

**Water Quality and Ground-Water Recharge
Through Soil to a Shallow Aquifer**

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INTRODUCTION

Soil Macropores and Shallow Ground-Water Systems

Shallow ground-water systems pose one of the greatest challenges to soil scientists and hydrogeologists because their nearness to the land surface renders them highly susceptible to contamination from a wide range of sources.

Hagen (1986) and Hoyle (1987) monitored shallow water-table fluctuations and ground-water quality, and conducted several aquifer tests in order to determine hydraulic characteristics. Both investigators documented considerable variation in water quality with respect to both time and space. They attributed fluctuations in water quality and water level to rapid recharge through soil macropores.

Acre (1989) and Ross (1988), who studied the unsaturated zone, installed eight soil-water suction lysimeters and four neutron probe access tubes. Ross (1988) discovered significant short term water-quality variations in the unsaturated zone. Variations in soil-moisture content also led Acre to conclude that soil macropores influence infiltration.

Froneberger (1989) examined soil water movement through the unsaturated zone by means of surface applied bromide and chloride tracers. He found that large spikes of the tracers appeared in the lysimeters after a short time, and he attributed this phenomenon to the vertical movement of water through soil macropores.

The idea that soil macropores could affect water and solute flow through soil was being considered as early as the mid 1800s. Lawes et al. (1882) noted that macropores control infiltration, moving rainwater to considerable depths with little change in composition. Since that time, work on the soil macropore theory has abounded, and this has resulted in extensive literature on the topic.

Brewer (1964) categorized soil fabric on the basis of size, using macro to mean pores that are at least 100 micrometers in diameter. Luxmoore (1981), who expanded Brewer's work, described three classes of macropore sizes. Skopp (1981) refined size classification by incorporating function in the definition of macroporosity. Techniques for measuring macropore size include timing and measuring water flow through 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., 1988a). Beven et al. (1982) grouped macropores on the basis of type (i.e., cracks and fissures, soil fauna, and plant roots).

Researchers, such as Cheng (1988), Hoogmoed (1980), Beven and German (1981), Armstrong and Arrowsmith (1986), and McIntyre and Sleeman (1982), demonstrated the importance of macropores in the infiltration of rainwater. Bouma et al. (1978) described this process of rapid flow through macropores as "short circuiting."

Rogowski and Simmons (1988) verified that soil macropores cause field-measured hydraulic conductivities to be greater than the nature of aquifer material or laboratory calculated values might indicate. Further substantiation of this exists in the works of Rogowski and Richie (1984) and Heard et al. (1988).

A considerable number of articles document the fact that macropores enhance chemical migration through the soil. Quisenberry and Phillips (1976) found that macropores cause water laced with chloride to percolate through a silt loam aquifer with very little change in composition. In a similar study, Priebe and Blackmer (1989) observed the same behavior using oxygen-18 labeled water and nitrogen-15 labeled urea. Other studies utilizing tritium, chloride, and lime provide further evidence for enhanced chemical migration (Edwards et al., 1988b; Minhas and Khosla, 1986; Black et al., 1973).

Bromide as a Tracer

There are numerous examples of the use of bromide tracers to evaluate the effect of macropores on infiltration and ground-water recharge and contaminant transport. Chan and Mead (1989), who tracked the migration of bromide-laced "rain" into the soil by taking core samples, concluded that macropores significantly decrease runoff. Zachman et al. (1987) used bromide to show that worm burrow-formed macropores increase infiltration to a considerable depth. The fact that macropores cause field measured values of hydraulic conductivity to be greater than those measured in the laboratory was demonstrated by Tennyson and Settergren (1980) using bromide. Germann et al. (1984) employed bromide to verify that water infiltrates deeper into soils containing macropores. Other similar studies include Gerritse and Singh (1988), Smith and Davis (1974), Onken et al. (1977), LeBlanc and Garabedian (1986), and D'Lugsoz (1976).

Bromide is used to mimic nitrate movement in soils. Jabro et al. (1992) used bromide as a tracer to study macropore flow under saturated soil conditions. Onken et al. (1977) used bromide concentrations in soil water ranging from 0.06 mM to 0.50 mM. Onken et al. (1977) concluded that nitrate and bromide moves similarly in soil under field conditions. Bromide can be used in field experiments at low but detectable concentrations, posing no health or pollution problem (Schmotzer et al., 1973). Davis et al. (1980) concluded that bromide is a good tracer in ground-water studies. Bromide has low toxicity and occurs in concentration less than 0.01 mM bromide in natural waters.

Breakthrough curves for nitrate and bromide movement in subsoil columns illustrate that bromide simulates the movement of nitrate (Smith and Davis, 1974). Bromide closely mimics the movement of nitrate in soils because both are 1) monovalent anions, 2) similar in ionic radii, and 3) taken up by plants. The ionic radius of bromide is 0.196 nanometers, compared to 0.189 nanometers for a nitrate ion (Sidgwick, 1950). Bromide is not considered to be toxic to plants (Martin, 1966). 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 bromide had been taken up by plants (Owens et al., 1985).

Although not as popular as bromide, iodide has proven to be a reliable ground-water tracer. A study by Haaser (1978) demonstrated that iodide can be used successfully as a tracer in shallow soil systems. Osmin (1977) used iodide to determine hydraulic conductivity and ground-water flow direction. Bradbury and Green (1985) measured matrix diffusion with an iodide tracer. Rowe et al. (1965) traced water circulation in underground hot springs and geysers with iodide. Leap and Sun (1987) utilized iodide in tracer tests in southern Nevada. Soil extracts were analyzed for iodide tracer ions by Bowman (1984).

Water Movement in Soils

Piston flow

A commonly held concept of soil-water movement is that of piston or displacement flow. The piston flow concept works on the premise that 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. Bodman and Colman (1943) concluded that the maximum water content attained in the soil was approximately field capacity. A very good example of this flow is presented in the film developed by Walter Gardner (Walter P. Gardner, *Water Movement in Soils*, 16 mm with sound. Available from Agronomy Club, Agronomy Dept., Washington State University, Pullman, WA 99163). The film shows water movement in sieved, air-dry soil that is packed in columns.

Flow through macropores

The movement of water and solutes through macropores is an important soil phenomenon. Lawes et al. (1882) were the first to note flow through macropores when they found that water, added to soil profiles, moved rapidly through the profile via open channels. 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. The shape of the pores is noted along with size and quantity class.

Bouma and Dekker (1978a) coined the phrase "short circuiting" to describe vertical saturated flow through macropores in unsaturated soils. The source of these macropores are many and various. Macropores include cracks along ped faces of shrinking soils, worms and insect activity, and plant roots. Chen 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.

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. Blake et. al. (1973) also found that soil coatings on the outer surface of the peds in this soil had a higher tritium concentration than soil material from the inner portions of the peds. This was attributed to the tritium moving down the cracks then being absorbed into the outer surface of the peds. 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. Zachmann et al. (1987) used bromide to trace water movement into soils that had worm populations added to them and found that these soils showed evidence of macropore flow through worm burrows. Edwards et al. (1988a) found that continuous worm burrows were important factors for rapid infiltration into a non-tilled silt loam soil during intense rainstorms. In a laboratory study using undisturbed soil cores, Germann and Beven (1981) illustrated that with a continuous water supply macropore flow, the hydraulic

conductivity of the soil increases. Ghodrati and Jury (1990) used dyes to track the pathway of water into a loamy sand soil. Preferential saturated flow was contributed to weak grades of soil structure for both lateral and vertical movement indicated by solutes added to that soil (Ghodrati and Jury, 1990). 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). 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.

The objectives of this research were 1) to determine rate of movement of surface applied solutes through soil to a shallow aquifer and 2) to determine the change in ground-water quality after recharge from surface applied water containing bromide and iodide. A site was selected that contained soil occurring naturally with distinct soil macroporosity.

MATERIALS AND METHODS

Site Description

The site lies within the northeast 1/4 section 11, T 19 N, R 2 E in the city limits of Stillwater, Oklahoma. The soil at the site has been mapped as the Ashport silt loam series (Henley et al., 1987). Henley et. al. (1987) classify the Ashport soil as a Fine-silty, mixed, thermic Fluventic Haplustoll that occurs on floodplains along streams in Payne County. Ross (1988) provides a description of the soil profile at the site (Figure 1, p.21). A buried soil occurs at 1 m below land surface. This buried soil profile extends to a depth of 8.4 m, and the uppermost horizon has been radiocarbon dated at 1300 +/- 70 years before present (Ross, 1988). A lower buried soil extends from 8.4 m to 10 m and has been dated at 10,600 +/- 170 years before present (Ross, 1988). The

aquifer is contained within these buried alluvial soils, and the water table fluctuates between about 1.25 m and 3.5 m below land surface.

Field Methods

Plot design

Field plots were designed to place bromide- or iodide-laden water in areas surrounding a cluster of groundwater monitoring wells (D1 through D5) (Figure 2, p.22). The main plot had an area of 5.5 m² and two smaller plots, each of which covered 1.5 m². Surface applied bromide and iodide-laden water were contained within the plot area with plastic landscaping border partially buried to a depth of about 2.5 cm. Loose soil was packed on the 7.5 cm above ground portion of 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 2) that received the same amount of rainfall as the research plots. Equal amounts of water were applied to both the bromide and iodide treated plots and boundary area. Water was applied to the boundary area by 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 by 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. The second test was made to substantiate bromide tracer impact on ground water. For the second test only, ground-water samples were taken and analyzed.

Tracer application

The application of the bromide and iodide tracer to the treatment areas involved applying 7.5 cm of water to each plot over a three hour period. One hundred 50 l storage buckets were filled with deionized distilled water and then KBr and KI were added to them to produce a 6.3 mM bromide or iodide concentration. The 5.5 m² plot received 412.5 l of tracer-laden water. Each of the smaller 1.5 m² plots received 112.5 l of water. To apply the water to the surface of the plots, several hoses running from the buckets 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 monitoring changes in the soil moisture content, taking soil cores that were evaluated to monitor bromide movement in the soil, and collecting ground-water samples used to monitor bromide and iodide tracer. Soil moisture content was monitored at 15 cm depth increments for several months before, during, and after the test with a neutron probe depth moisture gauge (Troxler Electronic Laboratories Inc. model 3333, Research Triangle Park, North Carolina).

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 test. Water levels taken before testing began verified ground-water flow toward wells from the tracer application area. A pressure transducer in the well continuously measured depth to water during the experiment.

Soil cores were taken after the complete application of the bromide. At time intervals determined prior to the test, the soil within the largest plot was cored to a maximum depth of 2.4 m with 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 put in approximately 30 cm layers, and each layer was compacted with a metal rod.

Sample preparation in the field

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 bag for storage. This bag was then put into another bag to prevent the loss of moisture.

Laboratory Methods

Each soil sample that was collected in the field was taken to a laboratory for analysis. To determine the bromide content in each sample, a saturated paste extract was made from each sample according to the method described by Rhoades (1982). The only variance from Rhoades was the extraction of soils using a Baroid press rather than a vacuum filter funnel. After being collected, the extracted water was filtered through a 0.2 um membrane filter. After filtering, a 1:10 dilution of extract and distilled water was made. One ml of this dilution was then analyzed on an ion chromatograph (Dionex Corporation model 2000i, Houston, Texas) to determine the concentration of bromide in each sample. Iodide was used for measuring ground-water samples in the same manner. Three bromide and iodide standards were used to calibrate the ion chromatograph. The separator column used was a Dionex corporation model HPIC AS4A. The eluant used was 1.8 mM Na₂CO₃/1.7 mM NaHCO₃, flowing at a rate of 2 ml/min. To regenerate the column, 0.0125 M H₂SO₄ was used.

RESULTS AND DISCUSSION

Soil-Water Content

Soil-water content increased from the soil surface to a depth of 115 cm (Figure 3, p.23) after the application of water and bromide tracer. Within several hours after application of water, the soil-water content of the upper 40 cm of the surface increased from 20 to 35% saturation. During the next 24 hours after application of water, soil-water content within the upper 40 cm of the surface decreased by 5 to 20% saturation. Within soil depths of 40-115 cm, soil-water content continued to increase after application of water by 5 to 25% saturation. There was no change in soil-water content detected by neutron probe within the first 24 hours after application of water at soil depths from 115 to 200 cm. Any water reaching the shallow aquifer by water flow through the soil within the first 24 hours was not detected by the neutron probe.

Soil-Bromide Content

Soil-bromide content increased rapidly within several hours after application of water and bromide tracer from the 0 to 105 cm soil depth (Figure 4, p.24). After 48 hours, soil-bromide content in the 0 to 105 cm soil depth had decreased compared to the first 24 hours after water and bromide tracer application but still remained above background levels. There was little change in soil-bromide content from 48 to 150 hrs after water and bromide tracers applications within the 0 to 105 cm soil depth. Bromide was detected above background levels within the soil discontinuously from the 115 to 200 cm soil depths. At 4.0 hours after water and bromide-tracer application, soil-bromide content reached 0.53, 0.57, 1.52, 1.87, and 1.04 meq. per liter in core A at 135 cm, core B at 125 cm, and core C at 115,125, and 175 cm soil depths, respectively. At 5.7 hours after water and bromide-tracer application, soil-bromide content reached 0.99,11.91, 8.10,

0.48, and 0.49 meq. per liter in core B at 125 cm and core C at 115, 125, 145 and 175 cm soil depths, respectively. At 10.4 hours after water and bromide tracer application, soil-bromide concentration reached 0.52, 0.49, 0.69, 1.07, 1.78, and 1.19 meq. per liter in core A at 125, 165, and 175 cm and core C at 115, 125, and 135 cm soil depths, respectively. At 23.1 hours after water and bromide-tracer application, soil-bromide concentration reached 4.07, 0.63, 1.06, 4.69 and 0.52 meq. per liter within cores B and C at 115 and 125 cm, and within core C at 135 cm soil depths, respectively. At 57.6 hrs after water and bromide-tracer application soil-bromide concentration reached 0.47 meq. per liter with cores A and B at 195 and 185 cm soil depths, respectively. At 151 hours after water and bromide tracer application, soil-bromide concentration reached 0.85, 0.54, 1.56, 0.55, and 0.50 meq. per liter within core A at 115 cm and core C at 115, 125, 175, and 195 cm soil depths, respectively. All other soil cores below the 115 cm depth did not have soil-bromide concentrations above background levels.

Bromide Content in Wells

The surface of the shallow aquifer was 2.5 m below ground surface. Well D1 did not contain water during the experiment. Wells D2 and D3 were monitored and were found to contain bromide after water and bromide application to the soil surface (Figure 5, p.25). At 3 and 6 hrs after the start of surface water and bromide application, wells D2 and D3, respectively, contained bromide above background levels. Bromide concentration in well D2 remained 1.5 to 2 times higher than background for 5 hrs after initial bromide detection above background levels. Bromide concentration in well D3 remained .5 times higher than background for 1 hour after initial detection of bromide above background levels. Bromide above background levels was not detected within well D4. Bromide applied to the soil surface was detected first and for longer duration in well D2 than in well D3 because well D2 was monitoring the surface of the shallow aquifer. Well D3

detected bromide at lower concentrations and for shorter periods of time compared to well D2 because it was cased below D2 and the aquifer surface.

Iodide Concentration in Wells

Iodide concentration in wells D1 and D2 was above background levels after water and iodide application to the soil surface (Figure 6, p.26). Iodide concentration reached 3.0-3.5 mg per liter in well D1 7 hrs after surface application of water and iodide and only 1 hr after initial detection of iodide in well D2. Iodide concentration 11 hrs after surface application of water and iodide was 1 mg per liter in well D2. Although well D1 was closer to the soil surface than well D2, iodide did not reach well D1 until 8 hrs after beginning of surface application of water and iodide. Well D1 was not fully developed (slotted area at bottom of well housing was not fully emersed in aquifer) in the aquifer, and this may have delayed entry of water into well D1. Wells D3 and D4 did not contain iodide during the study.

CONCLUSIONS

Surface applied soluble salts reached a shallow, unconfined aquifer before the overlying soil was fully impacted by this water and salt. Bromide and iodide tracers (surface applied) reached an aquifer 2.5 m below ground surface within several hours. The upper 1 m of the aquifer was impacted by surface applied tracers. Water content and bromide concentrations indicated that the upper 1 m of soil was rapidly (within several hours) and continuously influenced by surface applied water. Bromide and iodide concentrations found within the soil-water (1 to 2 m depths) and aquifer were 150 to 750 times lower than surface applied concentrations. As expected, soil has a tremendous buffering capacity. Soil macropores, including pores and root channels, and soil structure account for the preferential flow that transmits tracers to shallow aquifers. Water

extracted from soil cores from 1 to 2 m below ground surface contained discontinuous but elevated (above background levels) bromide concentrations 4 to 150 hours after surface applied water and bromide tracer application. The impact of bromide and iodide tracer on water wells was greatest within 1 hr after detection within the well and declined following this peak. The upper part of the aquifer containing surface applied tracers moved away from the surface application site by lateral ground-water flow. Further rain events are needed to move additional tracer from the soil into the shallow aquifer.

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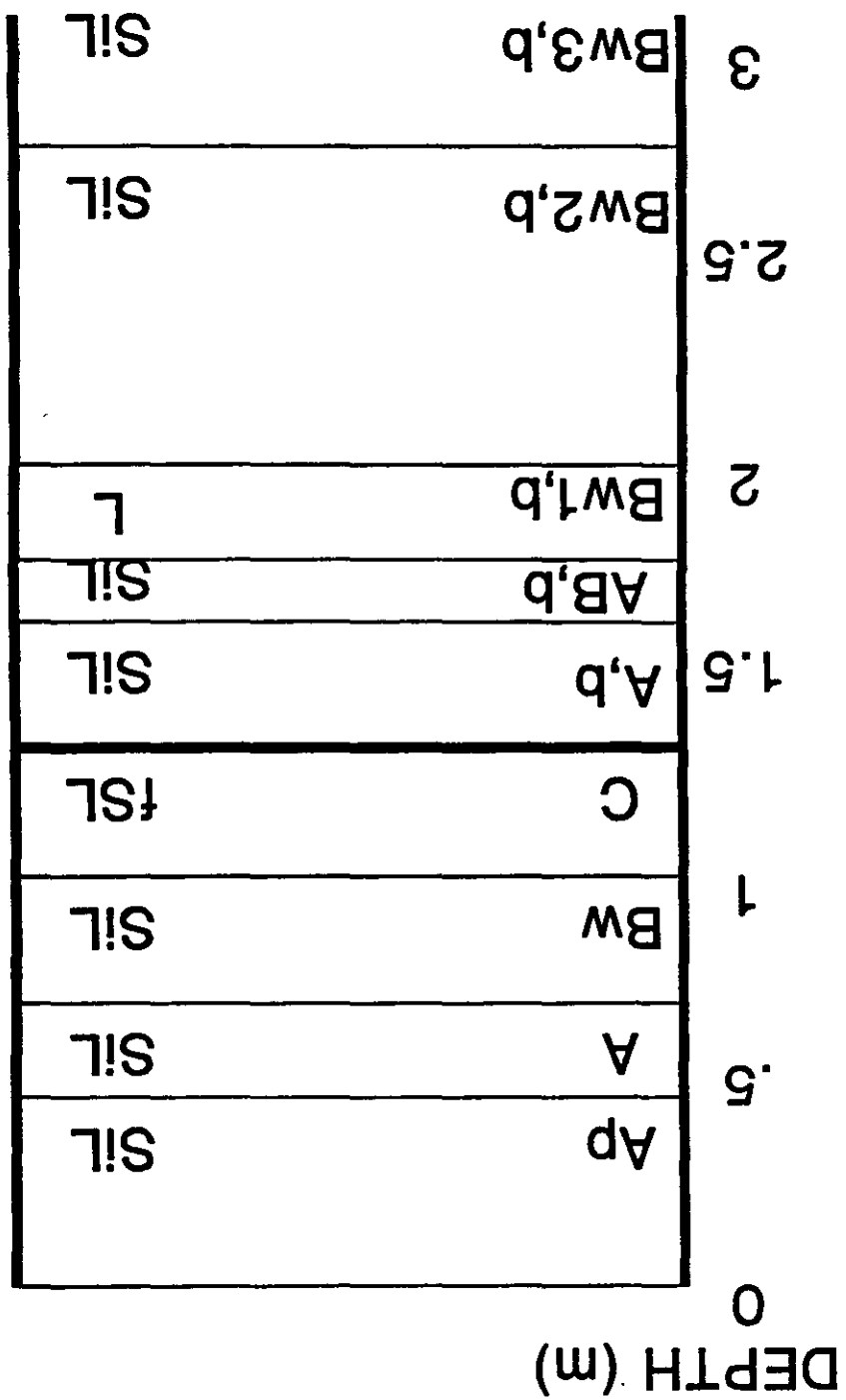
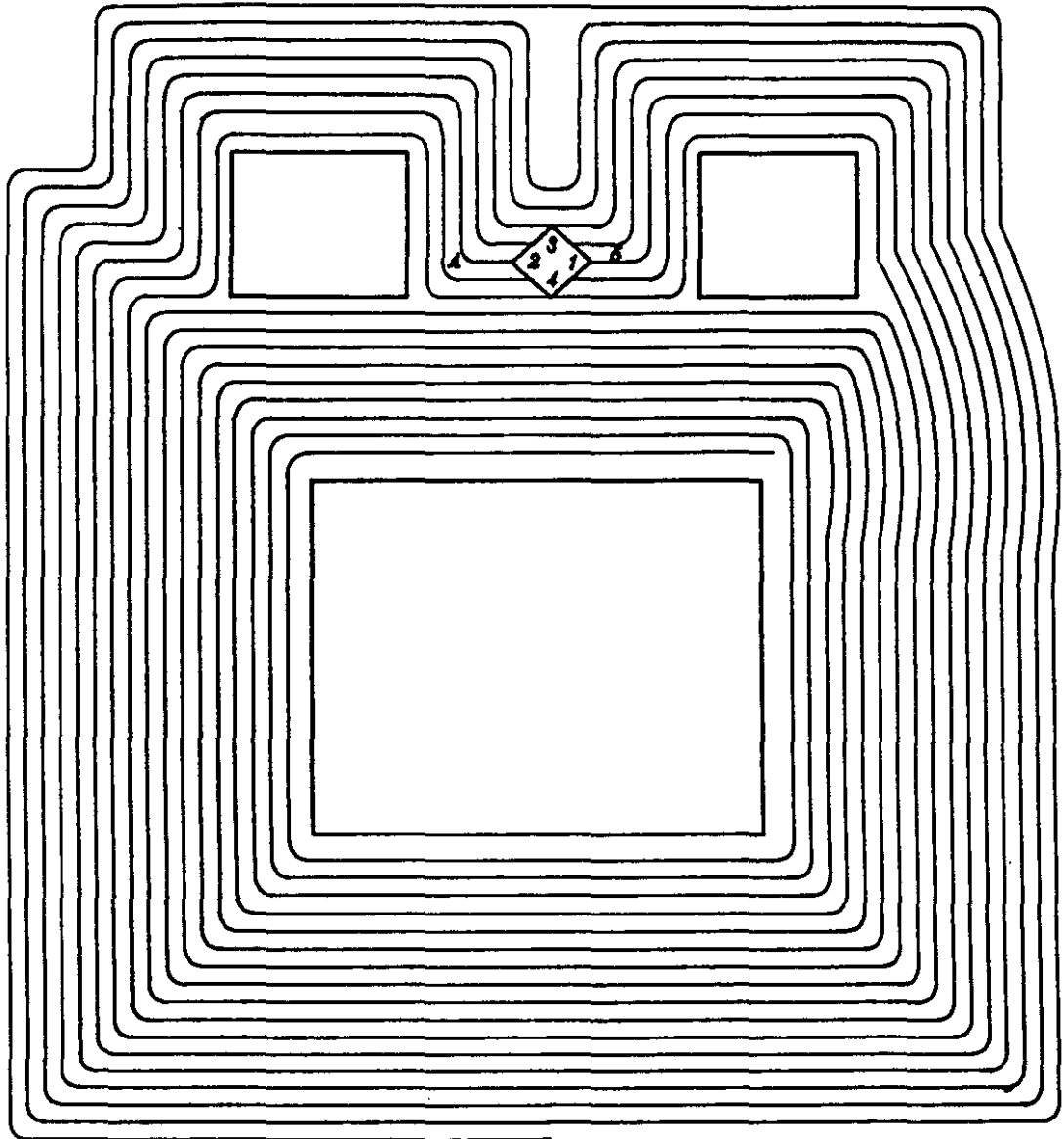


Figure 1

Figure 2



<i>KEY</i>		<i>SCALE- 1/4" = 1'</i>
◇	CONCRETE PAD	
◇	TRACER APPLICATION PLOT	
A	SOIL MOISTURE NEUTRON PROBE ACCESS TUBE	
1,2...5	D WELLS	
—	IRRIGATION TUBING	

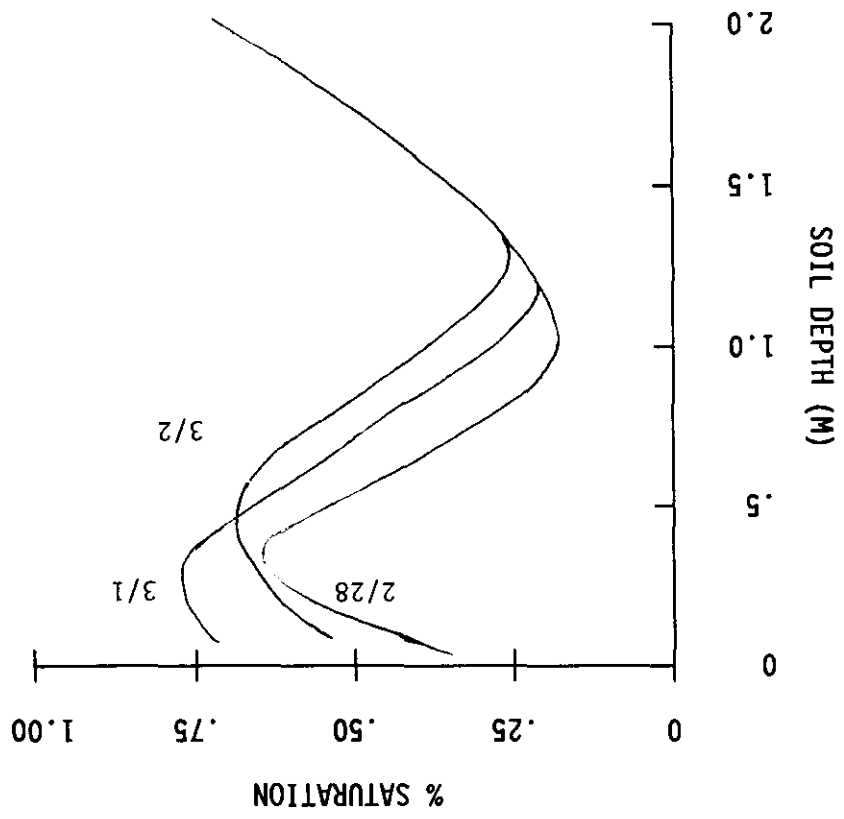


Figure 3

Figure 4

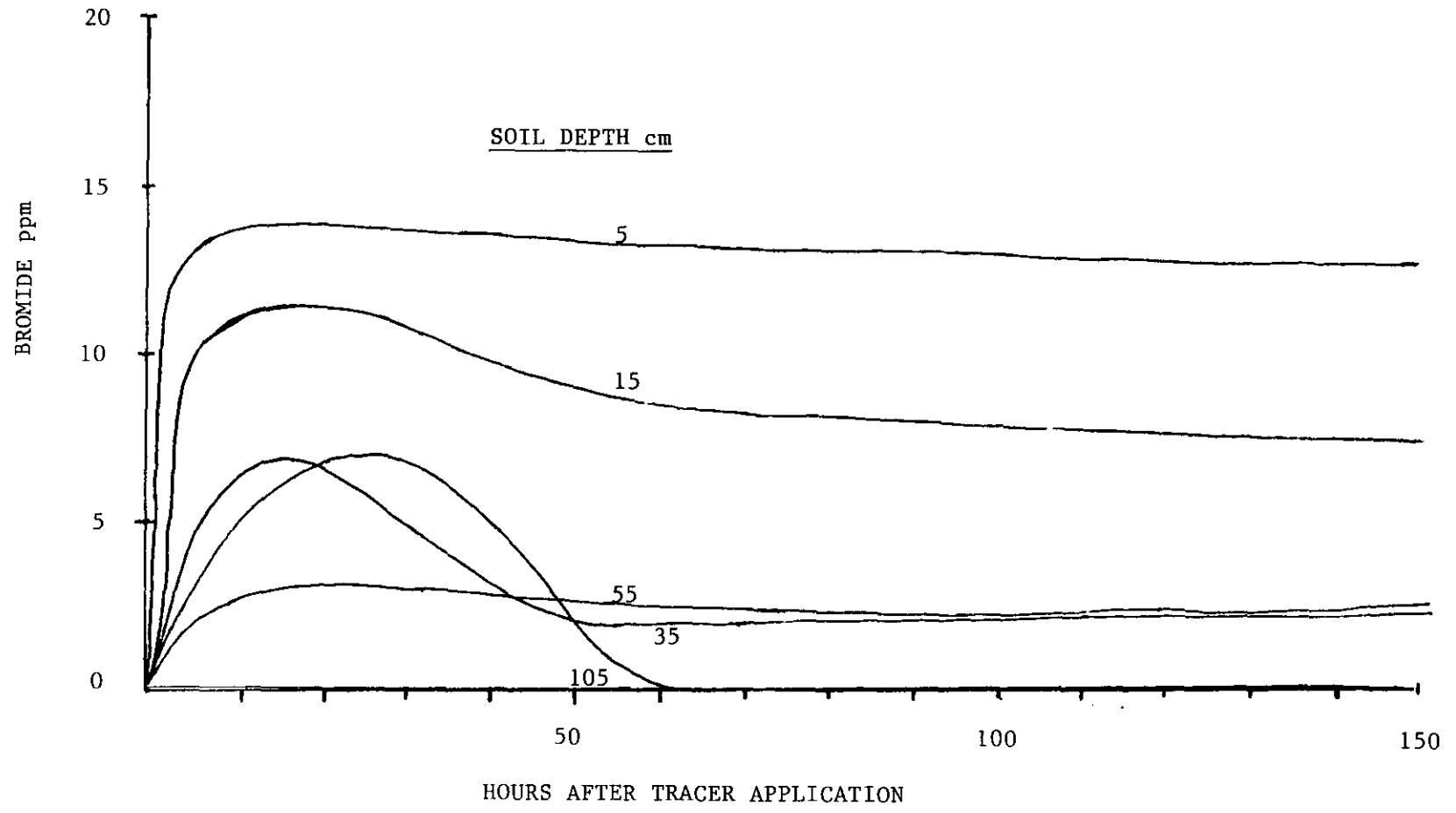


Figure 5

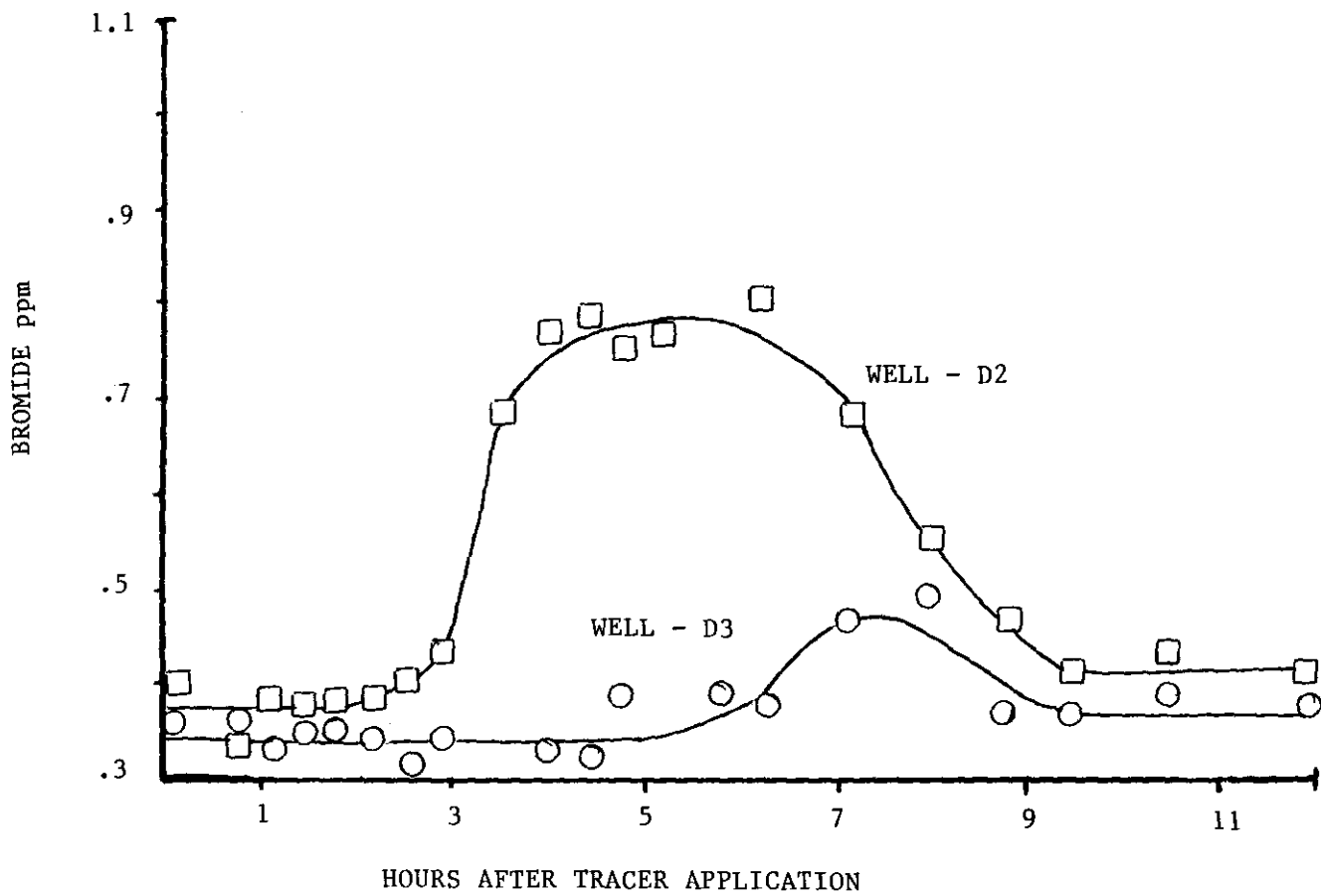


Figure 6

