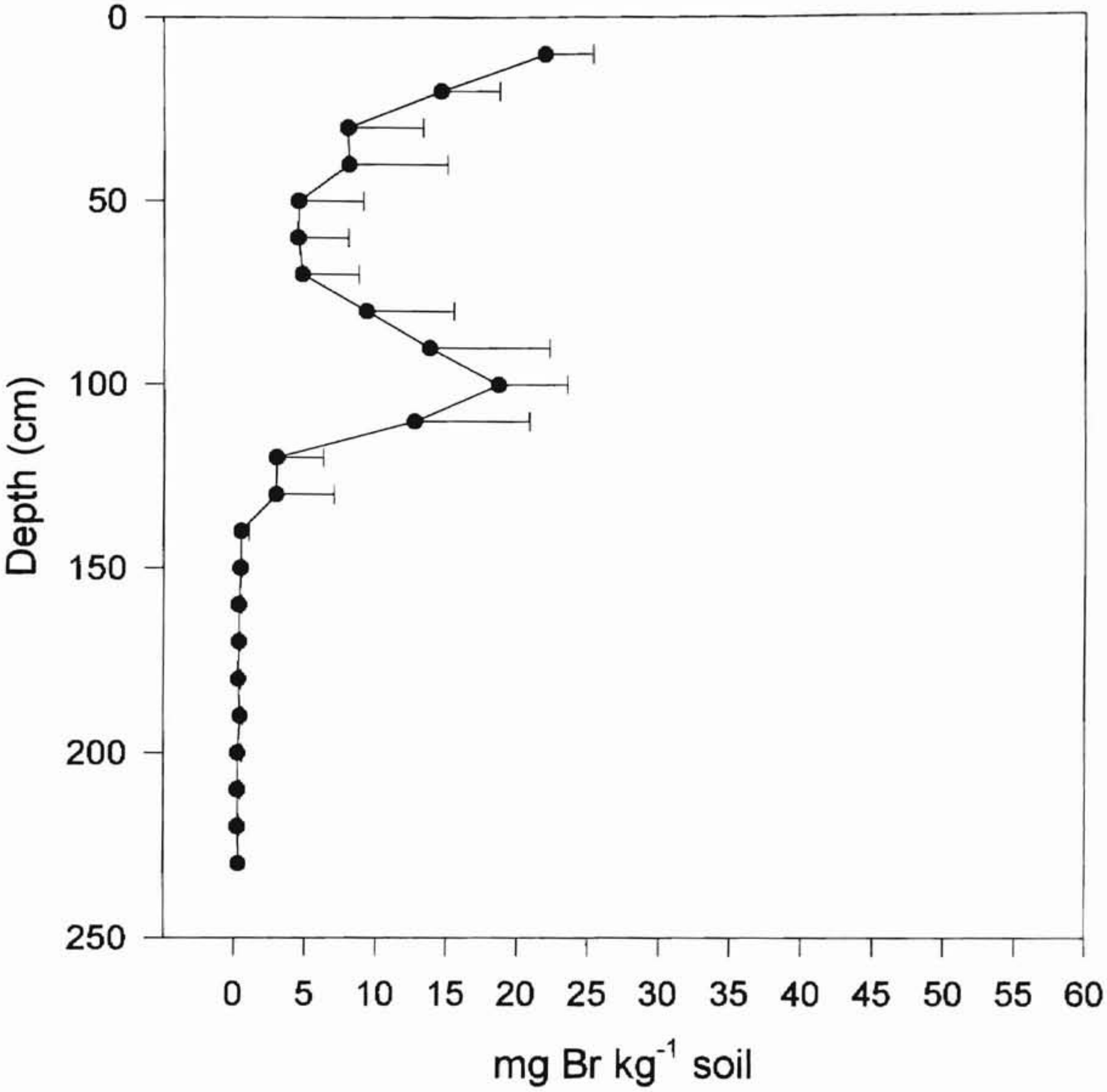


Figure 4(e). Changes in Br$^-$ concentration with depth at 23.1 hours after application. Bars represent positive component of standard deviation.

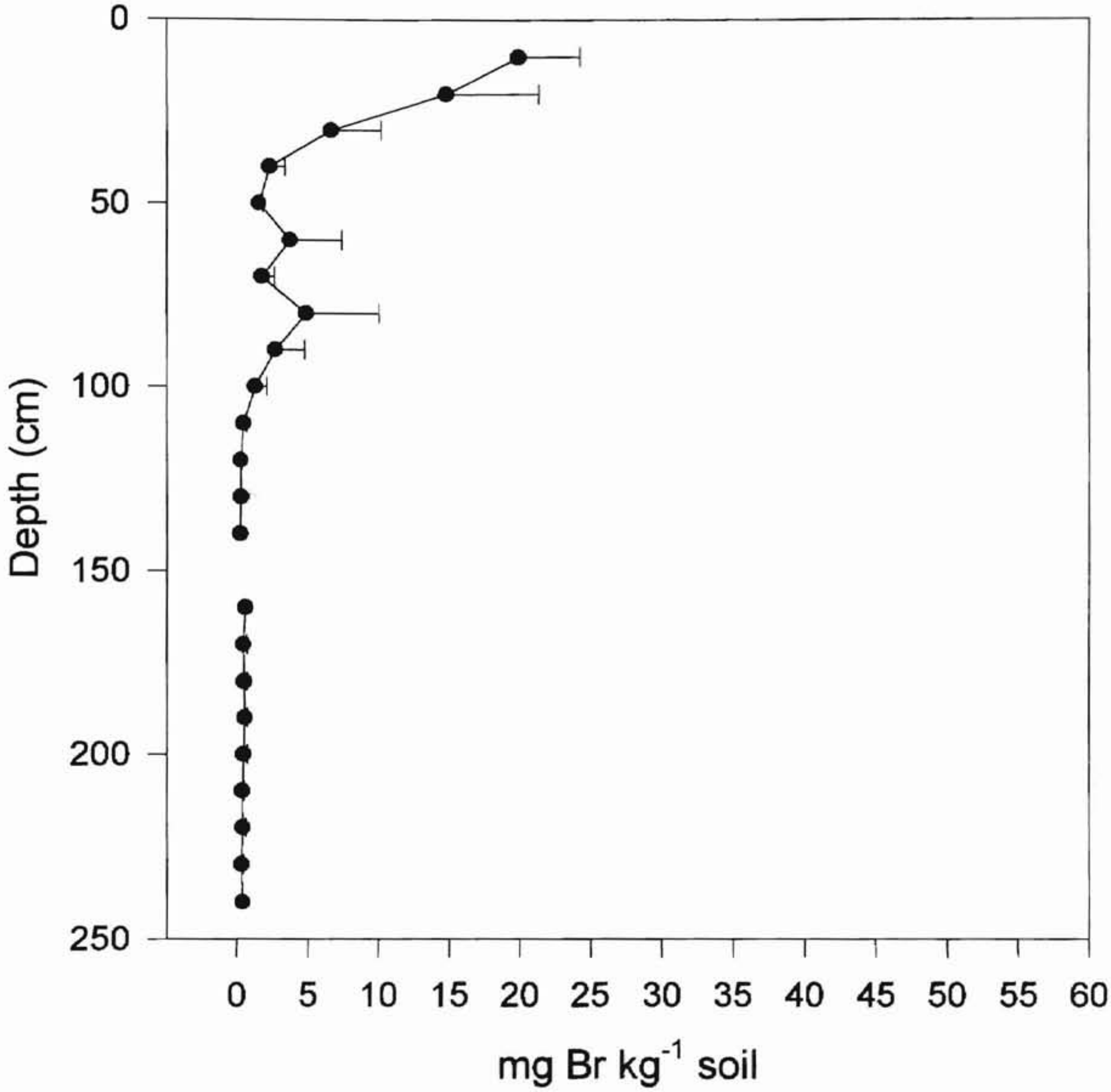


Figure 4(f). Changes in Br$^-$ concentration with depth at 57.6 hours after application. Bars represent positive component of standard deviation.

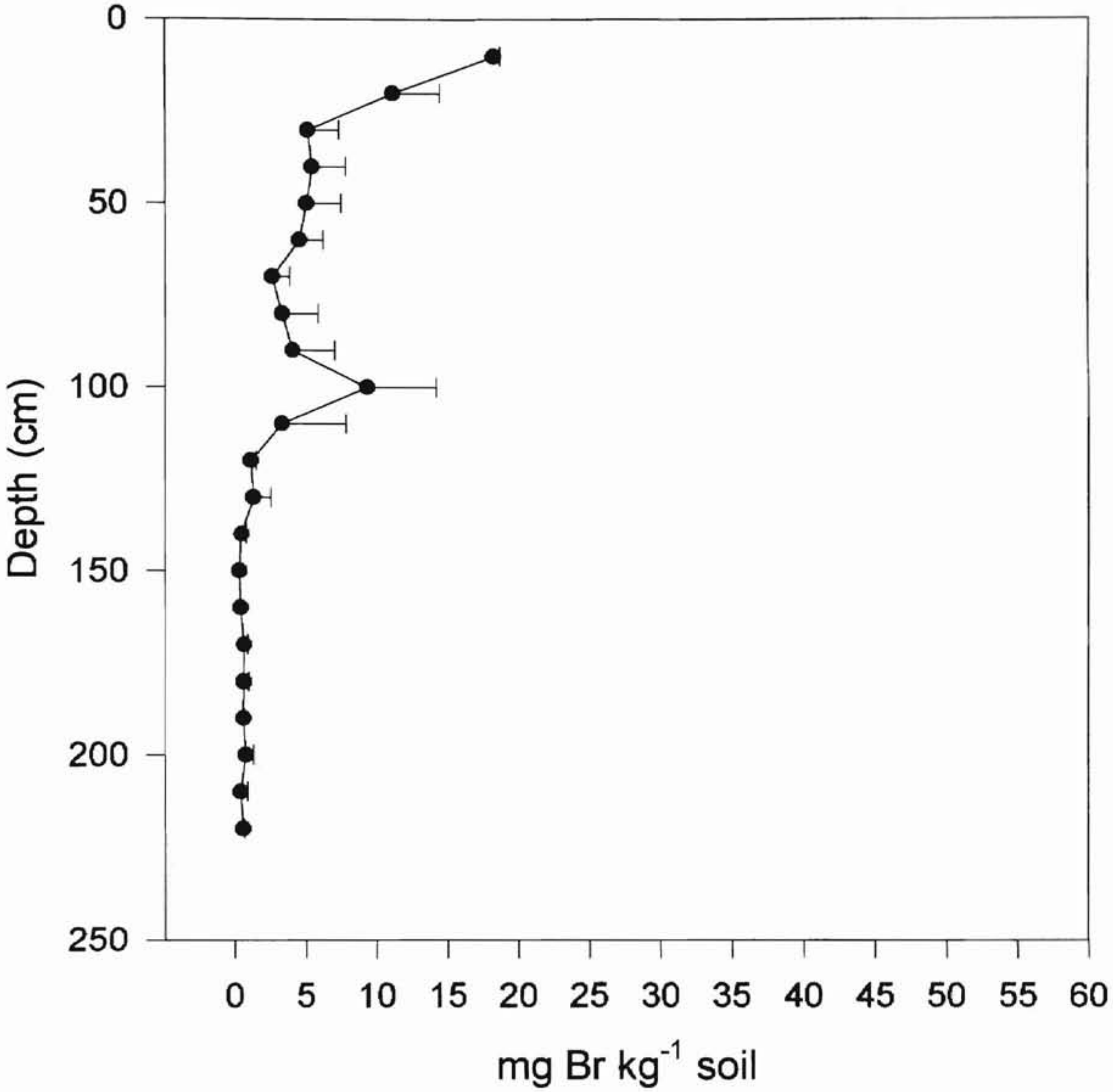


Figure 4(g). Changes in Br$^-$ concentration with depth at 151 hours after application. Bars represent positive component of standard deviation.

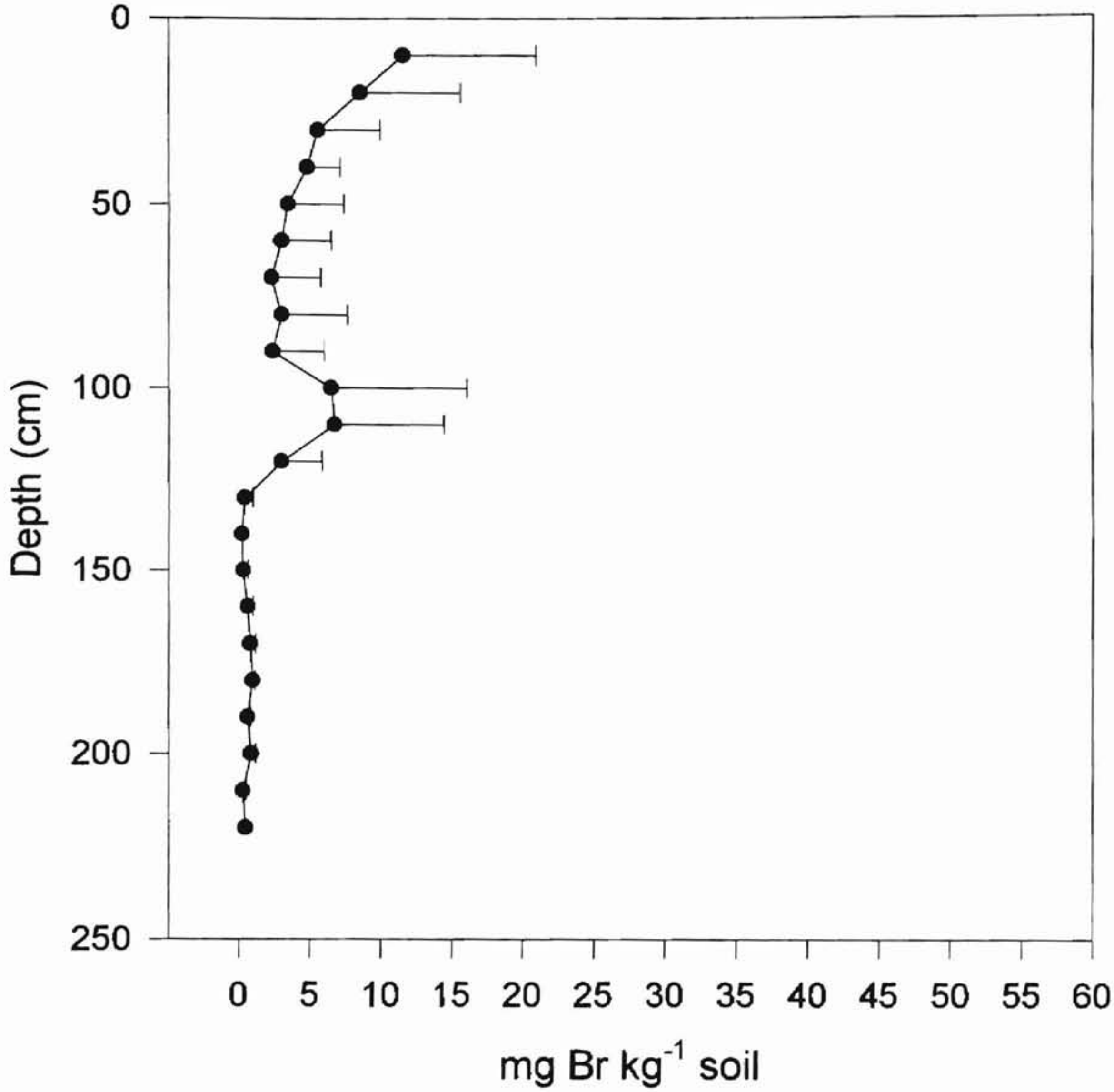


Figure 4(h). Changes in Br$^-$ concentration with depth at 2 months after application. Bars represent positive component of standard deviation.

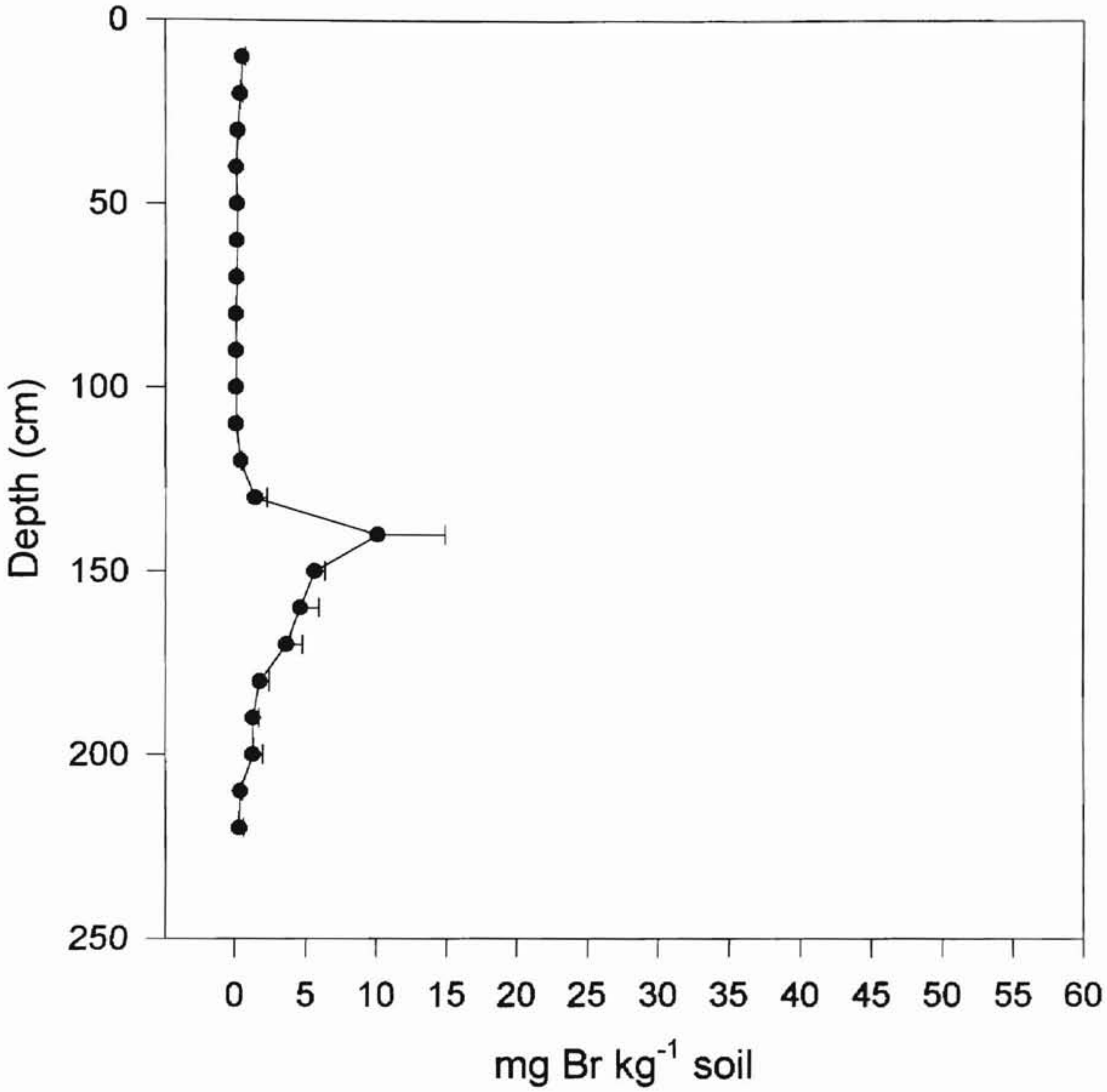


Figure 4(i). Changes in Br$^-$ concentration with depth at 3.4 years after application. Bars represent positive component of standard deviation.

Figure 5
Bromide in Wells D2 and D3 After Bromide Tracer Application - March 1, 1991

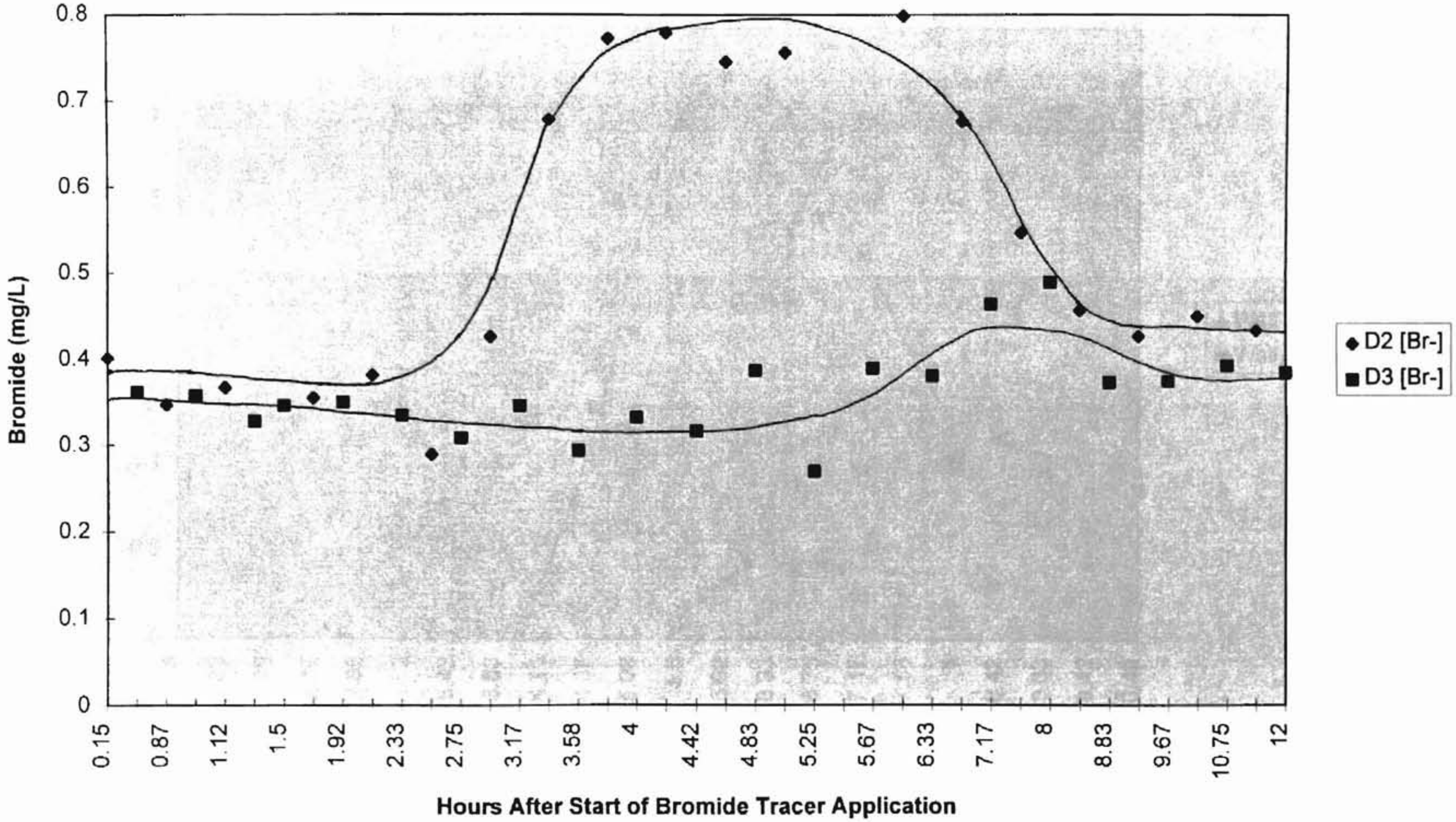


Figure 6

Iodide in Wells D1 and D2 After Iodide Tracer Application - April 29, 1991

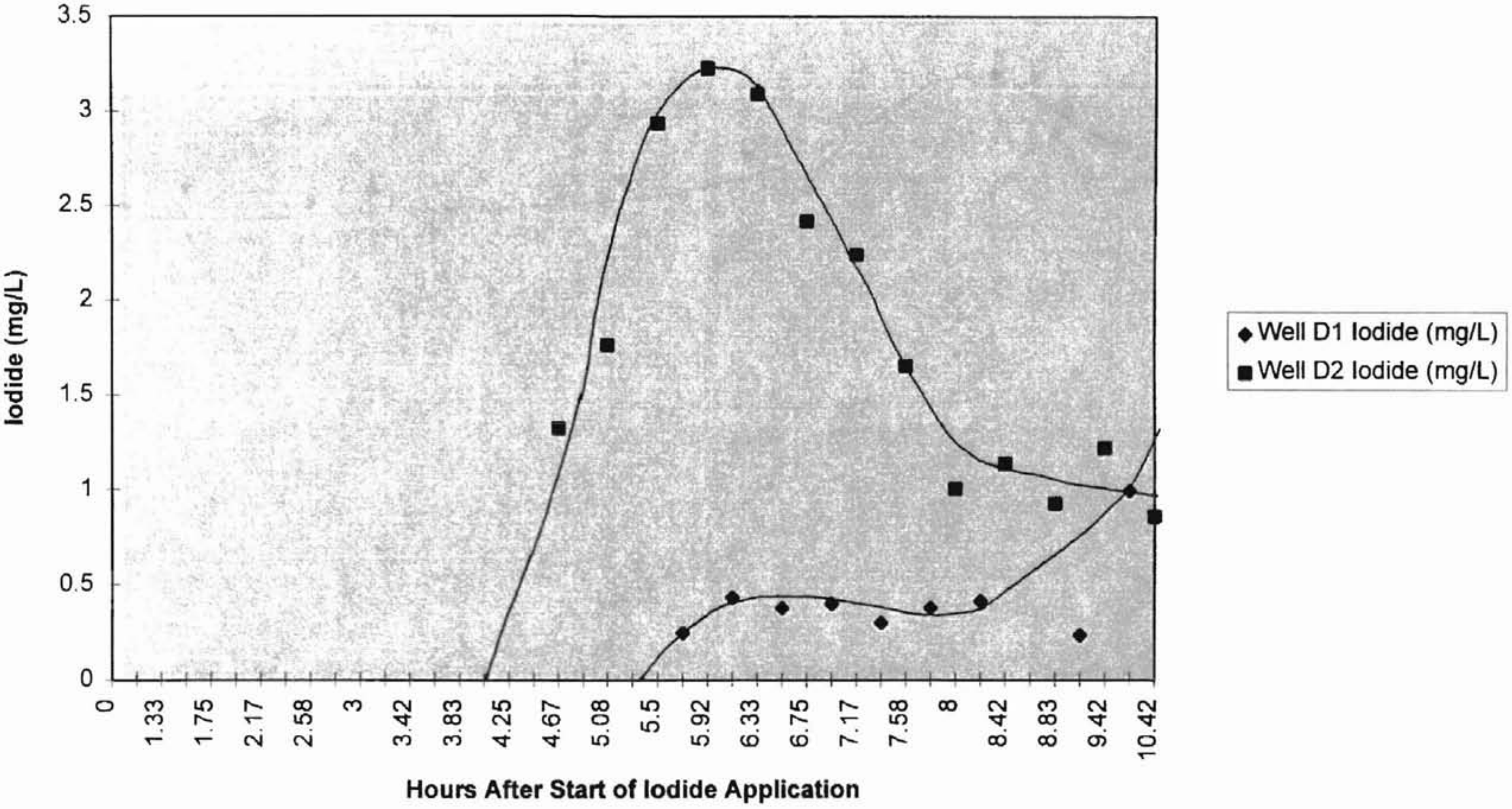
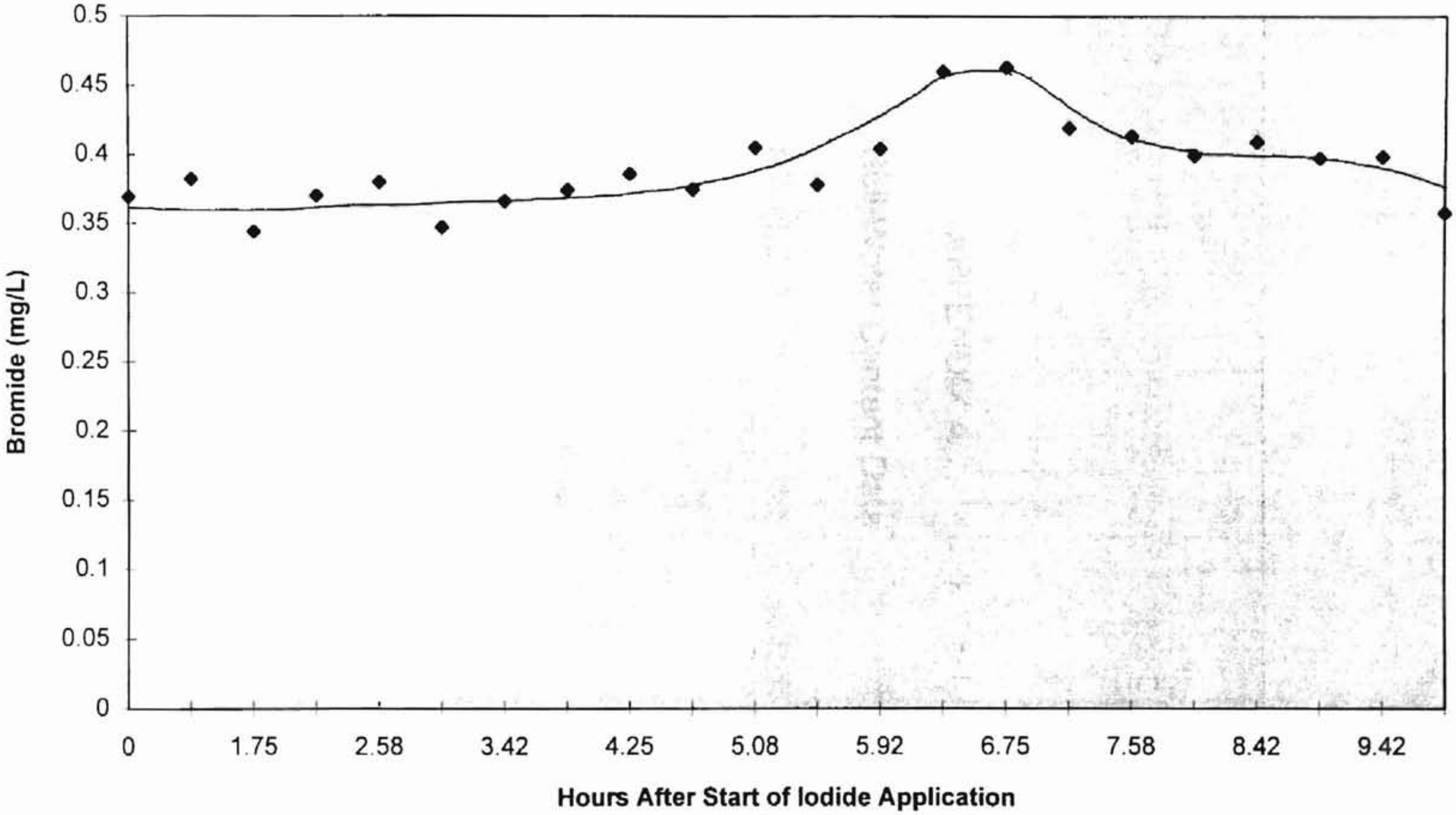


Figure 7

Bromide in Well D2 After Iodide Tracer Application - April 29, 1991



APPENDIX A

Soil-Water Content Data

Volumetric Water Content - Bromide Tracer Test					
Depth (cm)	**Bkgrnd A vol.**	**Bkgrnd B vol.**	**Bkgrnd C vol.**	**Bkgrnd Mean**	**Bkgrnd Std. Dev.**
0-10	0.26	0.26	0.14	0.22	0.07
10-20	0.23	0.27	0.21	0.24	0.03
20-30	0.25	0.24	0.28	0.25	0.02
30-40	0.28	0.27	0.28	0.28	0.01
40-50	0.25	0.36	0.30	0.30	0.06
50-60	0.20	0.29	0.27	0.26	0.05
60-70	0.13	0.26	0.24	0.21	0.07
70-80	0.10	0.29	0.25	0.21	0.10
80-90	0.09	0.21	0.25	0.19	0.08
90-100	0.11	0.18	0.19	0.16	0.04
100-110	0.15	0.28	0.19	0.20	0.07
110-120	0.16	0.31	0.24	0.24	0.07
120-130	0.22	0.30	0.24	0.26	0.04
130-140	0.24	0.31	0.26	0.27	0.04
140-150	0.26	0.30	0.28	0.28	0.02
150-160	0.25	0.31	0.28	0.28	0.03
160-170	0.25	0.30	0.28	0.27	0.03
170-180	0.24	0.27	0.27	0.26	0.02
180-190	0.25	0.26	0.27	0.26	0.01
190-200	0.24		0.26	0.25	0.01
200-210	0.25		0.38	0.32	0.10
210-220				mean=	
220-230				0.25	
230-240					

Volumetric Water Content - Bromide Tracer Test					
Depth (cm)	4 hours A	4 hours B	4 hours C	4 hours Mean	4 hrs Std. Dev.
0-10	0.28	0.25	0.33	0.29	0.04
10-20	0.28	0.26	0.28	0.27	0.01
20-30	0.31	0.29	0.31	0.30	0.01
30-40	0.31	0.29	0.30	0.30	0.01
40-50	0.32	0.30	0.35	0.32	0.02
50-60	0.33	0.33	0.35	0.33	0.01
60-70	0.30	0.28	0.35	0.31	0.04
70-80	0.28	0.29	0.34	0.31	0.03
80-90	0.24	0.21	0.29	0.25	0.04
90-100	0.21	0.17	0.31	0.23	0.07
100-110	0.23	0.19	0.30	0.24	0.06
110-120	0.30	0.27	0.30	0.29	0.02
120-130		0.30	0.26	0.28	0.02
130-140	0.27	0.27	0.28	0.27	0.01
140-150	0.28	0.32	0.33	0.31	0.03
150-160	0.30	0.30	0.32	0.31	0.01
160-170	0.32	0.30	0.32	0.31	0.01
170-180	0.30	0.31	0.31	0.31	0.00
180-190	0.30	0.32	0.32	0.31	0.01
190-200	0.30	0.31	0.33	0.31	0.01
200-210	0.29	0.32	0.31	0.31	0.02
210-220	0.27	0.30	0.29	0.29	0.02
220-230	0.29		0.28	0.28	0.01
230-240	0.27		0.29	0.28	0.01
				mean=	
				0.29	

Volumetric Water Content - Bromide Tracer Test					
Depth (cm)	5.7 hours A	5.7 hours B	5.7 hours C	5.7 hours Mean	5.7 hrs Std. Dev.
0-10	0.31	0.24	0.33	0.29	0.04
10-20	0.29	0.28	0.31	0.29	0.01
20-30	0.31	0.32	0.33	0.32	0.01
30-40	0.31	0.32	0.32	0.32	0.00
40-50	0.31	0.36	0.31	0.33	0.03
50-60	0.30	0.32	0.31	0.31	0.01
60-70	0.29	0.31	0.30	0.30	0.01
70-80	0.27	0.28	0.30	0.28	0.02
80-90	0.24	0.26	0.27	0.26	0.02
90-100	0.26	0.29	0.31	0.28	0.02
100-110	0.29	0.29	0.32	0.30	0.02
110-120	0.30	0.29	0.30	0.30	0.01
120-130	0.27	0.29	0.29	0.28	0.01
130-140	0.29	0.27	0.33	0.30	0.03
140-150	0.32	0.30	0.33	0.32	0.02
150-160	0.30	0.31	0.34	0.31	0.02
160-170	0.30	0.30	0.31	0.31	0.01
170-180	0.32	0.30	0.32	0.31	0.01
180-190	0.29	0.31	0.32	0.30	0.01
190-200	0.28	0.30	0.31	0.30	0.01
200-210	0.28	0.32	0.30	0.30	0.02
210-220	0.29	0.31	0.29	0.30	0.01
220-230	0.29	0.30	0.29	0.29	0.01
230-240		0.31		0.31	
				mean=	
				0.30	

Volumetric Water Content - Bromide Tracer Test					
Depth (cm)	**10.4 hours A**	**10.4 hours B**	**10.4 hours C**	**10.4 hours Mean**	**10.4 hrs Std. Dev.**
0-10	0.25	0.24	0.33	0.28	0.05
10-20	0.30	0.28	0.30	0.29	0.01
20-30	0.28	0.28	0.30	0.29	0.01
30-40	0.32	0.29	0.30	0.30	0.01
40-50	0.33	0.34	0.34	0.34	0.01
50-60	0.30	0.31	0.36	0.32	0.03
60-70	0.30	0.29	0.30	0.30	0.01
70-80	0.27	0.30	0.29	0.28	0.02
80-90	0.25	0.27	0.26	0.26	0.01
90-100	0.23	0.30	0.28	0.27	0.04
100-110	0.29	0.32	0.30	0.30	0.01
110-120	0.31	0.32	0.29	0.30	0.02
120-130	0.28	0.28	0.30	0.29	0.01
130-140	0.29	0.28	0.30	0.29	0.01
140-150	0.32	0.32	0.33	0.32	0.01
150-160	0.31	0.32	0.35	0.32	0.02
160-170	0.30	0.33	0.34	0.32	0.02
170-180	0.30	0.31	0.33	0.31	0.01
180-190		0.32	0.33	0.33	0.01
190-200		0.32	0.32	0.32	0.00
200-210		0.32	0.31	0.32	0.00
210-220		0.32	0.31	0.32	0.00
220-230		0.30	0.29	0.30	0.00
230-240		0.28		0.28	
				mean=	
				0.30	

Volumetric Water Content - Bromide Tracer Test					
Depth (cm)	**23.1 hours A**	**23.1 hours B**	**23.1 hours C**	**23.1 hours Mean**	**23.1 hrs Std. Dev.**
0-10	0.23	0.26	0.24	0.24	0.02
10-20	0.28	0.30	0.26	0.28	0.02
20-30	0.27	0.33	0.30	0.30	0.03
30-40	0.08	0.34	0.33	0.25	0.15
40-50	0.30	0.32	0.34	0.32	0.02
50-60	0.31	0.31	0.30	0.31	0.01
60-70	0.30	0.29	0.31	0.30	0.01
70-80	0.26	0.27	0.29	0.27	0.01
80-90	0.28	0.27	0.29	0.28	0.01
90-100	0.28	0.29	0.29	0.29	0.01
100-110	0.33	0.31	0.29	0.31	0.02
110-120	0.30	0.31	0.30	0.31	0.01
120-130	0.32	0.29	0.29	0.30	0.02
130-140	0.31	0.30	0.31	0.30	0.00
140-150	0.44	0.32	0.32	0.36	0.07
150-160	0.30	0.32	0.33	0.31	0.01
160-170	0.29	0.32	0.34	0.32	0.02
170-180	0.27	0.32	0.33	0.31	0.03
180-190	0.28	0.32	0.32	0.31	0.02
190-200	0.28	0.29	0.33	0.30	0.03
200-210	0.29	0.29	0.31	0.30	0.01
210-220		0.29	0.30	0.30	0.01
220-230		0.29	0.31	0.30	0.01
230-240			0.30	0.30	
				mean=	
				0.30	

Volumetric Water Content - Bromide Tracer Test					
Depth (cm)	**57.6 hours A**	**57.6 hours B**	**57.6 hours C**	**57.6 hours Mean**	**57.6 hrs Std. Dev.**
0-10	0.23	0.23	0.23	0.23	0.00
10-20	0.28	0.29	0.28	0.28	0.01
20-30	0.32	0.32	0.30	0.31	0.01
30-40	0.32	0.31	0.28	0.30	0.02
40-50	0.34	0.31	0.32	0.32	0.01
50-60	0.31	0.32	0.29	0.30	0.01
60-70	0.29	0.30	0.30	0.30	0.01
70-80	0.27	0.28	0.27	0.27	0.01
80-90	0.26	0.25	0.26	0.26	0.00
90-100	0.27	0.29	0.28	0.28	0.01
100-110	0.30	0.30	0.30	0.30	0.00
110-120	0.32	0.30	0.30	0.31	0.01
120-130	0.30	0.29	0.30	0.30	0.01
130-140	0.30	0.32	0.32	0.31	0.01
140-150	0.31	0.33	0.33	0.32	0.01
150-160	0.30	0.32	0.35	0.32	0.02
160-170	0.31	0.33	0.33	0.32	0.01
170-180	0.30	0.30	0.32	0.31	0.01
180-190	0.31	0.30	0.32	0.31	0.01
190-200	0.31	0.30	0.30	0.30	0.00
200-210	0.29	0.29	0.29	0.29	0.00
210-220	0.29	0.28	0.31	0.29	0.01
220-230	0.28	0.28		0.28	0.00
230-240	0.28			0.28	
				mean=	
				0.30	

Volumetric Water Content - Bromide Tracer Test					
Depth (cm)	**151 hours A**	**151 hours B**	**151 hours C**	**151 hours Mean**	**151 hrs Std. Dev.**
0-10	0.21	0.22	0.22	0.22	0.01
10-20	0.27	0.28	0.28	0.28	0.01
20-30	0.30	0.32	0.28	0.30	0.02
30-40	0.33	0.32	0.31	0.32	0.01
40-50	0.33	0.34	0.34	0.34	0.00
50-60	0.30	0.60	0.32	0.41	0.17
60-70	0.29	0.29	0.28	0.29	0.00
70-80	0.26	0.27	0.27	0.27	0.00
80-90	0.23	0.51	0.23	0.32	0.16
90-100	0.42	0.26	0.27	0.32	0.09
100-110	0.34	0.27	0.27	0.29	0.04
110-120	0.30	0.26	0.30	0.29	0.03
120-130	0.30	0.33	0.30	0.31	0.02
130-140	0.30	0.29	0.31	0.30	0.01
140-150	0.31	0.32	0.32	0.32	0.01
150-160	0.30	0.31	0.32	0.31	0.01
160-170	0.31	0.34	0.36	0.34	0.02
170-180	0.30	0.31	0.33	0.31	0.02
180-190	0.30	0.32	0.33	0.32	0.01
190-200	0.27	0.75	0.32	0.44	0.26
200-210	0.29	0.03	0.31	0.21	0.16
210-220	0.29	0.42	0.31	0.34	0.07
220-230		0.22	0.31	0.26	0.07
230-240		0.29		0.29	
				mean=	
				0.31	

APPENDIX B

Soil-Bromide Content Data

Soil-Bromide Content Data					
Background	**A data**	**B data**	**C data**	**Mean**	**Standard Dev.**
Depth (cm)	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**
0-10	0.06	0.17	0.05	0.09	0.07
10-20	0.06	0.69	0.03	0.26	0.37
20-30		0.05		0.05	
30-40	0.04			0.04	
40-50	0.04	0.06		0.05	0.01
50-60	0.04			0.04	
60-70	0.02	0.05	0.13	0.07	0.06
70-80	0.01	0.03		0.02	0.01
80-90	0.02	0.21	0.11	0.11	0.10
90-100	0.08			0.08	
100-110	0.03		0.05	0.04	0.02
110-120	0.04		0.02	0.03	0.01
120-130	0.16	0.15	0.07	0.12	0.05
130-140	0.12	0.35	0.07	0.18	0.15
140-150	0.12		0.19	0.16	0.05
150-160	0.11	0.54	0.29	0.31	0.22
160-170	0.09	0.17	0.57	0.28	0.26
170-180	0.12	0.08	0.54	0.25	0.25
180-190	0.12	0.37	0.53	0.34	0.21
190-200	0.04		0.40	0.22	0.25
200-210	0.04		0.58	0.31	0.38
210-220					
220-230					
230-240					

Soil-Bromide Content Data					
4 Hours	A data	B data	C data	Mean	Standard Dev.
Depth (cm)	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil
0-10	27.42	23.86	40.77	30.68	8.91
10-20	17.78	2.04	21.11	13.64	10.19
20-30	8.03	0.05	16.25	8.11	8.10
30-40	6.02	0.07	10.24	5.44	5.11
40-50	3.10	0.03	9.17	4.10	4.65
50-60	3.06	0.03	6.28	3.12	3.12
60-70	2.88	0.10	1.32	1.43	1.40
70-80	2.06	0.23	1.06	1.12	0.92
80-90	0.11		3.54	1.82	2.42
90-100	0.02	0.24	6.30	2.19	3.56
100-110	0.07	0.05	9.85	3.32	5.65
110-120	0.07	0.04	2.44	0.85	1.38
120-130		0.94	2.78	1.86	1.30
130-140	0.80	0.05	0.15	0.34	0.40
140-150	0.26	0.06	0.11	0.14	0.10
150-160	0.23	0.12	0.19	0.18	0.05
160-170	0.22	0.23	0.16	0.21	0.04
170-180	0.33	0.22	1.68	0.74	0.81
180-190	0.38	0.36	0.34	0.36	0.02
190-200	0.32	0.21	0.30	0.28	0.06
200-210	0.32	0.16	0.24	0.24	0.08
210-220	0.10	0.13	0.22	0.15	0.07
220-230	0.10		0.16	0.13	0.05
230-240			0.10	0.10	

Soil-Bromide Content Data					
5.7 Hours	A data	B data	C data	Mean	Standard Dev.
Depth (cm)	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil
0-10	30.98	20.19	30.48	27.22	6.09
10-20	11.97	9.91	14.19	12.02	2.14
20-30	5.53	6.93	7.80	6.75	1.15
30-40	7.21	5.56	14.49	9.09	4.75
40-50	4.44	2.81	5.88	4.38	1.54
50-60	3.45	3.16	7.34	4.65	2.33
60-70	3.09	3.43	6.53	4.35	1.90
70-80	1.93	3.39	12.96	6.09	5.99
80-90	0.38	3.12	26.26	9.92	14.22
90-100	0.09	0.52	37.80	12.80	21.65
100-110	0.08	0.12	44.30	14.83	25.52
110-120	0.26	0.08	19.22	6.52	11.00
120-130	0.09	1.63	13.39	5.04	7.28
130-140	0.18	0.11	0.76	0.35	0.35
140-150	0.33	0.29	0.86	0.50	0.32
150-160	0.48	0.38	0.49	0.45	0.06
160-170	0.52	0.37	0.57	0.49	0.10
170-180	0.51	0.43	0.82	0.58	0.21
180-190	0.40	0.36	0.50	0.42	0.07
190-200	0.27	0.64	0.64	0.52	0.21
200-210	0.18	0.36	0.43	0.32	0.13
210-220	0.11	0.24	0.44	0.26	0.16
220-230	0.17	0.20	0.39	0.25	0.12
230-240		0.31		0.31	

Soil-Bromide Content Data					
10.4 Hours	A data	B data	C data	Mean	Standard Dev.
Depth (cm)	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil
0-10	17.22	15.60	34.25	22.36	10.33
10-20	9.00	13.71	31.31	18.00	11.76
20-30	2.85	3.59	11.94	6.12	5.05
30-40	3.69	3.54	13.57	6.94	5.75
40-50	1.57	5.82	8.46	5.29	3.48
50-60	1.88	4.35	14.15	6.80	6.49
60-70	0.72	2.58	6.60	3.30	3.01
70-80	0.92	4.61	13.62	6.38	6.53
80-90	1.40	8.74	16.60	8.91	7.60
90-100	0.45	7.28	27.31	11.68	13.96
100-110			11.57	11.57	
110-120			1.63	1.63	
120-130	0.83	0.21	2.99	1.34	1.46
130-140	0.54		2.01	1.28	1.04
140-150	0.61	0.51	0.44	0.52	0.09
150-160	0.63	0.59	0.22	0.48	0.23
160-170	0.78	0.68	0.24	0.57	0.29
170-180	1.08	0.70	0.31	0.70	0.39
180-190		0.43	0.77	0.60	0.24
190-200		0.70	0.44	0.57	0.18
200-210		0.51	0.36	0.43	0.11
210-220			0.22	0.22	
220-230		0.43	0.22	0.32	0.15
230-240		0.50		0.50	

Soil-Bromide Content Data					
23.1 Hours	**A data**	**B data**	**C data**	**Mean**	**Standard Dev.**
Depth (cm)	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**
0-10	20.00	25.90	20.29	22.06	3.33
10-20	9.98	16.27	17.79	14.68	4.14
20-30	1.95	11.81	10.39	8.05	5.33
30-40	0.43	9.88	14.06	8.12	6.98
40-50	0.72	3.33	9.65	4.56	4.59
50-60	0.40	6.26	6.87	4.51	3.57
60-70	0.51	5.58	8.37	4.82	3.99
70-80	2.31	11.89	13.87	9.36	6.18
80-90	4.10	17.83	19.66	13.86	8.51
90-100	24.31	16.49	15.42	18.74	4.85
100-110	7.37	22.15	8.78	12.77	8.16
110-120	0.53	6.76	1.70	3.00	3.31
120-130	0.27	1.02	7.63	2.97	4.05
130-140	0.14		0.89	0.51	0.53
140-150	0.53		0.42	0.48	0.08
150-160	0.53	0.17	0.38	0.36	0.18
160-170	0.42	0.27	0.45	0.38	0.09
170-180	0.18	0.35	0.49	0.34	0.16
180-190	0.36	0.43	0.57	0.45	0.11
190-200	0.09	0.19	0.57	0.28	0.25
200-210	0.14	0.21	0.46	0.27	0.16
210-220		0.15	0.37	0.26	0.15
220-230			0.33	0.33	
230-240					

Soil-Bromide Content Data					
57.6 Hours	**A data**	**B data**	**C data**	**Mean**	**Standard Dev.**
Depth (cm)	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**
0-10	16.92	18.10	24.89	19.97	4.30
10-20	7.39	19.26	17.99	14.88	6.52
20-30	3.42	10.47	6.18	6.69	3.55
30-40	1.80	3.56	1.61	2.32	1.07
40-50	1.65	1.82	1.25	1.57	0.29
50-60	1.12	2.26	7.95	3.78	3.66
60-70	0.79	1.91	2.60	1.77	0.91
70-80	0.93	3.06	10.74	4.91	5.16
80-90	0.36	3.38	4.34	2.70	2.08
90-100	0.32	1.89	1.61	1.27	0.84
100-110		0.32	0.62	0.47	0.21
110-120		0.36	0.19	0.27	0.12
120-130	0.30	0.30	0.27	0.29	0.02
130-140		0.25		0.25	
140-150					
150-160	0.58			0.58	
160-170	0.60		0.27	0.44	0.23
170-180	0.70	0.41	0.40	0.50	0.17
180-190	0.53	0.72	0.38	0.55	0.17
190-200	0.74	0.32	0.28	0.45	0.26
200-210	0.52	0.33	0.24	0.36	0.15
210-220	0.53		0.25	0.39	0.20
220-230	0.43	0.26		0.34	0.12
230-240	0.39			0.39	

Soil-Bromide Content Data					
151 Hours	A data	B data	C data	Mean	Standard Dev.
Depth (cm)	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil	mg Br/kg soil
0-10	17.80	18.49	18.59	18.29	0.43
10-20	7.58	14.22	11.65	11.15	3.35
20-30	3.05	7.47	4.86	5.13	2.22
30-40	2.70	7.11	6.47	5.43	2.38
40-50	2.88	4.58	7.68	5.05	2.43
50-60	2.62	5.20	5.78	4.53	1.68
60-70	1.85	1.97	4.03	2.62	1.22
70-80	1.30	2.49	6.15	3.32	2.53
80-90	0.64	5.60	5.94	4.06	2.97
90-100	9.19	4.47	14.31	9.32	4.92
100-110	0.39	0.93	8.53	3.28	4.55
110-120	1.36		0.87	1.11	0.35
120-130	0.53	0.68	2.68	1.29	1.20
130-140	0.20		0.66	0.43	0.33
140-150	0.29			0.29	
150-160	0.38			0.38	
160-170	0.44		0.79	0.61	0.25
170-180	0.33	0.50	0.97	0.60	0.33
180-190	0.58	0.61	0.49	0.56	0.06
190-200	0.16	1.19	0.81	0.72	0.52
200-210		0.04	0.71	0.38	0.47
210-220		0.47	0.62	0.54	0.10
220-230					
230-240					

Soil-Bromide Content Data					
2 Months	A data	B data	C data	Mean	Standard Dev.
Depth (cm)	A mg Br/kg soil	B mg Br/kg soil	C mg Br/kg soil	mg Br/kg soil	mg Br/kg soil
0-10	22.22	8.33	4.23	11.59	9.43
10-20	16.11	7.59	1.97	8.56	7.12
20-30	10.11	5.35	1.35	5.60	4.39
30-40	7.44	4.12	2.96	4.84	2.32
40-50	8.02	1.71	0.72	3.48	3.96
50-60	7.08	1.38	0.61	3.02	3.53
60-70	6.32	0.45	0.14	2.31	3.48
70-80	8.41	0.50	0.20	3.04	4.66
80-90	6.63	0.51	0.05	2.40	3.67
90-100	17.58	1.90	0.10	6.53	9.61
100-110	15.64	3.12	1.60	6.78	7.71
110-120	6.28	1.72	1.02	3.01	2.86
120-130	1.07	0.14	0.04	0.42	0.57
130-140	0.12	0.26	0.31	0.23	0.10
140-150	0.25	0.08	0.66	0.33	0.30
150-160	0.34	0.49	1.02	0.62	0.36
160-170	0.54	0.67	1.21	0.81	0.36
170-180	0.99	0.80	1.12	0.97	0.16
180-190	0.87	0.42	0.59	0.62	0.23
190-200	1.16	0.59	0.81	0.86	0.29
200-210	0.50	0.22	0.14	0.29	0.19
210-220	0.48	0.48		0.48	0.00

Soil-Bromide Content Data					
3.4 Years	**A data**	**B data**	**C data**	**Mean**	**Standard Dev.**
Depth (cm)	**A mg Br/kg soil**	**B mg Br/kg soil**	**C mg Br/kg soil**	**mg Br/kg soil**	**mg Br/kg soil**
0-10	0.78	0.37	0.45	0.53	0.22
10-20	0.36	0.54	0.25	0.38	0.15
20-30	0.25	0.08	0.26	0.20	0.10
30-40	0.05	0.14	0.08	0.09	0.05
40-50	0.23	0.08	0.15	0.15	0.07
50-60	0.16	0.09	0.16	0.14	0.04
60-70	0.17	0.09	0.05	0.10	0.06
70-80	0.05	0.11	0.08	0.08	0.03
80-90	0.06	0.12	0.05	0.08	0.04
90-100	0.12	0.06	0.04	0.08	0.04
100-110	0.13	0.02	0.05	0.07	0.06
110-120	0.35	0.34	0.47	0.39	0.07
120-130	2.34	1.15	0.71	1.40	0.84
130-140	13.18	12.56	4.57	10.11	4.80
140-150	5.22	5.16	6.45	5.61	0.73
150-160	6.10	4.01	3.68	4.60	1.31
160-170	3.99	4.54	2.33	3.62	1.15
170-180	1.91	2.31	0.98	1.74	0.68
180-190	1.37	1.59	0.82	1.26	0.40
190-200	1.76	1.51	0.45	1.24	0.70
200-210	0.25	0.45		0.35	0.14
210-220	0.06		0.50	0.28	0.31

Bromide Mass Data				
Background	**A data**	**B data**	**C data**	**Mean**
Depth (cm)	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**
0-10	36.98	110.94	33.46	60.46
10-20	50.29	559.93	21.29	210.50
20-30		45.25		45.25
30-40	31.97			31.97
40-50	35.45	49.20		42.33
50-60	33.75			33.75
60-70	16.31	40.30	107.73	54.78
70-80	10.37	21.32		15.84
80-90	14.21	167.00	90.09	90.43
90-100	68.07			68.07
100-110	22.24		43.23	32.73
110-120	30.57		17.05	23.81
120-130	123.05	116.23	51.26	96.85
130-140	91.37	274.50	54.31	140.06
140-150	100.75		153.61	127.18
150-160	92.95	441.90	232.01	255.62
160-170	72.73	144.98	473.18	230.29
170-180	99.87	65.51	450.17	205.18
180-190	103.54	322.22	459.97	295.24
190-200	38.22		345.27	191.75
200-210	33.79		514.55	274.17
210-220			total mg=	2526.28
220-230				

Bromide Mass Data				
4 Hours	**A data**	**B data**	**C data**	**Mean**
Depth (cm)	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**
0-10	18246.66	15881.36	27132.21	20420.08
10-20	14375.88	1646.76	17070.04	11030.89
20-30	6890.45	47.01	13940.80	6959.42
30-40	5166.63	60.57	8785.02	4670.74
40-50	2622.21	24.05	7770.54	3472.26
50-60	2593.92	26.87	5319.55	2646.78
60-70	2411.23	83.69	1103.94	1199.62
70-80	1722.46	190.19	886.21	932.95
80-90	87.74		2840.39	1464.07
90-100	17.53	192.01	5058.45	1756.00
100-110	57.90	44.70	8125.65	2742.75
110-120	58.41	29.15	2009.88	699.15
120-130		736.38	2174.23	1455.30
130-140	623.19	42.79	119.85	261.95
140-150	211.90	48.23	92.11	117.41
150-160	184.69	100.34	155.26	146.77
160-170	186.89	194.98	137.22	173.03
170-180	273.38	184.49	1403.82	620.56
180-190	324.91	306.91	290.24	307.35
190-200	279.50	179.93	258.52	239.32
200-210	283.94	141.68	216.75	214.12
210-220	85.18	115.18	197.75	132.71
220-230	85.52		143.06	114.29
230-240			88.55	88.55
			total mg=	61866.06

Bromide Mass Data				
5.7 Hours	**A data**	**B data**	**C data**	**Mean**
Depth (cm)	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**
0-10	20615.32	13433.33	20287.35	18112.00
10-20	9675.90	8014.62	11469.58	9720.03
20-30	4742.79	5944.47	6691.45	5792.90
30-40	6183.91	4772.88	12433.23	7796.67
40-50	3758.82	2380.85	4981.22	3706.96
50-60	2924.10	2675.78	6214.72	3938.20
60-70	2580.46	2863.38	5459.78	3634.54
70-80	1615.92	2831.99	10834.56	5094.16
80-90	301.44	2504.52	21087.44	7964.47
90-100	73.13	414.58	30351.92	10279.88
100-110	63.06	95.28	36549.75	12236.03
110-120	213.15	65.28	15852.97	5377.13
120-130	72.75	1269.91	10460.42	3934.36
130-140	139.14	88.90	590.35	272.80
140-150	272.08	237.05	702.07	403.73
150-160	394.47	305.61	397.93	366.00
160-170	432.73	310.17	478.28	407.06
170-180	422.22	358.31	684.09	488.21
180-190	345.29	313.01	427.76	362.02
190-200	231.58	549.26	556.67	445.84
200-210	157.64	317.40	382.84	285.96
210-220	95.73	216.03	387.71	233.16
220-230	148.48	175.02	349.07	224.19
230-240		277.62		277.62
			total mg=	101353.91

Bromide Mass Data				
10.4 Hours	**A data**	**B data**	**C data**	**Mean**
Depth (cm)	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**
0-10	11462.31	10382.12	22791.10	14878.51
10-20	7275.37	11081.80	25311.68	14556.28
20-30	2444.16	3079.26	10240.99	5254.80
30-40	3169.50	3041.05	11647.22	5952.59
40-50	1332.26	4930.82	7166.43	4476.50
50-60	1592.94	3685.64	11987.83	5755.47
60-70	599.22	2158.11	5517.46	2758.26
70-80	765.05	3852.13	11385.31	5334.16
80-90	1127.20	7014.42	13328.75	7156.79
90-100	359.91	5846.21	21930.37	9378.83
100-110			9544.15	9544.15
110-120			1340.92	1340.92
120-130	647.97	166.66	2332.44	1049.02
130-140	421.98		1571.95	996.96
140-150	499.19	415.31	355.79	423.43
150-160	509.00	481.56	177.10	389.22
160-170	655.71	564.59	197.24	472.51
170-180	902.78	585.52	258.81	582.37
180-190		373.59	661.99	517.79
190-200		601.04	379.71	490.37
200-210		453.82	318.35	386.08
210-220			192.36	192.36
220-230		380.61	190.45	285.53
230-240		438.46		438.46
			total mg=	92611.37

Bromide Mass Data				
23.1 Hours	**A data**	**B data**	**C data**	**Mean**
Depth (cm)	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**
0-10	13308.00	17238.69	13502.48	14683.06
10-20	8068.67	13154.00	14383.42	11868.69
20-30	1674.74	10134.04	8912.49	6907.09
30-40	370.78	8473.03	12066.61	6970.14
40-50	605.70	2821.27	8170.61	3865.86
50-60	339.76	5302.68	5818.25	3820.23
60-70	423.01	4665.29	7000.68	4029.66
70-80	1933.57	9939.79	11591.54	7821.63
80-90	3290.31	14314.85	15786.88	11130.68
90-100	19517.73	13243.48	12379.66	15046.96
100-110	6083.50	18272.39	7241.28	10532.39
110-120	435.30	5575.79	1406.57	2472.55
120-130	214.49	796.34	5956.65	2322.49
130-140	105.49		691.89	398.69
140-150	430.84		344.01	387.43
150-160	433.50	140.23	305.80	293.17
160-170	352.38	228.03	373.30	317.90
170-180	149.49	290.06	409.63	283.06
180-190	308.98	369.18	488.21	388.79
190-200	81.34	160.99	488.89	243.74
200-210	129.10	191.08	408.95	243.04
210-220		135.97	329.32	232.64
220-230			291.28	291.28
230-240			total mg=	104551.20
240-250				
250-260				

Bromide Mass Data

57.6 Hours Depth (cm)	A data Bromide (mg)	B data Bromide (mg)	C data Bromide (mg)	Mean Bromide (mg)
0-10	11258.53	12043.51	16561.17	13287.74
10-20	5974.53	15574.34	14543.17	12030.68
20-30	2933.42	8982.29	5298.82	5738.18
30-40	1540.35	3050.40	1381.65	1990.80
40-50	1395.14	1542.14	1060.99	1332.76
50-60	948.58	1913.12	6734.17	3198.62
60-70	664.43	1595.18	2176.73	1478.78
70-80	776.63	2556.17	8979.07	4103.96
80-90	291.57	2717.51	3485.34	2164.81
90-100	253.65	1514.96	1292.34	1020.32
100-110		261.93	508.85	385.39
110-120		294.42	156.11	225.26
120-130	231.13	236.93	208.13	225.40
130-140		197.03		197.03
140-150				
150-160	473.71			473.71
160-170	502.38		229.61	366.00
170-180	584.47	346.35	335.47	422.09
180-190	461.71	625.11	325.99	470.94
190-200	640.83	278.42	242.19	387.15
200-210	466.55	293.00	210.28	323.28
210-220	474.25		219.15	346.70
220-230	376.59	225.99		301.29
230-240	342.09			342.09
			total mg=	50812.94

Bromide Mass Data				
151 Hours	**A data**	**B data**	**C data**	**Mean**
Depth (cm)	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**
0-10	11846.16	12305.22	12369.85	12173.74
10-20	6126.12	11493.19	9416.29	9011.87
20-30	2618.44	6407.49	4172.26	4399.40
30-40	2315.63	6098.64	5553.10	4655.79
40-50	2440.00	3876.19	6504.06	4273.41
50-60	2215.90	4405.10	4895.29	3838.76
60-70	1547.60	1649.83	3369.87	2189.10
70-80	1089.20	2083.12	5144.80	2772.38
80-90	512.43	4494.82	4772.71	3259.99
90-100	7380.54	3589.76	11490.35	7486.88
100-110	323.18	764.49	7034.56	2707.41
110-120	1118.03		715.07	916.55
120-130	412.60	529.89	2089.50	1010.66
130-140	153.58		516.65	335.11
140-150	237.01			237.01
150-160	306.61			306.61
160-170	367.19		660.53	513.86
170-180	279.36	416.75	812.45	502.85
180-190	500.64	528.26	422.77	483.89
190-200	140.68	1025.24	696.80	620.91
200-210		36.59	632.92	334.76
210-220		416.09	548.19	482.14
220-230			total mg=	62513.08
230-240				

Bromide Mass Data				
2 Months	**A data**	**B data**	**C data**	**Mean**
Depth (cm)	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**
0-10	14786.01	5543.75	2814.89	7714.88
10-20	13022.05	6136.42	1593.80	6917.42
20-30	8673.24	4587.22	1155.76	4805.41
30-40	6381.33	3532.63	2541.52	4151.83
40-50	6794.97	1448.30	610.89	2951.39
50-60	5993.18	1164.83	519.07	2559.03
60-70	5285.55	379.16	120.03	1928.24
70-80	7029.51	420.06	163.17	2537.58
80-90	5324.38	408.44	42.91	1925.24
90-100	14115.73	1526.69	79.09	5240.51
100-110	12901.03	2570.64	1318.26	5596.64
110-120	5183.42	1416.36	840.39	2480.06
120-130	836.82	105.70	34.22	325.58
130-140	96.49	203.39	239.43	179.77
140-150	199.45	65.96	539.01	268.14
150-160	274.49	396.81	833.56	501.62
160-170	451.82	556.28	1014.63	674.24
170-180	824.90	670.26	938.11	811.09
180-190	753.68	358.36	506.20	539.41
190-200	1004.28	513.24	700.60	739.37
200-210	444.04	197.09	124.66	255.26
210-220	425.39	424.19		424.79
			total mg=	53527.51

Bromide Mass Data

3.4 Years	**A data**	**B data**	**C data**	**Mean**
Depth (cm)	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**	**Bromide (mg)**
0-10	519.47	244.91	300.99	355.12
10-20	288.59	438.72	198.52	308.61
20-30	210.48	71.65	222.79	168.31
30-40	43.42	123.03	72.37	79.61
40-50	192.61	69.13	129.57	130.44
50-60	136.97	76.50	138.20	117.22
60-70	141.08	73.33	45.38	86.60
70-80	38.30	88.12	70.37	65.60
80-90	46.17	98.58	43.72	62.82
90-100	97.47	50.06	34.35	60.63
100-110	106.75	20.57	37.53	54.95
110-120	291.06	284.23	389.79	321.69
120-130	1824.41	901.87	556.64	1094.30
130-140	10297.45	9810.59	3573.02	7893.69
140-150	4252.77	4203.59	5253.13	4569.83
150-160	4965.19	3264.87	2995.00	3741.69
160-170	3333.35	3796.48	1949.60	3026.48
170-180	1599.75	1930.78	822.03	1450.85
180-190	1179.53	1373.17	706.27	1086.33
190-200	1519.30	1301.75	385.37	1068.81
200-210	224.40	400.51		312.45
210-220	55.63		446.60	251.11
			total mg=	26307.14

APPENDIX C

Well Data (Bromide)

Wells D2 & D3 - Bromide Concentration (mg/L) vs. Time (hrs.)						
D2 Hours	D3 Hours	Hours	D2 [Br-]	D3 [Br-]	D2 Time	D3 Time
0.15	0.2	0.15	0.401		909	912
0.87	0.92	0.2		0.362	952	955
1.12	1.15	0.87	0.347		1007	1009
1.83	1.5	0.92		0.358	1050	1030
2.25	1.92	1.12	0.367		1115	1055
2.67	2.33	1.15		0.328	1140	1120
3.08	2.75	1.5		0.346	1205	1145
3.5	3.17	1.83	0.355		1230	1210
3.92	3.58	1.92		0.35	1255	1235
4.33	4	2.25	0.381		1320	1300
4.75	4.42	2.33		0.335	1345	1325
5.17	4.83	2.67	0.289		1410	1350
5.58	5.25	2.75		0.308	1435	1415
6.17	5.67	3.08	0.425		1510	1440
7	6.33	3.17		0.345	1600	1520
7.83	7.17	3.5	0.678		1650	1610
8.67	8	3.58		0.293	1740	1700
9.5	8.83	3.92	0.772		1830	1750
10.5	9.67	4		0.332	1930	1840
11.75	10.75	4.33	0.779		2045	1945
	12	4.42		0.316		2100
		4.75	0.745			
		4.83		0.386		
		5.17	0.756			
		5.25		0.269		
		5.58				
		5.67		0.388		
		6.17	0.798			
		6.33		0.379		
		7	0.676			
		7.17		0.463		
		7.83	0.546			
		8		0.488		
		8.67	0.455			
		8.83		0.372		
		9.5	0.425			
		9.67		0.373		
		10.5	0.448			
		10.75		0.391		
		11.75	0.432			
		12		0.383		

APPENDIX D

Well Data (Iodide)

Iodide Tracer Test (4/29/91) - Test started at 10:45 am

Wells D3, D4, and D5 - No iodide above detection limit

D1 Hours after start	Well D1 Iodide (mg/L)	D1 Time		D2 Hours after start	Well D2 Iodide (mg/L)	D2 Time
0		953		0		1021
1.25		1200		1.33		1205
1.67		1225		1.75		1230
2.08		1250		2.17		1255
2.5		1315		2.58		1320
2.92		1340		3		1345
3.33		1405		3.42		1410
3.75		1430		3.83		1435
4.17		1455		4.25		1500
4.58		1520		4.67	1.319	1525
5		1545		5.08	1.759	1550
5.42		1610		5.5	2.938	1615
5.83	0.246	1635		5.92	3.227	1640
6.25	0.431	1700		6.33	3.09	1705
6.67	0.376	1725		6.75	2.417	1730
7.08	0.399	1750		7.17	2.239	1755
7.5	0.3	1815		7.58	1.647	1820
7.92	0.378	1840		8	1.003	1845
8.33	0.413	1905		8.42	1.136	1910
8.75		1930		8.83	0.926	1935
9.25	0.233	2000		9.42	1.217	2010
10.17	0.994	2055		10.42	0.858	2110

APPENDIX E

Well Data (Bromide After Iodide Test)

Iodide Tracer Test (4/29/91)		**(Test started at 10:45 am)**		
Well D1 - no bromide above background level				
Well D3 - " " " " "				
Well D4 - " " " " "				
Well D5 - " " " " "				
Hours after start	Well D2 Bromide (mg/L)		Time	
0	0.369		1021	
1.33	0.382		1205	
1.75	0.344		1230	
2.17	0.37		1255	
2.58	0.38		1320	
3	0.347		1345	
3.42	0.366		1410	
3.83	0.374		1435	
4.25	0.386		1500	
4.67	0.375		1525	
5.08	0.405		1550	
5.5	0.378		1615	
5.92	0.404		1640	
6.33	0.46		1705	
6.75	0.463		1730	
7.17	0.419		1755	
7.58	0.413		1820	
8	0.399		1845	
8.42	0.409		1910	
8.83	0.397		1935	
9.42	0.398		2010	
10.42	0.357		2110	

VITA

Mark Alexander Everett

Candidate for the Degree of

Master of Science

Thesis: MOVEMENT OF BROMIDE AND IODIDE THROUGH AN ASHPORT SOIL PEDON AND IMPACT ON A SHALLOW UNCONFINED AQUIFER

Major Field: Agronomy

Biographical:

Personal Data: Born in Albuquerque, NM, on February 5, 1971.

Education: Graduated from Stillwater High School, Stillwater, Oklahoma in May 1989; received Bachelor of Science degree in Biology from the University of Tulsa, Tulsa, Oklahoma in May 1993. Completed the requirements for the Master of Science degree at Oklahoma State University in December, 1996.

Experience: Employed by Oklahoma State University, Department of Agronomy, as a teaching assistant for Agron 2124 - Fundamentals of Soil Science (8/1/94 - 5/15/96).

Professional Memberships: Soil Science Society of America