
**AGRICULTURAL IMPACT ON WATER QUALITY
IN A SHALLOW CONFINED AQUIFER AND
IN THE OVERLYING SATURATED GLACIAL TILL
IN EASTERN NORTH DAKOTA:
MOVEMENT OF WATER AND TRACERS**

By

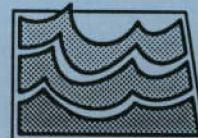
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EXECUTIVE SUMMARY

The results of the Carrington ground-water contamination experiment conducted from the fall of 1987 through the spring of 1993 can be summarized as follows.

1.0 For a semi-confined aquifer, underlying a loamy glacial till at a depth of about 6.8 m (22 ft.) , and with a water level in the overlying glacial till at about 2.7 to 4.0 m (9 to 13 ft.) below land surface, recharge is a highly complex process.

1.1 Spatial variability of recharge, even on apparently level terrain, is large and is governed principally by microtopographic features and climate. Variability of soil hydraulic properties on a coarse loamy glacial till did not affect local recharge as much as surface topography.

1.2 Surface positions can be characterized as "primary active", "intermediate active", and "inactive" recharge sites. Primary active sites are those through which all water reaching or cycling through the soil and vadose profile to the water table passes vertically from the surface through the root zone. Inactive sites are those through which all water draining to the water table, or cycling through the soil and vadose profile to the water table, has an initial source in ground water that moves upward under capillary force as the water table adjusts to drainage on other more active recharge sites. Intermediate active sites are those through which water moving to the water table has a source in both surface water draining vertically through the root zone; and ground water cycling upward and recharging, in response to external sources and sinks.

1.3 Water moves from inactive surface sites to sites of larger surface infiltration activity as runoff. Concentrated waters then move through the soil- and subsoil-vadose zone to the water table where they form a mound. The mound then redistributes laterally to water-table positions underlying less active sites, where capillary adjustment of rising ground water causes upflux into the vadose zone. Upflux may reach as high as the soil profile. Later, in response to pumping of the aquifer (or other sinks), capillary waters drain in response to the receding water table.

1.4 Following a recharge event each site, or pedon, is characterized by a pattern of drainage and upflux resulting from the specific configuration of localized ground-water recharge mounds with which it interacts hydrologically.

1.5 Total cycling of water through each site profile can be quantified using appropriate water budget procedures. Such procedures must account for direct measurement of water movement through the soil zone, changes in water storage to the water table, upflux of water from the water table during redistribution events, and direct recharge to the aquifer at each site during recharge events.

1.6. There is evidence that the saturated ground water serves as a site integrator between inactive and active sites. Despite large differences in local recharge from the surface and through the soil, it appears that the total amount of water cycling through each soil and vadose profile is frequently similar for all measurement sites.

1.6. The spatial variability, and the process of surface redistribution of water described in 1.2 provides, a "non-macropore" mechanism for preferential flow to the water table, and a means for increasing solute movement from the surface. Solute movement is enhanced by (1) movement of water across the soil surface to the recharge site; (2) concentrated movement of water through the recharge site; (3) redistribution to a position underlying other surface sites; and (4) ground-water movement upward into the soil and vadose zone under capillary influence, which can enhance either deposition in non solute-laden areas or dissolution of more solute through contact in the soil zone entered. Finally, (5) solute can be "pulled" to the water table and to the aquifer through drainage of saturated till water and capillary drawdown of water in the soil and vadose zone in response to pumping, or other sinks in the area of the site.

1.7 Active pumping of the aquifer was an important influence in moving water to the aquifer. Pumping of the Carrington aquifer increased the hydraulic gradient between the saturated till and the surface of the aquifer seasonally by a factor as large as four. This, in turn, caused drawdown of the saturated till, and capillary drawdown of unsaturated capillary water in the vadose and soil zones. The result was mixing of waters in all three layers.

1.8 Upflux of water from the lower vadose profile into the upper vadose and soil zone occurs during the winter in response to freezing. Usually, the depth of frost-water

accumulation was between 1.0 and 1.5 m (3.3 and 5 ft.). The average amount of water accumulation due to frost was approximately 3 to 4 cm (1.2 to 1.8 inches). Usually, frost water fully redrained as the ice thawed from the soil profile in late April. Usually, there was no infiltration beneath the soil zone during the winter. However, during one unseasonable thaw event (February of 1992) substantial winter recharge occurred.

1.9 Hydrologic evidence indicates that the experiment site is a recharge source site for the Carrington aquifer. The experiment site lies in the transit zone for surface water moving to a tributary of Scotts slough. The overlying till is locally less less thick than for most of the aquifer, which means that impedance to recharge is locally less. In addition, the piezometric gradients of the till are orthogonal to the gradients of the underlying aquifer. Direction of flow lines in the glacial till is northeast to southwest (toward the zone of thinner till, and also toward the irrigation pump located on section 31). And finally, vertical hydraulic gradients from the till to the aquifer are increased substantially by the pressure drawdown of an irrigation well field. All of these factors likely contribute to the amount of local recharge.

2.0 Tracers applied to the field were detectable at all levels (vadose samplers at 1.5 m and 2.1 m [5 ft. to 7 ft.], saturated till samples at 3.4 and 4.5 m [11 and 15 ft.], and Carrington aquifer samples at 6.8 m [22 ft.]).

2.1 During the year of application, tracers were usually detected at virtually all levels of the measured hydrologic system, including the surface of the Carrington aquifer at 6.8 m (22 ft.). Usually, first year detections were of lower concentrations, indicating that preferential flow paths were most influential in expediting movement.

2.2 During the year of application, slightly elevated concentrations of fluoride were detected in the deep-vadose zone and in the saturated till. Because mixing in the calcium-bicarbonatic soil solution and slow movement through the unsaturated soil would be expected to cause immediate precipitation, some early fluoride movement through large pores from the soil surface to below the root zone during large storms is thought to occur. This is consistent with bromide evidence.

2.2 During years following application tracers tended to concentrate just below the root zone. After two years, concentrations similar to those in the shallow vadose zone

would appear briefly during recharge periods in the saturated till. However, deep detections were ephemeral and did not remain at relatively constant levels as in the shallow vadose zone. The movement of larger concentrations of tracers at later times may indicate greater influence of intermittent slugs of bulk flow, compared with earlier influence of preferential flow paths. This is reasonable because most of the solute is no longer at or near the surface to be washed into large pores and cracks.

2.3 Three or more years after application, appearances of tracer in the Carrington aquifer were spatially sporadic and most frequently not repeated on other site replicates.

2.4 Tracer and nitrate concentrations at all levels corresponded approximately with topographical zones of maximum surface-water concentration mapped during a storm in 1991. These observations support the conclusions of hydrologic analysis indicating the importance of microtopographic redistribution and concentration of water in determining the activity of surface sources of recharge.

2.5 Tracer and nitrate peaks were distinct and of short duration in the vadose zone, and corresponded to periods of rising water in the saturated till. However, tracer and nitrate levels in the saturated till, and particularly in the Carrington aquifer, were prolonged and corresponded as well to a slightly later period of pressure drawdown in the Carrington aquifer, which was caused by pumping the aquifer for irrigation use. Bromide movement to the aquifer was not observed during a year in which pressure drawdown was small. Tracer and nitrate data support the hydrologic analysis which indicates that pressure drawdown from pumping is an important component influencing water movement to the Carrington aquifer.

2.6 During the period from spring 1990 through spring 1993 there were only two brief periods of nitrate movement to the Carrington aquifer. There were more frequent periodic flushes of nitrate to the saturated till.

2.7 During the period from spring 1990 through spring 1993 nitrate-N never exceeded 1 mg/L on any sample from the Carrington aquifer. In the saturated till nitrate-N reached the 10 mg/L EPA-MCL level on only one site replicate for a brief period in July of 1990.

2.8 There was no indication of an upward trend of nitrate-N in either the saturated till or in the Carrington aquifer during the period from fall 1987 to spring 1993.

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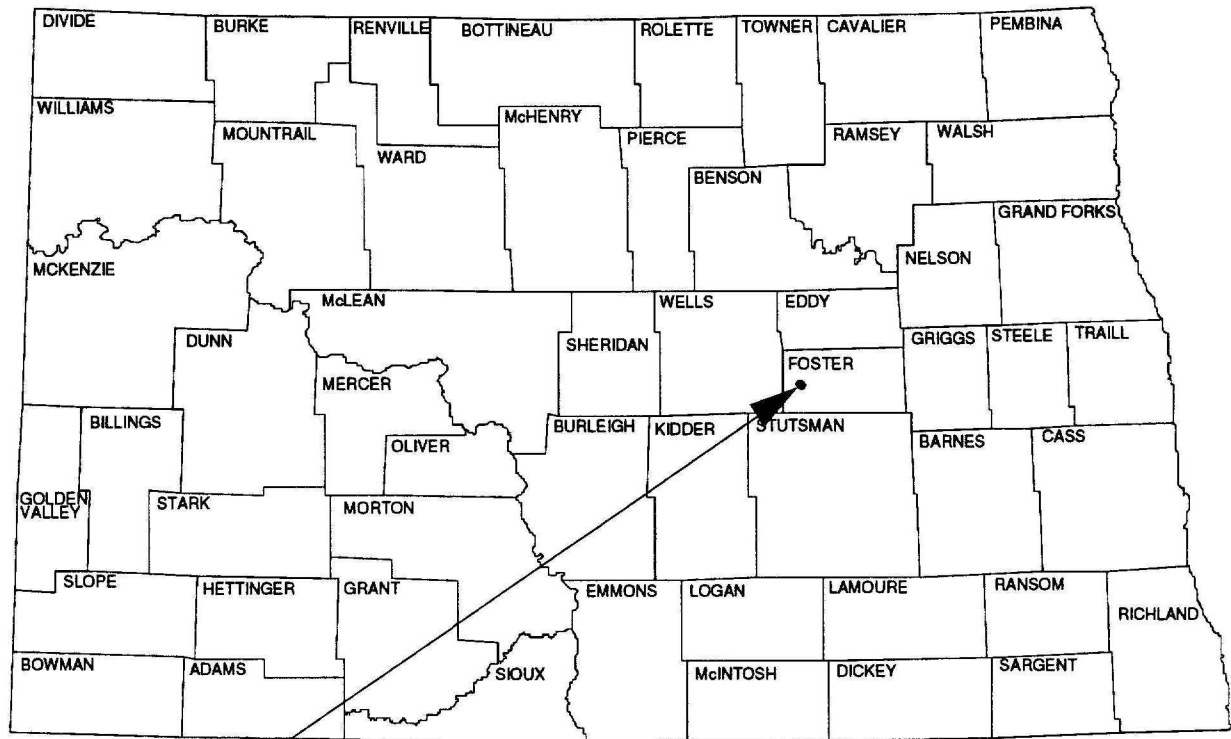
INTRODUCTION

In the fall of 1987 an experiment was initiated on the lands of the Carrington Research Extension Center Station, in Foster County North Dakota (Figure 1), to investigate the relationship between ground-water recharge and the movement of contaminants on a level agricultural field, using common cropping practices for East Central North Dakota. Five years of monitoring were undertaken between the spring of 1988 and the spring of 1993. Components of the experiment included (1) year round water level monitoring of the Carrington aquifer and of the overlying saturated till; (2) root- and vadose-zone water balance measurements during the frozen period of the year; (3) local root-zone and vadose-zone water balance and drainage determinations during the non frozen portion of the year; (4) monitoring for changes in basic water quality constituents; (5) tracking the movement of surface applied tracers in relation to movement of recharge waters; and (6) tracking the movement of applied pesticides. The purpose of this report is to present local recharge determinations measured on the experiment site; to discuss the mechanisms by which that recharge occurs as determined through hydrologic and tracer analyses; and to evaluate the relationship between local site recharge and recharge for the Carrington aquifer as a whole. Movement of pesticides will be described in another report.

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NORTH DAKOTA



Carrington

Figure 1. Map of experiment location.

LOCATION AND NUMBERING SYSTEM

The location and numbering system used in this report is based on the public land classification system used by the U.S. Bureau of Land Management. The system is illustrated in Figure 2. The first number denotes the township north of a base line, the second number denotes the range west of the fifth principal meridian, and the third number denotes the section in which the well or test hole is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). For example, well 147-067-4ADD is located in the SE 1/4 SE 1/4 NE 1/4 sec. 4, T. 147 N., R. 67 W. Consecutive terminal numerals are added if more than one well or test hole is located within a 10 acre tract.

CLIMATE

The climate of Foster County North Dakota is continental, having cold winters and hot summers. The onset of cold weather usually begins in early November. The frost usually leaves the soil in mid April. The moisture regime is borderline between semi-arid and sub-humid, with a long-term average annual precipitation of about 48 cm (19 inches).

GEOLOGY AND SURFACE DRAINAGE FEATURES

The landscape near Carrington ND was formed by the deposition of approximately 30 m (100 ft.) of glacial drift in late Wisconsinian time, on top of bedrock shale of the Cretaceous Pierre formation (Bluemle 1965, Wanek and Meyer 1989). The Carrington aquifer (Figure 3) was formed by the deposition and elutriation of sand and gravel between a bedrock ridge oriented northwest to southeast near Carrington and a glacial boundary of similar orientation north of Carrington. The Carrington aquifer was later covered with about 12.3 m (40 ft.) of glacial till in a later (Grace City Phase) ice advance. Overall till particle-size distribution (excluding fractions coarser than sand) is about 33-percent sand, 45-percent silt, and 22-percent clay. However, the till is extremely heterogeneous, and frequently includes sand and gravel varves and lenses imbedded within masses of predominantly finer materials.

Land surface in Foster County near Carrington is a low relief type, having semi-integrated drainage, and formed in glacial ground moraine along a corridor between the Missouri coteau and an older relic coteau to the east. It is thus somewhat atypical of the prairie pothole topography common to the region. Surface topography generally slopes east at 3 m (10 ft.) per mile. Scotts Slough, a

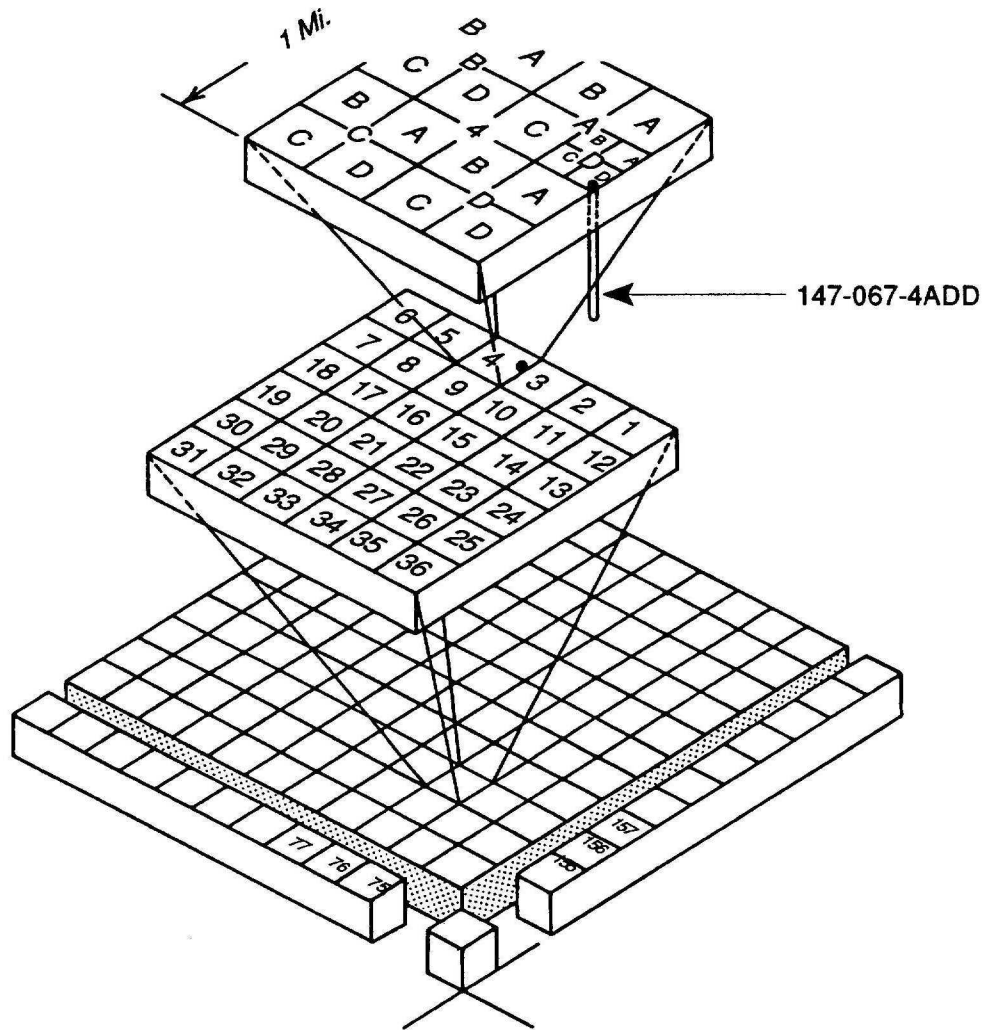


Figure 2. Map location and numbering system used in this report (from U.S. Bureau of Land Management).;

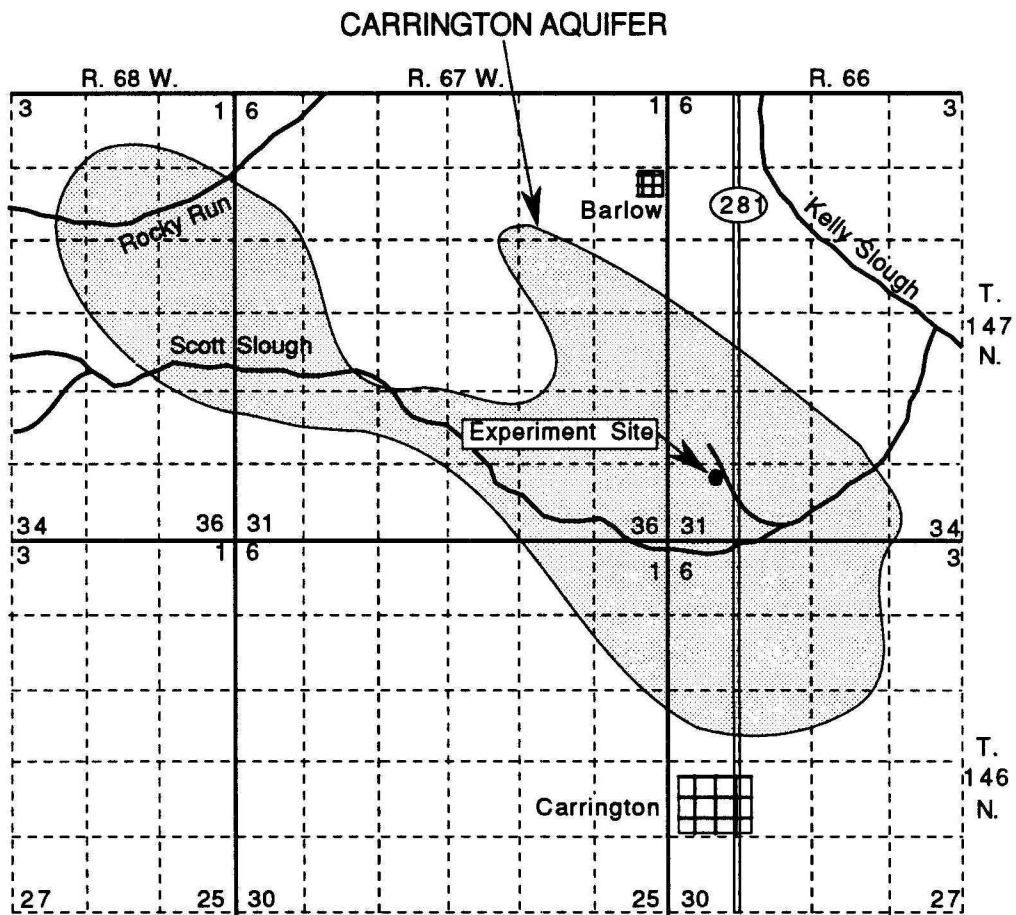


Figure 3. Map illustration of the Carrington aquifer.

glacial-marginal surface drainage feature cuts a channel about 7.6-m (25-ft.) deep and 213-m (700-ft.) wide through glacial till overlying the aquifer. Despite its name designation as a slough, it is actually an underfit stream valley, and functions hydrologically as both a creek and a slough. Rocky Run, a similar feature, cuts across the northwest end of the aquifer. Kelly Creek, a broad channel located about two miles northeast of the Carrington aquifer, is a third surface drainage feature related to both Scotts Slough and Rocky Run (Figure 3.)

HYDROLOGY

The Carrington aquifer is a buried sand and gravel deposit approximately 19.3-km (12-miles) long, 6.4-km (4-miles) wide, and 9- to 18-m (30- to 60-ft.) thick. Its long axis is oriented northwest to southeast. The aquifer is unconfined along its southwest flank, but otherwise confined with an artesian head of up to 9-m (30-ft.) above the top of the aquifer. Although confined, pumping can draw down the aquifer water level creating an unconfined zone around the well. An irregular till/aquifer interface results in localized confined/unconfined areas. A 97-h aquifer test performed using an irrigation well one half mile southwest of the Carrington experiment site indicates an aquifer transmissivity of 4,800 m (16,000 ft.) per day and a storativity of 0.03. The sand and gravel is 12-m (40-ft.) thick at the aquifer test site, so the hydraulic conductivity is 120-m (400-ft.) per day.

In addition to domestic and livestock use, permitted water use from the Carrington aquifer is approximately 2570 cubic decameters (2090 acre-ft.) per year, including 400 cubic decameters (325 acre ft.) used as the municipal supply by the City of Carrington, and the remainder used for irrigation on 19 quarter sections in 1992.

The potentiometric surface of the Carrington aquifer indicates an overall flow direction toward the east. However, within the aquifer there are also localized flow gradients toward what appear to be discharge points along Rocky Run and Scotts Slough. Wanek and Meyer (1989) have hypothesized that most recharge to the Carrington aquifer is from precipitation. For most of the aquifer, waters have to pass through about 9 m (30 ft.) of till after infiltration before reaching the aquifer. However, in some cases Scotts Slough cuts through the till and provides a direct hydraulic connection from the surface to the aquifer. There are also areas of lesser till thickness where recharge from surface infiltration may be enhanced. Fractures in the till filled with sand and gravel may help to enhance the rate of recharge in some areas. According to Wanek and Meyer (1989) only a small amount of water in the Carrington aquifer is lost to evapotranspiration, and this likely occurs in the area occupied by Scotts Slough.

WATER QUALITY

Water from the Carrington aquifer is of the calcium-magnesium bicarbonate type. Total dissolved solids concentration (TDS) varies between 400 and 800 mg/L, and the sodium adsorption ratio (SAR) is generally less than 2. The water is hard (7.0 to 10.5 grains per gallon) and high in iron (0.3 to 5 mg/L, usually around 1 mg/L) for domestic use. Organic compounds are rarely detected. Waters near the periphery of the aquifer are sometimes higher in TDS (up to 1,200 mg/L), and some waters in proximity to the Pierre Formation have high sodium and chloride concentrations and TDS concentrations as high as 2,420 mg/L (Wanek and Meyer 1989).

LITERATURE REVIEW

Aquifer recharge through glacial tills, and the consequent movement of dissolved constituents to underlying aquifers, is a complex process. The hydraulic conductivity of till materials can vary widely, depending on composition. Fine unweathered till materials have been reported to have hydraulic conductivities as low as 10^{-10} m/s (Hendry, 1982). However, in the weathered zone fractures frequently occur which increase bulk hydraulic conductivities by one to several orders of magnitude. On one till site in south Dakota Cravens and Ruedisili (1987) reported median hydraulic conductivities of 10^{-7} m/s for an unweathered till, compared with 10^{-6} m/s for the weathered till.

In a study and literature review of recharge measurements through tills in North Dakota and on the Great Plains of Canada Rehm et al. (1982) estimated that recharge is generally between 2 and 9 percent of annual precipitation. However, there is likely to be much local variance in recharge between individual sites. Surface infiltration rates on tills are frequently much less than for sands, and much recharge has attributed to concentration in macro- and meso-depressional features (Freeze and Banner 1970). Schuh et al. (1993a, 1993b) have demonstrated that large variance in local recharge can be caused by surface micro topography of magnitude indiscernible to the eye. Other factors that may affect the amount and pathways of water movement on tills include macropores formed by climatic, floral, and faunal forces, finger flow (in cases where there is lithologic discontinuity), solute chemistry and interaction with the soil and vadose zone matrix, and winter frost cycling of water. These factors strongly influence the speed and quantity with which solute moves from the surface to ground water.

CONVECTION/DISPERSION/DIFFUSION MOVEMENT OF SOLUTE

Most movement of contaminants from the soil surface to ground water is through the bulk flow of water infiltrating at the surface. For homogeneous soil, the bulk flow of solute has been described using the convection/diffusion/ dispersion equation presented by Bresler (1973)

$$J = - [D_h (V) + D_p(\theta)] \frac{\partial c}{\partial x} + V \theta c \quad (1)$$

where J is total flux of solute, c is solute concentration in the soil solution, x is the flow direction coordinate, D_h is the mechanical dispersion coefficient, $D_p(\theta)$ is the diffusion coefficient, V is the convective velocity of water and θ is the volumetric soil water content. $V\theta$ is calculated as flux (q) using Darcy's Law

$$q = V \theta = -K(\theta) \left(\frac{\partial H}{\partial z} \right) \quad (2)$$

for hydraulic head H . The diffusion and dispersion terms account for the deviation of solution concentrations over time from mean bulk flow. Dispersion results from numerous factors, including tortuosity of large pores, the distribution of velocities in pores of different sizes, and the differences of flow velocities within pores caused by drag on boundary surfaces. Nielsen et al. (1961) described the trend of increasing concentrations of solute from initial breakthrough to full solute concentration, for experiments in which miscible displacement of soil water solutions were displaced by tracer solutions.

Movement of organic contaminants through soil columns is more complex than the movement of conservative tracers. Limitations in water solubility, and multiphase solubility and adsorption are important factors in the movement of organic compounds. The organic carbon partition coefficient (Hamaker and Thompson 1972) is one parameter used to evaluate the rate of movement of pesticides in soils. Rates and means of pesticide degradation are also important in determining the amount of a pesticide reaching the water table (Jury et al. 1987). The LEACHM model (Wagonet and Hutson 1987) for assessment of pesticide movement in the unsaturated zone requires input of water solubility, saturated vapor density, organic-carbon partition coefficient (K_{OC}), compound half-life, and soil organic carbon, in addition to basic soil hydrologic property data and root proliferation and evapotranspiration data. LEACHM was used by Knighton et al. (1990) to evaluate the relative leachability of nitrate and 18 pesticides on a sandy outwash plain in southeastern North Dakota.

PREFERENTIAL FLOW

Estimates of water and solute flux calculated using bulk-soil models based on laminar flow are frequently inadequate to fully describe field phenomena. Thomas and Phillips (1979) observed that rates of aquifer recharge often exceeded those expected from piston flow predictions. Under field conditions, the movement of solute frequently surpasses rates predicted using models accounting for convection, diffusion, and dispersion alone (Rice et al. 1986, Jaynes et al. 1988). Movement of water and solute through paths which bypass the bulk flow of water, and which exceed rates predicted by piston-flow models is called "preferential flow". Preferential flow can be caused by many mechanisms, including macropores formed under floral and faunal influence and fractures caused by contraction of the soil during drying; wicking of water on a plant and enhanced movement along the root-soil interface; and finger flow induced by flow instabilities resulting from water movement through certain specified soil material boundaries.

Macropore Flow

Considerable work has been published concerning the influence of large pores on solute transport. Bouma and Anderson (1977) described soil water as consisting of mobile and immobile water. Mobile water is water that moves in large pores, and immobile water is that which moves slowly in small pores. Because the laminar velocity of water in pores ideally varies according to the square of the pore radius, laminar flow through large pores would theoretically be expected to dominate the flow process. However, large pores with turbulent flow can also have a large affect in many field situations.

Macropore phenomena caused by floral (root), faunal, and climatic (shrink/swell) agents strongly effect the movement of soil water. Blake et al. (1973) demonstrated that drainage exceeded piston flow estimates beneath a soil having large shrinkage cracks. Important faunal effects include earthworms (Ehlers 1975), gophers (Hakonson 1986), harvester ants (Cline et al. 1980), and pocket mice (Cline et al., 1980). Hakonson (1986) observed that permanent surface channels formed drainage channels to gopher holes, and dominated the surface hydrology of a research site.

Floral effects are primarily caused by roots. Chaabra and Abrol (1977) demonstrated that rice roots enhanced the drainage of water through sodic soils, but that little of the water touched the soil matrix because of the predominance of macropore flow. Generally, fibrous roots are limited to the top 0.9 to 3 m (3 to 10 ft.) from the soil surface. However, various forbs, shrubs and trees can root as deeply as 360 to 570 m (1,200 to 1,900 ft.) (Foxy et al. 1984). For cropped fields, almost all of the roots are in the top 1.2 m (4 ft.). About 80% of the roots are in the top 0.6 m (2 ft.). Most macropores created by floral and faunal influence do not penetrate to depths greater than one meter.

Finger Flow

Research has shown that under conditions where fine soil overlies coarse soil, water may coalesce into saturated fingers beneath the soil boundary, resulting in direct piping of water and solute to the water table (Glass et al. 1988, Hill and Parlange 1972). Hill and Parlange (1972) attributed finger flow to "Taylor instability". Conditions under which it is most likely to occur include small upper-boundary pressure (very shallow or intermittent ponding at the surface). Hill and Parlange (1972) also observed that the number of fingers per unit area increases with the velocity of flow. Fingers would be most likely to coalesce under conditions of large surface-ponded head. Glass et al. (1988) also observed that once fingers developed, they have a tendency to be maintained in the same positions under successive regimes of water application.

Depression Focused Recharge

Topographic influence in concentrating infiltration water can also be interpreted as a form of preferential flow. Before infiltration into the soil, runoff redistributes water to final infiltration locations. In the rolling pothole prairies of the northern great plains, much recharge has been found to be depression focused (Freeze and Banner 1970). However, it has also been found that even on a level landscape (less than 0.4% slope) large amounts of redistribution occur due to micro-topographic elevation differences of less than 2.5 cm (one inch), and that the initial redistribution of water can be the primary factor in separating a primary recharge position from a position having no recharge at all (Schuh et al. 1993a). The dominance of microtopography as an element of preferential flow was described by Schuh et al. (1993a, 1993b) for the Carrington experiment of this report, and will be discussed in greater detail later in the report.

Fracture Flow

One well documented form of preferential flow through glacial tills is fracture flow. Bulk movement of water and solute movement through glacial tills have been shown to be dependent on secondary permeability, or "fractures" (Hendry 1982, Keller et al. 1986, Ruland et al. 1991). Glacial till materials are frequently divided into weathered and unweathered groups. Weathered tills usually lie within the top six meters or so of the surface, although in some cases they may be deeper. It is in the weathered tills that both horizontal and vertical fractures are frequently found. Hendry (1982) reported that small fractures increased the hydraulic conductivity of a weathered till by about two orders of magnitude over that of the till matrix. Large fractures increased the bulk hydraulic conductivity by about four orders of magnitude over that of the till matrix. On fractured till soils the fractures provide the primary path for both water and solute. Unweathered tills, found at greater depths, seldom contain fractures.

Dynamic Factors

The effects of macropores are dependent on dynamic field hydraulic factors and on cropping practices. One limitation of macropore flow is that the pores must be continuous with the surface. Because of large hydraulic radius, water will not flow from overlying small pores into macropores. Under normal conditions, agricultural field soils are seldom fully saturated at depth when wetted from the surface because of soil layering which impedes flow and causes desaturation of the deeper layers. Also, plow pans and compaction layers tend to create a situation wherein saturated flow to large depths through macropores is limited (Schuh et al. 1991). Moldboard plowing can disrupt the continuity of large pores to the surface. However, at least one researcher noted a case wherein

moldboard plowing resulted in piping of water along the bottom of the plow layer to large pores (Tyler and Thomas, 1977).

During a rainstorm surface infiltration usually changes in a relatively short period of time. Soil swelling seals drying cracks during prolonged rainfall events. Also rainfall impact forms a surface seal (Sharma et al. 1981). Surface seals cause desaturation of the underlying soil, which prevents flow in macropores, except under conditions of deep ponding. Shainberg and Singer (1986) examined the effect of depositional crusts under surface irrigation with turbid water, and found that the hydraulic conductivity of the soil surface decreased by 2 to 3 orders of magnitude. Sumner et al. (1991) found that under a thin surface crust caused by application of turbid water, soil-water suctions were commonly about 15 to 40 cm, with an overlying ponded head of about 0.6 m (2 ft.). According to Poiseuille's law a circular pore flowing at 15-cm suction would have a theoretical diameter of 0.002 mm. Thus, macropore flow would not be important under such conditions.

Air entrapment can also affect flow in large pores. Under conditions of surface infiltration a certain amount of pores are always filled with entrapped air. For this reason, laboratory procedures for determining soil-water retention distinguish between full saturation and field saturation, which is the degree of saturation normally achieved under natural conditions of air inclusion from the wetting of the soil (Klute 1986). Constantz et al. (1988) cited literature indicating that the average air retention in wetted soil cores was 9.1%. Slack (1978) stated that on fine textured soils the volumetric water content of the transmission zone under infiltration was approximately 90% of total soil porosity on fine soils. Wilson et al. (1981) indicated that air-filled porosity increased with the coarseness of the soil. We have found that a common air-filled porosity for sands measured in near Oakes in southeastern North Dakota is 17%.

The laws of surface tension determine that most air entrapment will be in the largest pores. Air is displaced by water in small pores during wetting, and becomes entrapped in larger pores (Wilson and Luthin 1963). Schuh (1991) reported that under conditions of long term ponding (approximately 16 days) in the presence of a large amount of labile organic substrate the hydraulic conductivity of a sandy soil can increase by as much as two orders of magnitude due to the purgation of entrapped air from the soil caused by the respiration of oxygen to carbon dioxide and the subsequent removal of carbon dioxide gas through dissolution. These ponding and substrate conditions, however, are not common under normal field circumstances. Hydraulic evidence appears to indicate that the effectiveness of large pores in conducting solute under conditions of ephemeral ponding would be limited by air entrapment in many of the pores. Pore blockage by air, however, would likely be limited to the smaller portion of the large-pore range in which significant capillary attraction for water exists, and would not likely be effective in very large holes and channels such as gopher holes or large desiccation cracks.

Antecedent soil moisture is also an extremely important factor in determining the fate of water flowing in large pores. Freeze and Banner (1970) reported that on the northern Great Plains antecedent soil moisture was one of the most important determinants of aquifer recharge. Cline et al. (1993) also found that aquifer recharge on sandy and gravely soils in southeastern North Dakota was very much dependent on antecedent soil moisture. Soil water measurements on the Carrington site have indicated that under normal summer dry soil conditions, even after large rainfall events which result in substantial ponding, little increase in soil moisture occurs at more than 0.6 m (2 ft.) depth after 24 hours. For an extremely dry soil during the cropping season, water flowing through root channels and macropores of smaller size will tend to be adsorbed by the surrounding soil matrix before reaching great depths. However, in such conditions some water is still advanced beyond the level indicated by piston flow models.

Agricultural practices influence not only the use of chemicals, but the conditions of recharge and solute transport. It is well known that continuous pasture and zero-tillage practices increase large-pore continuity to the soil surface, and thereby enhance infiltration (Edwards 1982). Also, cropping practices that increase surface residue, surface random roughness, and canopy distribution during periods of heavy rainfall decrease runoff, and maintain water in positions suitable for local infiltration.

Finally, climatic influence in the amount and intensity of precipitation, the timing and speed of spring thaw, and the rate of evapotranspiration can strongly influence the amount of recharge, and the movement of solute to the water table.

The Field Context

Aside from macropore flow, many other factors influence recharge and solute movement in the field. It is well known that infiltration, and hydraulic conductivity properties have a large spatial variability (Warrick and Nielsen 1980, Jury 1985). This, however, can be dealt with in modeling applications through proper bracketing of the distribution of properties that affect flow. Other factors that are difficult to model are the interactions of the soil profile with the water table with the soil and vadose zone caused by winter frost-induced water flux, and also by the effect of vadose- and root-zone capillary response to water table movement.

FROST ZONE INFLUENCE ON SOIL WATER CYCLING AND SOLUTE MOVEMENT

Frost cycling of water and solute in the soil and vadose zones during winter has been well documented for northern climates. The amount and source of movement is dependent on the depth

to the water table, on soil texture and antecedent moisture. The phases in which water moves are dependent on soil-moisture content and also on depth in the soil profile.

Water moves in both liquid and vapor phases toward a freezing front, in response to both temperature and soil-water-potential gradients. Carey (1965, 1966) investigated the effects of combined water-potential and thermal gradients on water movement to a freezing front. Carey et al. (1979) stated that consideration of coupled heat and water transport was essential for any comprehensive consideration of water movement to the frost zone. However, Carey (1966) concluded that usually thermal gradients were too small to strongly influence water flow to the frost zone, and that soil-water potential was the largest influence. Generally, liquid phase movement in response to water-potential gradient has been reported to be the primary mechanism of movement. Carey and Mayland (1972) explained that the vapor pressure of ice controlled soil-water potential, and that water movement in the underlying vadose zone could likely be accounted using Darcian methods.

It is also known that water movement to the frost zone is almost negligible when vadose zone moisture is near the wilting point (Gray et al. 1985). Negligible water movement under dry conditions is consistent with extremely low hydraulic conductivity values governing unsaturated flow at low water contents. However, Gray et al. (1985) and Gray and Granger (1986) have provide evidence that in some instances vapor transport may be a significant portion of water movement to the freezing front, and have proposed that a coupled liquid and vapor flow may predominate. They have also stated (Gray and Granger 1986) that vapor transport seems to dominate in the upper 30 to 40 cm (12 to 16 inches) of the soil, while liquid flow predominates at larger depths.

Movement of water frequently continues after it reaches the frozen zone, due to freezing point depression affected by solute and colloidal clays. Fuchs, Campbell, and Papendick (1978) have noted that solute in water depresses the freezing point and allows for continued movement of water. Hoekstra (1966) theorized that water moved in thin films of unfrozen water on the surface of ice, and noted that the thickness of the film decreased quickly as temperatures dropped below freezing. Koopmans and Miller (1966) observed that there is significant mobility for water as low as -0.15 degrees C. Gray and Granger (1986) observed that on coarser (silty) soils water content commonly reached 80 to 85 % porosity before further movement ceased, while on finer soils as water accumulation caused by water movement to the frost zone commonly reached 93% porosity. The difference was attributed to the greater mobility of water within the frozen zone on clay soils due to the effect of clays in depressing the freezing front.

Solute movement corresponding to frozen-soil water movement has been documented. Campbell and Fergusson (1970) measured nitrate accumulation caused by water movement to a freezing front. Hoffman (1990) also demonstrated movement of solute to the freezing front and its

subsequent deposition there. Panday and Corapcioglu (1991) reported that dissolved compounds in liquid-phase water are excluded during the process of freezing, and that pockets of liquid water with large concentrations of salt are trapped in a frozen soil at sufficiently fast freezing rates. The net effect of soil-water movement to the frost zone on solute transport is likely dependent on the initial salt content of the water, and the method of transport. While upfluent water having low dissolved solids, or waters moving in vapor phase which excludes salts, would likely result in flushing of soil salts when redrained in spring, the deposition of salts in the soil profile from upward convective movement of salt-laden waters would also likely occur under some conditions. Processes of solute movement in relation to frost zone accumulation of water are thus extremely complex.

For a deep soil profile water movement to the frost zone usually consists of a redistribution of underlying vadose water (Hofmann 1990). However, significant movement of water from the water table to the upper soil zone has been shown to occur when the initial water table is near the surface. Willis et al. (1964) reported that 6.6 cm (2.54 inches) of water moved under frost influence from the water table to the soil zone on a glacial till soil having a water table within 1.2 to 1.8 m (4 to 6 ft.) of the surface. Benz et al. (1968) reported that gains of 2 to 4 cm (0.8 to 1.6 inches) of water within the soil and vadose profile occurred with a water table at 2 to 3 m (6.5 to 9.5 ft.) on a silt to silty-clay loam glacial-till soil. The significance of this amount of cycling of water can be better understood when compared with the range of ground-water recharge values of 0.2 to 12 cm (0.08 to 4.7 inch) reported by Rehm et al. (1982) for tills of the upper Great Plains of the United States and Canada. While frost recycling is strictly an internal redistribution of water, it may nonetheless comprise a major portion of the annual internal movement of water, and may have a correspondingly large effect on the placement and distribution of solute within the soil and vadose profile.

CROP SEASON WATER TABLE INFLUENCE ON WATER AND SOLUTE MOVEMENT

The effects of water table proximity to the surface on crop use through subirrigation (Benz et al. 1978, Benz. et al. 1981) and on evaporative discharge (Doering et al. 1967) are well known. Evaporative effects on salt distribution in the soil profile have also been demonstrated (Sommerfeldt and MacKay 1982, Arndt and Richardson 1988, 1989). However, Schuh et al. (1993 a,b) have also discussed additional paths of water and solute movement caused by the combination of micro-topographically focused recharge, localized recharge to the water table, lateral redistribution of the recharge mound at the water table, capillary upflux of laterally redistributed water to the vadose and soil zones, and later redrainage of upfluent capillary waters in response to the falling water table. These processes were described using the Carrington Site data, and comprise a part of the

Carrington experiment here reported. They will thus be discussed in greater detail in the description of Carrington site hydrology.

THE CARRINGTON EXPERIMENT

OBJECTIVES

The objectives of the Carrington experiment were (1) to investigate the detailed hydrologic processes occurring on an agricultural field, farmed using rotational crops and practices common to North Dakota; (2) to describe the manner in which these hydrologic processes contribute to ground water recharge in both the saturated till and the underlying Carrington aquifer; and (3) to investigate and characterize the effect of local hydrologic processes on the movement of tracers and nitrates. Pesticides were also monitored and will be reported elsewhere.

SITE LOCATION AND CHARACTERISTICS

The experimental site (Figure 4) consists of a 30- x 30-m (100- x 100- ft.) area at 147-66-31AAB located on the land of the Carrington Research Extension Center. The site consists of coarse loamy glacial till overlying a finer fractured till with intermittent and discontinuous horizontal fractures. There are boulder lag layers about 0.31-m (1-ft.) thick at 1.5-m (5-ft.) and 4.6-m (15-ft.) depths. The lithology from a test hole drilled on the experiment site is presented in Appendix Table A.1. The soil type is Heimdal loam (coarse-loamy mixed udic Haploboroll). The soil solution is saturated with respect to calcium bicarbonate, and has a pH of about 8.1 and ECE between 800 and 1100 $\mu\text{hos cm}^{-1}$. Parent materials between the root zone and the saturated till have higher pH values (8.1 to 8.6). Clay content varies from negligible in the sand and gravel filled fractures to as high as 25% in the soil profile. Most layers have clay content between 10 and 20%. Soil descriptions, with particle-size distribution, pH, ECE, organic matter percent, and 15-bar moisture are summarized for three locations (samples taken from neutron probe access tube holes) on the experimental site on Appendix Table A.2.

The depth to the Carrington aquifer on the experimental site is about 6.7 to 7.0 m (22 to 23 ft.). The aquifer is confined. The depth to the aquifer is thus less than the overall (12 m [40 ft.]) average cited by Wanek (1989) for the Carrington aquifer, which is opportune for local recharge. The water level in the glacial till varies from 3 m (10 ft.) to approximately 4.8 m (16 ft.) below land surface, although the 3-m (10-ft.) depth cited was measured in the fall of 1987 following the addition of water to the site for measurement of unsaturated flow properties, and is likely unrepresentative of the natural site water level. Two irrigation wells are located approximately 700 m (2,300 ft.) southwest of the experimental plot.

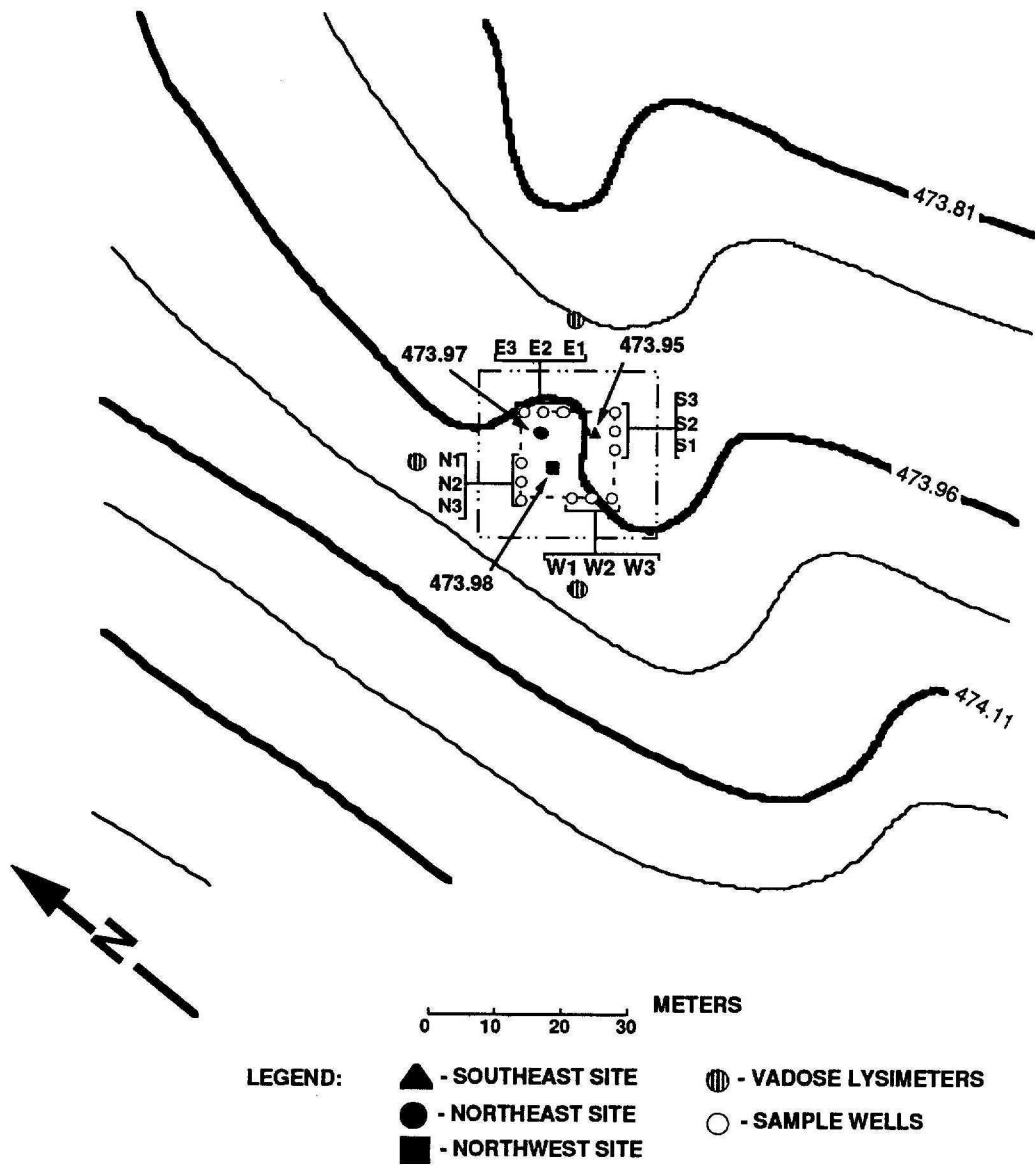


Figure 4. Site map of experimental site layout

The experiment site has a slope of less than 0.4%, and is located about 176 m (600 ft.) west of a tributary to Scotts Slough (Figure 4). The overall slope of the land is in the direction of Scotts Slough, and during large rainfall and thaw events the field tends to be covered with a sheet of overflow water from fields to the west of the experiment site. The site is located approximately 150 m (500 ft.) south of a road ditch, which also provides a conduit of runoff waters to the tributary of Scotts Slough. Both the road ditch and the Scotts Slough tributary likely comprise local recharge areas. The experiment site also likely comprises a component of the extended recharge area associated with these features, receiving overflow waters in transit to Scotts Slough during large precipitation and snow-melt events. The status of the local site as a moderately active recharge area is also enhanced by the local thinning of the till above the Carrington aquifer as described above.

SITE INSTRUMENTATION AND LAYOUT

The experiment site consists of a 12- x 12-m (40- x 40-ft.) square plot which was instrumented for full hydrologic analysis and for water quality sampling. The instrumented site was placed at the center 30- x 30-m (100- x 100-ft.) square buffer area. Both the experiment site and the buffer area were committed to the crop rotation described on Table 1. Instrumentation consisted of three replicate neutron probe access tubes, placed for monitoring soil- and vadose-zone water-content changes (Fig. 4) and corresponding stacks of thermocouples for monitoring soil temperature at 15- (6-), 30- (12-), 45- (18-), 60- (24-), 76- (30-), 91- (36-), 106- (42-) and 136-cm (54-inch) depths. Thermocouple data were recorded using a Campbell 21X data recorder. An additional four sets of neutron probe access tubes (without accompanying thermocouple sets) were placed outside of the 12- x 12-m (40- x 40-ft.) perimeter, but within the 30- x 30-m (100- x 100-ft.) buffer area (Figure 4), and were used to help determine the difference between water movement to the frost zone from the water table in the winter, and water entering from the surface during ephemeral melts.

During winter each of the inner three inner neutron-probe access tubes was insulated internally with a foam "sausage" (see photo on Figure 5), and externally with a 8-cm (6-inch) diameter foam-lined PVC tube outer cap. Three of the four outside sampling wells were similarly insulated, but in addition tarpaulins were placed around the tubes to prevent water influx during ephemeral winter thaws. The fourth outside neutron-probe access tube, without insulation or tarpaulin ground cover, was placed to provide a gauge of the effect of freezing temperatures on a bare aluminum access tube on soil water movement and measurements.

A Campbell Scientific weather station was used to monitor air temperature, wind speed, precipitation, relative humidity, and solar radiation on a grass strip approximately 701 m

Table 1. Agronomic treatments and practices for the Carrington experiment site. For pesticides, (EC) is emulsifiable concentrate, (S) is soluble. For fertilizer, DAP is diammonium phosphate. For tillage, DI is disk, CU is cultivate, RT is rotary till. Fertilizer reported (N-P₂O₅-K₂O) according to industry convention.

Year	Crop	Planting Date	Pesticide (common name)	Application Date	Active Ingredient (lb./A)	Pesticide Form	Fertilizer lb./acre active ingredient (N-P ₂ O ₅ -K ₂ O)	Application Date	Form	Tillage	Yield bu/A (*lb/A)
1980 to 1985	Alfalfa		none								
1986	wheat		diclofop	5/29	1.03	EC	70-30-0		DAP* and Urea		50
			bromoxynil	5/29	0.25	EC					
			MCPA	5/29	0.25	EC					
1987	wheat		diclofop	5/29	0.94	EC	90-30-0	4/22	DAP* and Urea		40
			bromoxynil	5/29	0.25	EC					
			MCPA	5/29	0.25	EC					
1988	wheat		diclofop	6/3	1.13	EC	0.36-0-0	9/22	Ammonium -Sulfate	1-DI, 1 CU	22
			bromoxynil	6/3	0.25	EC					
			MCPA-ester	6/3	0.25	EC					
			propicanizole	6/13	0.113	EC					
			dimethoate	6/17	0.188	EC					
glyphosate	9/22	0.75	S								
1989	sunflower	6/1	trifluralin	6/1	0.75	EC	59-23-0	5/21	DAP and Urea	RT	1650*
			methyl-parathion	8/9	0.75	S					
1990	soybean	5/22	trifluralin	5/22	0.75	EC	8.8-42		DAP and Urea	1 CU	24
1991	wheat	4/18	diclofop	5/28	0.94	EC	30-0-522	4/18	Urea and Muriate of Potash	1-DI, 1 CU	
			bromoxynil	5/28	0.375	EC					
			MCPA	5/28	0.0625	EC					
			propicanizole	6/13	0.1125	EC					
			dimethoate	6/17	0.5	EC					
1992	sunflower	5/29	glyphosate	5/22	1	S	30-0-0	5/29	Ammonium -Nitrate	1-DI, 1 CU	1025*
			2,4-D amine	5/22	0.15	S					
			trifluralin	5/29	0.75	EC					
			ethyl parathion @	8/7	1	S					
			ethyl-methyl parathion	8/21	1	S					

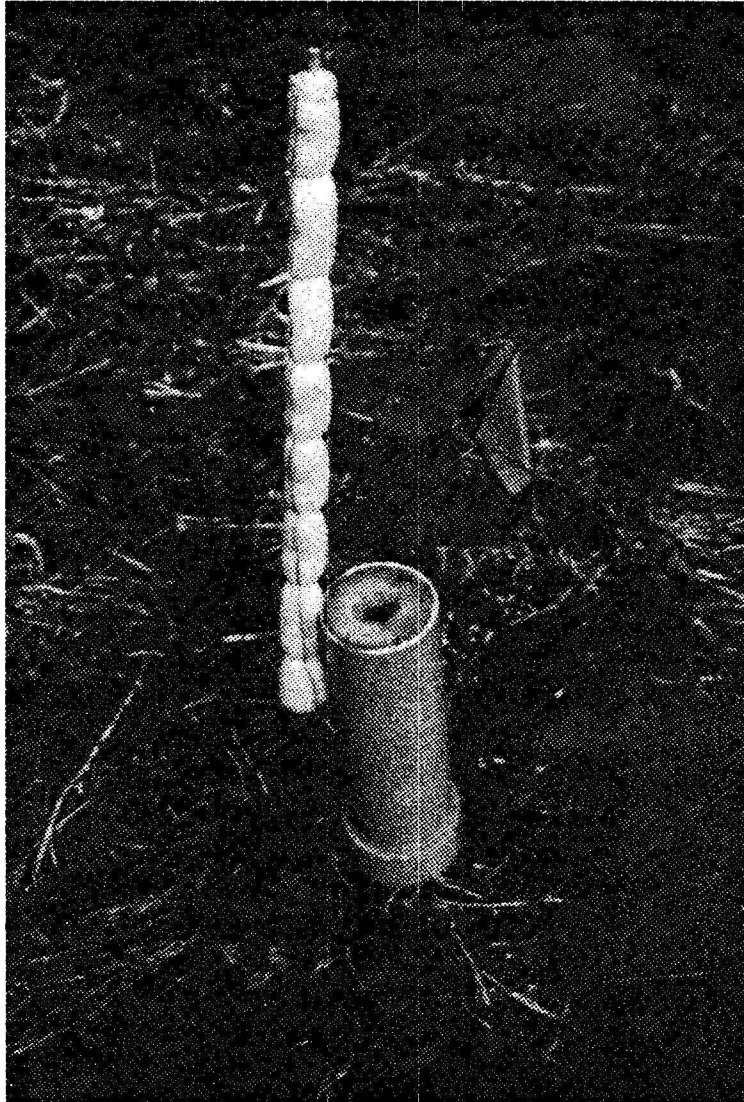


Figure 5. Photo-illustration of internal and external winter insulation and protection for neutron probe access tubes. Includes foam rubber "sausage" used to prevent convective heat transfer within the neutron probe access tube and an outer foam rubber insulated "shell" to prevent direct contact between aluminum tube and atmospheric temperature and wind.

(2,300 ft.) southwest from the experiment site. An additional relative humidity sensor was placed within the experimental site, and hourly readings of humidity were recorded and averaged daily.

Replicate sets of monitoring and sampling wells were placed on each of four sites around the perimeter of the 12- x 12-m (40- x 40-ft.) interior plot area. Each well had a 0.3-m (one-ft.) screen. Each nest of wells consisted of one well screened in the top of the Carrington aquifer at approximately 6.7 to 7.0 m (22 to 23 ft.); one well screened in the deeper saturated till at approximately 4.4 to 4.7 m (14.4 to 15.4 ft.); and one well screened in the shallow saturated till at approximately 3.3 to 3.6 m (10.8 to 11.8 ft.). The deep (Carrington aquifer) well was drilled using a forward-rotary drill rig. The annular space between the well casing and the wall of the drilled hole was filled with bentonite grout to just below the soil surface. The remainder of the annular space was filled with soil. The deep till wells were also installed using a forward-rotary drill rig. The annular space was cemented to just below the soil surface, and the remainder filled with soil. The shallow (till) wells were placed using a power auger. Bentonite was also placed around the shallow till well. Each well was constructed of 5-cm (2-inch) diameter rigid PVC joined using stainless steel screws. No glues were used in well construction. Each well was capped with a threaded well cap. A small air hole was drilled in the top of the cap.

When not being sampled the capped wells were always covered with two polyethylene bags, which were tied individually to the well stem with string, or fastened with tape. Bags were changed frequently. After each chemical application bags were changed immediately. Beginning in 1992, the bags were replaced with a 10-cm (4-inch) rigid PVC cover, which was placed inverted over the well stem. Wells are labeled and referenced according to relative location (N for north, E for east, S for south, and W for west) and depth (1 for shallow till wells [appr. 3.4 m], 2 for deep till wells [appr. 4.5 m]; and 3 for Carrington aquifer wells [appr. 6.8 m]), as shown on Figure 4). For example, N3 is the north replicate of the Carrington aquifer wells, while W2 is the west replicate of the deep till wells.

In the fall of 1987 vadose samplers consisting of porous 5-cm (2-inch) diameter 1-bar ceramic tips and 5-cm PVC barrels from the sampling point to the surface were installed at 30-, 60-, 91-, and 193-cm (12-, 24-, 36-, and 76-inch) levels at three sites within the plot. During 1988 these samplers were found to be inadequate because of the ease with which detritus and exterior contaminants could enter the sampler. They were replaced in the spring of 1989 with three sets of vadose samplers which were better protected against contamination. The replacement samplers consisted of a 5-cm (2-inch) diameter by 15-cm (6-inch) long porous 1-bar ceramic cups, sealed on the top with a teflon plug glazed to the ceramic cup (no glues were used). A teflon pressure fitting was used to join the 0.032-cm (1/8-inch) O.D. teflon access tubing, which was extended to the surface. Above the surface the two teflon tubes were terminated in stainless-steel fluid couplers. Complementary-fluid couplers

were used to connect the vadose samplers to the field sampling apparatus shown on Figure 6A. Photographs of the vadose sampler used and of its placement are on Figure 6B.

The vadose samplers used in this experiment were installed in April of 1989, prior to the application of chemicals for the 1989 crop season. However, because small-grain pesticides had already been applied in the 1988 season, special care was taken to avoid contamination of the vadose sampler hole. Topsoil was removed to a depth of one ft. (0.3 m), and a hand auger was used to clean the hole for placement. Three vadose samplers were placed on each of three locations, north (N), east (E), and west (W) on the experiment site (Figure 4). Two samplers were placed at the 1.5-m (five ft.) level because it was expected that the soil during the crop season would dry more quickly at the shallower depth, and that two samplers would likely be needed to provide a sufficient quantity of water for measurement of pesticides. One vadose sampler was placed at the 2.1-m (7-ft.) level. After placement of the sampler, a clean silt slurry was tremmied into the hole to help insure good hydraulic contact between the sampler and the surrounding soils. Dry clean silt was poured to approximately 0.3 m (one ft.) above the sampler, and the soil augured from the hole was replaced and packed with the tremmie rod. Packing was used to insure less influx of water at the point of sampler placement. The teflon tube was also looped, approximately 0.15-m (6 inches) below the surface, to help insure against piping down the tubing to the sampler.

AGRONOMIC PRACTICES

Agronomic practices are summarized on Table 1. During 1988 and 1989 the field surrounding the buffer area was planted to different crops than those used in the experiment. However, it was decided that a larger chemical buffer area would be desirable, and beginning in 1990 the site and the surrounding field were planted to the same crop. The introduction of soybeans into the rotation after sunflowers is not a common rotational practice. However, this exception was made to synchronize the measurement site with the larger field rotation.

Background field fertility was evaluated using soil tests taken in the fall of 1987, and in 1991 and 1992. Results are shown on Appendix Table A3. Soil tests and fertility evaluation were made by the North Dakota State University Soil Fertility Laboratory, Fargo ND. Small N applications were based on an initial high background soil nitrate-N level, probably resulting from the extended period in alfalfa production which ended in the fall of 1985. Soil samples for Nitrate N were taken from the top 0.6 m (two ft.) of soil. Potassium (K_2O) levels were high to moderately high through the spring of 1991, so that no potassium was applied. The large application of potassium in 1991 was made in the form of muriate of potash for chloride tracer application. Phosphorus (P_2O_5) levels varied from



A.



B.

Figure 6. Photo-illustration of vadose samplers. A. Closed ceramic porous 1-bar sampler. B. Stainless steel fluid couplers for surface connection.

medium to high. Soil pH did not vary greatly during the experiment. pH values indicate that the topsoil soil solution is saturated with respect to calcium bicarbonate.

For most years, tillage consisted of either one pass with a disc and one pass with a field cultivator to incorporate the herbicide, or to smooth the surface for planting. An exception was 1990 when a single pass with a cultivator was used to incorporate trifluralin before planting soybeans (Table 1). For two years of row cropping (1988 and 1989) the soil was also row cultivated for weed control. In 1989 there were two row cultivations. In 1990 there were also two row cultivations during the month of July. Near field apparatus, where tillage implements could not reach, attempts were made to simulate the mechanical tillage operation as closely as possible. Shovels were used (with a side twisting motion) to simulate discing, and rakes were used to simulate the field cultivator.

Pesticide applications were planned according to common weed and insect control practices. Because the objective was to monitor the movement of agricultural chemicals, planned insecticide applications were made regardless of the size of insect populations. It is recognized that this policy places a liberal application bias on the results of the experiment.

HYDROLOGY OF THE CARRINGTON SITE

Instrumentation for hydrologic measurements was described above under SITE INSTRUMENTATION AND LAYOUT. Three neutron probe access tubes within the 40- x 40-ft. (12- x 12-m) site area (Figure 4) and one set of piezometers was used to measure recharge and water redistribution using a combined transient flow and water budget (TFWB) procedure for the vadose zone between the soil surface and the water table in the saturated glacial till. Darcy's law was used to measure recharge from the saturated glacial till into the underlying aquifer. The combined transient flow and water budget procedures used have been described in detail previously (Schuh et al. 1993a, Schuh et al. 1993b). Previous applications of a similar water budget procedure were made by Sophocleus and Perry (1985), and by Steenhuis et al. (1985). Another component of analysis is direct recharge from the saturated till to the underlying Carrington aquifer.

ESTIMATION OF RECHARGE TO THE CARRINGTON AQUIFER (\bar{R}_j)

Transient flow water budget (TFWB) procedures were used to provide an indirect estimate of site recharge to the Carrington aquifer (labeled \hat{R}_j^{TFWB}) using three vertical partitions of analysis (Figure 7) to describe cumulative drainage at specified depths. The three partitions include (1) drainage through the root zone at 1.06 m (3.5 ft.) below land surface, labeled $D_{j,1.06}$; (2) drainage through the upper vadose zone at 1.83 m (6 ft.) below land surface labeled $D_{j,1.83}$; and (3) drainage directly to the water table, labeled $D_{j,WL}$. The 1.83-m (6-ft.) lower limit of the upper vadose zone layer was the maximum depth of practical water-content measurement using the neutron probe available for this experiment.

Partition 1: Root Zone Drainage ($D_{j,1.06}$);

$D_{j,1.06}$ (cm) was monitored by applying the Darcy's law,

$$D_{j,1.06} = \int_{t_{j-1}}^{t_j} K(\theta) \left(\frac{d\psi}{dz} + 1 \right) dt \quad (3)$$

where $K(\theta)$ is the unsaturated soil hydraulic conductivity corresponding to soil-water volume fraction θ , and ψ is negative soil-water pressure head. Hydraulic properties for calculating $D_{j,1.06}$ were calculated from neutron-probe θ readings, using in-situ soil hydraulic property data measured for each field monitoring position according to the instantaneous profile method (Hillel et al. 1972). Soil hydraulic properties used for each site are in Appendix A.5. The 1.06 m level was selected because it

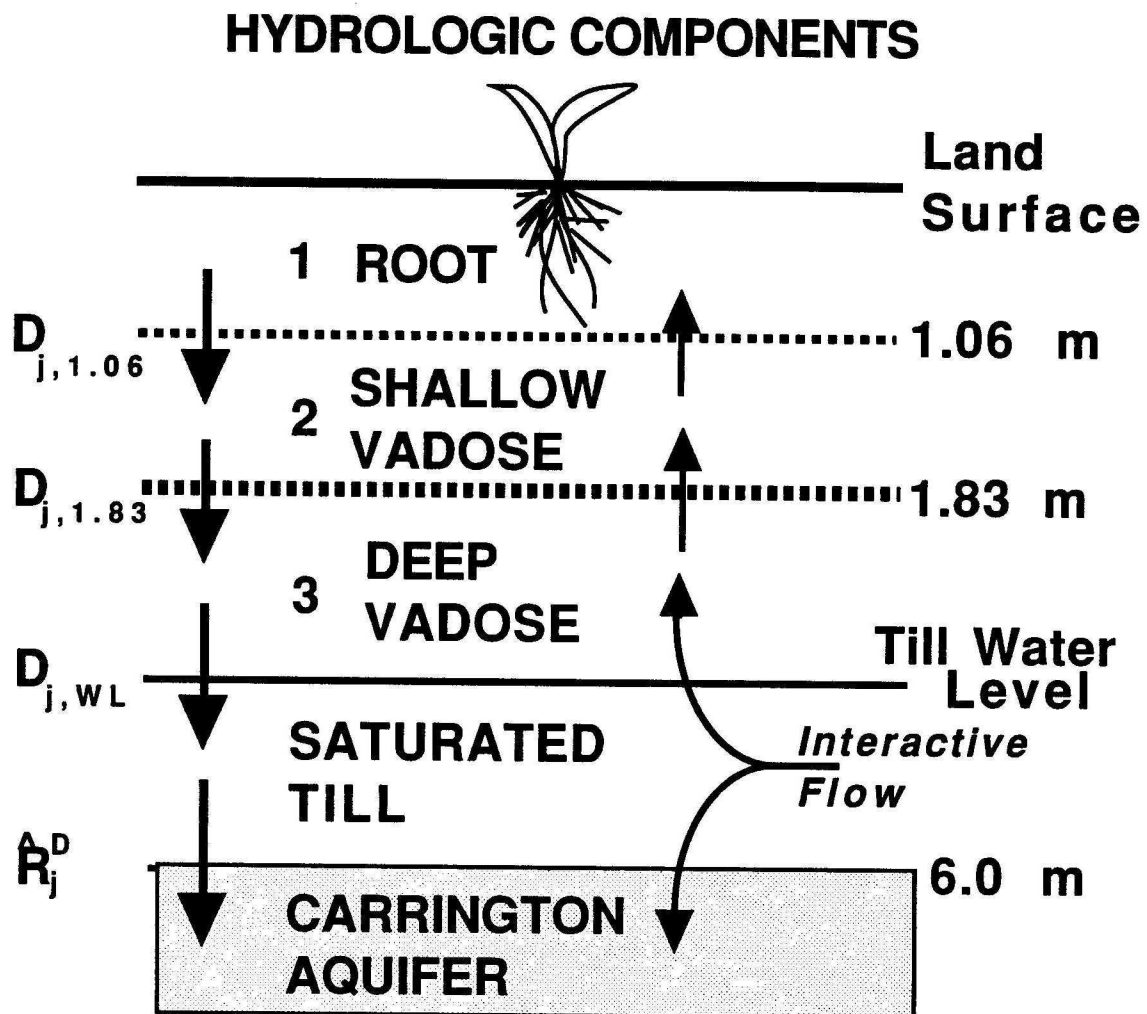


Figure 7. Illustration of partitions of TFWB analysis on the Carrington site.

calculated from neutron-probe θ readings, using in-situ soil hydraulic property data measured for each field monitoring position according to the instantaneous profile method (Hillel et al. 1972). Soil hydraulic properties used for each site are in Appendix A.5. The 1.06-m (3.5-ft.) level was selected because it was found to be the shallowest level below which root extraction of soil water was negligible (Schuh et al. 1993a).

Hydraulic properties for the 1.06 m soil layer were measured in-situ using the instantaneous profile method (Watson 1966, Hillel et al. 1972). Field instrumentation, layout, and procedures were identical to those described by Schuh and Cline (1990). Tensiometers were placed at 15.2-cm (6-inch) increments to 1.52 m (5 ft.) and accompanying neutron probe tubes were placed to a depth of 2 m (6.5 ft.). For each instrument site a 3-m by 3-m (10-ft. x 10-ft.) square area was saturated to a depth beneath the deepest tensiometer, for approximately 24 hours. Field measurements of $\theta(\psi)$ and $K(\theta)$ were made to estimate field capacity during the fall of 1987, and the in-situ main drying curve for $\theta(\psi)$ was measured from field capacity to about 800-cm ψ during the spring and summer of 1988. The drying curve was assured by the lack of deep penetrating rainfall during the dry conditions of 1988.

Tensiometers and neutron probe tubes were left in place after measurement of soil hydraulic properties to ensure that field monitoring sites corresponded exactly to measured soil properties. Soil θ and ψ were monitored for the period beginning after final soil thaw (JD 111) to the beginning of freezing conditions (JD 305) in 1988. Neutron probe readings were taken at time intervals varying from daily following rainfall events to as long as 3 weeks during dry periods. Most readings were taken at approximately 10 day intervals. Late in 1988 tensiometers were disconnected and covered. Thereafter soil-water hydraulic gradients were determined from θ data alone. Field measured θ and ψ data were used to determine $K(\theta)$ and hydraulic gradient for application of eq. 3 and for determination of $S_{j,k}$ in applying eq. 4,5, and 6. Precipitation was measured using data from a Campbell Weather Station 700 m (2,300 ft.) southwest of the experimental site and from a U.S. Weather Station 800-m (2,600-ft.) south of the site.

Partition 2: Upper Vadose Zone Drainage ($D_{j,1.83}$)

$D_{j,1.83}$ (cm) is monitored by applying the water budget procedure

$$D_{j,1.83} = D_{j,1.06} - S_{j,1.06 \text{ to } 1.83} \quad (4)$$

where $S_{j,1.06 \text{ to } 1.83}$ is the cumulative change in soil water storage between the 1.83-m (6-ft.) and 1.06-m (3.5-ft.) levels. Changes in soil-water storage for each time interval are measured at 15-cm (6-inch) increments within the soil profile. Methods of field measurement and calculation were

described previously (Schuh et al. 1993a, 1993b). Accuracy of eq. 4 depends upon negligible direct root extraction and transpiration occurring beneath the 1.06-m (3.5 ft.) level. Previous work on the lands of the Carrington Research Extension Center has indicated that wheat has a common rooting depth of about 1 m (3.3 ft.), and corn and sunflowers have a common rooting depth of about 1.2 m (4 ft.) (Stegman and Valer 1972 , Lundstrum and Stegman 1983). A slight overextension of roots should not have a large effect on overall water balance using the TFWB procedure because most water extraction occurs in the upper soil profile where most roots proliferate.

Partition 3: Deep Vadose Drainage ($D_{j,WL}$)

$D_{j,WL}$ consists of drainage to the shallow water level in the glacial till overlying the Carrington aquifer such that

$$D_{j,WL} = D_{j,1.83} - S_{j,1.83 \text{ to WL}} \quad (5)$$

where $S_{j,1.83 \text{ to WL}}$ is the cumulative change in water storage for the vadose layer having an upper boundary at 1.83 m (6.5 ft.) and a lower boundary at the fluctuating water table. $S_{j,1.83 \text{ to WL}}$ is described as

$$S_{j,1.83 \text{ to WL}} = S_{j-1,1.83 \text{ to WL}} + \Delta S_{j,1.83 \text{ to WL}} \quad (6)$$

where $S_{j,1.83 \text{ to WL}}$ is the change in water storage between the fluctuating water table and the 1.83-m (6.5 ft.) depth. $\Delta S_{j,1.83 \text{ to WL}}$ can be expressed as

$$\Delta S_{j,1.83 \text{ to WL}} = \int_{Z=Z^*}^{z=1.83} (\theta_j - \theta_{j-1}) dz \quad (6a)$$

where Z^* is an arbitrary reference depth beneath the maximum depth of water table recession for the period of measurement. Equation 6a can be solved either by using direct neutron probe readings from 1.83 m (6.5 ft.) to Z^* , or by using the soil water-retention curve according to the expression

$$\Delta S_{j,1.83 \text{ to WL}} = (WL_{j-1} - WL_j) \int_{y=WL_{j-1}-1.83}^{y=WL_j-1.83} \theta d\psi \quad (6b)$$

where WL_{j-1} is the initial and WL_j is the final measured water level in the till confining layer for the period of measurement. The water-retention method can be used where the water table is below

the maximum depth of neutron-probe measurement, providing that equilibrium conditions between the saturated and unsaturated zone can be assumed.

For this experiment $\Delta S_{j,1.83 \text{ to } WL}$ was calculated using a soil water-retention curve. A composite soil water-retention curve consisting of the average water-content values for three in-situ measured depths between 0.91 m (3 ft.) and 1.5 m (5 ft.) on all three neutron-measurement sites combined is illustrated on Figure 8. Composite water-retention data are closely approximated by a linear function between 0- and 200-cm ψ values (corresponding to an interval of 0- to 2-m (0 to 6.6 ft.) above the water table). Using a single fitted linear function for the mean composite soil-water retention curve for all three sites, eq. 6b can be solved analytically as

$$\Delta S_{j,1.83 \text{ to } WL} = 0.000187 \left[(WL_f * 100 - 183)^2 - (WL_i * 100 - 183)^2 \right] \quad (7)$$

where WL_f is the final depth to till water level, and WL_i is the initial depth to till water level for a defined time interval.

CALCULATING RECHARGE TO THE CARRINGTON AQUIFER (\bar{R}_j^{TFWB}) USING TFWB PROCEDURES

If water-storage capacity of the saturated till does not vary with time or saturated depth (which should be valid for a shallow saturated till), then for a soil pedon which is perfectly level and homogeneous, and for which vertical flow and recharge are uniform at all positions on the landscape,

$$\bar{R}_j^{\text{TFWB}} \approx D_{j,w} \quad (8).$$

However, considerable spatial variability of recharge activity results from preferential flow paths (such as gopher holes and worm holes) and topographical influences such as depressional areas and recharge wetlands. Moreover it has been demonstrated (Schuh et al. 1993a,1993b) on the Carrington experimental site, and on similar sites elsewhere (Sophocleus and Perry 1985), that considerable surface redistribution of water occurs between relatively level sites due to microtopographic influence.

For conditions where flow is nonhomogeneous and where "interactive flow" predominates Schuh et al. (1993b) developed a water-budget procedure for calculating recharge to the water table and to the underlying aquifer which accounts for the complex cycling of water between the fluctuating water table and the vadose zone. The computational procedures developed also account for the

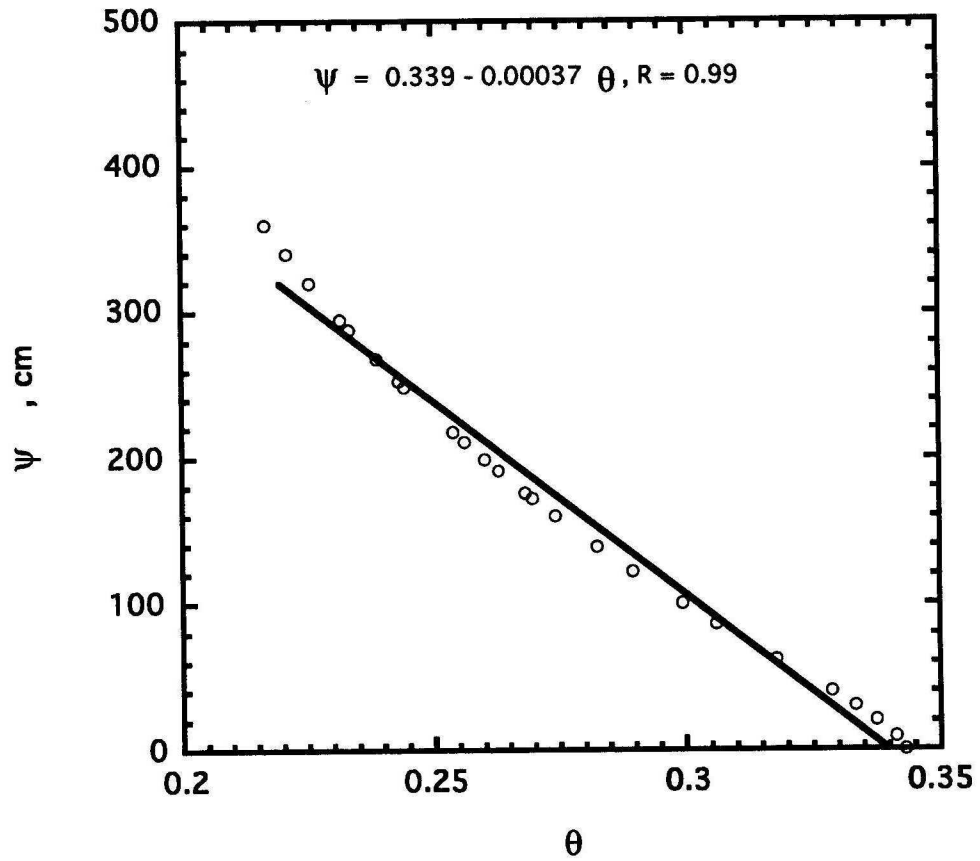


Figure 8. Composite soil water retention curve for all of the neutron-probe monitoring sites.

detailed partitioning of water within the soil and vadose profile. Although the "interactive flow" computational procedure will be used to describe the annual cycling of water on the Carrington experiment in this report, readers interested in the procedure and its implementation are referred to the source paper (Schuh et al. 1993b).

Darcian estimation of Recharge to the Carrington Aquifer (\widehat{R}_j^D)

Local stratigraphy consists of soil and vadose zones formed in loamy to coarse-loamy glacial till overlying a sand and gravel aquifer (The Carrington Aquifer) at a depth of about 6.8 m (22 ft.). The existence of a saturated zone in the till with water table varying between approximately 2.0 m (6.6 ft.) and 4.0 m (13.2 ft.) below land surface enables the application of Darcy's law for direct measurement of saturated recharge to the Carrington aquifer. Using in-situ measured saturated hydraulic conductivity values for the saturated till, and hydraulic gradients calculated from piezometric measurement at the surface of the Carrington aquifer and in the saturated till, the Darcian direct estimate of recharge (\widehat{R}_j^D) is calculated according to:

$$\widehat{R}_j^D = \sum_1^j K \frac{(t_j - t_{j-1})}{2} \left[\frac{(h_{WL} - h_{ca})_{j-1}}{b_{j-1}} + \frac{(h_{WL} - h_{ca})_j}{b_j} \right] \quad (9)$$

where K is the hydraulic conductivity of the saturated till, t_j is the time corresponding to a given time coordinate j, h_{WL} is the piezometric head of the till, h_{ca} is the piezometric head of the Carrington aquifer near the till boundary, and b_j is the thickness of the saturated till at time t_j .

K was calculated by substituting calculated \widehat{R}_j^{TFWB} for \widehat{R}_j^D in eq. 9 for a period during 1990. That K (0.198 cm/d) was then used to calculate \widehat{R}_j^D for the rest of the experiment. The predictive accuracy of this substitution depends on the homogeneity of the hydrologic system. Homogeneity, in turn, is dependent upon the spatial variability of the measured $D_{j,1.83}$ component and its influence on the accuracy of the sample pedon consisting of the three neutron-probe monitoring sites as a representative of overall field values. Homogeneity also assumes that till water levels are reasonably constant over the measured area, and that large quantities of localized flow are not occurring between measurement sites. These assumptions are frequently untrue (Schuh et al. 1993a, 1993b), but can be approximated for limited periods of time. By delimiting a period of time with no large or significant rainfall events, potentially large variabilities in $D_{j,1.83}$ caused by topographic variability, and by dynamic flow through the root zone can be minimized. Moreover, by insuring that the period of measurement corresponds to a gradually falling water table, well after any period of recharge,

localized flow considerations are eliminated, maximizing the likelihood of validity for the homogeneity assumptions.

K was measured for a period of falling water table between Julian Day (labeled JD) 204 and JD 288 of 1990 on all four piezometer sets. K values indicated no overall trend with depth (Figure 9) and were thus represented by a single statistical mean for the experimental site. 95 % confidence interval limits indicated that the calculated geometric mean ($\bar{K} = 0.198 \text{ cm/d}$) was within 12% of the true geometric mean. (Figure 9).

Computational Procedures

Annual cycles of recharge were compared for measurement years beginning and ending on November 1. This date was chosen because it marks well the end of crop harvest, and the beginning of frost advance in North Dakota.

\widehat{R}_j^D measurements were made using approximate monthly piezometric readings during time periods of active surface recharge (the frost free period). From initiation of frost advance (early November) to final soil thaw (between April 5 and May 5) it was assumed that drainage from the surface or from the soil zone to the water table was negligible, and that the interaction between the water table and the soil and vadose profile was controlled by the complex internal cycling of water between the water table and the moist vadose zone and the advancing freezing front. Because of lack of recharge events during this time, piezometric readings were made every two, and in one case, three months. For each year, the water level in the till receded slowly as saturated till waters continued to drain into the Carrington aquifer.

The Darcian methods used for computation of $\widehat{R}_j^{\text{TFWB}}$ were only applicable to frost free periods. In North Dakota frost advance commonly reaches 1.5 to 2 m (5 to 6.5 ft.) below land surface. For winter computation it was assumed that drainage from the frost zone did not occur. ($D_{j,1.83} = 0$) and that water below 1.83 m was in equilibrium with the water table ($\Delta S_{j,1.83 \text{ to WL}}$ was calculated using eq. 7). Thus, for the frost season it was estimated that $\widehat{R}_j^{\text{TFWB}} = \Delta S_{j,1.83 \text{ to WL}}$. This is an imperfect assumption for a highly complex season. However, the practical effect of this assumption will be seen in the resulting comparative data. $D_{j,1.83}$ was used in computation of $\widehat{R}_j^{\text{TFWB}}$ following removal of frost from the soil.

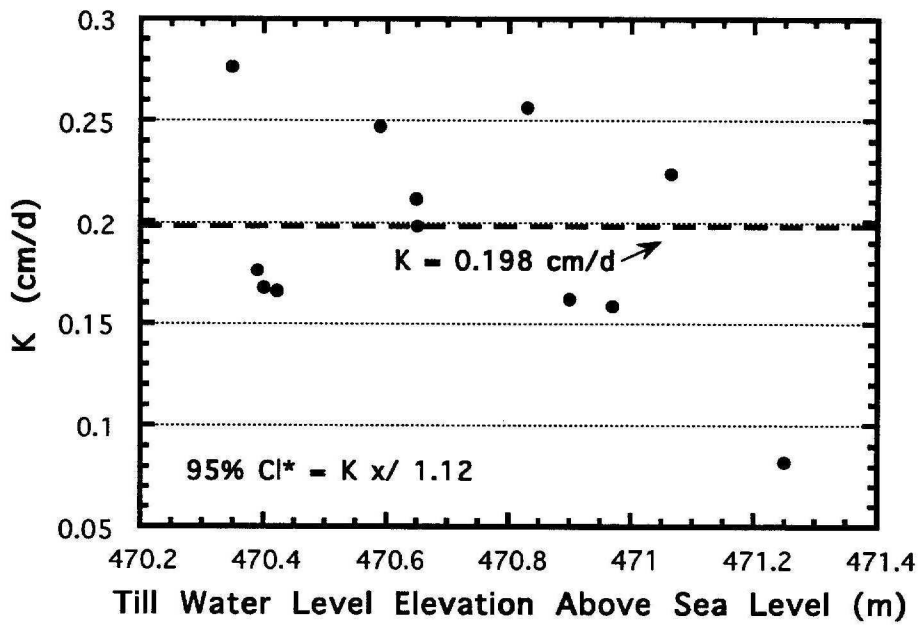


Figure 9. Hydraulic conductivity values calculated for the saturated glacial till. CI* indicates "confidence interval" for the geometric mean.

SPATIAL VARIABILITY OF ROOT ZONE DRAINAGE

Using 1988 through 1990 data for the Carrington experiment Schuh et al. (1993a) described two hydrologic phenomena governing local recharge. First, it was found that there was large spatial variability of drainage through the root zone (drainage at 1-m depth) for the three measurement sites within the 40- x 40-ft. (12- x 12-m) measurement area. $D_{j,1.06}$ varied from a maximum of 4.52 cm (1.77 inches) on the NE site to as little as 0.51 cm (0.20 inches) on the SE site in 1988. In 1989 the maximum was 19.76 cm (7.75 inches) on the SE site while the minimum was -0.72 cm (-0.28 inches) on the NE site. During 1990 the maximum was 9.11 cm (3.58 inches) on the SE site and the minimum was 0.14 cm (0.06 inches) on the NW site. Except for 1988 the SE site had by far the largest amount of root zone drainage, and the NW site had the least.

The main cause of variability was found to be surface microtopography (Schuh et al. 1993a, Schuh et al. 1993b). $D_{j,1.06}$ on the three measurement sites was governed by difference in surface relief totaling less than 3 cm between the NW site with the highest elevation and the SE site with the lowest elevation. Evidence of microtopographic dominance of drainage through the root zone included (1) hydrologic measurements (the SE site with the lowest surveyed elevation consistently had the most recharge). In addition (2) measured preliminary infiltration rates on each of the sites were nearly identical. Field data also included (3) soil-hydraulic properties [both $K(\theta)$ and water-retention properties] which indicated that the SE site would be expected to have the slowest rates of water movement, and (4) an actual map of the time sequence of ponded water distribution during and after a major (> 4 cm in less than 2 hours) storm in May of 1991 (Figure 10). The only site found to be directly ponded following the observed storm was the SE site.

The tighter distribution of $D_{j,1.06}$ and the smaller $D_{j,1.06}$ value for the SE site in 1988 were caused by dry conditions. 1988 was a drought year, with no large storms having runoff. Also, 1988 was the first measurement year and it began with a high water table, influenced partly by plot flooding in the fall of 1987 for measurement of in-situ soil hydraulic properties. $D_{j,1.06}$ in 1988 was thus governed by capillary response to the falling water table, rather than to surface infiltration caused by precipitation (Schuh 1993a). In 1988 drainage from the root zone was not a result of surface recharge, but a response to drought induced water depletion.

The second hydrologic phenomenon described by Schuh et al. (1993a) was that of upflux of water from the water table into each of the measurement site vadose zones following major storm periods. Following storms with large runoff and redistribution of surface water, water was measured moving upward as capillary water through the 1.83 m layer from the water table. This was measured as negative incremental flux, or a decreasing cumulative flux (decreasing $D_{j,1.83}$). In some instances upward flux was measured into the soil zone (decreasing $D_{j,1.06}$). This

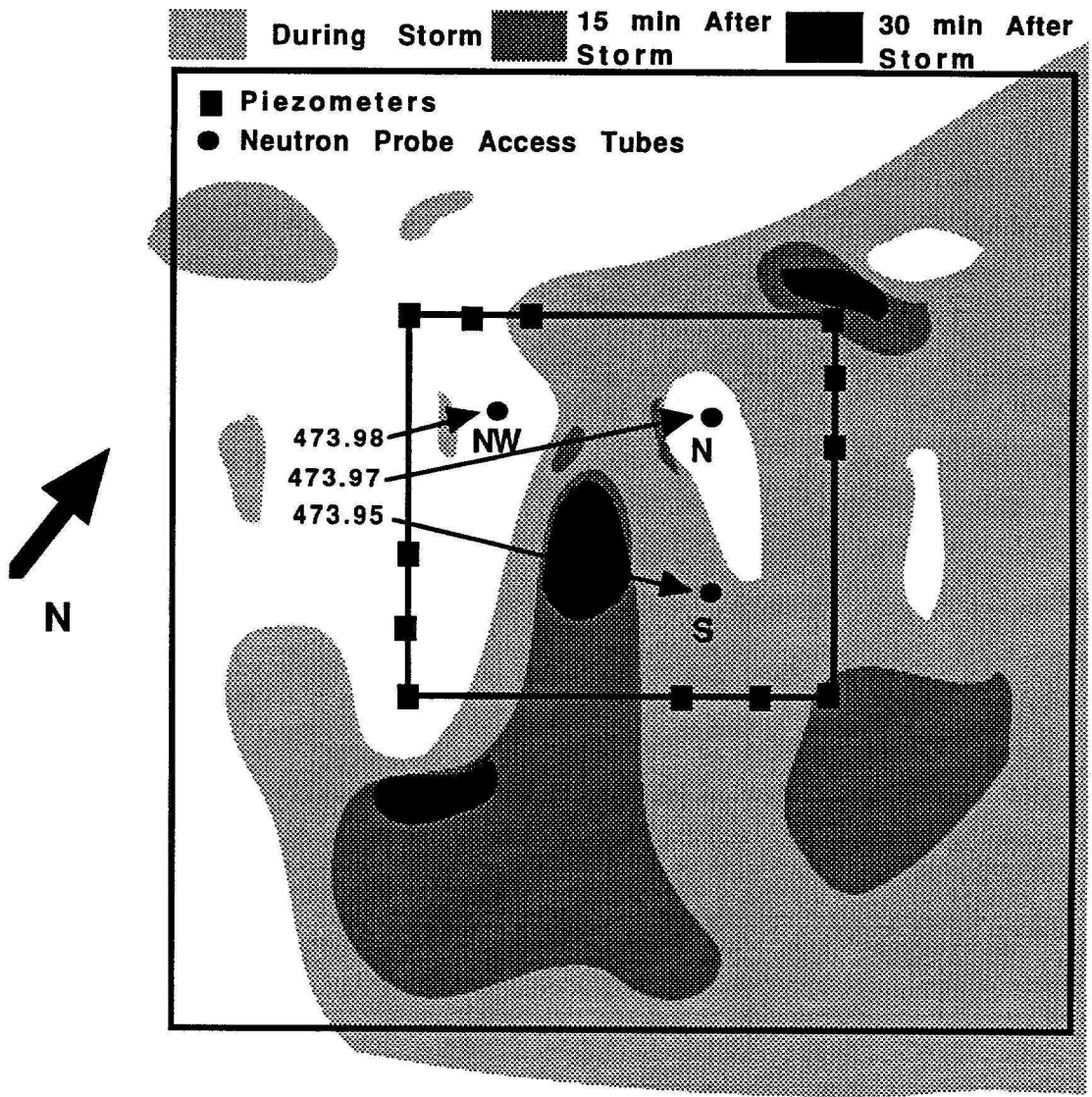


Figure 10. Map of ponded water following a storm on May 22, 1991.

phenomenon is illustrated for 1989 and 1990 on Figures (11 and 12). The clearest example is 1990 (Figure 12).

It was further observed (Schuh et al. 1993a) that the characteristic patterns of upflux were related to overlying surface recharge through the root zone ($D_{j,1.06}$). Sites having large local surface recharge (SE site 1990, Figure 12) tended to have the largest amount of surface upflow (the exception of the 1989 SE site will be explained shortly), while those having less drainage through the root zone tended to have longer periods of upflux characterized by repeated surges of upflux of lesser quantity (NE and NW sites, 1990, Figure 12). The complex pattern of water movement characterizing these observed phenomena was called "interactive flow".

INTERACTIVE FLOW

In the described hydrologic system upfluent waters are required by conservation of mass to have a source in surface locations other than those directly measured. This requires that some form of local "preferential" recharge must be occurring. The nature of that preferential flow may be diverse, and may include such site factors as ground-squirrel (*Spermophilus* sp.) and field mouse (*Peromyscus* sp. or *Microtus* sp.) burrows which were observed on the site. However, a major component of preferential flow appears to have occurred in infiltration "cells" of varying size and extent which are caused by the leveling properties of water responding to very subtle nuances in microtopographic elevation. This flow is preferential in that it entails localized drainage of large amounts of water, which are much larger than the average drainage for the field. However, In this case preferential flow is Darcian, and the complex movements of water described are caused primarily by the spatial variability of local surface infiltration, combined with the interaction of recharge waters with a water table at recharge sites, and subsequent effects of recharge waters on the water content of the vadose zone on surrounding sites.

The nature of local preferential recharge is clarified somewhat by a map (Figure 10) of ponded surface water distribution which was drawn during the course of an intense (4.2 cm [1.7 inches] in 2 hours) storm on May 22, 1991. Of the three monitored sites, only the SE site was ponded for part of the storm. The NE and NW sites were at elevations above the ponded water levels, and were therefore sources of runoff. Using persistence of ponding as a criterion, other (non measured) positions on the landscape exhibited longer term surface infiltration status following the storm, and some topographically defined positions were found to be collection and infiltration mini basins with extended effect for as much as one hour following the storm. It is likely that other micro-basins were present which were too small to observe or map.

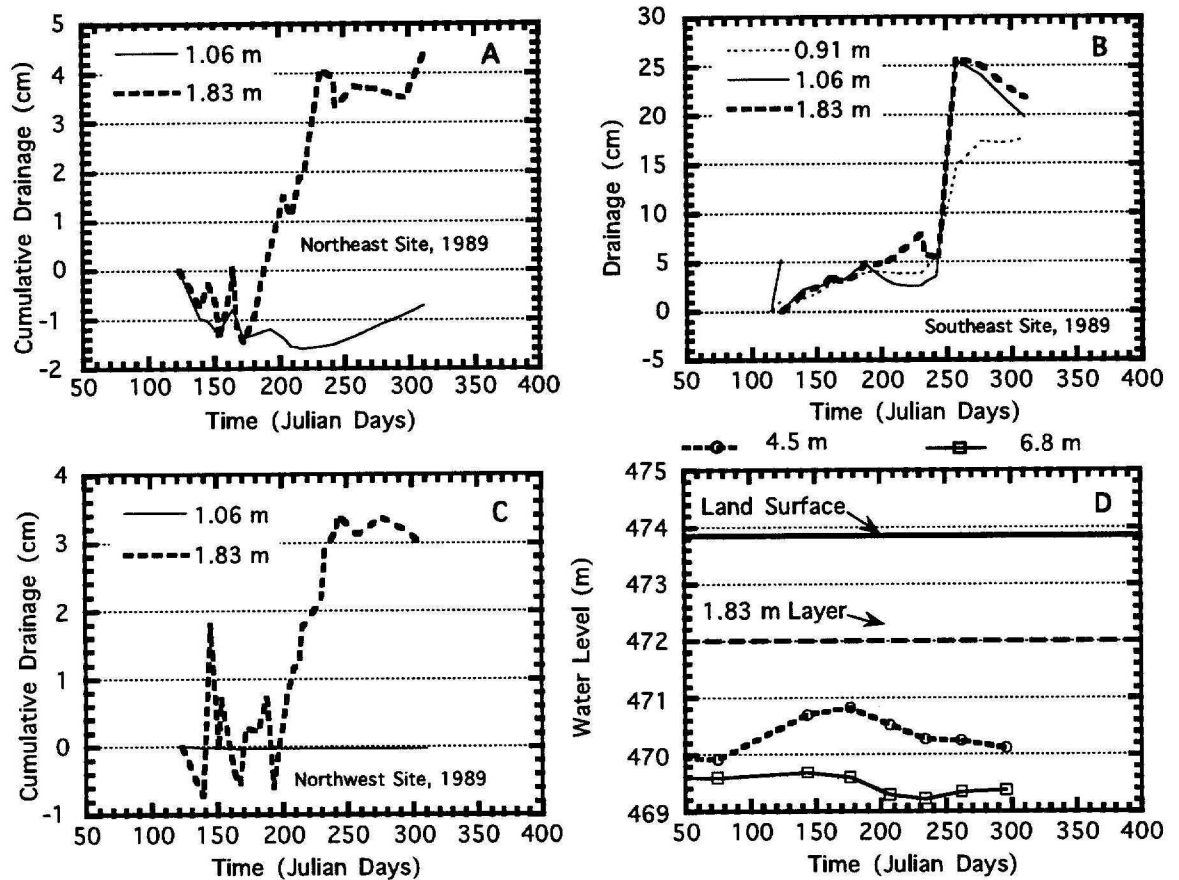


Figure 11. Graph of soil and vadose zone water movement for A. NW, B. SE, and C. NE soil water measurement sites, and D. water levels for the saturated till and the Carrington aquifer during 1989.

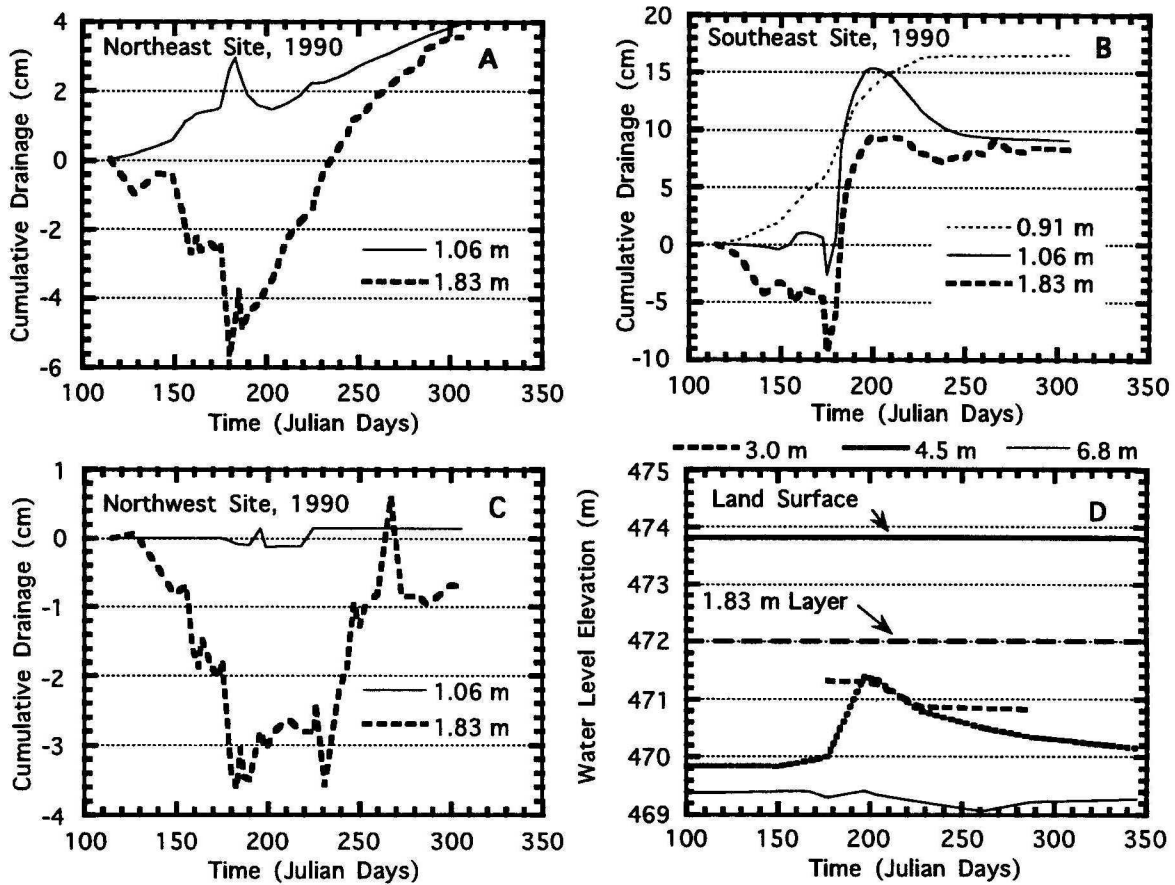


Figure 12. Graph of soil and vadose zone water movement for A. NW, B. SE, and C. NE soil water measurement sites, and D. water levels for the saturated till and the Carrington aquifer during 1990.

On the basis of hydrologic evidence and the observed behavior of surface water, Schuh et al. (1993a) described the surface landscape as consisting of three typical recharge regimes. The first regime was defined as a "primary active" site, in which all transfer of water between the surface and the water table consists of local downward flux. On a primary active site, surface recharge is sufficiently dominant to negate the potential entry of water from other recharge sites into the vadose zone through water table redistribution. The second type of site was defined as an "inactive" recharge site, in which no surface infiltration waters move past the root zone, and in which all interaction with the water table is dominated by upward flux (and subsequent redrainage) of water from the water table which has been recharged at other sites of greater activity. The third regime was defined as "intermediate active" sites, in which varying degrees of both surface recharge through the root zone, and periodic upflux of water from the water table having surface sources at other sites of greater activity, occur. Water received on a given site from capillary response to water-table redistribution, while originating in recharge on other sites, was labeled "interactive flow". These regimes are illustrated on Figure 13.

The movement of water during the recharge process in this type of soil and water system can be described as follows. During a rain storm of sufficient intensity to induce runoff, water flows from microtopographic high elevations (inactive sites) to microtopographically lower elevations. Receiving areas include intermediate lower elevations and transitional paths to other optimally low (primary active) water receiving areas. Provided that potential surface infiltration rates are large enough so that evaporation is minor, waters recharge locally according to the time and depth of water received. Resulting waters which move locally through the root zone to the water table form local recharge mounds, or "pimples" with size and depth of effective ground-water transmission varying according to the surface area of the recharge site and the amount of water moving through the site. The behavior of such recharge mounds under conditions of long term steady-state deliberate ponding has been described analytically by Hantush (1967) and by Marino (1974).

According to this model, following a major "recharge" rainstorm the water table can be viewed as a three dimensional surface of recharge mounds, having different depths, durations, and times of initiation and completion. These characteristics depend on the size of the recharge source area, the amount of water entering that area, and the velocity and distribution of water transmission through the root zone. The mounds begin to redistribute laterally immediately upon formation. From analogy with behavior of mound distribution under artificial recharge basins, effective depth of transmission of recharge waters under each surface position is known to be related to the size of the recharge area and the amount of water moving through it (Bouwer 1962). Following a recharge event, the water table elevation under each landscape position is defined by the unique characteristic of overlapping or sequential pulses of water from surrounding redistributing water-table mounds occurring at that

position. As each pulse of rising water occurs under a given site, the vadose zone (and the soil zone if sufficiently close to the water table) responds with a capillary upflux corresponding to the in-situ pressure-release curve water content for each height (or corresponding gravitational head unit) above the water table. This process of redistribution is described graphically in Figure 13.

In terms of the defined activity regimes, a primary active site would be expected to receive no upward flux pulses from surrounding areas because of its surface recharge dominance. An inactive site, on the other hand, would be expected to receive an extended succession of pulses of varying amount and time duration, because the lack of any local downward flux would result in a local situation in which virtually all recharge pulses from sites within effective distance, regardless of size, duration, or time of travel, would affect local vadose zone water balance. The locally inactive site would receive water from other nearby sites through the water table redistribution process. Intermediate active sites would vary between these extremes.

Characteristically, local downward flux and upward flux from surrounding sites would interchange in dominance. Most frequently, it would be expected that local downward flux would predominate early, and that interactive flow from surrounding sites would later predominate because of the time lag effect from surrounding sites. Generally, the activity regime would be expected to have some relative consistency from event to event or from year to year. However, where the activity regime is determined by micropotography, sensitivity to changes in tillage and cropping practices, and to other events or practices affecting surface runoff would be expected to alter the activity regime on any given site.

These expectations are consistent with field observations. In both 1989 and 1990 the NW site, which is inactive, was characterized by successions of pulses of interactive flow extending over a period of long duration at the 1.83 m level. The NE site, which usually is of intermediate activity, is characterized by both limited root zone drainage, and a moderate amount of local upflux. Numbers of interactive flow pulses are generally less than those on the NW site. The SE site usually had the largest activity of the three measured sites and in one year (1989) functioned as what appears to be a primary active site, with almost no water entering the soil profile from below. In 1990, a single (or few) large combined pulses of interactive flow dominated the local recharge regime until local recharge began to dominate at about 175 JD (Figure 12). On the NW site, where no local root zone drainage occurred, pulses of interactive flow continued until 230 days, caused by pulses of smaller magnitude (and greater travel distance and time) than would affect the SE site.

Additional hydrologic data for 1991 and 1992 are shown on Figures 14 and 15. The 1991 data for the NW and NE sites are similar to 1988 and 1989 data, with no local drainage through the root zone and a prolonged period of repeated pulses of interactive flux into the upper vadose zone on the NW site. About 5 cm (2 inches) of root zone drainage, and a brief period of interactive flow into

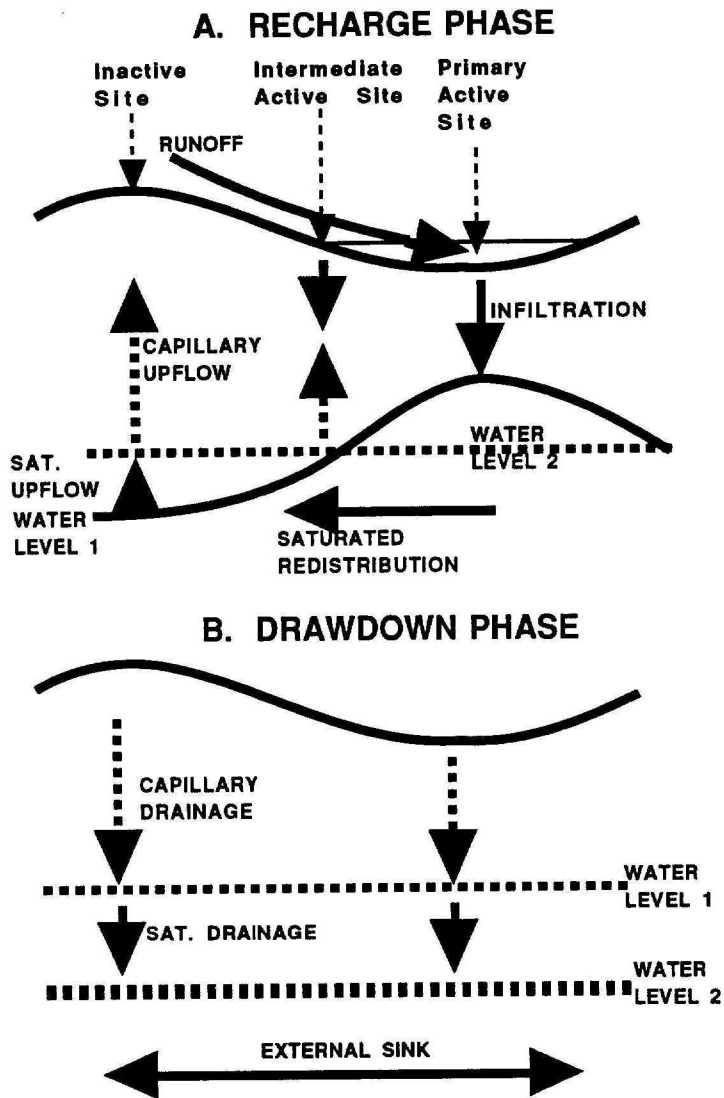


Figure 13. Illustration of flow paths resulting in "interactive flow" phenomena.

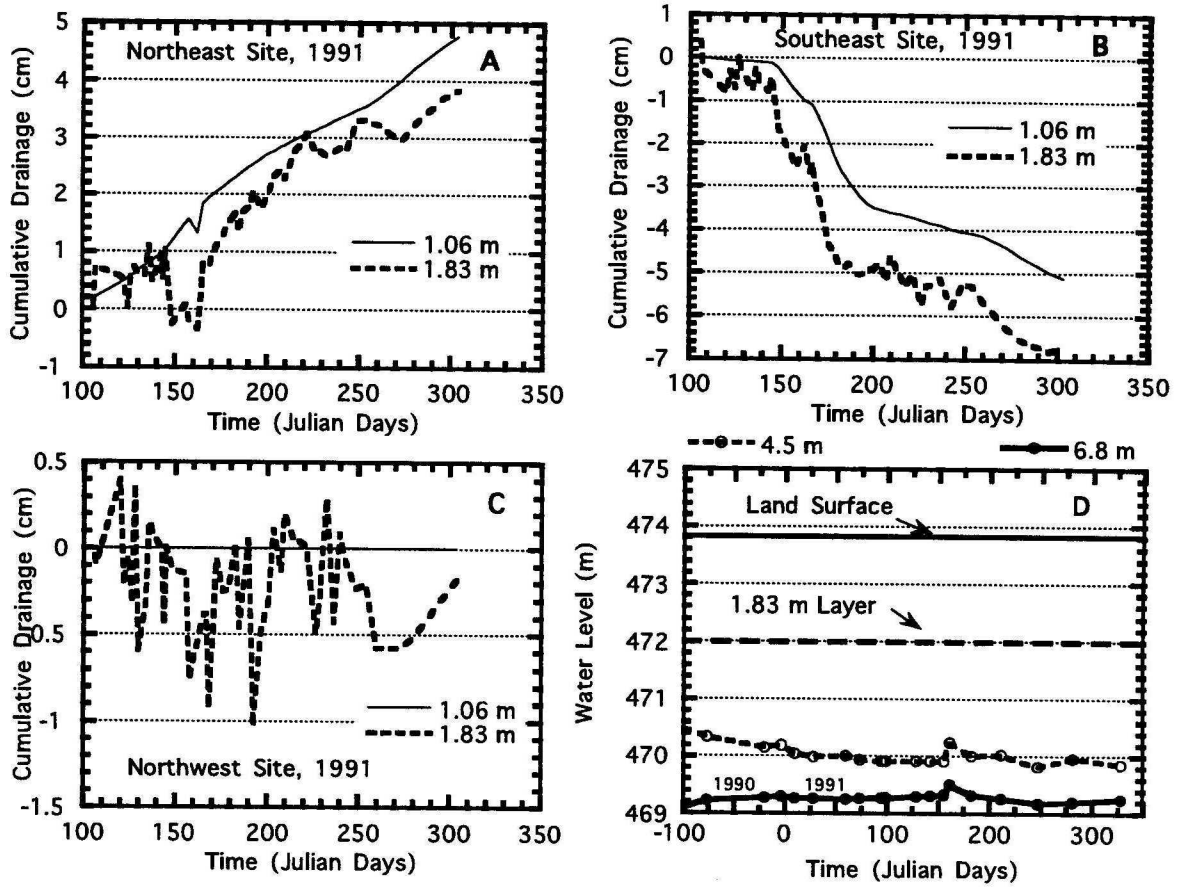


Figure 14. Map of soil and vadose zone water movement for A. NW, B. SE, and C. NE soil water measurement sites, and D. water levels for the saturated till and the Carrington aquifer during 1991.

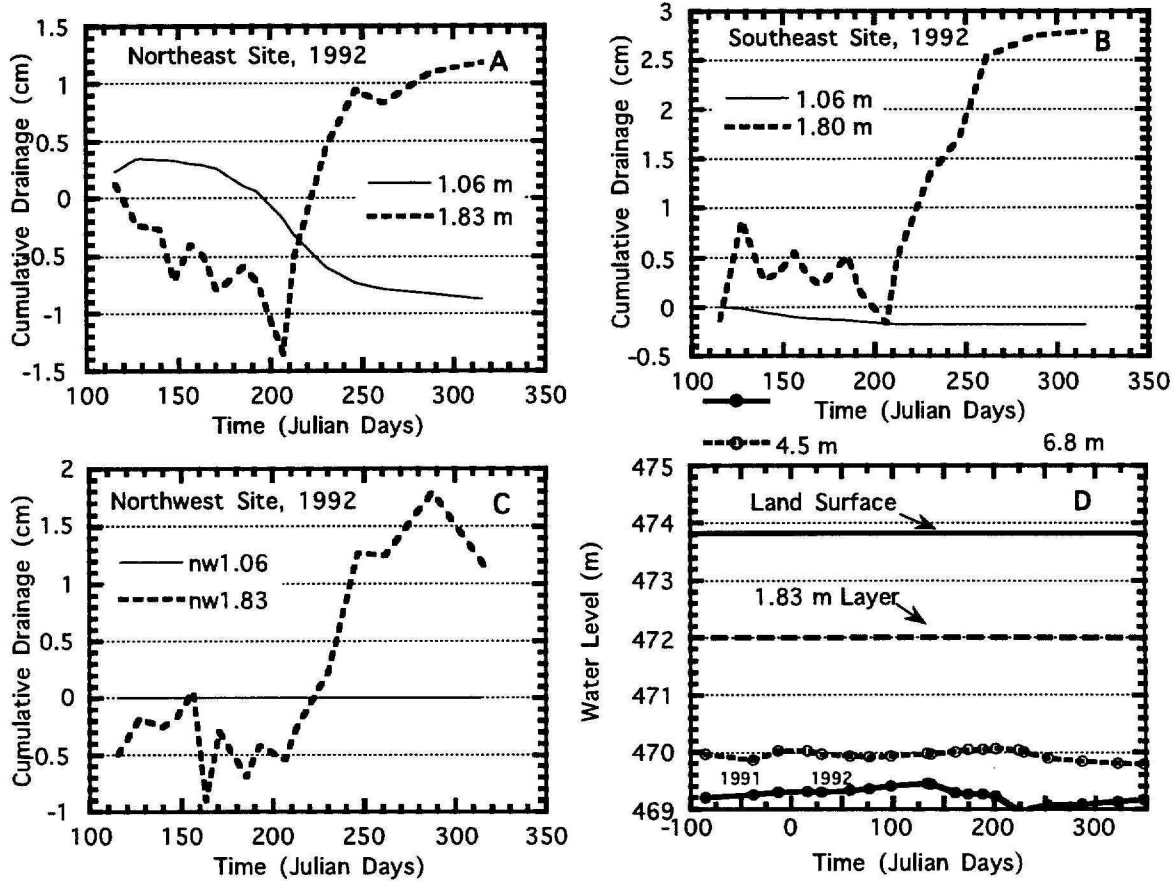


Figure 15. Map of soil and vadose zone water movement for A. NW, B. SE, and C. NE soil water measurement sites, and D. water levels for the saturated till and the Carrington aquifer during 1992.

the root zone occurred on the NE site, corresponding to a very small period of measured rise in the till water level. The cause of the constantly decreasing cumulative flux on the SE site in 1991 is not understood at the time of writing.

In 1992, no measured drainage occurred through the root zone during the measured growing season. Some early interactive flow was measured at the 1.83-m (3.5 ft.) layer. However, in February of 1992 there was an early snow melt that caused flooding of the plot (photo Figure 16). It is thus likely that part of the total flux to the water table for the year occurred before TFWB measurements as infiltration through the frozen soil. The total water balance for the year (discussed later) indicates that as much as 7 cm (2.75 inches) of water moved to the water table during the February event. It is likely that some of the interactive flow indicated for all three sites between JD 100 and JD 200 originated in the early recharge event.

Rises in till water levels were detectable, but very minor in 1991 and 1992. This can be attributed to both climatic and crop factors. In 1992 precipitation events were ample but of low intensity (Figure 17), which would tend to prevent runoff, preferential flow, and interactive flow at the water table. In 1992, the crop on the field was wheat, which has a dense and highly distributed canopy, which also distributes rainfall impact and prevents runoff. In 1992 both drainage through the root zone and interactive flow into the upper vadose zone are small compared with other years. In both 1991 and 1992 the initiation of drainage from the upper vadose zone began with the period of decreasing piezometric pressure in the Carrington aquifer (Figures 14D and 15D). In 1991 the till water level began to rise at approximately JD 170, and in 1992 it began to rise slightly at approximately JD 210.

EFFECT OF EXTERNAL SINKS

Drainage, water table redistribution, and capillary upflux into the vadose zone are only a part of the recharge process. After draining to the water table, major sinks for till water are (1) recharge to the underlying Carrington aquifer; possibly (2) transpiration from low areas in the tributary to Scott's Slough, located approximately 350 ft. (106 m) east of the experiment site, and (3) road ditches located within 500 ft. (300 m) north of the experiment site. Small measured transpirational draw of water from beneath 1 m, the large quantity of measured local recharge to the Carrington aquifer, and the close correspondence of recharge measurements using \bar{R}_j^D and \bar{R}_j^{TFWB} procedures indicate that direct local recharge to the Carrington aquifer is the primary sink for local till water.



Figure 16. Photo illustration of the late February 1992 thaw and field flooding event.

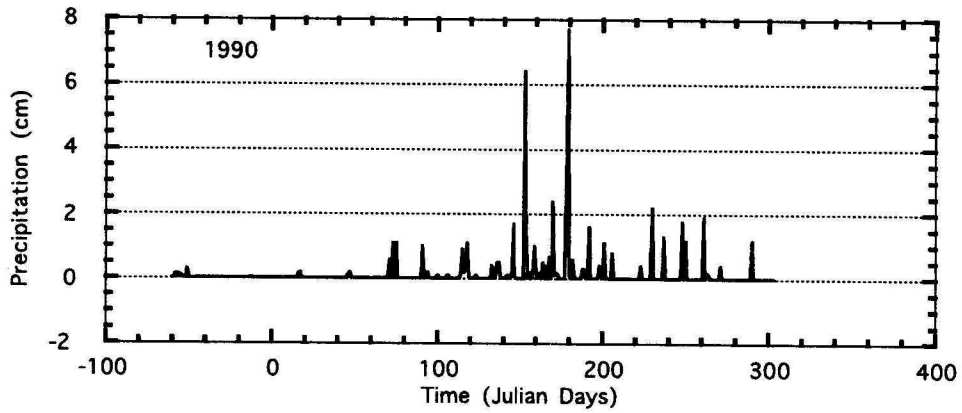
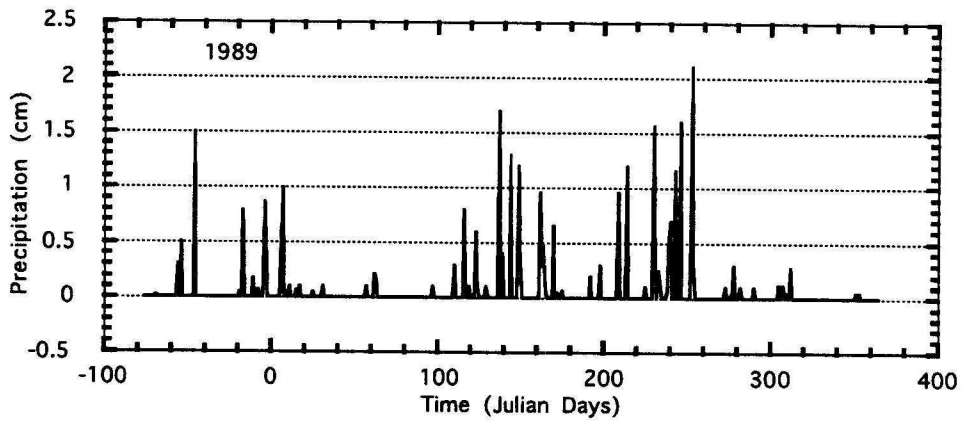
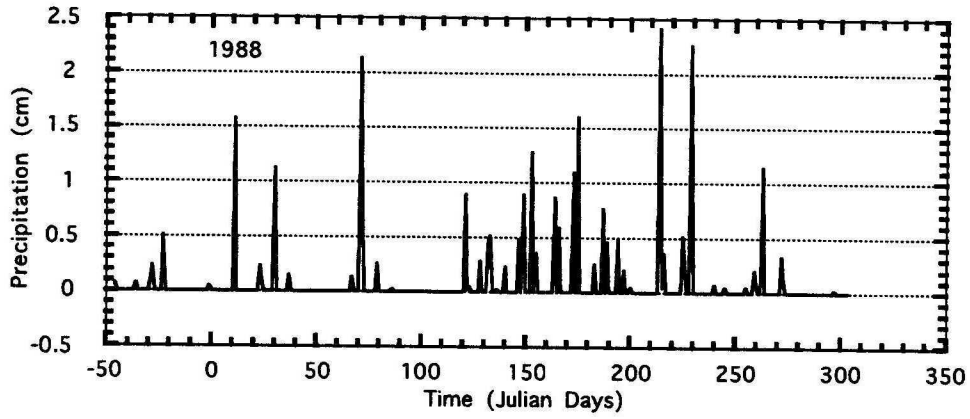


Figure 17. Precipitation at the Carrington Site from 1988 through 1992 (continued next page).

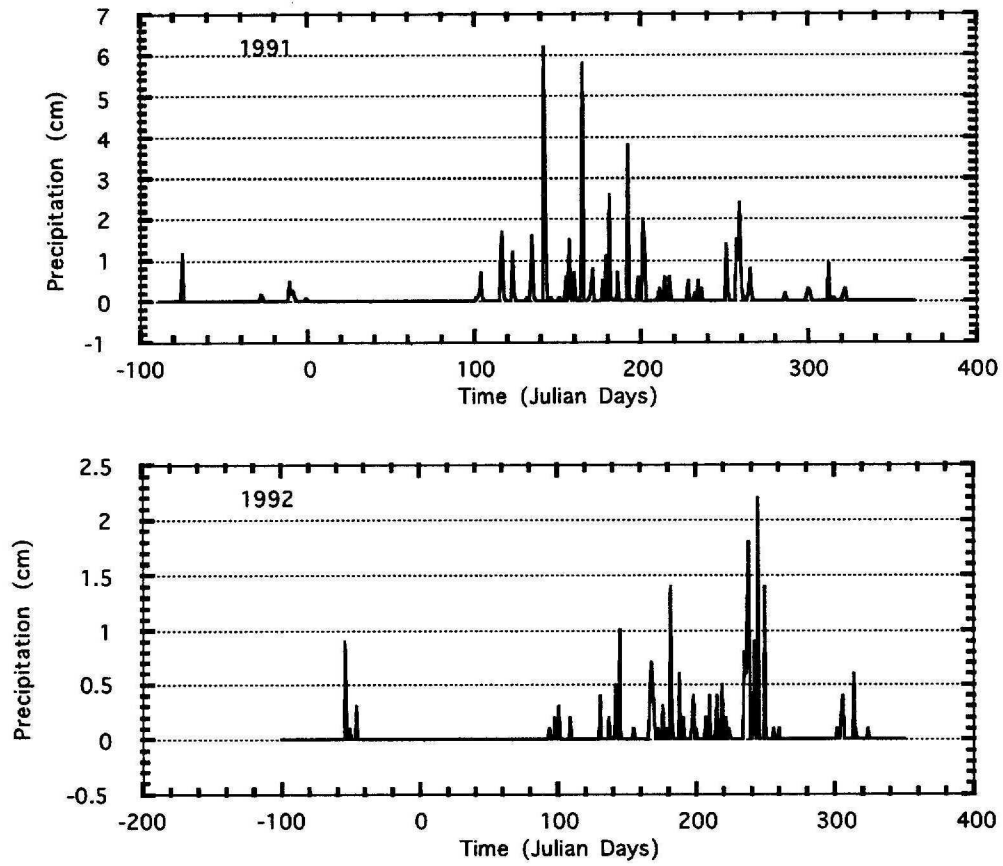


Figure 17 (continued). Precipitation at the Carrington Site from 1988 through 1992.

On the experiment site recharge to the Carrington aquifer remained relatively constant at approximately 20 cm (7.9 inches) per year from 1988 through 1992 (Table 2). The till water acted as a reservoir, mediating the differences in climatic input which varied from drought conditions in 1988 to above normal precipitation in 1990 and 1991. Over the period from 1988 through 1992 the water level in the till dropped from approximately 472 m (1548 ft.) to approximately 470 m (1542 ft.) above sea level. However, except for brief periods following recharge events, the till water table has remained relatively constant at about 470 m (1542 ft.) since the spring of 1989.

Table 2. Total annual recharge and precipitation on the Carrington site.
*Precipitation from U.S. Weather Service Station, Carrington ND.

Year	Total Recharge cm	Precipitation cm
1988	NA	29
1989	22.11	43
1990	19.58	53
1991	20.19	62
1992	19.80	32

Despite the overall annual constancy of recharge from the saturated till to the Carrington aquifer, the hydraulic gradient, and subsequent recharge measured from the till to the top of the aquifer varies by a factor as large as four over the course of the year in response to pumping of irrigation wells on the Carrington Research Station. This is shown on Figure 18. Thus, irrigation use is an important component of the cycling of water on and through the soil of the experimental plot. Enhanced movement of water from the till to the aquifer, caused by the drop in aquifer water pressure in response to pumping, results in a subsequent drop in the till water level, and a corresponding

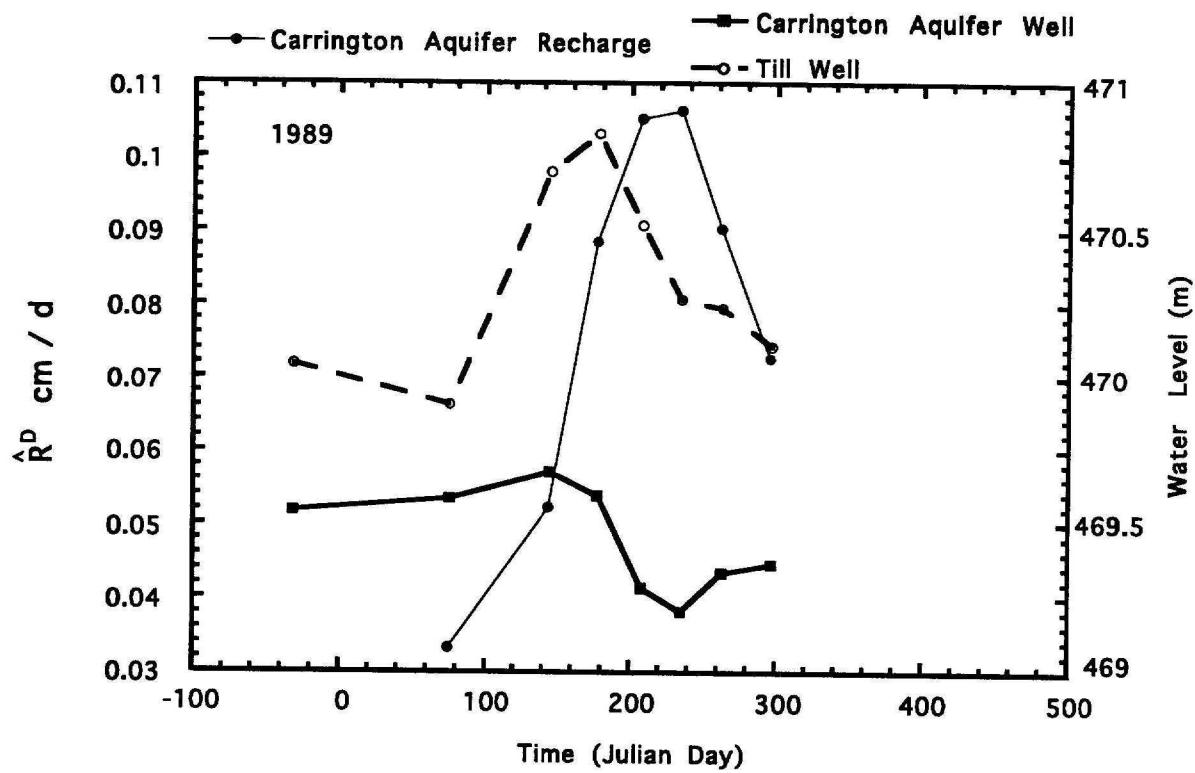


Figure 18. Variation of recharge from the saturated glacial till to the Carrington aquifer in 1989.

drawdown of capillary water which moved upward into the vadose profile through interactive flow during surface recharge events.

INTERNAL CYCLING OF RECHARGE WATER

Winter Water Budget

Soil-water content was monitored during the winter for each of the years of the experiment. During each of the frozen periods, upward movement of water in the soil and vadose profile to the freezing front was observed. However, during the first two years (1987 to 1988 and 1988 to 1989) neutron-probe tubes were exposed directly to cold air, and it is likely that some of the measured changes in water concentration might have occurred as direct migration to the chilled aluminum tube. Because of this concern, neutron-probe tubes were insulated both internally and externally for all subsequent winters. Insulation consisted of a plastic foam "sausage" placed to a depth of approximately 1.5 m (4.9 ft.) within each tube, and a plastic foam lined cap of 15-cm (6-inch) PVC which was placed over the top of the exposed portion of each tube. The purpose of the cap and "sausage" was to minimize effects of both conductive (through the tube metal) and convective (air movement within the tube) transfer of heat from the soil to the atmosphere.

Four neutron-probe tubes were also placed on the experimental site, and were used for further winter measurements beginning in the fall of 1989. Three of the additional neutron-probe tubes were insulated in a manner similar to the SE, NW, and NE site tubes, but the measurement area surface was covered with tarpaulins to prevent infiltration of water during the winter. The purpose of the covered sites was to help discern the difference in flux caused by frost-induced movement and short term infiltration events caused by winter thaws. The fourth neutron-probe tube was left without insulation, and with uncovered surface to provide an evaluation of the potential effects of bare aluminum tubes on frost-zone water measurements. A series of snow surveys was also conducted during the winter of 1989 to 1990 to provide a quantitative assessment of local snow cover.

Detailed analysis of winter data remains to be done. However, for this report we will briefly discuss the fall 1989 through spring 1992 data for the SE, NE, and NW sites. The winter data for the fall 1987 through spring 1989 period are not reported because the neutron-probe tubes had not yet been insulated, and because the effects of direct heat loss through non insulated aluminum access tubes on water accumulation have not yet been evaluated.

Figures 19, 20, and 21 summarize the winter budgets for each of the measured soil and vadose zone profiles. The graphs are of cumulative water content change from the surface to the designated depth, from the beginning day of measurement to the assigned measurement date. Thus,

the depth having the largest water accumulation is also the maximum depth of frost-induced water accumulation. Because accumulated water is totaled from the surface to each designated depth, soil and vadose layers deeper than the maximum water accumulation depth must have lost water in order to exhibit less cumulative increase in water than the overlying layer, even though a net cumulative increase in water content from the surface may be indicated.

Winter data for 1989 to 1990 (Figure 19) indicate two main periods of water content change. The first period extends from late October to the middle of March (approximately JD 70), and is characterized by frost upflux into the soil and vadose zone. The depth of maximum frost-water accumulation varies from a minimum of 1.22 m (4 ft.) on the SE site, to a maximum of 1.83 m (6 ft.) on the NW site. The NE site was intermediate with a cumulative maximum accumulation depth of 1.52 m (5 ft.). For each site total cumulative water increase to the maximum accumulation depth is close to 4 cm (1.6 inches). Loss of water from depths between the maximum measured depth and the 1.83 m depth on two of the three sites indicates that some of the accumulated water at the frost zone [1 to 2 cm (0.4 to 0.8 inches)] originated within the vadose zone above 1.83 m. Lack of water increase in the topsoil for most of the winter indicated that little of the flux was caused to the addition of surface water. Also, less than 1 cm (0.4 inches) of precipitation occurred during winter before late February.

The second period of water influx began at approximately JD 70 (1990), and consisted of combined melt water and precipitation beginning at that time. However, because of the small amount of snow cover, most of the additional water was likely introduced through direct precipitation and runoff. Amounts of total cumulative infiltration ranged from a maximum of about 5 cm (2 inches) on the SE site to a minimum of about 2 cm (0.8 inches) on the NW site. Again, the NE site was intermediate (about 3.5 cm). These observations are consistent with the effect of microtopography on distribution of surface waters and infiltration discussed earlier as "interactive flow".

The influx of water peaked in early April (1990), and began to decline. By mid April, all had drained except for about 3.5 cm (1.4 inches) on the SE site, 4 cm (1.6 inches) on the NE site, and 5.5 cm (2.2 inches) on the NW site. Although the precipitation waters seem to have drained from the soil and vadose profile before the period of initiation of Darcian soil and vadose soil profile measurements, it is observed that the amount of combined frost upflux and precipitation water to be drained from the soil profile in mid April is about 4.3 cm (1.7 inches)(average of the remaining values cited above). This is very close (within 1 cm) to the average infiltration water increase of about 3.5 cm (1.4 inch). Thus, subsequent TFWB drainage measurements would match fairly well the amount of rainfall input in early spring and would account for them. Similarly, an amount close to the frost upflux quantity would have been fully drained before the initiation of TFWB readings.

Winter data for 1990 to 1991 also indicate two periods of water accumulation. The first period, that of frost induced upflux, occurred from late October to early March (JD 60, 1991). The maximum depth of water accumulation was 1.06 m (3.5 ft.) on all three sites. The amount of maximum cumulative upflux varies from as much as 3 cm (1.2 inches) on the SE and NE sites to a minimum of about 2 cm (0.8 inches) on the NW site. There appears to be a period of thaw, most marked on the SE site, beginning on JD 70 (1991). A single low reading for the 1.83 m layer on the NE site on JD -20 and a set of anomalous readings at JD 60 on the NW site are not understood and may be results of misreported readings. This is suspected particularly because of the similarity of measurements before and after the apparent anomaly.

The second period of water accumulation began in mid April, and corresponded to a period of precipitation. Increased soil- and vadose-profile water during the late event ranged from about 3 cm (1.2 inches) on the SE site to about 2 cm (0.8 inches) on the NE and NW sites. These increases lie within the time period of Darcian flow measurements in the soil profile, and drainage of these waters should be fully accounted for in the TFWB measurement procedure described above. As in the previous year, frost upflux was fully drained by the beginning of TFWB readings and would not effect them.

Winter conditions for 1991 to 1992 differed from previous winters, in that an early storm of large magnitude occurred in early November while the soil was unfrozen. This added a significant amount of precipitation water to the soil and vadose profiles, particularly on the SE profile, which subsequently redrained (Figure 22) almost immediately. A second major event was an unseasonable thaw that occurred in late February. The effect of this thaw in adding water to the soil profile from the surface is seen for all sites beginning at JD 60. Thaw waters from this event were fully drained before mid April (JD 105), and are thus not accounted for in TFWB measurement procedures.

The maximum depth of frost upflux was shallow, varying from 91 cm (3 ft.) to 106 cm (3.5 ft.). This is likely due to the overall mild winter, the early snow cover, and the early thaw. Measured upfluent movement of water to the frost zone (at the depth of maximum accumulation) was about 2 cm (0.8 inches) of water on all sites (accounting for the initial accumulation caused by infiltration in the early storm). Frost upflux and early melt waters were fully drained from the soil and vadose profile before the initiation of TFWB measurements in spring.

A summary of winter events, then, includes the upward flux of between 2 and 5 cm of water from the lower-vadose zone (and in some cases the upper vadose zone) to the upper-vadose and soil zone. For each of three years, the frost upflux water, or an equivalent amount of water has fully redrained by the time of the initiation of spring water balance procedures using TFWB procedures. For two of three years, drainage of spring infiltration waters through the 1.83-m (6-ft.) layer did not occur until after the initiation of TFWB procedures and would be accounted for by TFWB

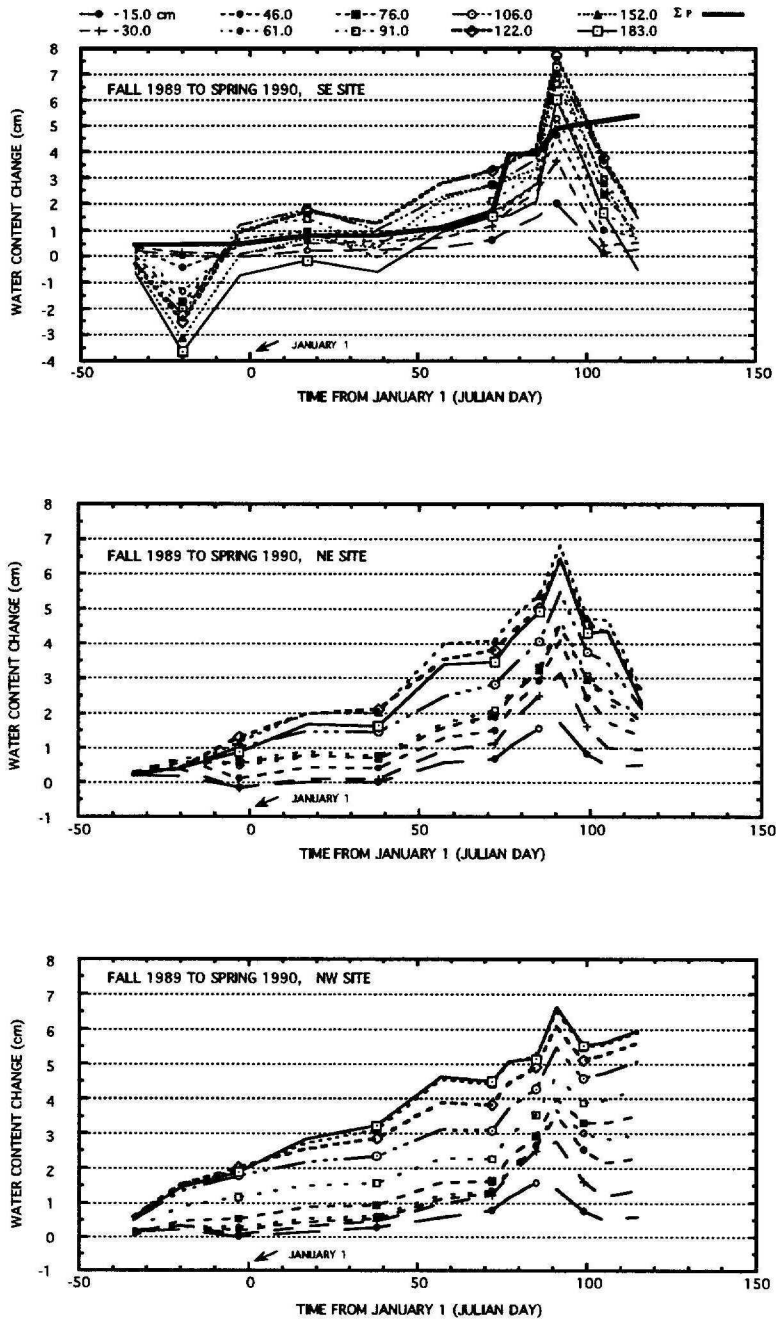


Figure 19. Soil water distribution for the winter of 1989 to 1990.

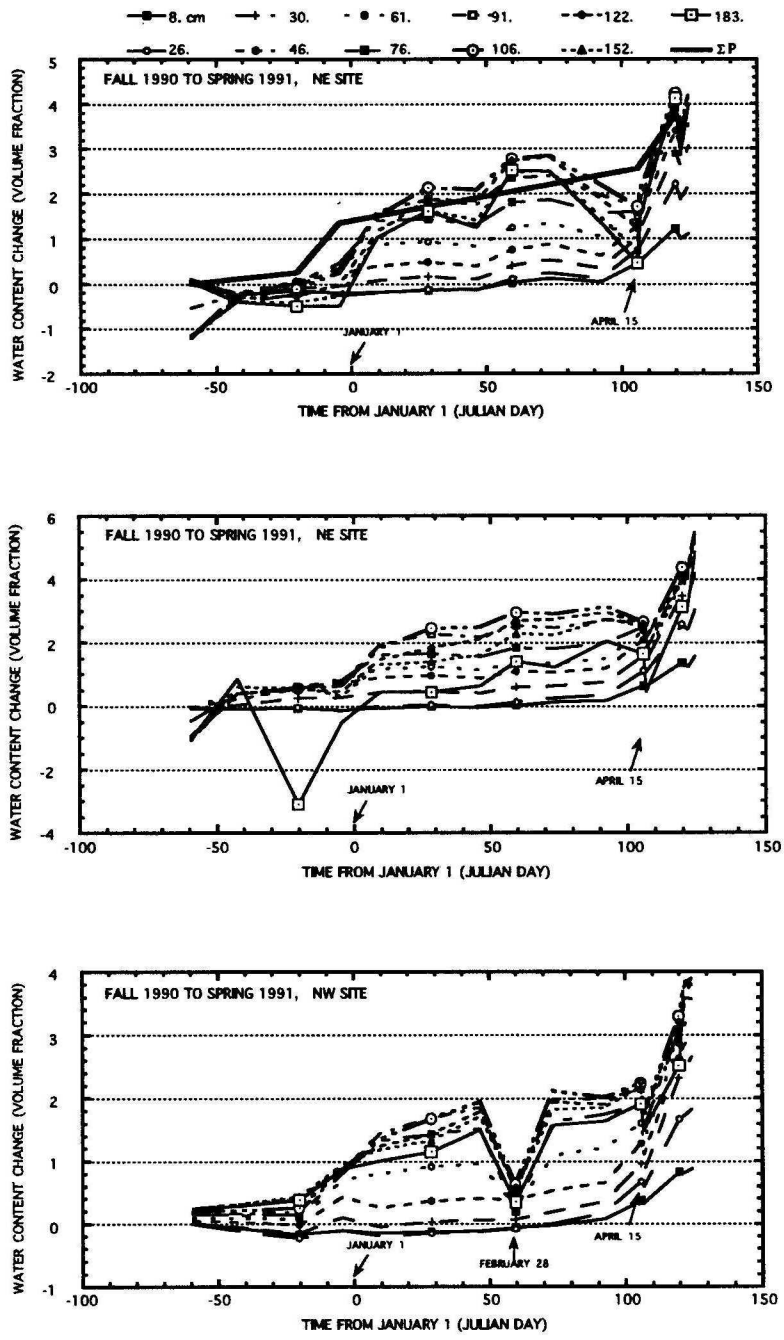


Figure 20. Soil water distribution for the winter of 1990 to 1991.

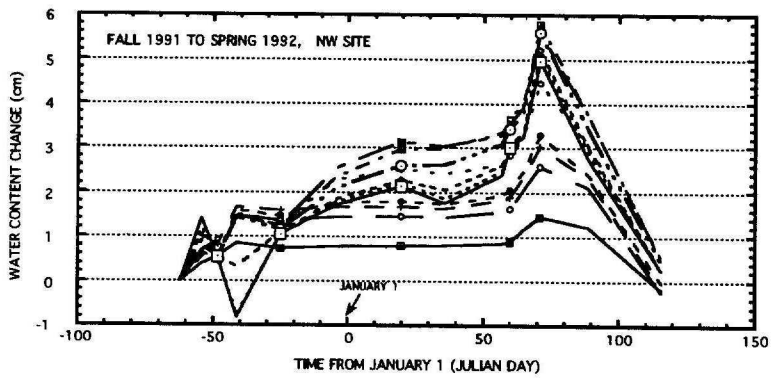
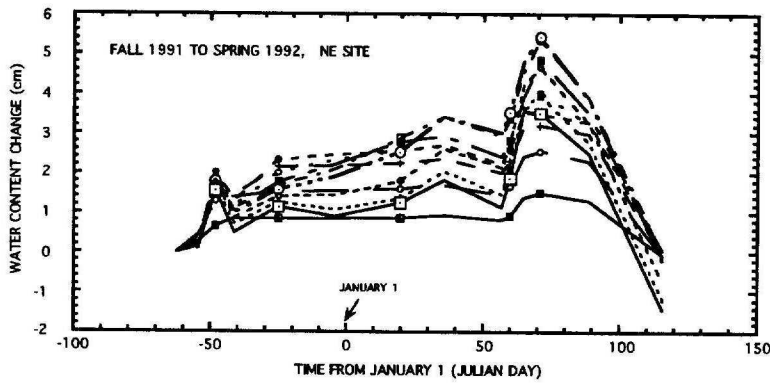
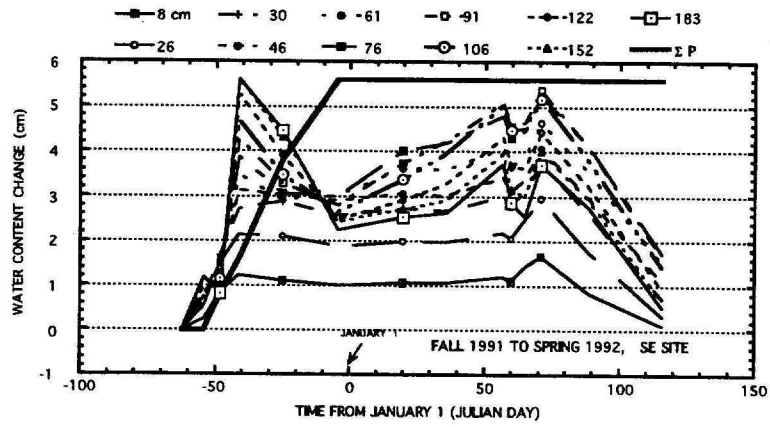


Figure 21. Soil water distribution for the winter of 1991 to 1992.

measurements. However, in 1992 an early winter storm, before the initiation of frost advance, and an early thaw event in late February resulted in substantial additions of infiltration waters that moved through 1.83-m (6-ft.) layer before the initiation of TFWB measurements, and therefore would not be accounted for in the overall water balance.

Frost Free Season

It has been shown (Schuh et al 1993a., Schuh et al. 1993b) that for a loamy glacial till overlying a water table at a depth as great as 3 to 4 m (9.8 to 13.1 ft.), the cycling of water can be extremely complex, and that a substantial amount of water passing through the soil and vadose profiles on some sites enters and redrains from below. This has been discussed briefly above as "interactive flow". Schuh et al. (1993b) developed a method for accounting for the total amount of water cycling through a soil and vadose profile, using TFWB procedures described above.

The TFWB procedure developed was found to account well for total recharge to the Carrington aquifer for 1988, 1989, and in 1990. It was also found that by using the full interactive flow accounting procedure and measuring the full cycling of water from the surface to the water table, much of the spatial variability of local recharge measurement using TFWB procedures was circumvented. Despite large variation in local drainage through the root zone, the full amounts of water cycling through each vadose and soil profile, including upward flux and redrainage from the water table, was surprisingly uniform. It appears that due to the integrating effect of water-table redistribution, the total amount of water moving the soil and vadose profile at all landscape positions on the Carrington site is similar.

The TFWB procedure used to account for the total cycling of soil- and vadose-zone water is based on accounting for redrainage of water entering from the water table, as well as water infiltration from the surface. Two simplifying assumptions of the procedure are (1) that no water passes through the frost zone during the winter, and (2) that all water cycled upward to the frost zone is fully redrained before the initiation of spring TFWB measurement methods. In the years 1988 through 1990 these assumptions held well. An analysis of winter cycling of water for 1990 was presented in the previous section.

Because the full TFWB analytical procedure is somewhat lengthy and entailed, we will not present the method fully here and will refer the reader to the method publication (Schuh et al. 1993b). However, we will summarize the findings of the 1988 through 1990 data reported by Schuh et al. (1993b) for the Carrington Site, and we will then present the conclusions of the 1991 and 1992 data.

Summary Comparison of Darcian and TFWB Estimates of Recharge to the Carrington Aquifer

TFWB and Darcian measurements of recharge to the Carrington aquifer in 1988 are shown on Figure 22, with contributions of individual TFWB components. Climatic regimes varied from year to year. 1988 was a drought year. Initial spring conditions were those of a high water table, influenced by the flooding of portions of the research site the previous fall. Piezometric readings were not initiated until mid summer. Although site data indicates that some water moved from the root zone (Figure 22), there was really no recharge originating in surface waters. Rather, water draining from the soil and vadose zones to the water table did so under the effect of capillary response to the receding water table. Observed drainage is drawdown rather than surface recharge.

For 1989 through 1992, TFWB calculations and Darcian calculations agreed well (Figures 23, 24, 25, and 26). However, in 1992, TFWB calculations beginning in April did not adequately account for recharge to the Carrington aquifer calculated using the Darcian method. The poor agreement was caused by two winter events, an early November storm before the soil was frozen, and an early thaw in late February, which resulted in surface recharge to the water table during the winter, in violation of the TFWB assumption of negligible winter flux. The amount of water entering the soil profile for each of the events was calculated, and added to the total TFWB calculation. Results (Figure 26) greatly improved agreement of the TFWB and Darcian methods. Calculated estimates of total local recharge to the Carrington aquifer for 1992 were within 3 cm (1.2 inches) between the two methods.

Quantification of Average Annual Water Budget Components;

Drainage to the water table and Carrington aquifer recharge were rather simple matters in 1988, during which all drainage was controlled by the receding water table. For other years, during which interactive flow occurred, the movement of water was more complex. Average site water budgets for each of these years (1989 through 1992) are illustrated on Figures 27 through 30. In discussion all numbers are rounded to the nearest tenth. On figures which contain computational balances, numbers are rounded to the nearest hundredth. While calculations were made to fractional levels field, methodologic, and instrumental error are sufficiently large that the reader should probably not take precision beyond the nearest cm value too seriously.

During 1989, under sunflowers, 14.9 cm (5.9 inches) of water entered the average composite site vadose and soil profile through recharge on other sites and interactive redistribution (Figure 27). Of this, 5.5 cm (2.2 inches) moved into the lower vadose zone and all but 0.4 cm (0.16 inches) subsequently redrained, 1.8 cm (0.7 inches) entered the upper vadose zone and redrained, and approximately 1.0 cm (0.4 inches) entered the soil zone and redrained. In addition, 6.7 cm (2.6 inches) of water drained to the water table through the soil (and possibly from the local surface) and 1.3 cm (0.5 inches) drained to the water table from water initially held in the upper vadose zone early

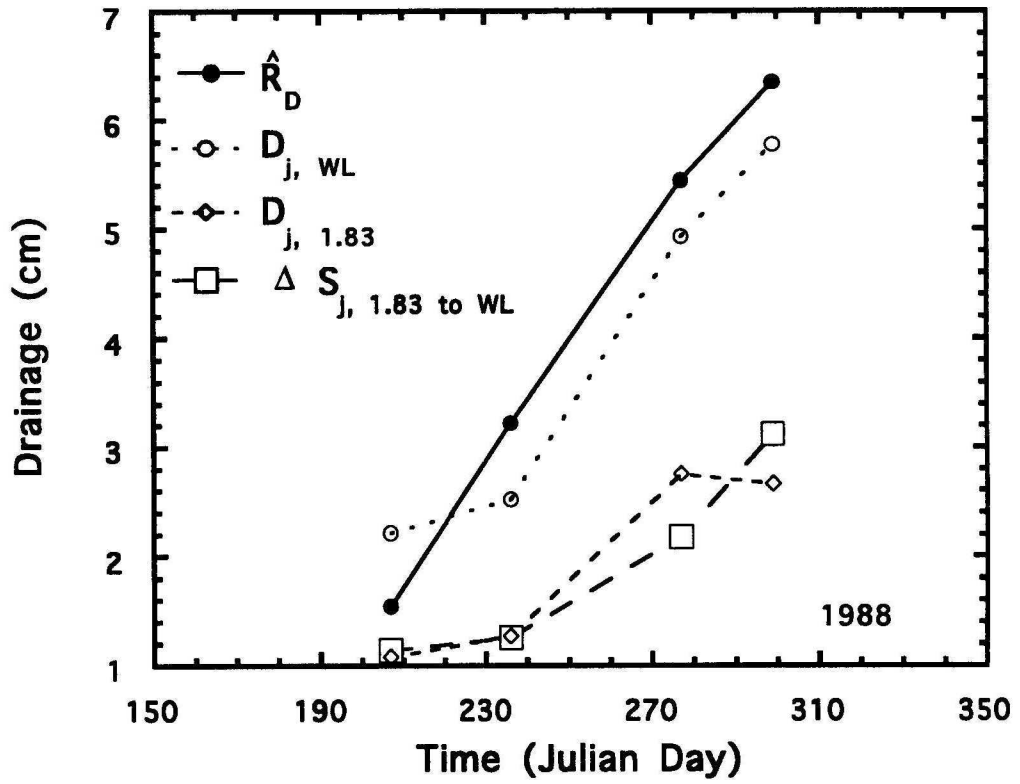


Figure 22. Summary of Darcian and TFWB estimates of recharge on the Carrington site in 1988. For homogeneous recharge $\hat{R}_j^{TFWB} = D_{j,WL}$.

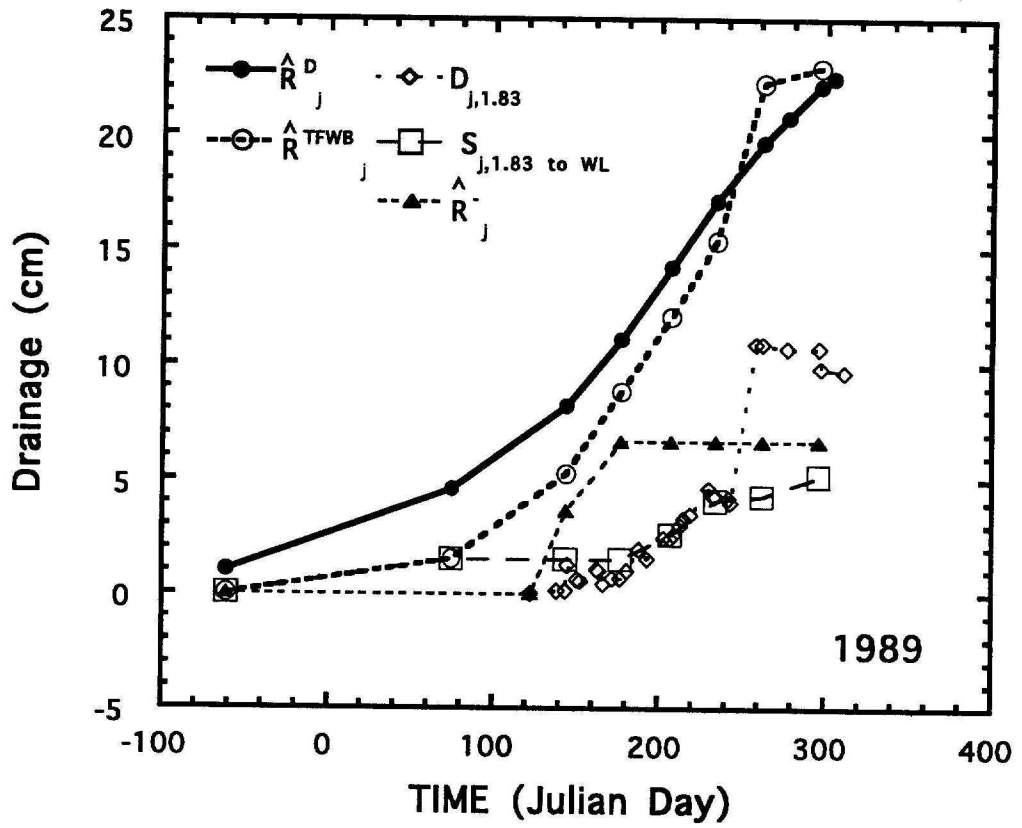


Figure 23. Summary of Darcian and TFWB estimates of recharge on the Carrington site in 1989.

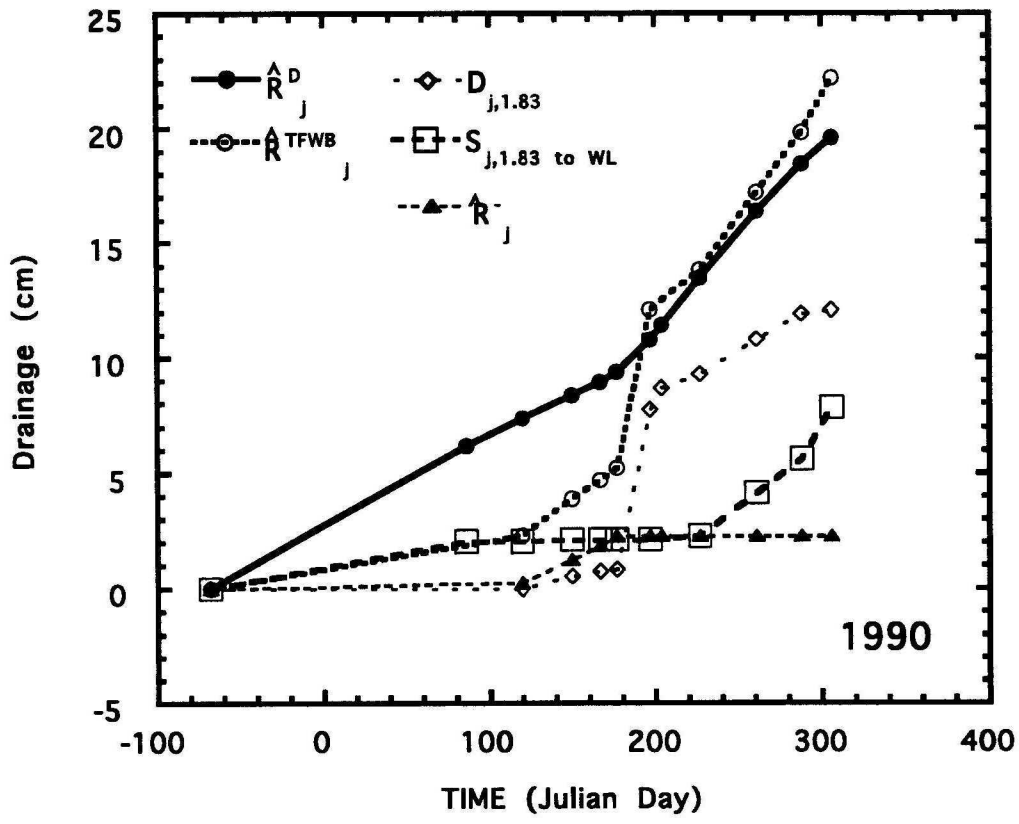


Figure 24. Summary of Darcian and TFWB estimates of recharge on the Carrington site in 1990.

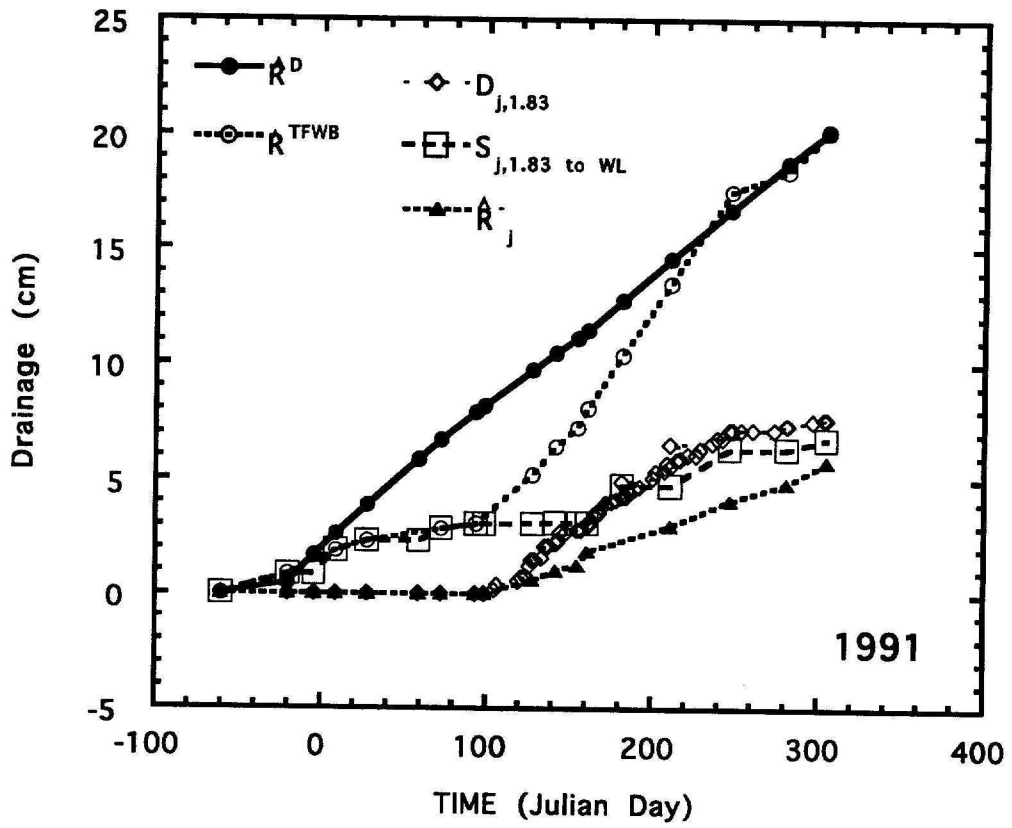


Figure 25. Summary of Darcian and TFWB estimates of recharge on the Carrington site in 1991.

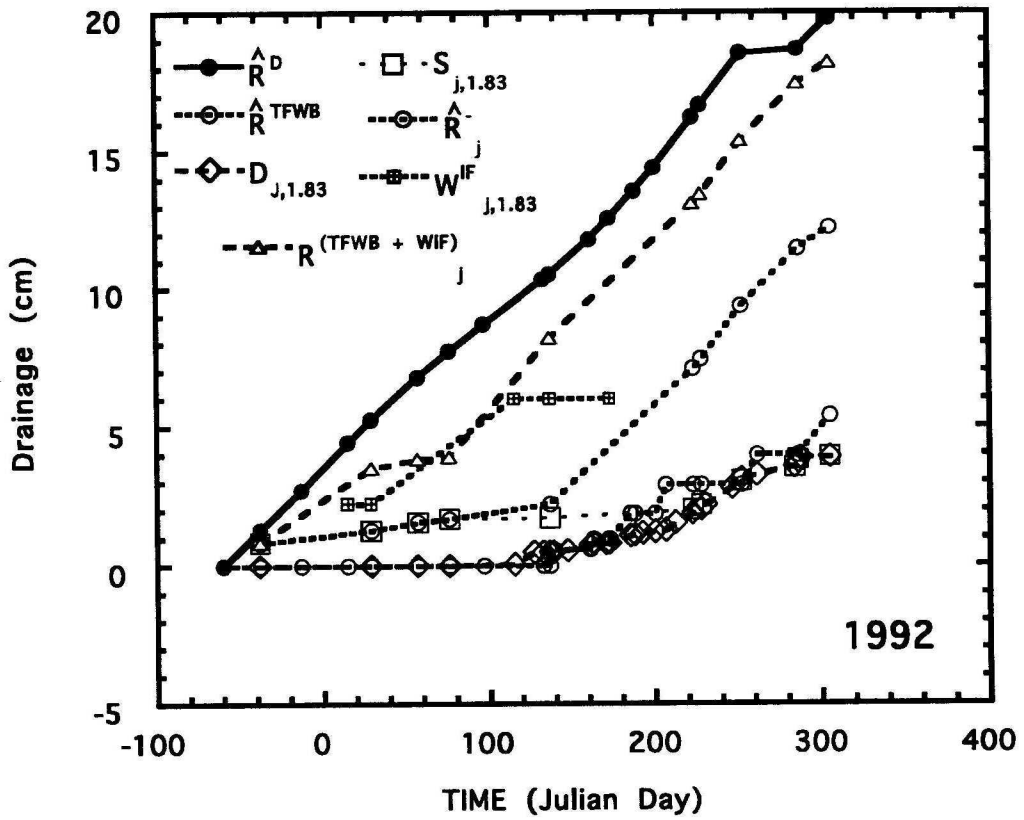


Figure 26. Summary of Darcian and TFWB estimates of recharge on the Carrington site in 1992.

in the year. 6.6 cm (2.6 inches) of the interactive flow recharged directly to the water table during the time of water table distribution, without entering the soil or vadose profile. At the end of 1989, the lower vadose profile retained 0.4 cm (0.2 inches) of the water that came from above, or of the interactive flow water that cycled through the soil and vadose profile.

For the composite site, only 30% of the water recharging the Carrington aquifer came from the local soil profile or from the soil surface, indicating that 70% of the recharge is occurring through local sites of greater activity. Some topographically determined locations for such recharge have been shown on Figure 10. Additional sites might be macropores, such as ground squirrel burrows. In 1989, the measurement pedon defined by the average of the three neutron-probe tubes on sites would be classified as a 30 % intermediate active site.

During 1990, under soybeans, a larger portion (18.8 cm or 7.4 inches) of water entered the soil and vadose profiles through interactive flow (Figure 28). Of this, 8.1 cm (3.2 inches) moved upward into the lower vadose layer, 7.31 cm moved upward into the upper vadose layer, and 1.2 cm (0.5 inches) moved upward into the soil layer. All of the water redrained, except for 0.8 cm (0.3 inches) which remained in the shallow vadose zone, and 0.2 cm (0.08 inches) which remained in the deep vadose zone. During the recharge events, 2.3 cm (0.9 inches) of interactive flow water moved directly to the water table without cycling through the soil and vadose profiles.

Only 20% of the water recharging the Carrington aquifer came from the local soil profile or from the soil surface, when considered as the average of the three measurement sites. 80% of the recharge occurred through local sites of greater activity. In 1990 the measurement pedon defined by the average of the three neutron-probe tubes on the experiment site would be classified as a 20% intermediate active site.

During 1991, under small grains, virtually all (20.9 cm or 8.2 inches) of interactive flow occurred as interactive flow. Of this 6.5 cm (2.6 inches) entered the deep vadose layer. All of this, and an additional 0.21 cm (0.1 inches) of stored water redrained from the lower vadose zone. 6.8 cm (2.7 inches) entered the shallow vadose layer and redrained, except for 0.9 cm (0.4 inches) which remained in storage. 1.8 cm (0.7 inches) of interactive water entered the surface soil and redrained (1.7 cm or 0.7 inches), except for approximately 0.13 cm (0.05 inches) which was transpired. 5.8 cm (2.3 inches) of the interactive flow water moved directly to the water table without cycling through the soil and vadose profiles. When considered as the average of the three measurement sites. 92% of the recharge occurred through local sites of greater activity. Only 8% recharged through the surface of the measured site pedon.

During 1992, under sunflowers, only 10.6 cm (4.2 inches) of total recharge occurred as interactive flow during the frost free season (Figure 30). Of this 3.5 cm (1.4 inches) entered the deep vadose zone, 2.2 cm (1 inch) entered the shallow vadose zone, and 0.5 cm (0.2 inches) reached the

root zone. All of the interactive flow water subsequently redrained. An additional 0.5 cm (0.2 inches) drained from the deep vadose layer, and an additional 1.7 cm (0.7 inches) drained from the shallow vadose zone. No water drained from the surface through the root zone. 4.4 cm (1.7 inches) of interactive water drained directly to the Carrington aquifer.

During the winter approximately 6.0 cm (2.4 inches) of water entered the soil profile during an early storm and during a February thaw event that caused flooding of the experiment site. 30% of the water recharging the Carrington aquifer came from the soil surface, when considered as the average of the three measurement sites. 53 % of the total recharge entered the measurement pedon through interactive flow, 10 % of the recharge drained to the water table from waters initially held in the vadose zone, and 7 % was unaccounted for. Although the measurement pedon would be considered a 30% intermediate active site for overall recharge, none of that surface recharge occurred during the unfrozen season of the year, so crop practice comparisons are difficult to derive from the activity level in 1992.

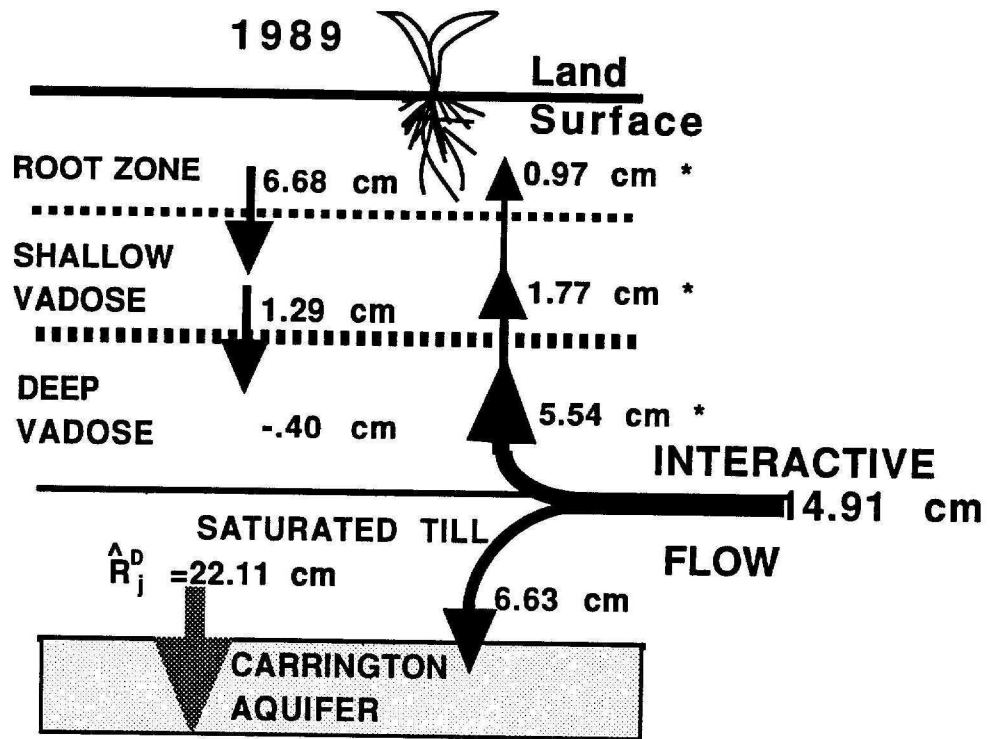
RELATIONSHIP BETWEEN SITE AND AREA HYDROLOGY

Proper interpretation of the Carrington experiment site data and application of experimental results to the broader area overlying the Carrington aquifer and other similar hydrologic settings, requires a comparison of local site conditions to those of the broader surrounding area.

Recharge to the Carrington aquifer at the experiment site is likely to be above average. The experiment site is considered to be at least a moderately active recharge area. Average measured site recharge of about 40% of average annual precipitation is well above the 2.5 to 9 % of annual precipitation measured by Rehm et al. (1982) for a fine-textured North Dakota upland site. However, the sites measured by Rehm et al. were of finer materials than the coarse-loamy materials measured on the Carrington Site.

There are additional indications that the experiment site is located in a recharge area. From the standpoint of surface infiltration the experiment site was located in an area topographic low, and in a flow-through zone to a drainage way 106 m (350 ft.) east of the site which is a tributary of Scotts Slough (Figure 4). Because of low slope, water travel for runoff is slow, allowing for enhanced recharge through local sites occupying microtopographic low elevations. Surficial features indicate that local recharge from the surface to the saturated till is likely to be above average for the area.

In addition, water-level data for the saturated till in the fall of 1988 indicate a rather steep hydraulic gradient from northeast to southwest, in the area of the experiment site (Figure 31). This gradient is almost orthogonal to the hydraulic gradient of the underlying Carrington aquifer (Figure 32). Three physical causes have been identified that may contribute to the hydraulic gradients



$$\hat{R}_i^{TFWB} = 6.68 + 0.97 + 1.77 + 1.29 + 5.54 - 0.40 + 6.63$$

$$= 22.48 \text{ cm}$$

Figure 27. Average water movement partition for the Carrington experiment site during 1989.

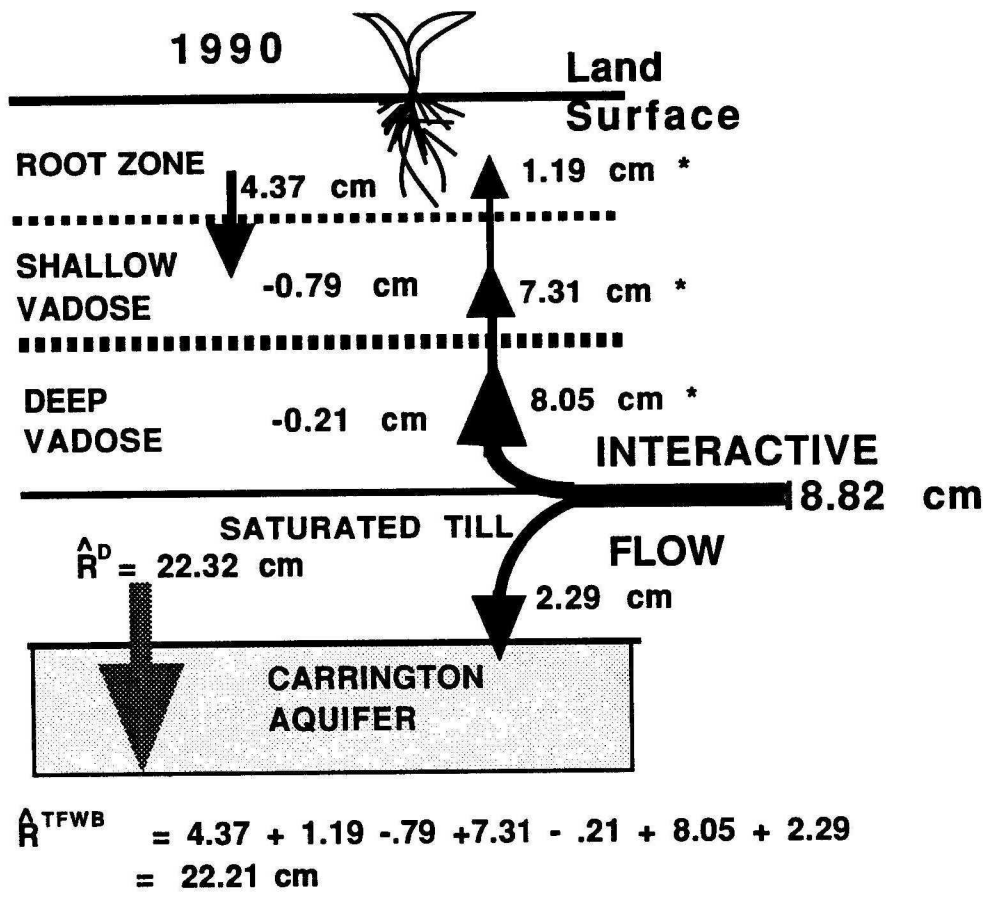


Figure 28. Average water movement partition for the Carrington experiment site during 1990.

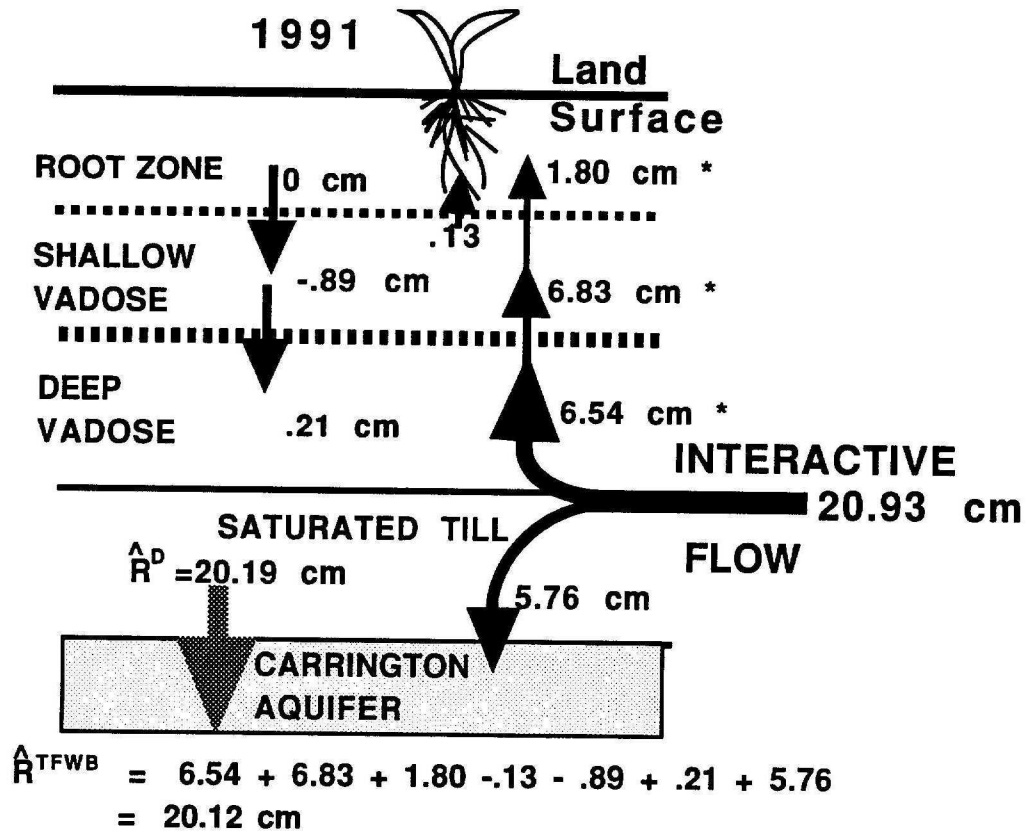


Figure 29. Average water movement partition for the Carrington experiment site during 1991.

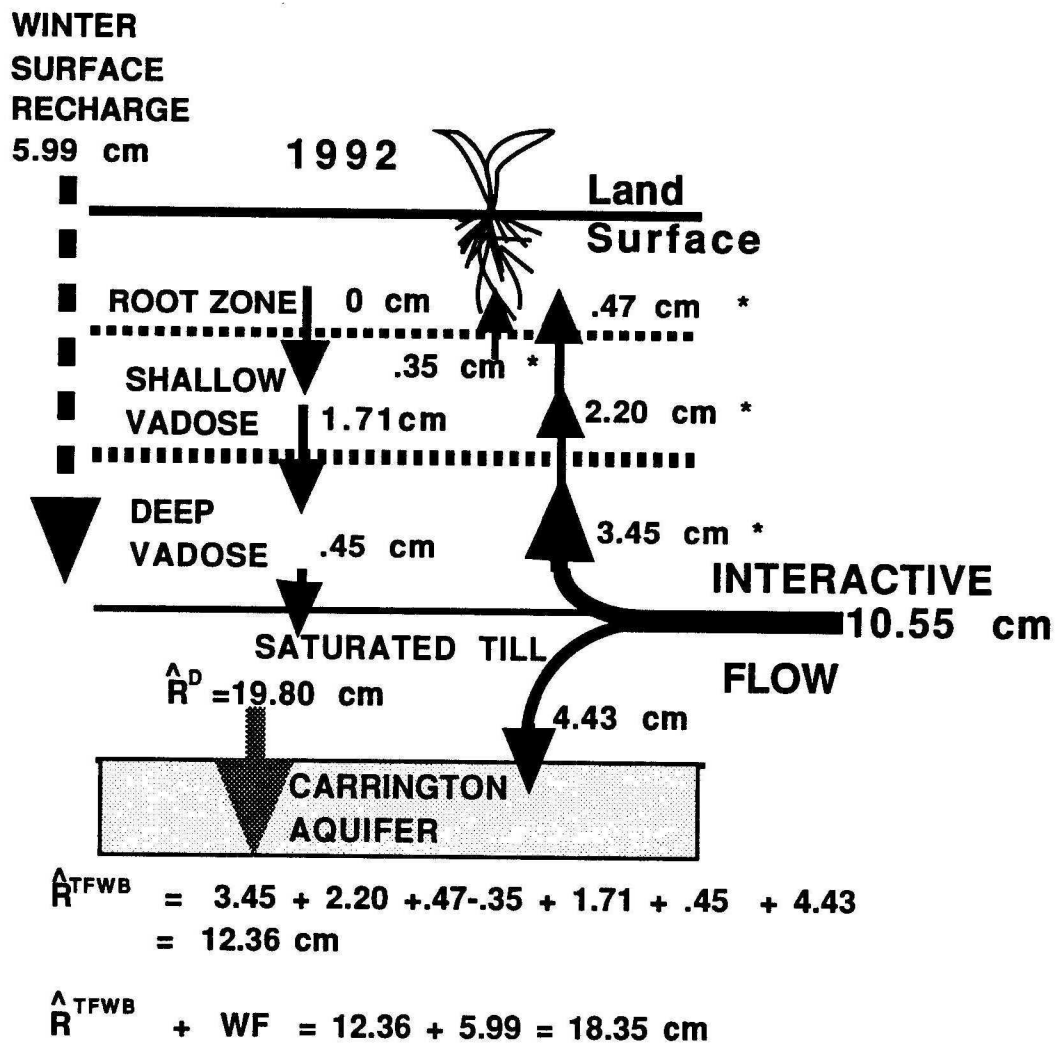


Figure 30. Average water movement partition for the Carrington experiment site during 1992.

occurring on and near section 31. First, a topographic rise northeast of section 31 likely contributes to the hydraulic gradient. The other two causes are the pumping of the aquifer for irrigation on section 31, and the thinning of the saturated till in the area of the experiment and southwest of the experiment, which enhances movement of till water to the Carrington aquifer.

The location of the irrigation pump is shown on Figure 31. Hydrologic analysis (described previously in this report) has indicated that the effect of irrigation pumping during summer is to increase the vertical hydraulic gradient between the saturated till and the aquifer by a factor of as much as four during mid summer. Both hydrologic analysis and tracer analysis have indicated that the steepening gradient increases recharge from the till to the aquifer. The experiment site, is 700 m (2,300 ft.) from the irrigation well. The hydraulic gradient and subsequent movement from the saturated till to the aquifer for the area closer to the well must be considerably larger. The horizontal ground-water gradient in the till in the northeast quarter of section 31 is toward the pumped well (Figure 31).

Local movement of water from the saturated till to the aquifer is further enhanced by the thinning of the saturated till overlying the Carrington aquifer. Till thickness (Figure 33) is less (about 22 ft., or 6.8 m) on the experiment site than for most other areas overlying the aquifer. The average overall thickness of the till is about 12 m (30 ft.) (Figure 33), and the till thickness approaches 18 m (40 ft.) in parts of the aquifer. Thus, total impedance for recharge from the soil surface is less on the Carrington site than for the aquifer in general. Generally speaking the till is thinnest where Scotts slough and appended tributaries have cut into the till. The experiment site is located near one of the tributaries.

Local topography and hydrologic data indicate that the experiment site is likely a local recharge area for the Carrington aquifer. This means that risk of ground-water contamination is likely to be higher for the measured site than for most of the area overlying the Carrington aquifer.

SUMMARY OF SITE HYDROLOGY, AND IMPLICATIONS FOR CONTAMINANT TRANSPORT TO THE WATER TABLE

The landscape position and local hydrology of the Carrington site characterize it as a recharge site. The landscape position is one of a gradually sloping, nearly level land surface which serves as an overland flow conduit for water from surrounding fields to a nearby tributary of Scotts Slough during large runoff events. However, the minimal slope also insures significant local retention time and entrapment of water within local microtopographic features, so that local recharge is enhanced. The relative thinness of the till overlying the aquifer on the experiment site minimizes total impedance of flux from the surface to the aquifer. The depth to the water table, varying from

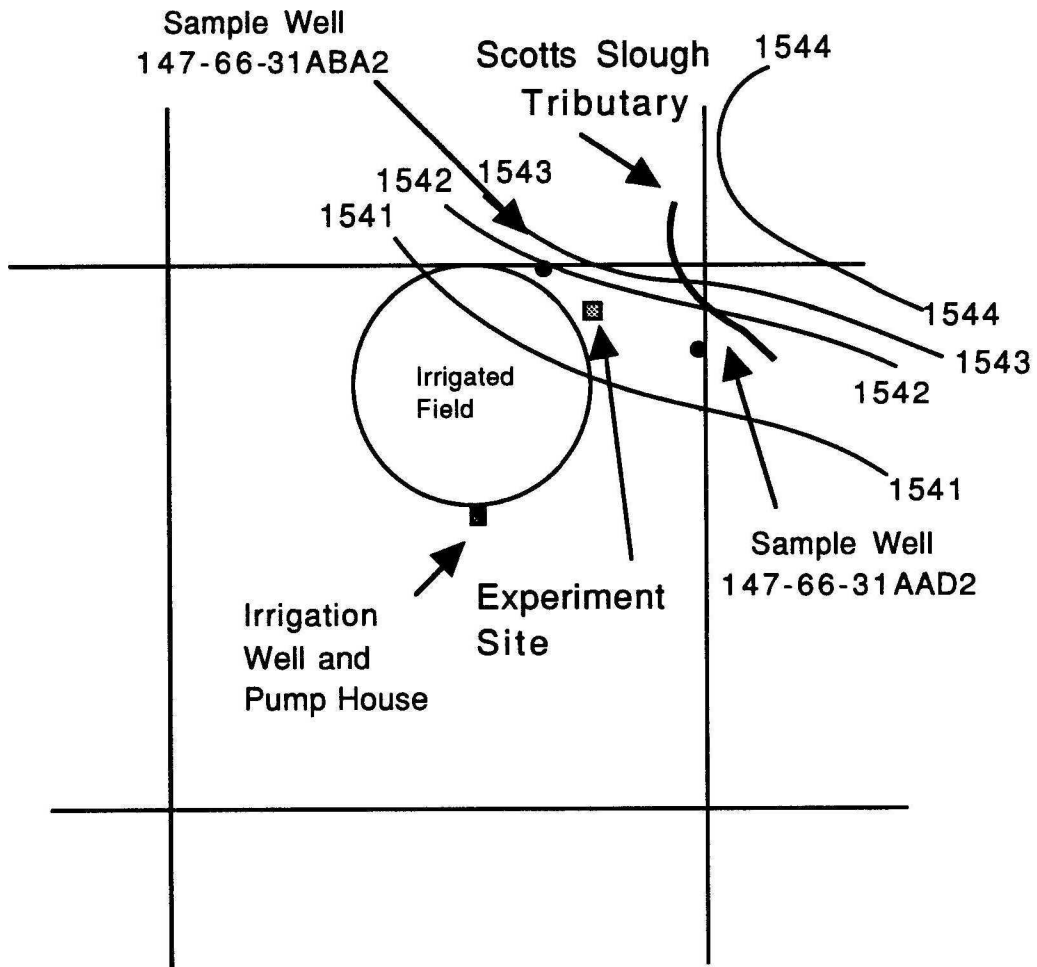


Figure 31. Piezometric head of the saturated glacial till (elevations in ft.) in November 1988.

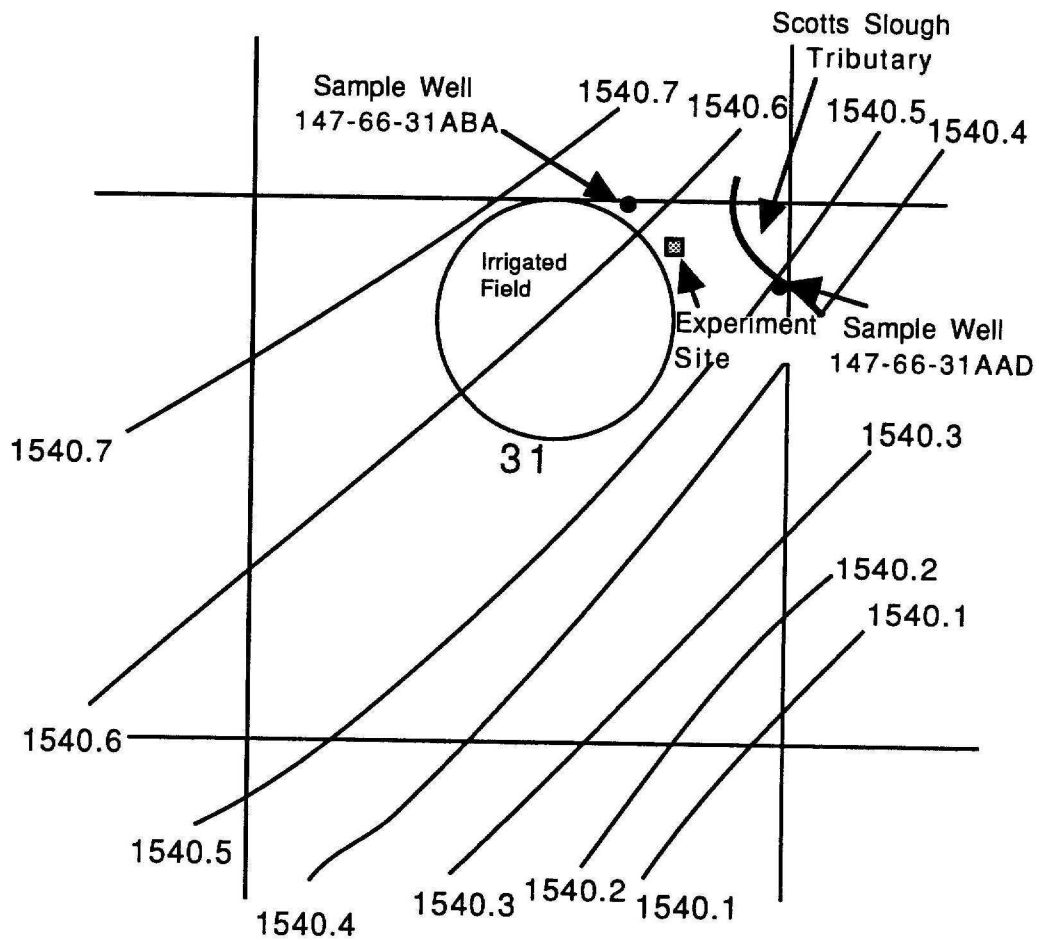


Figure 32. Map of Carrington aquifer piezometric head (elevations in ft.) in November 1988. Locations of sample wells exterior to experiment site as noted.

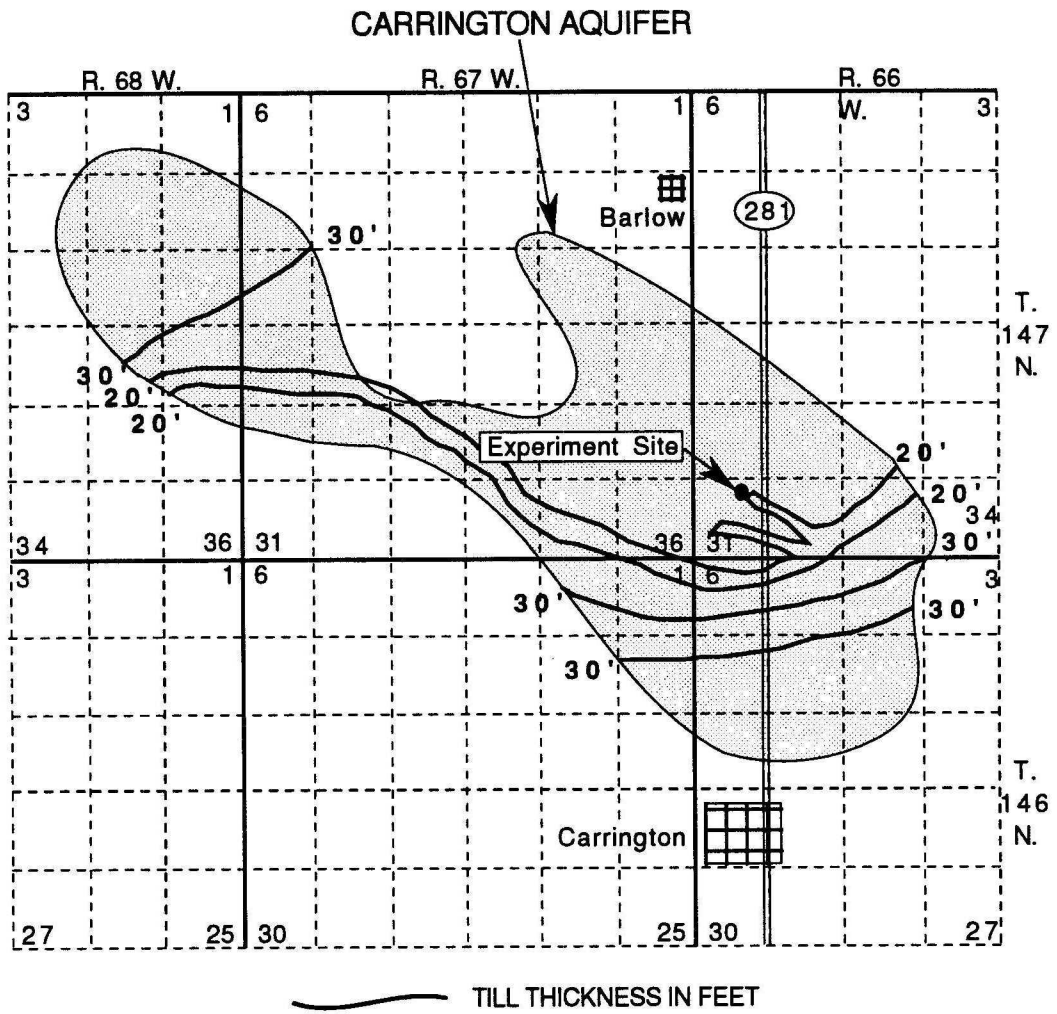


Figure 33. Thickness of the glacial till overlying the Carrington aquifer (in ft.).

approximately three to four m (9.7 to 13.1 ft.) from land surface, allows for significant capillary interaction between waters in the fluctuating water table and the upper vadose and lower soil zones. However, the water table is sufficiently deep to allow for little transpiration loss.

The flux of recharge water on the Carrington site is highly complex, owing to the dominant effects of (1) microtopography in governing recharge distribution; (2) proximity of the water table to the surface which causes secondary cycling of waters drained to the water table through the vadose and soil zones of neighboring sites (interactive flow); (3) the winter movement of water to the frost zone, and (5) summer pumping of irrigation wells which lowers the hydraulic head in the aquifer and increases the vertical hydraulic gradient from the overlying saturated till to the aquifer.

In general terms, local precipitation and runoff water from other fields during large intense rainstorms or snow melt events are redistributed locally to areas of microtopographically low elevation. Surface soil recharge status can be completely *inactive* (no movement out of the soil zone), completely locally active or *primary active* (all local cycling of water consists of downward flux through the root zone), or of *intermediate activity* (some water moving locally through the soil zone and other waters cycling through the soil and vadose profile from the water table. Land surface elevation differences of 0.4 to 0.8 inches (1 to 2 cm) have been demonstrated sufficient to govern this redistribution. On the Carrington site, the spatial distribution of surface elevation is far more influential on recharge than the spatial distribution of soil hydraulic properties.

Water moves overland to sites of increased activity, infiltrates through the surface, and drains locally to the water table. At the water table it redistributes laterally to other sites, where a portion of the laterally redistributing water drains directly to the aquifer, and a portion moves upward into the soil and vadose zone in capillary response to the rising water table. Upward capillary movement of water extends upward as far as 1.5 to 2.0 m (5 to 6.5 ft.) above the water table on the Carrington site.

The primary sink for the Carrington site recharge water is the irrigation well located approximately 700 m (2,300 ft.) southwest of the site. Decreasing pressure in the aquifer caused by irrigation contributes to a local four-fold increase in vertical hydraulic gradient between the saturated till and the Carrington aquifer in mid to late summer. This increases drawdown of saturated till water into the aquifer, and causes a commensurate drawdown of capillary water from the vadose and soil zone into the saturated till.

One additional factor of water cycling on the Carrington site is the upward movement of water from the water table and the lower vadose zone to the upper vadose and soil zones during the winter. Frost upflux is generally about 2 to 5 cm (0.4 to 2 inches) of water, with 3 cm (1.2 inches) typical. Depth of frost-zone ice accumulation varies from 1.06 m (3.5 ft.) to 1.83 m (6 ft.), but is more typically between 1.06 (3.5 ft.) and 1.5 m (5 ft.). Part, but not all of the water moving to the soil zone can be accounted for from water lost in the lower portion of the 1.06 to 1.83 m (3.5 to 6 ft.) layer in most

years. Generally, all of the frost induced upfluent water (or its equivalent) has redrafted before mid April. In most years, no significant amount of water moves through the frost zone from the surface. However, in one year (1992) an unusually warm period caused a thaw in February that caused significant local drainage to the water table from the surface.

Potential Effects of Water Cycling on Solute Transport

The complex cycling of water described above provides an equally complex regime for solute transport at the Carrington site, and may in fact provide enhanced pathways for movement. Each movement path of the water provides a means for further dissolution, mixing, and movement of contaminants. First, surface redistribution and concentration of water caused by microtopography provides a process which enhances soil contact with water and therefore increases both dissolution and movement of surface contaminants. Second, ponded water in concentrated positions (or movement through local macropores) provides enhanced contact of water with contaminants in moving through that local soil pedon. It also increases the depth of movement of dissolved contaminants. Because of local concentration of water, the likelihood of contaminants reaching the water table is greatly enhanced.

Third, horizontal redistribution of water at the water table provides a mechanism for movement of contaminants to lateral sites having less surface recharge activity, without actual local entry from the surface. Fourth, upward capillary water movement in response to water-table redistribution from highly active sites provides a mechanism for contamination of the lower vadose and soil zones on sites with limited local recharge activity. It also provides a mechanism for secondary dissolution of contaminants that might have reached the lower soil and upper vadose zones on those sites of lesser activity, but have moved no further toward the water table. Finally, enhanced recharge of the aquifer caused by increased vertical hydraulic gradients between the saturated till and the aquifer that result from pumping nearby irrigation wells, increases drawdown of the water level in the saturated till. This causes a corresponding drawdown of the capillary waters in the vadose and soil zones, and provides a mechanism for enhanced movement and mixing of contaminated waters in the soil and vadose zones to the saturated till and to the aquifer itself.

TRACERS AND NITRATE

Three tracers were used to help evaluate the relationship between the movement of water to the Carrington aquifer and the movement of solute from the surface. Tracers were used as qualitative indicators of the movement of water and of the potential maximum rate of movement of pesticides. No attempt was made at calculating a mass balance of tracers. However, the relative quantities of individual tracers at each depth was used to discern preferential flow from the bulk flow of water through the soil profile.

The applied tracers were (1) bromide (87 kg/ha), applied as potassium bromide to the soil surface on June 1, 1989; (2) fluoride (33 kg/ha), applied as sodium fluoride to the soil surface on May 22, 1990; and (3) chloride (426 kg/ha), applied as muriate of potash (potassium chloride) to the soil surface on April 18, 1991. Of these applied tracers, bromide and chloride are highly water soluble and have minimal adsorption and precipitation tendencies under normal field conditions. Fluoride is insoluble in the presence of calcium which is plentiful in the soil of the Carrington site. Moreover, sodium fluoride is hazardous until applied, and requires special precautions in application, including a respirator to avoid inhalation of the powder or concentrated solution. Fluoride was used with the expectation that it would quickly be immobilized in contact with the matrix, or in the soil solution held in smaller pores, which is saturated with respect to calcium bicarbonate. Fluoride movement was thus expected to be dependent on a relatively brief flow time through larger pores.

SAMPLE WELLS AND LYSIMETERS

Water samples were taken approximately at monthly intervals from four replicate sets of sample wells placed at three depths in the saturated till and in the Carrington aquifer, and also from ceramic lysimeters placed at 1.5 m (5 ft., just below the root zone), and at 2.1 m (7 ft.).

Sample wells were constructed of 5.1-cm (two-inch) O.D. rigid polyvinyl-chloride (PVC) casing. Well screen consisted of 0.304 m (one ft.) of 18 slot PVC well screen. All joints were secured with stainless steel screws. No solvent-weld glues were used. Screened intervals of replicate well sets were 3.2 to 3.5 m (10.5 to 11.5 ft.) and 4.3 to 4.6 m (14.4 to 15.4 ft.) in the till, and 6.7 to 7.0 m (22 to 23 ft.) in the Carrington aquifer, just below the till boundary. The 3.2- to 3.5-m (10.5- to 11-5 ft.) wells in the till were drilled using an auger. The 4.3-to -4.6 m (14.4- to 15.4 -ft.) well in the till and the well in the Carrington aquifer were drilled using a forward rotary drill. Annulus around the Carrington aquifer well casing was filled using bentonite slurry grout, and the subsidence zone after setting of the grout was filled with cuttings from the hole. The deep till well annulus was filled with cement grout. North, east, and south well set replicates (Figure 4) were used for sampling alone. An exception was

a brief period in 1989 when all wells were used for piezometric measurements to compare the consistency of water levels on site. The west set of wells was used for piezometric measurement as well as for sampling. Care was taken at all times to avoid any soil or object contact with the tape used for piezometric measurement.

Initially (fall of 1987), ceramic lysimeters consisting of extended PVC casing connected to a ceramic tip (Soil Moisture Equipment Inc., Model 1900) were placed at 30- (12-), 60- (24-), 90- (36-), and 183-cm (72-inch) depths at three sites within the plot area. These samplers were found to be inadequate because of the volume of air required for evacuation in sampling in the deeper units, and also because of the necessity to introduce tubing into the lysimeter at each sampling. Maintaining and carrying long lengths of flexible tubing, and keeping them free from contamination was extremely difficult. Finally, after a wheat leaf was found in one sampler, these were considered to be unreliable and abandoned. They were left in place and covered with rubber stoppers, to avoid disturbance of the plot area.

Three new replicate sets of lysimeters were placed at 1.5-m (5-ft.) and 2.1-m (7-ft.) depths in April of 1989. On each replicate lysimeter site (north, south, and east, Figure 4) there were two lysimeters placed at the 1.5-m (5-ft.) depth, and one at the 2.1-m (7-ft.) depth. The shallower samplers were doubled because it was considered likely that drier, and therefore slower water-yielding conditions would be more likely to prevail just below the root zone.

The new lysimeters (designed by Soil Moisture Equipment Corporation) consisted of an 20.3-cm (8-inch) length by 5-cm (2-inch) diameter 1-bar ceramic cup, closed on the top by a polytetrafluoroethylene (teflon) plug. The plug was tapped and glazed (or in some cases silicon glued) to the ceramic. No solvents or glues containing carbon compounds were used. The lysimeters were joined to 0.32-cm (1/8-inch) O.D. teflon evacuation lines by teflon pressure couplings. Teflon lines were fitted to sample containers at the surface using stainless steel pressure couplings.

The first (pilot set) of samplers was placed with Gidding hydraulic probe. All other holes for placement of lysimeters were hand augured. Before auguring, one ft. of topsoil was removed with a shovel from the area to avoid contamination through collapse of pesticide laden topsoil in the hole. A clean silica flour slurry was placed at the bottom of each hole through a tremmie pipe, and the lysimeters were placed in the slurry. About 30 cm (one ft.) of clean silica flour was placed over the top of the lysimeter. 15 cm (six inches) of bentonite pellets were placed over silica flour and wetted. Holes were then filled to the surface using cuttings taken (using a hydraulic probe) from a grass strip in a shelter belt where no pesticide applications have been made for many years. Cuttings were packed in the holes to prevent direct infiltration through the auger hole fill, and topsoil was replaced over the lysimeter area. Teflon lines were also looped in the top 6 inches to prevent direct piping along the tubing.

Stainless steel pressure couplings for lysimeters were wrapped in polyethylene bags and tied. These were placed within larger "zip-lock" bags. Finally, the entire covered bag assembly was placed within a 2-mil polyethylene bag, tied, and placed within a 5.08-cm (2-inch) PVC tube. Bags were changed frequently. Each of the sample wells was capped. However, there was a small breather hole in the cap. Two layers of polyethylene bags were placed over the top of each well and individually wrapped and tied tightly to the well stem. Bags were changed frequently, usually after each sampling. Bags were also changed immediately after each spray treatment. Later (1992) bags were replaced with a 10-cm (4-inch) PVC well casing cover which was fitted over each sample well. Well-casing covers were washed after pesticide applications.

Sample Procedures

In 1988 all samples were taken with a teflon bailer. Multiple washings with distilled water were applied between wells. Well sets were sampled sequentially. That is, Carrington aquifer wells were sampled as a group. Then deep till wells, followed by shallow till wells. In 1989 samples were taken with a PVC bailer following a similar sequence. From 1989 through 1991 separate bailers were used for deep till wells and Carrington aquifer wells. In 1990 and 1991, an additional hexane and acetone solvent rinse, followed by an additional distilled water wash was applied between wells. Finally, in 1992 new disposable teflon bailers were used for sampling each well at each time, and in addition a dedicated polyethylene bailer was left suspended in each well for purging the well before sampling. In all sampling one person (a clean worker) handled the bailers, and a utility worker did all of the peripheral work such as pouring water or uncapping wells and carrying bottles.

Before sampling five well volumes (25 to 30 bailer volumes for the Carrington aquifer) were purged before sampling. Tracer samples were stored in 500-ml polyethylene bottles. Each bottle was rinsed with distilled water or well water before adding the sample. Wherever possible bottles were filled to the top to avoid an air gap. All samples were placed in a shaded container immediately after sampling, and were refrigerated at approximately 3 degrees C within two hours of sampling. Samples were transported on ice to the North Dakota State Water Commission laboratory within 24 hours of sampling, and were there stored in a cooler for storage before laboratory determination, usually within one week of sampling. Because of the multiple anions to be determined, samples were not acidified. They were, however, kept cold. Two distilled water blank samples were prepared in the field on October 14 1992 to test for possible contamination from bottles. Blanks were treated in the same manner as field samples. Results indicated no detection's of nitrate, bromide, chloride, or fluoride.

Vadose-zone samples were taken by applying constant suction of about 800 mbar to the lysimeters using a peristaltic pump. The pump was connected to a sump and manifold consisting of a

500-ml glass Erlenmeyer flask with four teflon tubes fitted through a rubber stopper. One tube led to the pump, and the other three led to 500-ml glass sample flasks which were, in turn, connect through stainless-steel pressure couplers to the field lysimeter lines. In 1989 stainless steel couplers were cleaned with several streams of distilled water before coupling for sample extraction. Beginning in 1990 acetone and hexane washes, followed by another distilled water wash, were added to the cleaning of the couplings.

All glass flasks were cleaned in the laboratory. Cleaning included wash with low phosphate soap and tap water, followed by triple rinse with deionized water, an acetone rinse, a hexane rinse, and then drying. Teflon lines were rinsed with several vacuum drawn streams of deionized or distilled water. Stoppers and lines were fitted to the flasks in the laboratory, and all cleaned sample receivers were placed in polyethylene bags for protection from exterior contamination. Time of vacuum application varied from as little as two hours, to as much as 14 hours, depending on soil moisture conditions. Sample water was transferred from the Erlenmeyer flask to the sample bottle in the field. The lip of the Erlenmeyer flask was first rinsed with distilled water. Then the stopper was removed and the sample was poured into the receiving bottle. Because of limited water yield, there was usually an air space left with the tracer sample bottles. However, these samples were not stored for long periods.

Laboratory Procedures

During 1989 all bromide concentrations were measured in 40-ml water samples using a Corning model-250 ion analyzer and a Corning bromide ion-selective electrode. Samples were measured in the Carrington Research Extension Center laboratory within 24 hours of sampling. The electrode was calibrated before each sample set (< 20 samples per set) using 0.1-, 1-, 10-, 100-, and 1000-mg/L calibration blanks, according to the appropriate range of field sample measurements. At least one additional replication of the calibration was made for each sample set to test for repeatability and precision. In some cases multiple calibration checks were made. In addition, 22 samples (an average of 2 samples per sample set) were rerun.

Consistency and precision of calibration, as indicated by calibration reruns, varied according to the concentration value. Error at 1,000 mg/L averaged about 15% per run(10 replicates). Error at 100 mg/L averaged 4% per run (12 replicates). Error at 10 and 1 mg/L averaged 24% per run (11 and 13 replicates respectively). And error at 0.1 mg/L averaged 120 % per run. Results of average rerun determinations for field samples were within 4 % of the initial reading. While the 120 % deviation for 0.1-mg/L is high, the changes in field measurements of bromide were in orders of magnitude, so that field concentrations caused by bromide movement were large in relation to laboratory imprecisions. Thus, the results should be adequate for qualitative comparisons.

After the addition of fluoride in 1990, bromide and nitrate were determined using ion chromatography according to the EPA procedure described by Pfaff et al. (1989). Fluoride was determined for 25 ml samples using an Orion 9609-00 ion-specific fluoride electrode on a Beckman SS-2 pH meter. After the introduction of chloride tracer in 1991, chloride was also determined using ion chromatography (Pfaff et al. 1989).

TRACER AND NITRATE DETECTION AND MOVEMENT

Bromide Movement

Bromide concentrations for 1.5-m (5-ft.) and 2.1-m (7-ft.) vadose samplers and for 3.4-, and 4.5-m (11- and 15-ft.) saturated till wells, and the 6.8-m (22.5 ft.) well are shown on Figure 34. Each graph also shows a "sensitized trace" of piezometric response in the 4.5- and 6.8-m wells for comparison with bromide concentrations peaks. Sensitized traces (T_s) are dimensionless graphs of data transformed to enhance visual definition of piezometric response. They are calculated using a formula of the type

$$T_s = \frac{(h - C)}{(h_i - C)} \quad (13)$$

where h is water level elevation, h_i is the water level elevation at the initiation of the experiment, and C is a constant selected to enhance the visual recognition of changes in water level. T_s has no quantitative meaning. It serves only to assist in visual detection of relative response. A summary of absolute piezometer levels is shown on Figure 35. **The time scale used for all tracer and pesticide data is "experiment day" (Labeled ED), which is the time in days from the initiation of the experiment on January 1, 1988.**

All peaks of bromide concentrations (Figure 34) corresponded to periods of water table recharge, as shown on the experiment site hydrograph (Figure 35), and the amplitude of bromide spikes is frequently related to the amplitude of recharge to the saturated till. The two vadose samplers and the shallow (3.4-m) till well (Figure 33 A, B, and C) exhibited clear and distinct concentration maxima on July 25, 1989 (ED 571 from January 1, 1988) which corresponds precisely to the recharge peak maximum in the saturated till measured at 4.5 m. The peak concentration of bromide at all three levels is also similar (about 0.3 to 0.5 mg/L). In the deeper saturated till (4.5 m, Figure 34D) and in the Carrington aquifer (6.8 m, Figure 34E), peak concentrations were slightly lower (0.1 to 0.3 mg/L), and persisted and fluctuated for a more extended period, to approximate ED 700. Moreover, bromide levels in the Carrington aquifer exhibited a second peak on all replicates, which began at about ED 625 and extended to near ED 700. The beginning of the second bromide

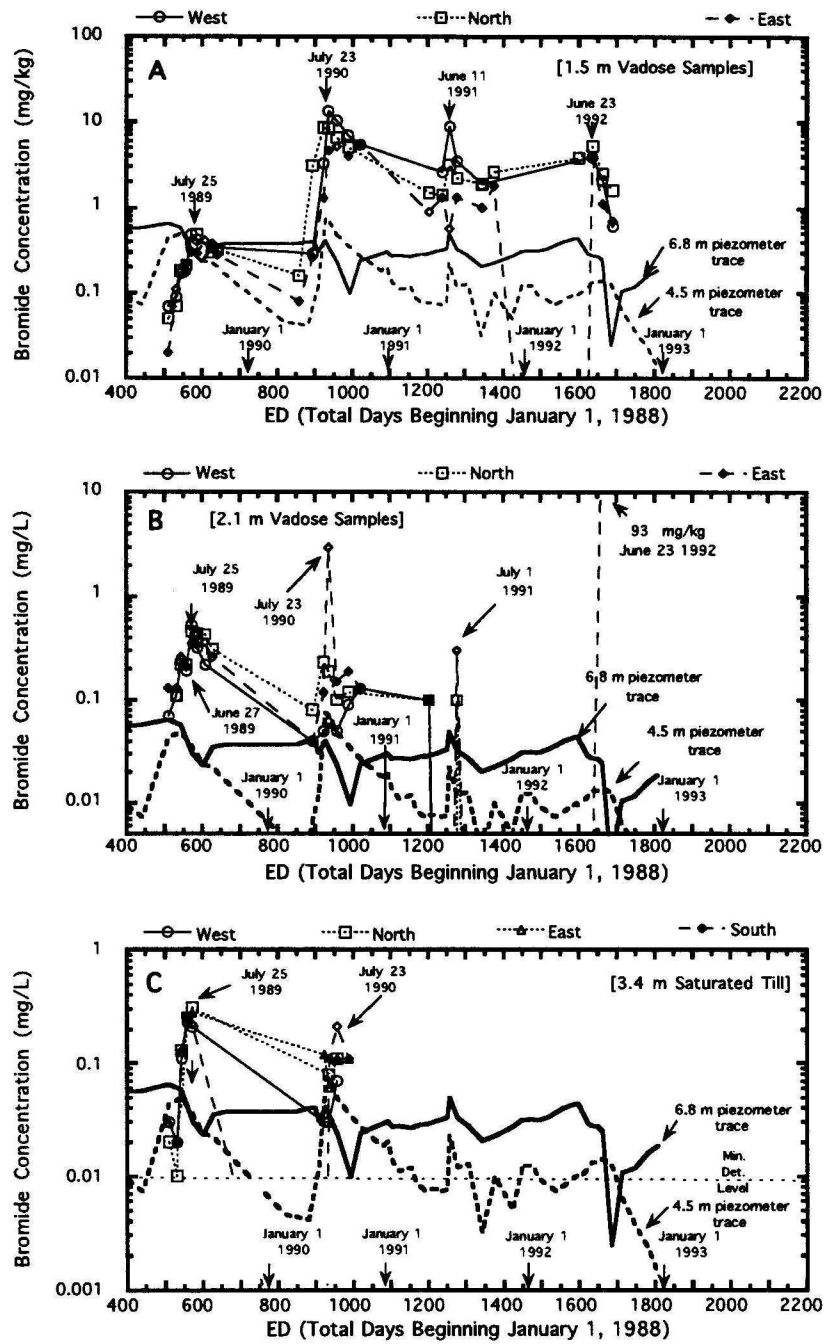


Figure 34. Bromide concentrations for water samples from A. 1.5-m (5-ft.) and B. 2.1-m (7-ft.) vadose samplers; and from C. the shallow (3.4-m or 11-ft.) and D. deep (4.5-m or 15-ft.) saturated till wells, and E. the Carrington aquifer (6.8-m or 22.5-ft.) sample wells. (Continue on next page.)

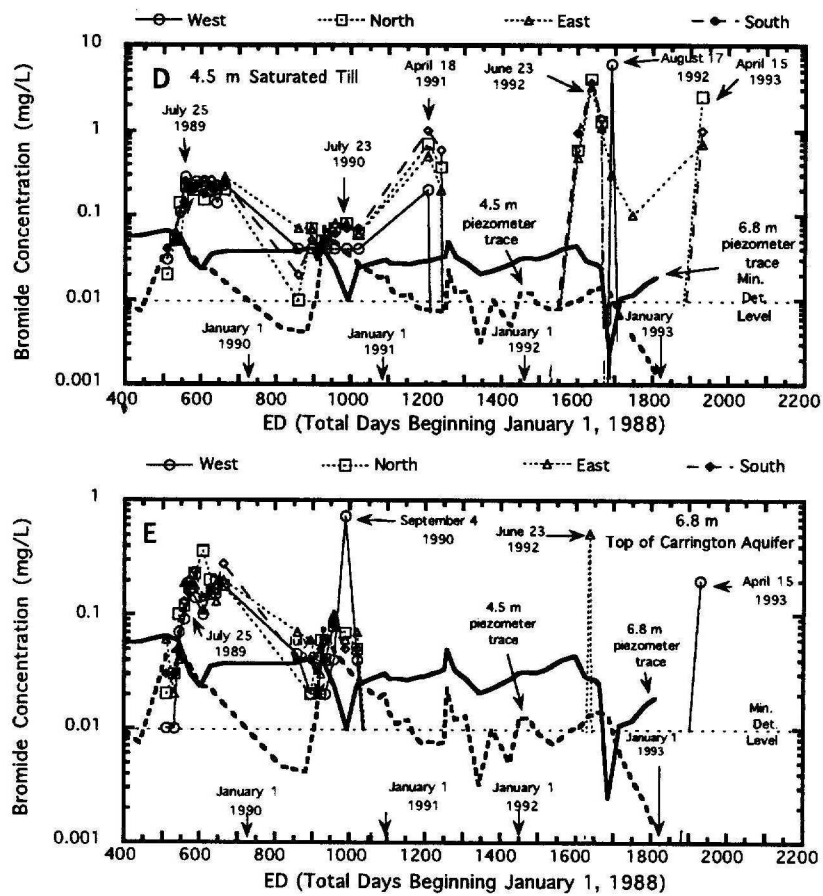


Figure 34. (Continued) Bromide concentrations for water samples from A. 1.5-m (5-ft.) and B. 2.1-m (7-ft.) vadose samplers; and from C. the shallow (3.4-m or 11-ft.) and D. deep (4.5-m or 15-ft.) saturated till wells, and E. the Carrington aquifer (6.8-m or 22.5-ft.) sample wells.

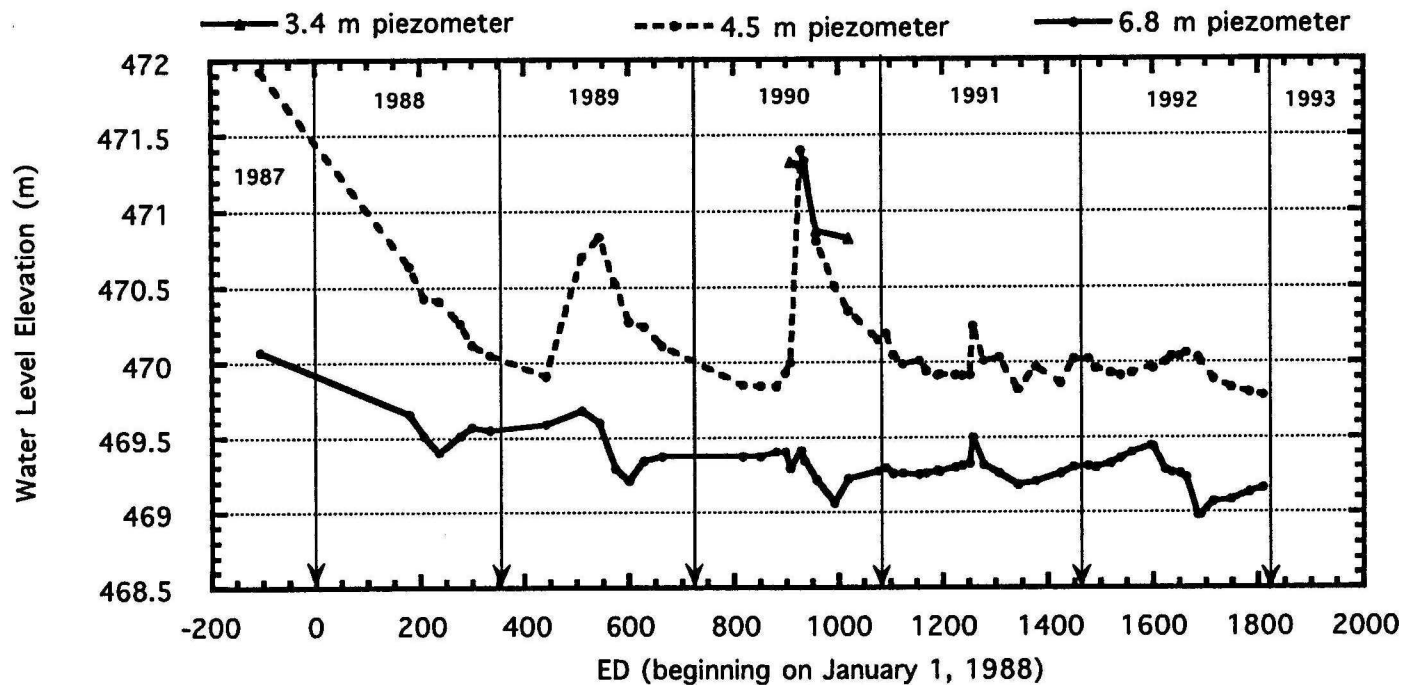


Figure 35. Water levels for the shallow till at 3.3 m (11 ft.) and 4.5 m (5 ft.), and for the top of the Carrington aquifer at 6.8 m (22.5 ft.).

peak in the Carrington aquifer corresponded to the end of the period of maximum drawdown of the Carrington aquifer in response to irrigation pumping.

The lower concentration values in the deep vadose and Carrington aquifer wells can likely be explained by dilution alone, as the saturated zone contains more water than the vadose zone for mixing. For example, the average saturated water content is about 35% of total volume, while the average in situ field capacity volumetric water content is about 17% of total volume. If the saturated till is at field capacity and yields water having a bromide concentration of 0.3, then the total concentration adjustment for full saturation is $17\% / 35\% \times 0.3 \text{ mg/L} = 0.15 \text{ mg/L}$. A similar calculation for a vadose water bromide concentration of 0.5 mg/L is 0.25 mg/L. These calculations are within the range of the concentrations measured for the Carrington aquifer (0.1 to 0.3 mg/L).

The difference between distinct and single bromide concentration peaks in the vadose zone, and extended bromide concentration peaks in the deep till and aquifer is consistent with the previously described recharge hydrology of the Carrington site. Hydrologic data indicate that recharge from the saturated till to the Carrington aquifer increases seasonally by a factor as large as four in response to the pumping of the aquifer. This, in turn, causes a drawdown of the saturated till which further draws capillary water from the vadose zone as it recedes. A first detection concentration peak corresponding to the peak of water table recharge, and an extended fluctuation continuing into the period of maximum aquifer pressure drawdown, illustrate the importance of well pumping in drawing water from the saturated till to the aquifer. It also provides evidence of the importance of well influence in drawing water from the vadose zone to the saturated till, in capillary response to recharge of the till water to the aquifer. The result is an extended period of enhanced mixing and movement of till water and aquifer water.

A similar phenomenon occurred in 1990, when distinct single peaks of bromide were observed on July 23 (experiment ED 934) for the shallow and deep vadose zone, and for the shallow saturated till. These peaks corresponded to the period of maximum recharge for the saturated till. However, deep saturated till and Carrington aquifer profiles indicated an extended and later peak bromide concentration for 1990 (between ED 950 and 1000) which corresponded to the period of pressure drawdown in the Carrington aquifer. Again, the role of drawdown from pumping in mixing and drawing solute into the aquifer is indicated.

In 1991 a slight pulse of bromide was observed at the 1.5-m (5 ft.) vadose level on June 11 (ED 1257) corresponding to a slight pulse of recharge to both the saturated till and the Carrington aquifer (Figure 34). The maximum bromide concentration in the deep vadose layer occurred about 20 days later (ED 1277). The shallow sample well was dry in 1991. An early pulse of bromide detected on April 18 in the deep saturated till cannot be explained by recharge indicators at the water table or pumping of the aquifer, but may be related to redrainage of waters that had moved upward to

the freezing front during the winter. However in this case, where there was minimal pressure drawdown in the Carrington aquifer, there were no detections in the Carrington aquifer itself, and there was no late summer addition to the deep saturated till. **The absence of solute detections in the absence of significant pressure drawdown further supports the hypothesis that aquifer pumping strongly influences movement of solute-laden water from the vadose zone to the saturated till, and from the saturated till to the aquifer itself.**

The significance of the 1991 anomaly is further illustrated by the return of the typical solute movement pattern in 1992. On June 23 (ED 1634) a small increase in bromide was detected at the 1.5-m (5-ft.) level, corresponding to a period of rising piezometer in the deep saturated till. There was no evidence of a similar pulse at the 2.1-m (7-ft.) level, and no samples were taken from the shallow till well which remained dry. However the deep saturated till exhibited a double concentration pulse at different sites, with three of the wells registering a pulse peaking on ED 1634, corresponding to the shallow vadose rise, and one of the wells registering a pulse on August 17 (ED 1690) which corresponded to the time of peak pressure drawdown in the Carrington aquifer. One pulse of bromide was also detected in the Carrington aquifer on June 23 (ED 1634), corresponding to a time of rising till and falling aquifer piezometric levels. **The return of characteristic bromide concentration pulses with the resumption of aquifer drawdown in response to pumping, after a hiatus of bromide detections in the aquifer in 1991, supports the previously described hypothesis that hydrologic interaction between the vadose zone water, the saturated till water, and the aquifer water in response to well field use, as a mechanism of solute mixing and transfer.**

Several other characteristics of bromide movement are important in describing the nature of water and solute movement on the Carrington site. First, increases in bromide occurred at virtually all levels of the vadose and saturated zones and in the aquifer, almost immediately after application on June 1, 1989. This occurred in response to a 1.8-cm (0.8 inch) precipitation event that occurred on June 11 through 13 (ED 527 through 531). **Detection of bromide at all levels indicates that there on the Carrington site are mechanisms for relatively rapid movement of soluble surface contaminants to virtually all till levels and to the surface of the aquifer. This finding is consistent with hydrologic determinations which indicated that preferential flow through "primary active" and "intermediate active" recharge sites occurred on the Carrington site. In analysis of site hydrology, activity was found to have been caused primarily by microtopographic redistribution and concentration of water on the surface, but it may have been enhanced as well by macropores such as gopher burrows that were common on the experimental site.**

Second, water-level data for 1989 indicates that recharge to the saturated till began to occur at least as early as May 15 (ED 500) and possibly earlier, which preceded the application of the

bromide tracer and the June 11 through 13 precipitation event. Because rising water levels measured were caused initially by a pulse of spring recharge water which had been moving through the vadose zone, detection of **bromide soon after the storm provides evidence that movement of bromide occurred as a coupled process involving preferential-flow water from the storm which "caught up with" and later moved with the predominant pulse of recharge waters to the saturated till and to the aquifer.**

Third, there appears to be a clearly defined difference in bromide concentrations between waters that had received initial bromide spikes through preferential flow, and waters which were characterized by bulk Darcian flow from the surface, and which later moved downward as a plume. In 1989, all sample levels were characterized by dilute maximum concentrations (approximately 0.5 mg/L) of bromide. A slight difference in bromide concentrations between shallower and deeper levels appeared to be caused by differences in water-filled porosity between the saturated and unsaturated zones, and could be attributed to dilution alone. However, beginning the following year (1990) bromide concentrations in the vadose zone reached a peak of 10 mg/L (almost two orders of magnitude larger than previous measured concentrations). Similar increased concentrations did not occur beneath the vadose zone. This further supports the hypothesis of preferential flow as the predominant mechanism of movement for bromide during the year of application.

While fluctuations of bromide concentrations in the vadose zone continued after 1990, concentrations continued to cycle in a range between 1 and 10 mg/L for three field measurement seasons, indicating that a bulk flow concentration of bromide had passed the root zone by the year following application, but that it had a tendency to remain in that zone. Site hydrologic evaluation indicates that periodic bromide losses at the 1.5-m (5-ft.) level were most likely caused by leaching, and not by evaporative upflux (there was little evidence of evaporative upflux below 1-m (3 ft.) during the measurement period).

The deep vadose layer at 2.1 m (7 ft.) exhibited a large bromide concentration (similar to the 1.5-m [5-ft.] level) only at the east replicate and for only one measurement. The larger bulk bromide concentration seems to have never reached the 2.1-m (7-ft.) layer, and concentrations seem to have trended downward in years following application. Similarly, the shallow till well did not indicate concentrations of bromide characteristic of the bulk flow concentration in the final measurements in 1990. In 1992, however, there is evidence of deeper penetration of the larger "bulk flow" concentration of bromide. During the summer of 1992 peak concentrations at all four deep till (4.5-m or 15-ft) sites fell within the 4- to 10-mg/L range, indicating that the bulk concentration of solute had likely reached the saturated till. Moreover, a single elevated detection at about one order of magnitude lower concentration from the east site of the Carrington aquifer, provides further evidence of that a feeder source in the overlying till water was present at that time.

In summary, (1) the correspondence of vadose-zone bromide detections with periods of piezometric response in the saturated till; and (2) the prolonged and multiple bromide concentration peaks and correspondence of peaks in the saturated till and in the Carrington aquifer corresponding to the pressure drawdown of the aquifer and rising water levels in the saturated till; indicate that movement of solute to the Carrington aquifer, and also to the saturated till is strongly influenced by the pumping of the aquifer and its effects on hydraulic gradients in the recharge zone. Absence of bromide movement to the aquifer when pump-pressure drawdown is not observed further confirms the importance of vertical hydraulic gradients between the till and the aquifer in enhancing movement of solute from the soil zone to the aquifer.

Following an early rainstorm, preferential flow caused movement of bromide to all sampled levels of the soil, the vadose zone, the saturated till, and the surface of the aquifer in dilute concentrations. Concentrations were approximately two orders of magnitude lower than the concentration of the bulk flow of bromide-laden water. The movement of bromide included preferential flow following a surface storm, coupled with a deeper moving pulse of spring recharge water. The main concentration of bromide moved through the root zone the year following application and remained approximately constant in that zone. By 1992 a pulse of bromide similar in concentration to the upper vadose-zone bromide concentration reached the deep saturated till for a brief period and then declined.

Fluoride Movement

Generally, fluoride background concentrations at the 1.5-m (5-ft.) level were between 1 and 2 mg/L and varied little (Figure 36 A and B). At the 2.1-m (7 ft.) depth initial concentrations were about 0.3 to 0.5 mg/L, and intermittently reached levels as high as 2 mg/L before declining. A similar initial concentration (about 0.2 to 0.5 mg/L) was found in the shallow saturated till well, the deep saturated till well (about 0.1 to 0.5 mg/L), and the Carrington aquifer (about 0.2 to 0.3 mg/L). Intermittent peaks and fluctuations were similar to those of bromide. **As with bromide, concentration peaks are single and distinct in the vadose zone at 2.1 m (7 ft.), and are more diffuse and prolonged in the deep saturated till and in the Carrington aquifer. Concentration peaks follow closely those of bromide, and support the previous analysis of water movement based on hydrologic and bromide analysis.**

Increased fluoride concentrations in vadose samples taken on July 23 1990 (ED 934) are particularly clear at 2.1 m (7 ft.), and are best defined on the east replicate site. This corresponds to the vadose bromide peaks for 1990, and follows two large rainfall events on ED 883 and ED 909. A similar, but slightly delayed (August 14, 1990, ED 957) concentration peak was observed in the west

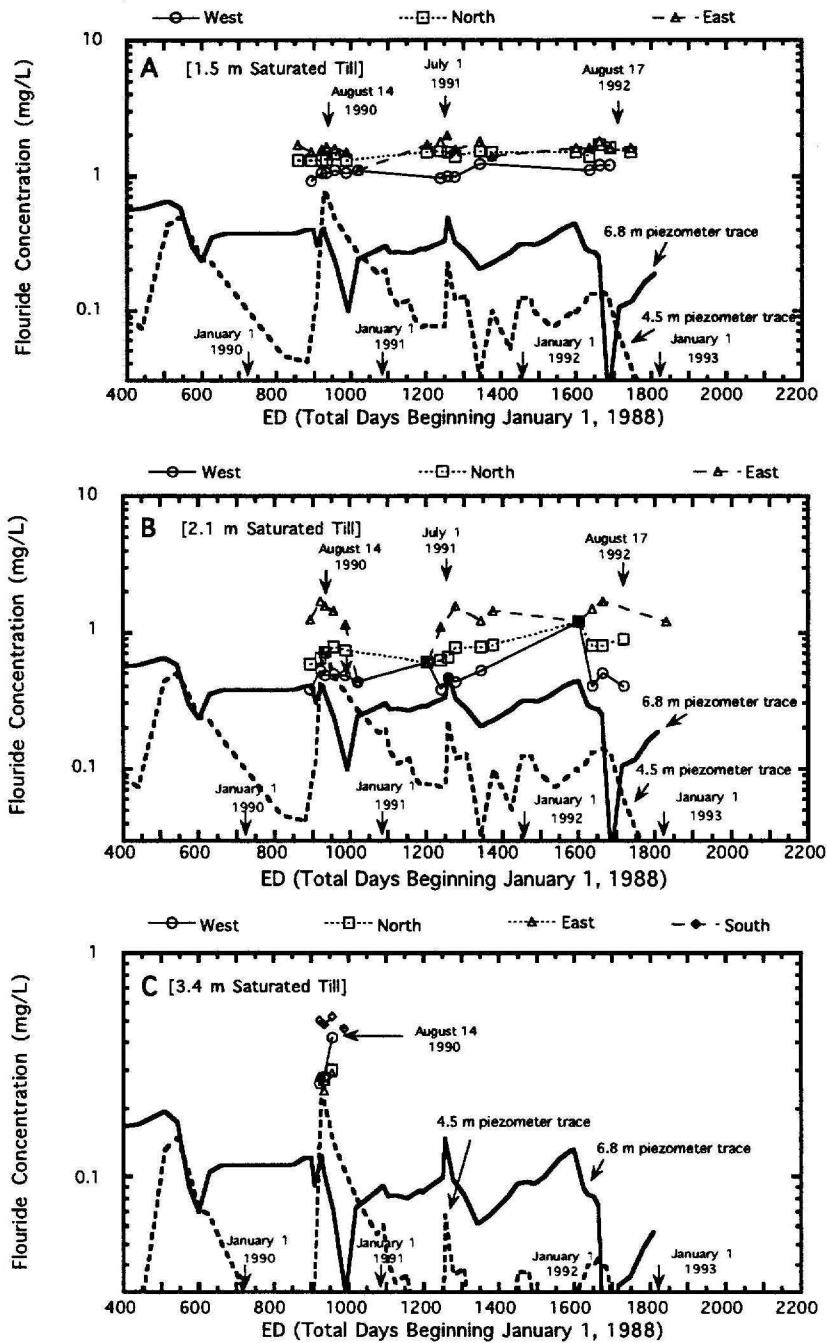


Figure 36 Fluoride concentrations for water samples from A. 1.5-m (5 ft.) and B. 2.1-m (7 ft.) vadose samplers; and from C. the shallow (3.4-m or 11-ft.) and D. deep (4.5-m or 15-ft.) saturated till wells, and E. the Carrington aquifer (6.8-m or 22-ft.) sample wells. (Continued on next page.)

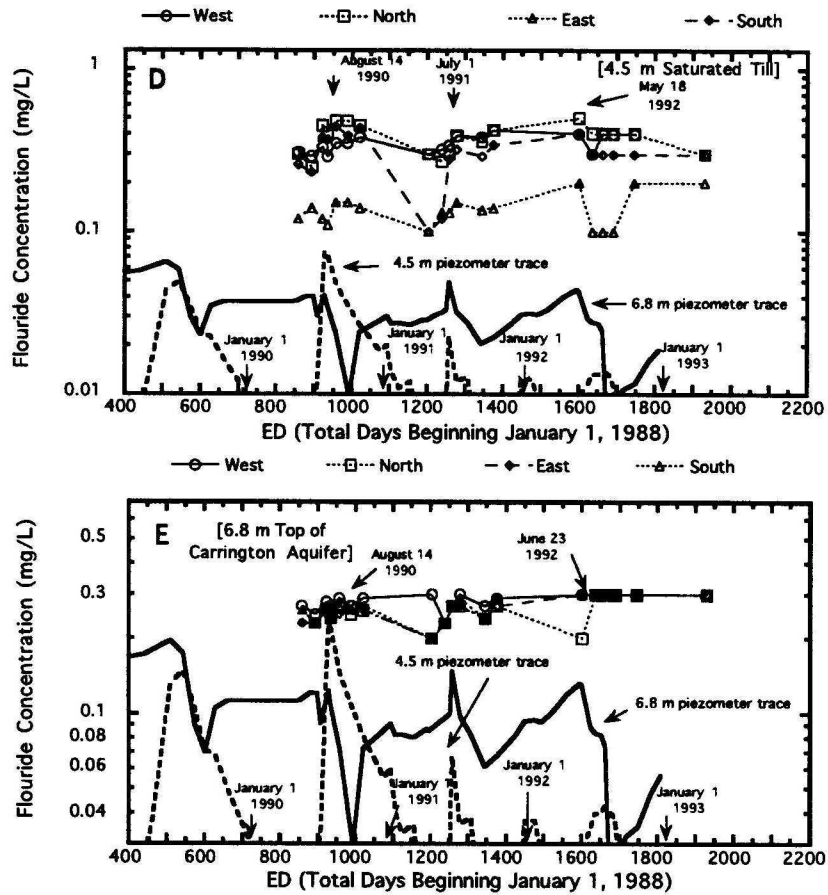


Figure 36 (Continued) Fluoride concentrations for water samples from A. 1.5-m (5-ft.) and B. 2.1-m (7-ft.) vadose samplers; and from C. the shallow (3.4-m or 11-ft.) and D. deep (4.5-m or 15-ft.) saturated till wells, and E. the Carrington aquifer (6.8-m or 22-ft.) sample wells.

and south replicates of the shallow saturated till. At 2.1 m (7 ft.) another fluoride concentration peak occurred in the east lysimeters on July 1 of 1991 (ED 1278), which corresponded to the bromide peak on the 2.1 m (7 ft.) site. This fluoride concentration peak also corresponded to a series of large rainfall events (Figure 17) between ED 1220 and ED 1295. In 1992 a fluoride concentration peak at 2.1 m (7 ft.) corresponded to a time period with a succession of moderate precipitation events between ED 1650 and ED 1690. Increases in fluoride concentration were only slightly discernible at the 1.5 m (5 ft.) level.

Increases of fluoride in the deep till well (Figure 36D) on July 1 1991 ED 1278), were most clearly indicated on the south and east well sets, and corresponded to a bromide peak at the 2.1 m (7 ft.) level. Strongest detection at the south and east sites is consistent with the map of surface water disposition following a large rain storm which indicated that east and south well sites were more active than north and west well sites for local infiltration of surface water. For the most part, fluoride concentrations in the till water did not change by a large margin. Fluoride concentrations at the top of the Carrington aquifer indicate a single large increase on the west well site on June 11, 1991 (ED 1257). While this single large increase may be spurious, there is a discernible corresponding upward trend at all well sites, and on the same date bromide at the 1.5 m (5 ft.) level increased on all sites (Figure 36). This single increase corresponds to a period of slight saturated till and Carrington aquifer recharge.

Because of fluoride insolubility in the presence of calcium and the ample presence of calcium in the soil of the experiment site, it is considered unlikely that detections of elevated fluoride resulted from slow flux in smaller pores. Detectable movement of fluoride likely occurred in large pores, or in preferential flow through macropores, where mixing of infiltration water with calcium-bicarbonate type water of the soil solution would be less likely to occur, and where dissolved solute could move at greater distance from the surface of the soil matrix.

Chloride Movement

Initial background chloride concentrations were measured in May of 1988 on the west and east experiment sites (Figure 37). Generally, chloride decreased exponentially between the surface and the Carrington aquifer. The surface of the aquifer had a background concentration of approximately 2 mg/L. The deep saturated till well had a chloride concentration of about 3 mg/L, the 1 to 2 m depth had a chloride concentration of about 8 to 10 mg/L, and the root zone had chloride concentrations of 1 to 20 mg/L.

Variability of chloride was largest near the soil surface. The variable distribution of soil chloride was likely caused by periodic additions of muriate of potash (KCl) as fertilizer over many years of agricultural use. Because of relatively large background chloride levels, it was necessary to

make a large application of chloride tracer (426 kg/ha) to assure that differences would be detectable. Initial (spring 1991) measured chloride concentrations of 3 to 10 mg/L at the 1.5-m (5-ft.) level, 3 mg/L at the 2.1-m (7 ft.) level, 2 mg/L in the deep till, and 1 to 2 mg/L in the top of the Carrington aquifer agree with the 1988 initial measurements (Figure 37).

Chloride peaks at 1.5-m (5 ft.) (Figure 38A) coincide with the detection peak of bromide on June 11 1991 (ED 1258). At the 2.1-m (7-ft.) level (Figure 36B) peaks occurred on the same (June 11 1991, ED 1258) days as the 1.5-m (7 ft.) level. Fluoride peaks are later (July 1 1991, ED 1278). Bromide peaks are also later (July 1 1991 ED 1278). A June 11 (ED 1258) bromide peak was measured in the deep saturated till, and in the surface of the Carrington aquifer on the same date (June 11 1991, ED 1258) as in the vadose samplers. For the 4.5-m (15-ft.) level, the fluoride peak was later and no corresponding increase in bromide was detected. At the 6.8 m level a single corresponding fluoride concentration peak was observed, but no corresponding bromide peak was noted.

Chloride peaks at 1.5 m (5 ft.) coincided with the detection peak of bromide on June 23 1992 (ED 1635). At the 2.1-m (7 ft.) level, 1992 peaks occurred on the same (June 23 1992, ED 1635) days as the 1.5-m (5-ft.) level. Fluoride peaks were indiscernible at the 1.5 m level, and were later (August 17, ED 1690) at the 2.1 m level. Bromide peak concentrations at 2.1 m (7 ft.) in 1992 agreed well with chloride at the 1.5-m (5 ft.) level (June 23, ED 1635), but were slightly later (July 1, ED 1643) at the 2.21-m (7 ft.) level. At 4.5 m (15 ft.) a slight increase in chloride concentration on June 11 (ED 1624) corresponded to increases in the overlying soil and vadose profile, but there were no corresponding increases in fluoride or bromide. In 1992, however, chloride increases at 4.5 m between June 23 (ED 1635) and August 17 (ED 1690) had corresponding large bromide increases. There was no corresponding fluoride increase. At the top of the Carrington aquifer a chloride peak on the south site on August 17 1992 (ED 1690) corresponded to a similar peak at 4.5 m (15 ft.), but had no corresponding peak detections of bromide or fluoride.

Detections of increased fluoride in the saturated till and in the Carrington aquifer in 1991 without corresponding increases in bromide, and later detections of chloride in the Carrington aquifer in 1992 without corresponding bromide and fluoride increases, suggest that first year transport of solute was dependent on macropores. Such a mechanism would enable direct transport of solute placed on the surface to deeper depths, without moving previously applied tracers now dissolved in waters held in smaller pores within the soil matrix.

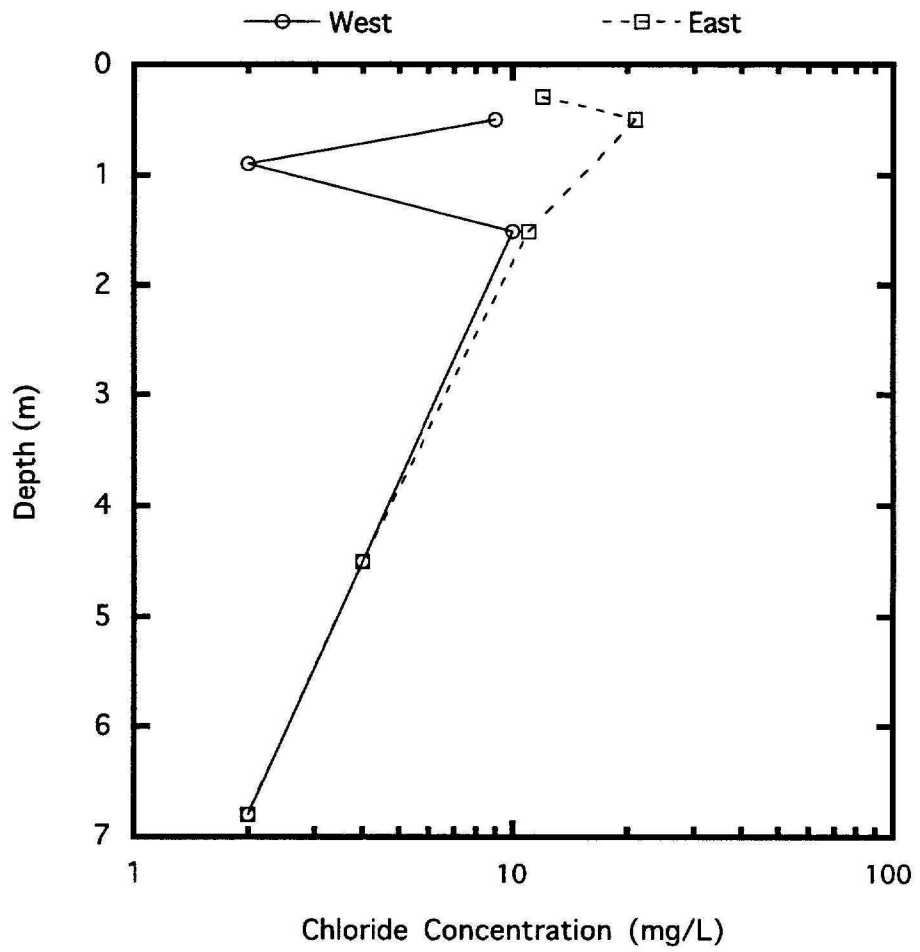


Figure 37. Initial background chloride levels measured in May of 1988.

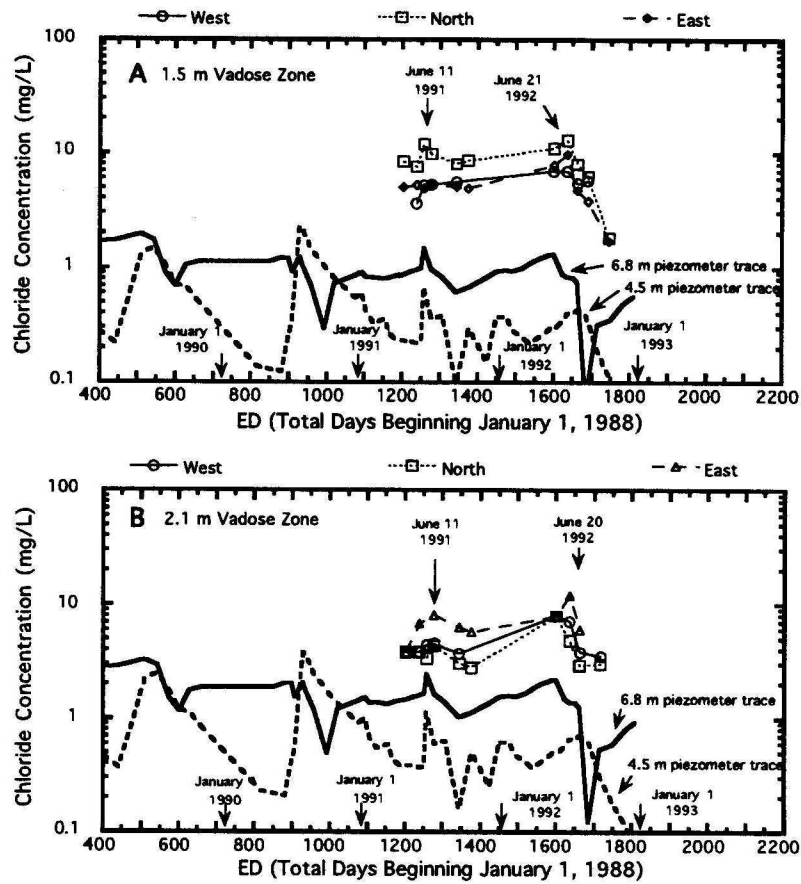


Figure 38. Chloride concentrations for water samples from A. 1.5-m (5-ft.) and B. 2.1-m (7-ft.) vadose samplers; and from C. deep (4.5 m or 15-ft.) saturated till wells, and D. the Carrington aquifer (6.8-m or 22-ft.) sample wells. (Continued on next page.)

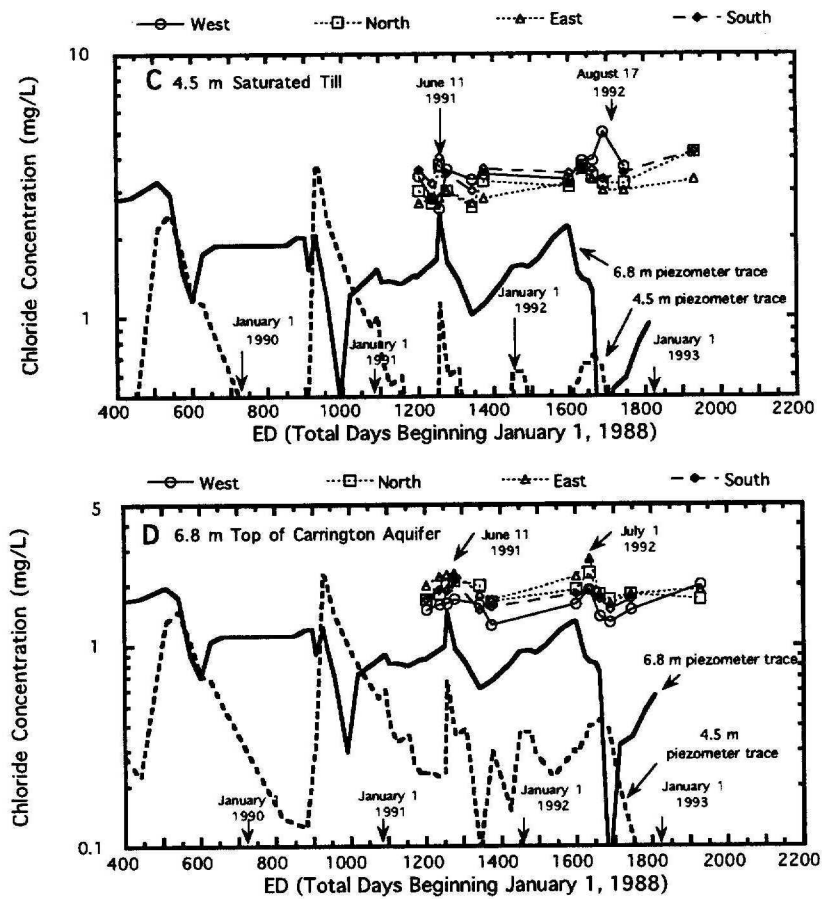


Figure 38 (Continued) Chloride concentrations for water samples from A. 1.5-m (5-ft.) and B. 2.1-m (7 ft.) vadose samplers; and from C. the deep (4.5-m or 15-ft.) saturated till wells, and D. the Carrington aquifer (6.8-m or 22-ft.) sample wells.

Nitrate Movement

Following construction of the wells in the fall of 1987, and again early in 1988 before the initiation of routine hydrologic measurements, water samples were taken for measurement of nitrate N. Initial well samples in 1987 (Figure 39) indicated that nitrate-N concentrations in the shallow till well varied from 1 to 4 mg/L while concentrations in the deep till well varied from 0.4 to 3 mg/L. The Carrington aquifer wells were all below 0.1 mg/L, except for the east well which was close to 1 mg/L. In early 1988 east and west wells were sampled. Vadose samplers near the wells were also sampled. Carrington aquifer sample concentrations were between 0.3 and 0.6 mg/L. Deep till sample concentrations ranged from 1 to 4 mg/L (the same range as in the previous fall). Samples from 0.9 m to 1.8 m (3 to 6 ft.) were 1 and 10 mg/L. Samples in the soil zone above 0.9 m (3 ft.) were between 10 and 30 mg/L. Generally, concentrations of nitrate-N decreased approximately exponentially with depth, and only in the soil zone were concentrations above the 10-mg/L U.S. Environmental Protection Agency suggested maximum-contaminant levels (EPA-MCL) for Nitrate N.

Following the addition of fluoride in 1990 Nitrate measurements were again made, and were continued on a regular basis through the spring of 1993. Nitrogen application times and amounts are shown on Table 1.

Initial (spring 1990) nitrate-N concentrations in the Carrington aquifer were approximately 0.01 to 0.04 mg/L. Movement of nitrate to the Carrington aquifer from spring 1990 through spring 1993 occurred as two distinct spikes (Figure 40). The first major spike occurred with peaks at the north, east, and south sites on July 23 1990 (ED 934) and on the west site on August 14 (ED 957). The second occurred only on the west site on July 1 1991 (ED 1278). At no time did nitrate levels exceed 0.7 mg/L, and only one measurement (July 23 1990, ED 934, east replicate) was above 0.3 mg/L. These measurements are consistent with the measurements made in 1987 and 1988 prior to the experiment.

In three years of measurement there were only two brief periods of nitrate influx to the aquifer. The only year in which nitrate movement to the aquifer was measured on all replicates was 1990, which had the single largest recharge event to the water table (Figure 35), and which had a simultaneous period of drawdown in the aquifer caused by pumping. For almost all samples nitrate-N concentrations were below 0.01 mg/L. No nitrate leaching to the aquifer was measured for 1992. The concentration peaks in the aquifer on July 23 1990 (ED 934) and July 1, 1991 (ED 1278) corresponded to increased nitrate-N concentrations in all overlying layers, including 2.1- (7-), 3.4- (11-), and 4.5-m (15-ft.) depths. The July 23 1990 (ED 934) detections in the aquifer corresponded to a single detection of bromide in the aquifer on the south replicate site. The largest concentration of nitrate N was also on the south replicate site, although increased concentrations were measured on all sites.

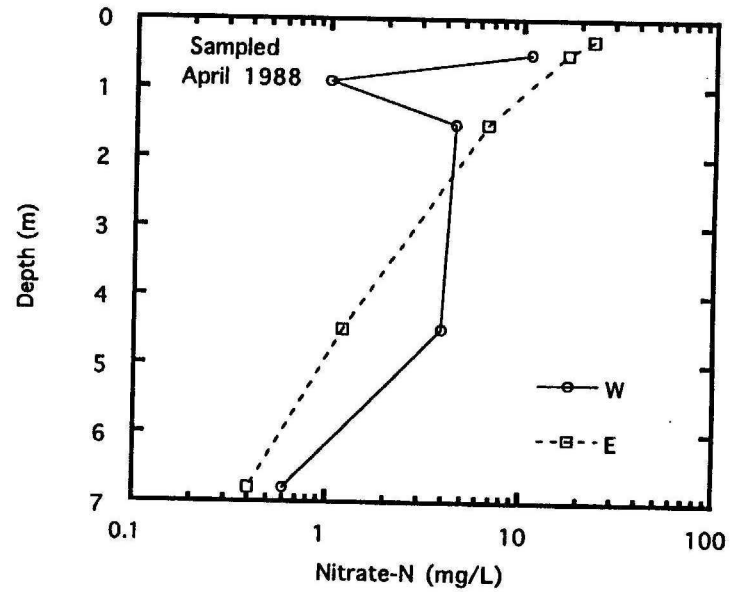
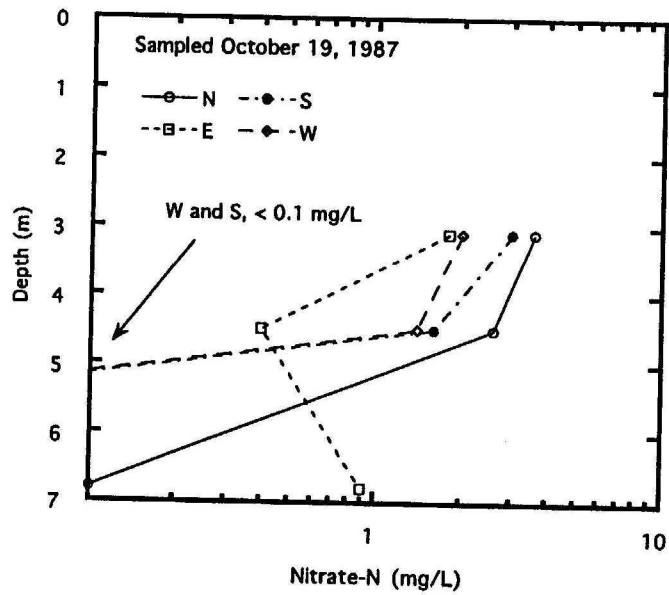


Figure 39. Initial nitrate-N levels in the Carrington aquifer and in the saturated till.

In the saturated till nitrate-N levels approached the 10-mg/L concentration only one time during the three year measurement period, and this was during the large recharge event that occurred in June of 1990, during which nitrate movement to the Carrington aquifer also occurred. In 1991 nitrate movement to the saturated till occurred, peaking in late June at about 3 mg/L on the south replicate. In 1992 an extended period of nitrate movement to the saturated till occurred from May through August. Nitrate movement to the saturated till corresponded well with nitrate movement within the overlying vadose zone. In general, the south replicate received the most nitrate. The east and north replicates received the second largest concentrations of nitrate, and the west replicate received the least.

Although there were brief periods of nitrate influx, there was no evidence of an upward trend in nitrate in either the saturated till or the Carrington aquifer over five years of measurement (initial measurements in fall of 1987 and spring of 1988, and detailed monthly measurements during 1990, 1991, 1992, and spring of 1993). Comparing similar times (spring and fall sampling periods) nitrate concentrations in the Carrington aquifer were most frequently below 0.1 mg/L at both the beginning and end of the experiments. Later measurements with lower detection ranges indicated that nitrate-N concentrations were frequently below 0.01 mg/L during 1990 through spring 1993. The upper levels of nitrate-N concentration during periods of influx measured from 1990 through spring 1993 did not exceed the maximum levels measured in the initial (April 1988) samples. Similarly, in the deep saturated till there was only one brief period in 1990 where nitrate-N concentrations on two replicates exceeded the initial measured range of nitrate-N values. At all other times the range of measured N values, including brief periods of influx of N, remained within a range very similar to the initial measured nitrate-N concentrations.

Surface Recharge Activity and Tracer Concentrations in Local Wells

Based on a map of surface-water distribution during a 1991 storm (Figure 10), the following order of local recharge to the Carrington aquifer would be expected. Most recharge would be expected on the east-well replicate. Second most would be expected on the south replicate, third the west well replicate, and least on the north replicate.

For nitrate N largest concentrations in the Carrington aquifer were detected on the south site, followed by the east site. The west-site concentrations slightly exceeded the north-site concentrations. For bromide the order of detected concentrations for 1989 was north, followed by south and east. Concentrations on the west site were lowest. In 1990 the west site had the largest concentration, followed by the south site. East- and north- site concentrations were similar. In 1992 the single detection was on the south site. For chloride the order in 1991 was east, south, and north replicates, followed by west with the lowest chloride concentration. In 1992 east and north replicates had largest concentrations, followed by south and then west. In 1992 west and north were largest.

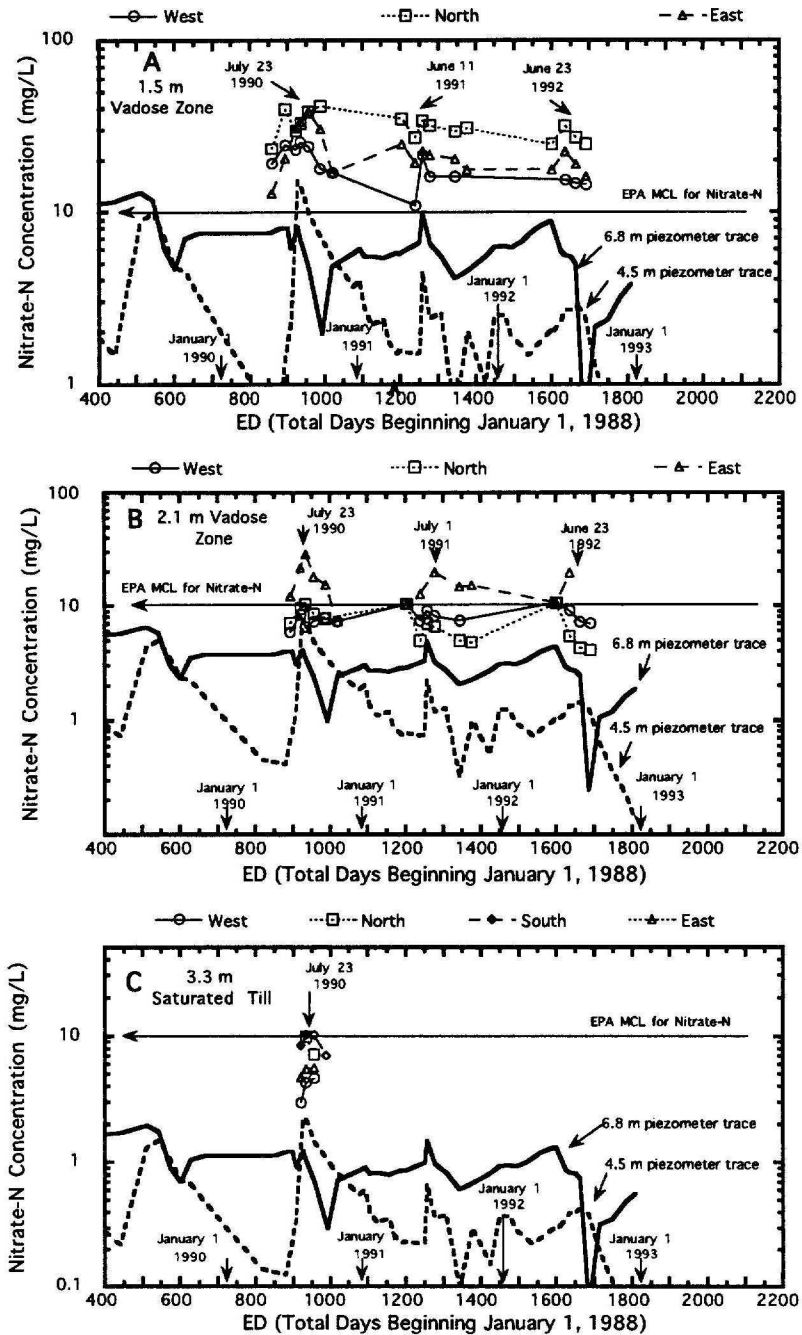


Figure 40. Nitrate-N concentrations for water samples from A. 1.5-m (5-ft.) and B. 2.1-m (7-ft.) vadose samplers; and from C. the shallow (3.4-m or 11-ft.) and D. deep (4.5-m or 15-ft.) unsaturated till wells, and E. the Carrington aquifer (6.8-m or 22-ft.) sample wells. (Continued on next page)

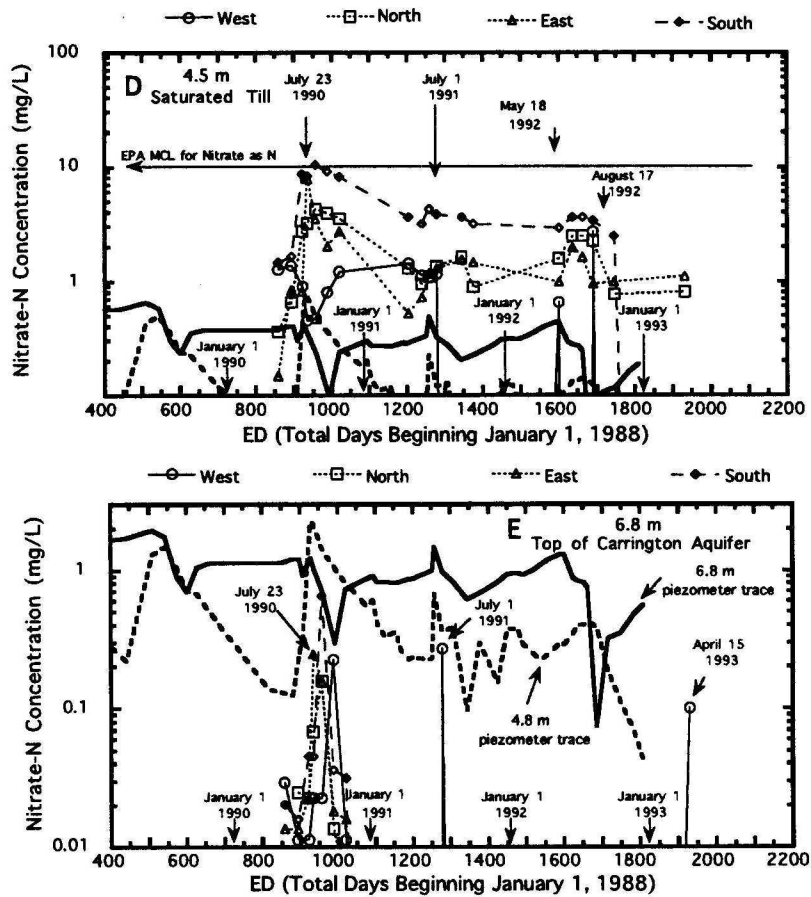


Figure 40 (Continued). Nitrate-N concentrations for water samples from A. 1.5-m (5-ft.) and B. 2.1-m (7-ft.) vadose samplers; and from C. the shallow (3.4-m or 11-ft.) and D. deep (4.5-m or 15-ft.) unsaturated till wells, and E. the Carrington aquifer (6.8-m or 22-ft.) sample wells.

For fluoride a reliable pattern is difficult to discern. Although the west site tended to maintain the largest concentrations, it also had the largest initial concentration. Generally, the greatest concentrations of nitrates did correspond approximately to the Carrington aquifer well replicates in areas mapped as having relatively larger surface infiltration activity.

For the saturated till, most recharge would be expected on the south replicate, second would be the east replicate (which should be very close or may even exceed the south replicate). Third would be the north replicate, and last would be the west replicate. As with the east and south replicates, the west and north might exchange positions.

Largest concentrations of nitrate N in the saturated till were on the south replicate, followed by the east and north replicates, respectively. Although all bromide concentrations were similar on the year of application (1989), in 1991 the order of concentration was east, north, and south, followed by west. North-, east-, and south-site concentrations were nearly identical in 1992. A single large concentration of nitrate-N was detected on the west site in late 1992. The south site usually had the largest chloride concentration. In August of 1992 the west site had the largest chloride concentration. As with the Carrington aquifer wells, it is difficult to find a consistent concentration pattern for fluoride. The low values for the east site seem to be as result of low initial background levels.

For the vadose sites largest water movement would be expected on the east site, followed by the north site. Least would be expected on the west site.

For the vadose zone, deepest vadose movement is on the east site. All other sites had similar smaller concentrations. For the shallow vadose level the largest concentrations during recharge periods were on the north site, followed by the east site. The west site indicated the lowest recharge concentrations. For bromide, concentrations at all replicates in the year of application were similar at deep and shallow vadose levels. Thereafter, the order of concentration is east and north, with least concentrations on the west replicate for the deep-vadose zone. For the shallow vadose zone, values were similar for all sites through the entire measurement period, with slightly higher concentrations of bromide on the west site in some cases. For chloride, concentrations were largest for the north site, followed by the east site at the shallow level. At the deep vadose level concentrations were largest on the east site. North and west sites were similar. Shallow vadose concentrations of fluoride were highest on east and north sites, with somewhat lower concentration on the west site. Deep vadose levels of fluoride were highest on the east and west replicates respectively.

Although there were some exceptions, most concentrations of tracers and nitrates appeared to follow approximately the spatial pattern of surface recharge indicated by the mapped surface-water distributions during the storm of May 22 1991. These observations

support the general findings of the hydrologic investigation concerning the importance of microtopography in determining sites of highly active local recharge.

SUMMARY OF TRACER AND NITRATE MOVEMENT

The following general conclusions are drawn from analysis of tracer and nitrate movement on the Carrington site.

(1) During the year of application, tracers were usually detected at virtually all measured levels at the Carrington site, including the surface of the Carrington aquifer at 6.8 m (22 ft.).

(2) Usually, first year detections were dilute, indicating that preferential flow paths, and perhaps macropores, were providing the primary movement conduits. Brief elevated fluoride concentrations in the vadose zone and saturated till during the year of application also support the hypothesis of macropore influence, since mixing of highly insoluble fluoride ion with calcium-bicarbonatic matrix water would likely cause precipitation of fluoride.

(2) During years following application tracers tended to concentrate just below the root zone. After two years, concentrations similar to those in the shallow vadose zone, would appear briefly during recharge periods in the saturated till. However, they did not remain at relatively constant levels as in the shallow vadose zone. The movement of larger concentrations of tracers at later times may indicate greater influence of intermittent slugs of bulk flow, compared with earlier influence of preferential flow paths. This is reasonable because most of the solute is no longer at or near the surface to be washed into large pores and cracks.

(3) Three or more years after application, appearances of tracer in the Carrington aquifer were spatially sporadic and most frequently not repeated on other site replicates.

(4) Tracer and nitrate concentrations at all levels corresponded approximately with topographical zones of maximum surface-water concentration mapped during a storm in 1991. These observations support the conclusion of the hydrologic data indicating the importance of microtopographic redistribution and concentration of water in determining the activity of surface sources of recharge.

(5) Tracer and nitrate peak concentrations were distinct and brief in the vadose zone, and corresponded to periods of rising water in the saturated till. However, tracer and nitrate peak concentrations in the saturated till, and particularly in the Carrington aquifer were prolonged and diffuse, and coincided also with a slightly later period of pressure drawdown in the Carrington aquifer which was caused by the pumping of the aquifer for irrigation use. Bromide movement to the aquifer was not observed in a year in which pressure drawdown was small. Tracer and nitrate data support the hydrologic analysis which indicates that pressure drawdown from pumping is an important

component influencing the overall amount water and path of water movement to the Carrington aquifer.

(6) During the period from spring 1990 through spring 1993 there were only two brief periods of nitrate influx to the Carrington aquifer. There were more frequent periodic flushes of nitrate to the saturated till.

(7) During the period from spring 1990 through spring 1993 nitrate-N never exceeded 1 mg/L on any sample from the Carrington aquifer. In the saturated till nitrate-N reached the 10 mg/L EPA-MCL concentration on only one well replicate for a brief period in July of 1990.

(8) There was no indication of an upward trend of nitrate-N in either the saturated till or in the Carrington aquifer during the period from fall 1987 to spring 1993.

REFERENCES

- Arndt, J.L. and J.L. Richardson. 1988. Hydrology, salinity, and hydric soil development in a North Dakota prairie wetland system. *Wetlands* 8:93-108.
- Arndt, J.L. and J.L. Richardson. 1989. Geochemistry of hydric soil salinity in recharge-throughflow discharge prairie-pothole wetland system. *Soil Sci. Soc. Am. J.* 53:848-855.
- Bartelson, Norene, and Scott Radig. 1992. North Dakota groundwater monitoring program, 1992 Report (Draft 2). North Dakota State Department of Health and Consolidated Laboratories: Division of Water Quality. Bismarck ND.
- Benz, L.C., W.O. Willis, F.M. Sandoval, and R.H. Mickelson. 1968. Soil water translocation in a high water table area. *Water Resour. Res.* 4:95-101.
- Benz, L.C., G.A... Reichman, E.J. Doering, and R.F. Follett. 1978. Water table depth and irrigation effects on applied-water-use efficiencies of three crops. *TRANSACTIONS of the ASAE* 21(4):723-728.
- Benz, L.C., E.J. Doering, and G.A. Reichman. 1981. Water table management saves water and energy. *TRANSACTIONS of the ASAE* 24(4):995-1001.
- Blake, G.R., E. Schlichting, and U. Zimmerman. 1973. Water recharge in a soil with shrinkage cracks. *Soil Sci. Soc. Am. Proc.* 37:669-672.
- Bluemle, J.P. 1965. Geology and groundwater resources of Eddy and Foster Counties of North Dakota. Part 1 - geology; N.D. Geological Survey Bulletin #44. Grand Forks, ND. ND State Water Commission, Bismarck, N.D.
- Bouma, J. and J.L. Anderson. 1977. Water and chloride movement through soil columns simulating pedal soils. *Soil Sci. Soc. Am. J.* 41:766-770.
- Bouwer, H. 1962. Analyzing ground-water mounds by resistance network. *J. Irrig.. Drain. Div., Am. Soc. Civ. Eng.* 88:15-36.

- Bouwer, H. 1990. Agricultural chemicals and ground water quality-issues and challenges. *GWMR*. Winter:71-79.
- Bresler, E.. 1973. Simultaneous transport of solutes and water under transient unsaturated flow conditions. 9: 975-986.
- Campbell, C.A., W.S. Ferguson, and F.G. Warder. 1970. Winter changes in soil nitrated and exchangeable ammonium. *Can. J. Soil Sci.* 50:151-162.
- Carey, J.W. 1965. Water flux in moist soil: thermal versus suction gradients. *Soil Sci.* 100:168-175.
- Carey, J.W. 1966. Soil moisture transport due to thermal gradients: practical aspects. *Soil Sci. Soc. Amer. Proc.*, 30:428-433.
- Carey, J.W. and H.F. Mayland. 1972. Salt and water movement in unsaturated frozen soil. *Soil Sci. Soc. Am. Proc.* 36:549-555.
- Carey, J.W., R.I. Papendick, and G.S. Campbell. 1979. Water and salt movement in unsaturated frozen soil: principles and field observations. *Soil Sci. Soc. Am. Proc.* 43:3-8.
- Chhabra, R. and I.P. Abrol. 1977. Reclaiming effect of rice grown in sodic soils. *Soil Sci.* 124:49-55.
- Cline, J.F., K.A. Gano, and L.E. Rogers. 1980. Loose rock as biobarriers in shallow land burial. *Health Physics* 39:497-504.
- Contstanz, Jim, W.N. Herklerath, and Fred Murphy. 1988. Air encapsulation during infiltration. *Soil Sci. Soc. Am. J.* 52:10-16.
- Cravens, S.J. and Lon C. Ruedisili. 1987. Water movement in till of east-central South Dakota. *Ground Water* 25:555-561.
- Doering, E.J., R.C. Reeve, and K.R. Stockinger. 1964. Salt accumulation and salt distribution as an indicator of evaporation from fallow soils. *Soil Sci.* 97:312-319.

Edwards, W.M. Predicting tillage effects on infiltration: In David M. Kral (ed.). Predicting tillage effects on soil physical properties and processes. ASA special publication No. 44. Madison, WI. p105-115.

Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Sci. 119:242-24

Foxx, T.S., G.D. Tierney, and J.M. Williams. 1984. Rooting depths of plants on low-level waste disposal sites. LA-10253-MS, UC-70B, Los Alamos National Laboratory, New Mexico.

Freeze, R. Allan, and James Banner. 1970. The mechanism of natural ground-water recharge and discharge 2. laboratory column experiments and field measurements. 6(1):138-155.

Fuchs, M., G.S. Campbell, and R.I. Papendick. 1978. An analysis of sensible and latent heat flow in a partially frozen unsaturated soil. Soil Sci. Soc. Am. J. 42:379-385.

Glass, R.J., T.S. Steenhuis, and J.Y. Parlange. 1988. Wetting front instability as a rapid and far-reaching hydrologic process in the vadose zone. Journal of Contaminant Hydrology. 3. 207-226.

Gray, D.M. Gray, R.J. Granger, and G.E. Dyck. 1985. Overwinter soil moisture changes. Trans. ASAE. 28:442-447.

Gray, D.M. and R.J. Granger. 1986. In situ measurements of moisture and salt movement in freezing soils. Canadian journal of earth sciences. 23:696-704.

Hakonson, T.E. 1984. Influence of small mammal burrowing activity on soil erosion and surface hydrology on a simulated waste burial cap at Los Alamos. Agronomy Abstracts. ASA, Madison, WI.

Hakonson, T.E., and J.H. Nyhan. 1986. Evaluation of geologic materials to limit biological intrusion into low-level radioactive waste disposal sites. LA-10286-MS, Los Alamos National Laboratory, New Mexico.

Hakonson, T.T., J.L. Martinez, and G.C. White. 1982. Disturbance of low-level waste burial site cover by pocket gophers. Health Physics 42:868-871.

- Hamaker, J.W., and J.M. Thompson. 1972. Adsorption. In C.A.I. Goring and J.W. Hamaker (ed.) Organic chemicals in the soil environment. Marcel Dekker, Inc., New York. Pp 49-144.
- Hantush, M.S. 1967. Growth and decay of groundwater mounds in response to uniform percolation. Water Resour. Res. 14:844-856.
- Hendry, M.J. 1982. Hydraulic conductivity of a glacial till in Alberta. Ground Water, 20:162-169.
- Hill, D.E., and J.Y. Parlange. 1972. Wetting front instability in layered soils. Soil Sci. Soc. Am. Proc. 36:697-702.
- Hillel, D., Krentos, V.D., and Stylianou, Y. 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics in situ. Soil Sci. 114:395-400.
- Hoekstra, Pieter. 1966. Moisture movement in soils under temperature gradients with the cold-side temperature below freezing. Water Resour. Res. :241-250.
- Hofmann, L.L. 1990. Freezing effects on water and solute redistribution in unsaturated soils. M.S. Thesis. Soil Science. North Dakota State University, Fargo, ND.
- Hofmann, L.L., R.E. Knighton, and J.R. Fleeker. 1992. Pesticide mobility in irrigated Northern Great Plains Soils. In. Preliminary Oakes test area study program draft interim status report. U.S. Department of the Interior, U.S. Bureau of Reclamation. Great Plains Region. November.
- Jaynes, D.B., R.S. Bowman, and R.C. Rice. 1988. Transport of a conservative tracer in the field under continuous flood irrigation. Soil Sci. Soc. Am. J. 52:618-624.
- Jury, W.A. 1985. Spatial variability of soil physical parameters in solute migration: a critical literature review. EA-4228, Research Project 2485-6, University of California, Riverside.
- Jury, W.A., D.D. Focht, and W.J. Farmer. 1987. Evaluation of pesticide groundwater pollution potential from standard indices of soil-chemical adsorption and biodegradation. J. Environ. Qual. 16:422-428.

Keller, C.K., G. van der Kamp, and J.A. Cherry. 1986. Fracture permeability and groundwater flow in clayey till near Saskatoon, Saskatchewan. *Canadian Geotechnical Journal*. 23:229-240.

Klute, A. 1986. Water retention: laboratory methods. In A. Klute (ed.), *Methods of soil analysis*. *Agronomy* 9:635-662.

Knighton, R.E., 1990. Factors affecting pesticide movement to ground water. North Dakota Water Quality Symposium, March 20-21, Fargo ND. NDSU Extension Service. pp 71-88.

Koopmans, R.W. and R.D. Miller. 1966. Soil freezing and soil water characteristic curves. *Soil Sci. Soc. Am. Proc.* 30:680-685.

Marino, M.A. 1974. Growth and decay of groundwater mounds induced by percolation. *J. Hydrol.* 22:295-301.

Mickham, J.T., R. Bellandi, and E.C. Tiff. 1989. Equipment decontamination procedures for ground water and vadose zone monitoring programs: status and prospects. *GWMR*:100-121.

Panday, Sorab, and M. Yavuz Corapcioglu. 1991. Solute rejection in freezing soils. *Water Resour. Res.* 27:99-108.

Parker, L.V., T.F. Jenkins, and P.B. Black. 1989. Evaluation of four well casing materials for monitoring selected trace level organics in ground water. U.S. Army Corps of Engineers CRREL Report 89-18.

Pfaff, J.K., C.A. Broppckhoff, and J.W. O'Dell. 1989. Test Method: The determination of inorganic anions in water by ion chromatography, Method 300.0. USEPA, Environmental Monitoring and Systems Laboratory. Cincinnati, OH.

Rehm, B.W., S.R. Moran, and G.H. Groenewold. 1982. Natural groundwater recharge in an upland area of central North Dakota, U.S.A. *J. Hydrol.* 59:293-314.

Rice, R.C., R.S. Bowman, and D.B. Jaynes. 1986. Percolation of water below an irrigated field. *Soil Sci. Soc. Am. J.* 50:855-859.

- Ruland, W.W., J.A. Cherry, and Stan Feenstra. 1991. The depth of fractures and active groundwater flow in a clayey till plain in southwestern Ontario. *Ground Water* 29:405-417.
- Shainberg, I. and M.J. Singer. 1986. Suspension concentration effects on depositional crusts and soil hydraulic conductivity. *Soil Sci. Soc. Am. J.* 50:1537-1540.
- Sharma, P.P., C.J. Gantzer, And G.R. Blake. 1981. Hydraulic gradients across simulated rain-formed soil surface seals. *Soil Sci. Soc. Am. J.* 45:1031-1034.
- Slack, D.C. 1978. Predicting ponding under moving irrigation systems. *Proc. Am. Soc. Civ. Eng.* 104(IR4):446-451.
- Schuh, W.M., and R.L. Cline. 1990. Effect of soil properties on unsaturated hydraulic conductivity pore-interaction factors. *Soil Sci. Soc. Am. J.* 54:1509.
- Schuh, W.M. 1991. Effects of an organic mat filter on artificial recharge with turbid water. *Water Resour. Res.* 27:1335-1344.
- Schuh, W.M., Meyer, R, Sweeney, M.D., and , D, and Gardner, J. 1993a. Spatial variation of root-zone and shallow vadose-zone drainage on a loamy glacial till in a sub-humid climate. 148:1-26.
- Schuh, W.M., Klinkebiel, D., and Gardner, J. 1993b. Use of an integrated transient flow and water budget procedure to predict and partition components of local recharge. *J. Hydrol.* 128: 27-60.
- Sommerfeldt, T.G. and D.C. MacKay, 1982. Dryland salinity in a closed drainage basin at Nobleford, Alberta. *J. Hydrol.* 55:25-41.
- Sophocleus, Marios, and Charles A. Perry. 1985. Experimental studies in natural groundwater-recharge dynamics: the analysis of observed recharge events. *J. Hydrol.* 81:297-332.
- Steenhuis, T.S., Jackson, C.D., Kung, S.K.J., and Brutsaert, W. 1985. Measurement of groundwater recharge on eastern Long Island, New York, U.S.A. *J. Hydrol.*, 79: 145-169.

- Stegman, E.C. and J.D. Valer. 1972. Irrigation scheduling by computational methods: crop data and evaluations in North Dakota. N.D. Agr. Exp. Sta. Res. Report No. 41. 16 p.
- Stocking, M.A. 1988. Assessing vegetative cover and management effects. In. R.Lal (ed). Soil erosion research methods. SWCS, 7515 Northeast Ankeny Road, Ankeny IA. p163-185.
- Sumner, D.M. W.M. Schuh, and R.L. Cline. 1991. Field experiments and simulations of infiltration-rate response to changes in hydrologic conditions for an artificial-recharge test basin near Oakes, southeastern North Dakota. U.S. Geological Survey. WRIR 91-4127. 46pp.
- Thomas, G.W., and R.E. Phillips. 1979. Consequences of water movement in macropores. J. Environ. Qual. 8:149-152.
- Tyler, D.D, and G.W. Thomas. 1977) Lysimeter measurement of nitrate and chloride losses from soil under conventional and no tillage corn. J. Environ. Qual. 6:63-66.
- Wagenet, R.J., and J.L. Hutson. 1987. LEACHM: Leaching Estimation And Chemistry Model, version 1.0. Vol(2). Continuum Water Res. Inst. Center Env. Res., 468 Hollister Hall, Cornell University, Ithaca, NY.
- Wanek, Alan, and R.F. Meyer. 1989. Characteristics of the Carrington aquifer. North Dakota Farm Research. 47:10-13.
- Warrick, A.W. and D.R. Nielsen. 1980. Spatial variability of soil physical properties in the field. In Hillel, D. (Ed.) Applications in soil physics. Academic Press. 319-344.
- Watson, K.K. 1966. An instantaneous profile method for determining the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 2:709-713.
- Willis, W.O., H.L. Parkinson, C.W. Carlson, and H.J. Haas. 1964. Water table changes and soil moisture loss under frozen conditions. Soil Sci. 98:244-248.
- Wilson, L.G., and J.N. Luthin. 1963. Effect of air flow ahead of the wetting front on infiltration. Soil Sci. 92:136-143.

Wilson, B.N., D.C. Slack, and C.L. Larson. 1981. An infiltration model: Development and evaluation of its parameters. *Trans. ASAE* 24:670-677.

APPENDIX A: SITE DESCRIPTION

Table A.1. Drill log for test hole at T147N, R66W, section 31, AAB.

Depth Interval (m)	Thickness (m)	Description
0.00 to 0.30	0.30	Topsoil
0.30 to 3.96	3.66	Clay; dark yellowish brown, 30%, w/silt, sand&gravel (oxidized, silty-sandy till); low plasticity.
3.96 to 6.40	2.44	Clay; olive black, 35%, with silt, sand & gravel, (till); moderately plastic.
6.40 to 12.80	6.40	Sand; coarse grained, moderately well sorted, subrounded; quartz, w/secomtant shale, carbonate, & dark silicate grains; some lignite.
12.80 to 26.52	13.71	Sand & gravel; 20% gravel, subangular to subrounded; quartz, shale, abundant lignite; medium sant to pebbles of gravel; primarily very coarse granules of gravel; by 80' most gravel is tertiary to cretaceous local bedrock material, including Pierre shale.
26.52 to 36.58	10.06	Shale/Clay; olive black clay to moderately indurated shale bedrock (Pierre Shale)

Table A.2. Summary of soil properties measured at three neutron probe access sites.

Site	Depth (cm)	Horizon	Sand %	Silt %	Clay %	pH	ECE dSm ⁻¹	O.M. %	θ _{1.5} g/g
NW	0.00-0.15	A	36	49	15	8.1	891	3.55	0.1034
	0.15-0.30	A	31	53	16	8.1	1108	3.42	0.1119
	0.30-0.41	B	25	60	15	8.1	663	2.25	0.0915
	0.41-0.74	Ck	26	50	25	8.3	602	1.05	0.0805
	0.74-1.24	C	55	38	0 8	8.2	792	0.41	0.0442
	1.24-1.57	C	61	33	0 6	8.1	842	0.54	0.0701
	1.57-1.80		45	38	17	8.3	1069	1.16	0.0876
	1.80-1.98		50	36	13	8.3	1325	0.41	0.0757
	1.98-2.16		42	50	0 8	8.4	1629	0.20	0.0644
	2.16-2.44		43	39	18	8.2	1108	0.41	0.0968
	2.44-2.79		51	40	10	8.2	1362	0.48	0.0667
NE	0.00-0.30	A	34	51	15	8.0	1108	3.49	0.1041
	0.30-0.53	B	23	58	20	8.4	890	2.26	0.1151
	0.53-0.83	C	27	57	17	8.6	798	1.02	0.0732
	0.83-1.30		59	33	8	8.1	919	0.37	0.0445
	1.30-1.73		68	30	2	8.2	698	0.37	0.0278
	1.73-2.13		57	33	10	8.4	809	0.41	0.0680
	2.13-2.46		44	39	17	8.0	631	0.48	0.0951
SE	0.00-0.30	A	35	51	14	8.1	1179	1.71	0.1161
	0.30-0.51	B	27	58	15	8.1	943	2.12	0.0904
	0.51-0.79	Ck	53	34	13	8.2	672	1.83	0.0575
	0.79-0.91	C	63	36	0 2	8.3	653	0.37	0.0329
	0.91-1.22		62	35	0 3	8.3	613	0.20	0.0273
	1.22-1.83		61	33	0 6	8.6	554	0.24	0.0501
	1.83-1.98		56	32	12	8.2	731	0.17	0.0683
	1.98-2.29		80	20	0 0	8.4	530	0.03	0.0246
	2.29-2.36		45	35	21	8.6	590	0.00	0.0968
	2.36-2.69		44	43	13	8.5	624	0.00	0.0790

Table A.3. Soil test data for the Carrington experiment site.

Sample Date	N (lb/A)	P ₂ O ₅ (lb./A)	K ₂ O (lb/A)	Organic Matter (%)	pH
Fall 1987	105	15 m	230	3.2	7.8
Spring 1991	63	17	180	3.6	8.1
Spring 1992	-	37	558	2.85	7.8

Table A.4. Laboratory water-retention and bulk-density (d_b) data for North (N), South (S) and East (E) soil sampling sites. ALL* is the composite average water content value for all soils of the designated horizon. n^* is the number of samples averaged for each water-content value.

Site	Depth (cm)	Horizon	n^*	d_b g/cm ³	Ψ 50 cm	Ψ 100 cm	Ψ 150 cm	Ψ 200 cm	Ψ 330 cm	Ψ 500 cm	Ψ 800 cm	Description
N	26	A	4	1.47	0.4062	0.3727	0.3541	0.3541	0.3139	0.3098	0.2923	black, loamy brown, loamy
	44	B	3	1.48	0.3731	0.3187	0.2949	0.2949	0.2495	0.2450	0.2249	
	52	B		1.34	0.4081	0.3634	0.3366	0.3381	0.2830	0.2800	0.2592	loamy loose sand, no sample
	81	C	3	1.32	0.3758	0.3262	0.3024	0.3028	0.2562	0.2527	0.2383	
	113	C	1	1.48	0.3247	0.2875	0.2666	0.2681	0.2189	0.2145	0.2041	
	155	C	4	1.61	0.2707	0.2338	0.2141	0.2156	0.1560	0.1545	0.1329	
	206	C	4	1.71	0.3091	0.2919	0.2830	0.2834	0.2543	0.2480	0.2346	
	E	30	A	4	1.38	0.4230	0.3850	0.3690	0.3660	0.3217	0.3135	0.2964
47		B	2	1.41	0.3850	0.3530	0.3336	0.3329	0.2666	0.2606	0.2338	
61		B	3	1.35	0.3642	0.3284	0.3098	0.3098	0.2517	0.2465	0.2301	
68		B		1.45	0.2666	0.2338	0.2249	0.2189	0.1832	0.1743	0.1638	
114		C	5	1.64	0.2824	0.2511	0.2341	0.2324	0.1683	0.1546	0.1367	
153		C	4	1.58	0.3686	0.3504	0.3366	0.3351	0.2476	0.2294	0.1962	
202		C	5	1.78	0.3515	0.3415	0.3347	0.3347	0.3102	0.2983	0.2770	
S		22	A	2	1.46	0.3977	0.3731	0.3582	0.3604	0.3225	0.3165	
	40	B	2	1.37	0.4096	0.3761	0.3530	0.3537	0.3016	0.3001	0.2793	
	46	B	1	1.41	0.3694	0.3262	0.2949	0.2949	0.2309	0.2309	0.2279	
	76	B	4	1.42	0.3403	0.3016	0.2755	0.2767	0.2294	0.2271	0.2126	coarse, sandy coarse, sandy coarse, sandy
	93	B	2	1.63	0.2522	0.2175	0.1936	0.1961	0.1435	0.1395	0.1221	
	102	BC	2	1.64	0.3232	0.2361	0.2100	0.2175	0.1653	0.1616	0.1393	
	168	C	4	1.67	0.3191	0.2487	0.2305	0.2350	0.1843	0.1798	0.1627	
	198	C	4	1.78	0.3377	0.3128	0.3050	0.3068	0.2841	0.2789	0.2666	
	219	C	2	1.72	0.3307	0.3001	0.2912	0.2919	0.2703	0.2644	0.2525	
	ALL*	30	A	10	1.43	0.4112	0.3777	0.3609	0.3601	0.3187	0.3126	
46		B	10	1.40	0.3841	0.3442	0.3214	0.3216	0.2653	0.2615	0.2423	
76		BC	7	1.37	0.3555	0.3121	0.2870	0.2879	0.2409	0.2381	0.2236	loamy
113		C	1	1.48	0.3247	0.2875	0.2666	0.2681	0.2189	0.2145	0.2041	loose sand
114		C	19	1.63	0.2864	0.2392	0.2197	0.2214	0.1656	0.1593	0.1408	coarse sandy
219		C	18	1.71	0.3405	0.3215	0.3122	0.3124	0.2736	0.2637	0.2446	loamy till

Table A.5 Empirical parameters for application of the van Genuchten functions for $K(\theta)$ and $\psi(\theta)$. Parameters include saturation moisture θ_s , residual moisture θ_r , saturated hydraulic conductivity K_s , the pore-interaction exponent ρ , and curve fitting parameters α , m , and n .

Site	Depth (cm)	θ_s *	θ_r *	α	m	n	K_s * cm/h	ρ
NW	0- 15	0.3981	0.0000	0.00922	0.145	1.170	1.226	33.35
	15- 30	0.3659	0.1400	0.00178	5.268	0.810	0.014	52.35
	30- 46	0.3928	0.0010	0.00390	1.677	0.404	0.193	11.58
	46- 61	0.3842	0.0800	0.00580	1.897	0.473	108	24.18
	61- 76	0.3806	0.0000	0.01040	1.336	0.252	34.4	18.35
	76- 91	0.3492	0.0818	0.00662	1.591	0.371	0.64	8.29
	91-106	0.3393	0.0802	0.00580	1.722	0.419	6.20	20.81
	106-122	0.3375	0.0808	0.00580	1.710	0.415	1.59	6.91
	122-152	0.3453	0.0000	0.00857	1.197	0.165	7.51	23.27
NE	0- 15	0.3839	0.0	0.0050	1.200	0.167	0.012	-96.25
	15- 30	0.3915	0.0	0.0027	1.875	0.467	0.022	-46.90
	30- 46	0.4016	0.0	0.0030	1.635	0.389	0.212	11.69
	46- 61	0.4041	0.0	0.0053	1.715	0.417	2.423	24.40
	61- 76	0.4022	0.0	0.0097	1.299	0.230	3.889	3.01
	76- 91	0.3483	0.0900	0.0071	1.681	0.405	0.613	1.70
	91-106	0.3374	0.0	0.0125	1.234	0.190	3.052	4.901
	106-122	0.3374	0.0	0.0125	1.234	0.190	3.052	4.901
	122-152	0.3317	0.1320	0.0035	3.467	0.712	0.009	17.76
SE	0- 15	0.4206	0.0000	0.0284	1.138	0.121	1.733	11.32
	15- 30	0.3883	0.1606	0.0044	5.023	0.800	0.009	19.44
	30- 46	0.3831	0.1658	0.0050	1.330	0.248	0.193	-
	46- 61	0.3650	0.1444	0.0054	7.430	0.865	0.234	10.04
	61- 76	0.3380	0.1372	0.0067	4.597	0.782	0.683	10.71
	76- 91	0.3513	0.0000	0.0103	1.567	0.362	0.902	5.70
	91-106	0.3640	0.0000	0.0110	1.546	0.354	0.862	-0.432
	106-122	0.3299	0.1664	0.0094	3.590	0.721	0.853	3.922
	122-152	0.3430	0.1659	0.0102	2.186	0.543	1.810	3.001

APPENDIX B: TRACER DATA

Table B.1. Bromide tracer data. (Continued on next page)

ED	Sample Date	1.5	1.5	1.5	2.1	2.1	2.1
		m West mg/L	m North mg/L	m East mg/L	m West mg/L	m North mg/L	m East mg/L
511	5/24/89	0.07	0.05	0.02	0.07		0.13
532	6/15/89	0.09	0.07	0.11	0.11	0.11	0.13
544	6/27/89	0.17	0.18	0.18	0.24	0.22	0.26
559	7/11/89	0.2	0.21	0.17	0.19	0.22	0.21
572	7/25/89	0.49	0.37	0.3	0.53	0.46	0.35
587	8/8/89	0.42	0.48	0.29	0.32	0.44	0.34
608	8/30/89	NS	NS	0.41	0.22	0.43	0.36
628	9/19/89	0.34	0.3	0.38	NS	0.31	0.26
642	10/3/89	NS	0.32	0.28	NS	NS	NS
662	10/23/89	NS	NS	NS	NS	NS	NS
858	5/7/90	NS	0.16	0.08	NS	NS	NS
893	6/11/90	0.29	3.1	0.26	0.04	0.08	0.04
922	7/10/90	3.3	8.5	1.28	0.05	0.23	0.12
935	7/22/90	13.3	8.39	4.6	0.06	0.19	2.96
957	8/14/90	10.3	6.53	5.1	0.05	0.1	0.15
988	9/4/90	6.9	5	4	0.09	0.12	0.19
1020	10/16/90	5.35	NS	5.35	0.13		0.13
1204	4/18/91	NS	1.5	0.9	0.1	0.1	0.1
1239	5/22/91	2.6	1.4	1.3	-	-	-
1258	6/11/91	8.8	3.15	0.57	-	-	NS
1278	7/1/91	3.5	2.2	1.3	-	-	0.3
1344	9/5/91	1.88	1.9	1	-	-	-
1376	10/7/91	NS	2.6	1.8	-	-	-
1600	5/18/92	NS	3.8	-	-	-	-
1636	6/23/92	3.9	5.2	3.7	-	-	NS
1663	7/19/92	2.1	2.5	1.1	-	-	93
1690	8/16/92	0.6	1.6	0.7	-	-	NS
1746	10/13/92	NS	NS	NS	NS		NS
1936	4/21/93	NS	NS	NS	NS		NS

Table B.1. (Continued) Bromide tracer data.

ED	Sample Date	3.4	3.4	3.4	3.4	4.5	4.5	4.5	4.5	6.8	6.8	6.8	6.8	
		m	m	m	m	m	m	m	m	m	m	m	m	m
		West	North	East	South	West	North	East	South	West	North	East	South	
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
511	5/24/89	0.03	0.02	0.03		0.03	0.02		0.04	0.01	0.02	0.03	0.06	
532	6/15/89	0.02	0.01	0.02	0.02		0.05	0.05	0.06	0.01	0.03	0.03	0.02	
544	6/27/89	0.11	0.13	0.05	0.13	0.11	0.14	0.05	0.1	0.07	0.1	0.05	0.04	
559	7/11/89	0.25	0.25	0.26	0.22	0.28	0.22	0.14	0.25	0.09	0.12	0.13	0.19	
572	7/25/89	0.21	0.31	0.28	0.22	0.2	0.22	0.21	0.19	0.16	0.17	0.2	0.18	
587	8/8/89	NS	NS	NS	NS	0.25	0.22	0.19	0.22	0.14	0.23	0.24	0.18	
608	8/30/89	NS	NS	NS	NS	0.25	0.15	0.26	0.18	0.1	0.36	0.14	0.11	
628	9/19/89	NS	NS	NS	NS	0.19	0.2	0.22	0.26	0.15	0.2	0.17	0.17	
642	10/3/89	NS	NS	NS	NS	0.14	0.2	0.2	0.23	0.15	0.19	0.18	0.13	
662	10/23/89	NS	NS	NS	NS	0.23	0.2	0.28	0.24	0.18	0.18	0.28	0.2	
858	5/7/90	NS	NS	NS	NS	0.04	0.01	0.07	0.02	0.05	NS	0.04	0.07	
893	6/11/90	NS	NS	NS	NS	0.04	0.07	0.07	0.05	0.02	0.02	0.04	0.06	
922	7/10/90	0.03		0.12	0	0.04	0.05	0.05	0.04	0.02	0.06	0.05	0.03	
935	7/22/90	0.03	0.08	0.06	0.11	0.04	0.05	0.06	0.05	0.02	0.04	0.04	0.06	
957	8/14/90	0.07	0.11	0.11	0.21	0.04	0.07	0.08	0.06	0.04	0.08	0.08	0.1	
988	9/4/90	NS	NS	0.11	0.11	0.04	0.08	0.08	0.07	0.73	0.07	0.05	0.06	
1020	10/16/90	NS	NS	NS	NS	0.04	0.06	0.06	0.07	0.04	0.05	0.05	0.07	
1204	4/18/91	NS	NS	NS	NS	0.2	0.7	0.5	1	-	-	-	-	
1239	5/22/91	NS	NS	NS	NS	-	0.37	0.2	0.59	-	-	-	-	
1258	6/11/91	NS	NS	NS	NS	-	-	-	-	-	-	-	-	
1278	7/1/91	NS	NS	NS	NS	-	-	-	-	-	-	-	-	
1344	9/5/91	NS	NS	NS	NS	-	-	-	-	-	-	-	-	
1376	10/7/91	NS	NS	NS	NS	-	-	-	-	-	-	-	-	
1600	5/18/92	NS	NS	NS	NS	-	0.59	0.48	0.95	-	-	-	-	
1636	6/23/92	NS	NS	NS	NS	-	4.04	3.3	3.64	-	-	-	0.51	
1663	7/19/92	NS	NS	NS	NS	-	1.3	1.1	1.4	-	-	-	-	
1690	8/16/92	NS	NS	NS	NS	6	-	0.3	-	-	-	-	-	
1746	10/13/92	NS	NS	NS	NS	-	-	0.1	-	-	-	-	-	
1936	4/21/93	NS	NS	NS	NS	-	2.5	0.7	1	0.2	-	-	-	

Table B.2. Fluoride tracer data. (Continued on next page).

ED	Sample Date	1.5	1.5	1.5	2.1	2.1	2.1
		m	m	m	m	m	m
		West	North	East	West	North	East
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
858	5/7/90	NS	1.3	1.7	NS	NS	NS
893	6/11/90	0.92	1.3	1.5	0.38	0.58	1.25
922	7/10/90	1.05	1.3	1.57	0.52	0.64	1.7
935	7/22/90	1.05	1.32	1.62	0.48	0.71	1.57
957	8/14/90	1.1	1.45	1.58	0.49	0.78	1.45
988	9/4/90	1.05	1.3	1.5	0.48	0.74	1.15
1020	10/16/90	1.1	NS	1.1	0.43	NS	0.43
1204	4/18/91	NS	1.5	1.7	0.6	0.6	0.6
1239	5/22/91	0.96	1.52	1.77	0.38	0.62	1.1
1258	6/11/91	1	1.5	2	0.46	0.66	NS
1278	7/1/91	0.99	1.4	1.56	0.43	0.77	1.56
1344	9/5/91	1.22	1.52	1.8	0.52	0.78	1.22
1376	10/7/91	NS	1.5	1.4	NS	0.81	1.45
1600	5/18/92	NS	1.5	1.6	1.2	1.2	1.2
1636	6/23/92	1.1	1.4	1.6	0.4	0.8	1.5
1663	7/19/92	1.2	1.7	1.8	0.5	0.8	1.7
1690	8/16/92	1.2	1.6	1.6	0.4	0.9	NS
1746	10/13/92	NS	1.5	1.6	NS	NS	1.2
1930	4/21/93	NS	NS	NS	NS	NS	NS

Table B.2. (Continued) Flouride tracer data.

ED	Sample Date	3.4	3.4	3.4	3.4	4.5	4.5	4.5	4.5	6.8	6.8	6.8	6.8	
		m	m	m	m	m	m	m	m	m	m	m	m	m
		West	North	East	South	West	North	East	South	West	North	East	South	
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
858	5/7/90	NS	NS	NS	NS	0.31	0.3	0.12	0.26	0.27	NS	0.23	0.26	
893	6/11/90	NS	NS	NS	NS	0.29	0.25	0.14	0.23	0.25	0.23	0.23	0.23	
922	7/10/90	0.26	NS	0.28	0.5	0.33	0.45	0.12	0.38	0.28	0.26	0.26	0.26	
935	7/22/90	0.28	0.27	0.24	0.48	0.29	0.4	0.11	0.37	0.27	0.24	0.24	0.24	
957	8/14/90	0.42	0.3	0.29	0.52	0.35	0.48	0.15	0.44	0.29	0.27	0.25	0.27	
988	9/4/90	NS	NS	NS	0.46	0.35	0.48	0.15	0.39	0.27	0.25	0.26	0.26	
1020	10/16/90	NS	NS	NS	NS	0.38	0.45	0.14	0.43	0.29	0.26	0.26	0.27	
1204	4/18/91	NS	NS	NS	NS	0.3	0.3	0.1	0.1	0.3	0.2	0.2	0.2	
1239	5/22/91	NS	NS	NS	NS	0.32	0.27	0.13	0.12	0.23	0.23	0.23	0.23	
1258	6/11/91	NS	NS	NS	NS	0.34	0.3	0.13	0.28	0.27	0.27	0.27	0.27	
1278	7/1/91	NS	NS	NS	NS	0.39	0.39	0.15	0.32	0.3	0.27	0.27	0.29	
1344	9/5/91	NS	NS	NS	NS	0.38	0.36	0.14	0.29	0.27	0.24	0.24	0.24	
1376	10/7/91	NS	NS	NS	NS	0.42	0.42	0.14	0.34	0.29	0.27	0.27	0.29	
1600	5/18/92	NS	NS	NS	NS	0.4	0.5	0.2	0.4	0.3	0.2	0.3	0.3	
1636	6/23/92	NS	NS	NS	NS	0.3	0.4	0.1	0.3	0.3	0.3	0.3	0.3	
1663	7/19/92	NS	NS	NS	NS	0.4	0.4	0.1	0.3	0.3	0.3	0.3	0.3	
1690	8/16/92	NS	NS	NS	NS	0.4	0.4	0.1	0.3	0.3	0.3	0.3	0.3	
1746	10/13/92	NS	NS	NS	NS	0.4	0.4	0.2	0.3	0.3	0.3	0.3	0.3	
1930	4/21/93	NS	NS	NS	NS	NS	0.3	0.2	0.3	0.3	0.3	0.3	NS	

Table B.3. Chloride tracer data.

ED	Sample Date	1.5 m West mg/L	1.5 m North mg/L	1.5 m East mg/L	2.1 m West mg/L	2.1 m North mg/L	2.1 m East mg/L
1204.0	4/18/91	NS	8.4	5	3.8	3.8	3.8
1239.0	5/23/91	3.6	7.6	5.2	3.8	3.8	6.8
1258.0	6/11/91	5.2	11.9	4.9	4.4	3.3	NS
1278.0	7/1/91	5.3	9.8	5.4	4.5	4.3	8.1
1344.0	9/5/91	5.6	8	5	3.7	3	6.3
1376.0	10/7/91	NS	8.6	4.9	NS	2.8	5.7
1600.0	5/18/92	6.9	11	7.8	7.9	7.9	7.9
1636.0	6/23/92	6.9	13	9.7	7.1	4.8	12
1663.0	7/20/92	5.4	8	4.7	3.8	2.9	6
1690.0	8/17/92	5.7	6.2	3.8	3.5	3	NS
1746.0	10/13/92	NS	1.8	1.7		NS	NS
1930.0	4/15/92	NS	NS	NS	NS	NS	NS

ED	Sample Date	3.4 m West mg/L	3.4 m North mg/L	3.4 m East mg/L	3.4 m South mg/L	4.5 m West mg/L	4.5 m North mg/L	4.5 m East mg/L	4.5 m South mg/L	6.8 m West mg/L	6.8 m North mg/L	6.8 m East mg/L	6.8 m South mg/L
1204.0	4/18/91	NS	NS	NS	NS	3.4	3	3.6	2.7	1.5	1.7	1.7	2
1239.0	5/23/91	NS	NS	NS	NS	2.8	2.7	3.2	2.8	1.6	1.8	1.9	2.2
1258.0	6/11/91	NS	NS	NS	NS	2.6	3.74	4.03	2.8	1.6	2	1.9	2.3
1278.0	7/1/91	NS	NS	NS	NS	3.6	3	3.5	3	1.7	2.1	2.1	2.3
1344.0	9/5/91	NS	NS	NS	NS	3.3	2.6	3	2.7	1.6	2	1.5	1.8
1376.0	10/7/91	NS	NS	NS	NS	3.5	3.3	3.6	2.8	1.3	1.7	1.6	1.7
1600.0	5/18/92	NS	NS	NS	NS	3.3	3.1	3.5	3.2	1.6	1.9	1.8	2.2
1636.0	6/23/92	NS	NS	NS	NS	3.9	3.7	3.7	3.6	1.9	2.3	1.9	2.7
1663.0	7/20/92	NS	NS	NS	NS	3.9	3.4	3.6	3.3	1.4	1.8	1.7	1.8
1690.0	8/17/92	NS	NS	NS	NS	5	3.2	3.3	3	1.3	1.7	1.5	1.6
1746.0	10/13/92	NS	NS	NS	NS	3.7	3.2	3.5	3	1.5	1.8	1.7	1.8
1930.0	4/15/92	NS	NS	NS	NS		4.2	4.2	3.3	2	1.7	NS	1.9

Table B.4. Nitrate-N data. (Continued on next page).

ED	Sample Date	1.5	1.5	1.5	2.1	2.1	2.1
		m	m	m	m	m	m
		West	North	East	West	North	East
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
858	5/7/90	19	23	13			
893	6/11/90	24	39	21	5.9	7.0	12
922	7/10/90	23	30	31	8.4	9.6	21
935	7/23/90	26	33	34	6.5	10	29
957	8/14/90	24	38	38	7.4	8.5	18
988	9/4/90	18	41	31	7.8	7.8	15
1020	10/16/90	17	NS	17	7.3	NS	7.3
1204	4/18/91	NS	35	25	10	10	10
1239	5/23/91	11	27	19	7.5	5.0	13
1258	6/11/91	21	34	23	9.0	7.0	NS
1278	7/1/91	16	32	21	8.1	6.5	20
1344	9/5/91	16	29	20	7.5	5.0	15
1376	10/7/91	NS	31	18	NS	4.8	15
1600	5/18/92	NS	25	18	11	11	11
1636	11/6/93	15	31	22	9.0	5.4	20
1663	8/7/93	15	27	19	7.2	4.3	NS
1690	5/8/93	14	25	16	7.0	4.1	NS
1746	1/10/93	NS	NS	NS	NS	NS	NS
1930	3/4/94	NS	NS	NS	NS	NS	NS

Table B.4. (Continued) Nitrate-N data.

ED	Sample Date	3.4 m	3.4 m	3.4 m	3.4 m	4.5 m	4.5 m	4.5 m	4.5 m	6.8 m	6.8 m	6.8 m	6.8 m
		West	North	East	South	West	North	East	South	West	North	East	South
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
858	5/7/90	NS	NS	NS	NS	1.3	0.36	0.15	1.5	0.029		0.014	0.020
893	6/11/90	NS	NS	NS	NS	1.4	0.65	0.84	1.6	0.011	0.025	0.014	0.016
922	7/10/90	3.0	NS	4.7	8.4	0.90	2.7	0.81	8.6	0.011	0.023	0.023	0.045
935	7/23/90	4.3	9.9	5.5	10	0.45	3.2	7.8	8.3	0.023	0.068	0.25	0.045
957	8/14/90	4.7	7.2	5.6	10	0.47	4.3	3.5	10	0.023	0.16	0.16	0.65
988	9/4/90	NS	NS	NS	7.1	0.80	4.0	2.0	9.1	0.23	0.014	0.018	0.036
1020	10/16/90	NS	NS	NS	NS	1.2	3.5	2.7	8.2	0.011	0.0045	0.016	0.032
1204	4/18/91	NS	NS	4.7	NS	1.4	1.3	0.52	3.6	-	-	-	-
1239	5/23/91	NS	NS	5.5	NS	1.1	0.95	0.72	3.2	-	-	-	-
1258	6/11/91	NS	NS	5.6	NS	1.1	1.1	1.2	4.3	-	-	-	-
1278	7/1/91	NS	NS	NS	NS	1.2	1.4	1.3	3.8	0.27	-	-	-
1344	9/5/91	NS	NS	NS	NS	-	1.6	1.5	3.6	-	-	-	-
1376	10/7/91	NS	NS	NS	NS	-	0.88	1.5	3.2	-	-	-	-
1600	5/18/92	NS	NS	NS	NS	0.65	1.6	0.99	2.9	-	-	-	-
1636	11/6/93	NS	NS	NS	NS	-	2.5	2.0	3.6	-	-	-	-
1663	8/7/93	NS	NS	NS	NS	-	2.5	1.6	3.6	-	-	-	-
1690	5/8/93	NS	NS	NS	NS	2.7	2.3	0.94	3.4	-	-	-	-
1746	1/10/93	NS	NS	NS	NS	-	0.77	0.99	2.5	-	-	-	-
1930	3/4/94	NS	NS	NS	NS	-	0.80	1.1	-	0.10	-	-	-