Vadose Zone Processes and Chemical Transport

Field-Scale Preferential Transport of Water and Chloride Tracer by Depression-Focused Recharge

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ABSTRACT

A tracer study was initiated in November 1993 to investigate depression-focused recharge and to monitor solute movement through the vadose zone into the shallow ground water in southeastern North Dakota. Granular potassium chloride (KCl) was surface-applied to two areas overlying subsurface drains and to one area instrumented with soil solution samplers, ground water monitoring wells, time domain reflectometry (TDR) probes, and temperature probes. One of the subsurface drain tracer plots was located on level ground while the other two sites were in small topographic depressions. Formation of ground water mounds beneath the depressions indicated that these areas are recharge sites. The applied Cl^- tracer was found to move rapidly to the shallow ground water under the depressional areas after infiltration of spring snowmelt in 1994. Excessive rainfall events were also responsible for focused recharge and the rapid transport of the applied Cl^- tracer. Water flow through partially frozen soil at the bottom of the depressions during thaw enhanced preferential movement of the tracer.

AGRICULTURE has long been named as a major contributor to nonpoint-source pollution of ground water resources. In areas of predominantly sandy soils and shallow water tables, the risk of ground water contamination is increased due to the high hydraulic conductivities of the soil and close proximity of the contaminant to the ground water. With the growing adoption of fertilizer and irrigation best management practices (BMPs) and site-specific variable rate technology, more emphasis is being placed on field variability. One area that needs to be investigated further is the spatial variability of ground water recharge and subsequent contamination relative to ground surface topography. We theorize in this study that in agricultural fields, previously thought of as primarily nonpoint sources of pollution, areas exist that act as point sources of ground water contamination.

In 1971, Lissey measured the vertical potential gradient in topographic depressions to study the ground water flow patterns. These areas were classified as depression-focused recharge, discharge, or transient areas. In the depressional areas, most of the water available for spring recharge came from snowmelt runoff that ponded due to frozen soils. This water infiltrates as the soils thaw causing these areas to act as focal points for recharge, resulting in a ground water mound (Knuteson et al., 1989; Lissey, 1971; Seelig and Richardson, 1994). Similarly, Freeze and Banner (1970) found that recharge in the spring was focused in depressions because infiltration was prohibited due to the frost lens and ran off into depressions until the frost lens thawed and the snow melt could infiltrate. Baker and Spaans (1997) found that rapid infiltration from ephemeral ponds occurred even in the presence of frozen subsoil. As a result, many portions of an area formerly considered a recharge area might never receive direct infiltration to the ground water, but recharge would be depression focused. In a lowland versus upland study conducted by Delin and Landon (1993), applied water and agricultural chemicals reached deeper depths and were found at higher concentrations in the lowland area. Schuh and Klinkebiel (1994) also found highly variable recharge due to surface microtopography variability.

Depression-focused recharge may be viewed as preferential flow on a field scale. Preferential flow is the general term used to describe rapid flow of water and solutes through the root zone to the water table by some means other than idealized piston flow (Kung, 1990; Rice et al., 1991; Tamai et al., 1987). It is this preferential flow that has the ability to bring surface-applied chemicals rapidly and directly to the ground water with little or no degradation (Kladivko et al., 1991). In the case of small depressions, ponded water takes with it any mobile chemicals, and sometimes immobile chemicals, as it infiltrates. If the ground water is shallow enough, the chemicals may reach the ground water before they can be degraded or a crop can use them.

Depression-focused preferential flow was investigated in this project. In order to investigate this phenomenon, tracer material was applied to the soil surface and its movement monitored through the unsaturated zone and into the ground water. A distinction was made between areas that are relatively flat and those areas that are topographic depressions. The objectives of this study were:

(i) To investigate the occurrence of depression-focused recharge and the movement of solute to a shallow water table aquifer due to depression-focused infiltration.
(ii) To investigate the possibility of rapid, preferential flow to subsurface drains during recharge events focused in topographic lows.

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Abbreviations: TDR, time domain reflectometry.

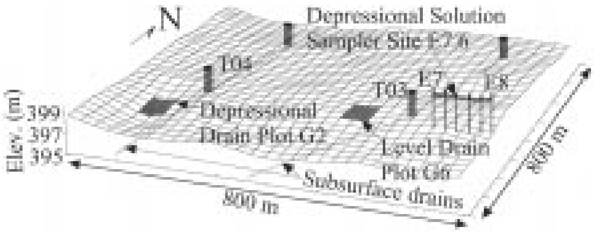

Fig. 1. Three-dimensional view of quarter section showing ground surface topography, subsurface drains, drain access manholes (T03 and T04), plot locations, and observation wells (E7 and E8).

MATERIALS AND METHODS

Site Description

The experiment was initiated in November 1993 within the northwest quarter of Sec. 29, T. 130 N, R. 59 W, in Dickey County, North Dakota, USA. Average annual rainfall for the area is 469 mm and on average, the mean daily air temperature remains below 0°C from 9 November through 27 March. Hecla loamy fine sand (sandy, mixed, frigid Oxyaquic Hapludoll) and Wyndmere fine sandy loam (coarse-loamy, mixed, superactive, frigid Aeric Calciaquoll) soils dominate this site. The depth to ground water averages slightly more than 2 m but comes to within 1 m of the ground surface in some locations. The field has been cropped to irrigated corn (*Zea mays* L.) since 1989.

One plot was located in a small depressional area approximately 100 m in diameter and with vertical relief of less than 1 m. This site is designated E7.6 in Fig. 1. The soil at this topographic depression was classified as a Ulen fine sandy loam (sandy, mixed, frigid Aeric Calciaquoll) on the edges and an Arveson loam (coarse-loamy, mixed, superactive, frigid Typic Calciaquoll) in the bottom of the depression. Saturated hydraulic conductivity (K_s) values were measured on 3 June 1993 with a compact constant head permeameter (Amoozegar, 1989). The average K_s measured at Sites E7, E7.6, and E8 were 4 cm h^{-1} at a depth of 25 cm and 2.2 cm h^{-1} at 75 cm. For reference, a ground water observation well at the west edge of the depression is labeled E7 and a well at the east edge is labeled E8 (Fig. 1). Measured from the southwest corner of the field, these wells are at 400 m north, 600 m east and 400 m north, 700 m east, respectively.

The second plot (G2) was located in a similar depression in another area of the field directly over a subsurface drain. This plot is located at 200 m north, 100 m east. The soil in this area was classified as Ulen.

The third plot (G6) was located on relatively flat ground and was also directly over a subsurface drain. This site was at 200 m north, 500 m east. The soil in this plot was classified as Hecla.

Instrumentation

Instrumentation at the depressional site (E7.6) included ground water observation wells, soil solution samplers, and soil moisture and soil temperature datalogging equipment (Fig. 2).

The field had previously been instrumented with ground water observation wells. The U.S. Bureau of Reclamation installed the wells in the fall of 1992. Clusters of two wells each were installed at 20-m intervals along a 300-m transect from 400 m north, 400 m east to 400 m north, 700 m east. One of the wells was screened at a depth of 0 to 0.9 m below the existing water table elevation. The elevation above mean sea level (MSL) of the top of the well casing and the length of pipe was recorded to allow for later measurement of water table elevation relative to the top-of-pipe elevation.

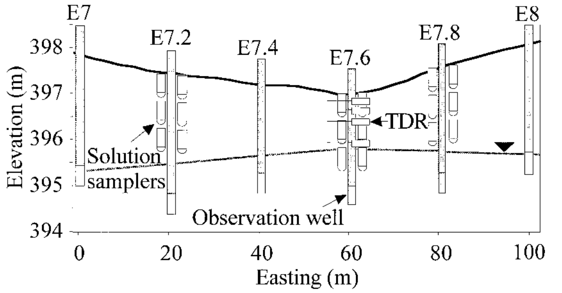

Fig. 2. Profile view of instrumentation, ground surface, and mean water table at the E7.6 transect depressional site. TDR = time domain reflectometry.

Soil solution samplers to monitor the tracer concentration in the soil solution were constructed and installed on 29 Sept. 1993 near the edges and in the bottom of the depression. The west and east edge locations are designated E7.2 and E7.8, respectively. The bottom of the depression is designated E7.6. The solution samplers consisted of a 100-kPa porous ceramic cup attached to a 30-cm length of 5-cm-diam. PVC pipe. A two-holed rubber stopper was inserted into the opposite end of the pipe. Two plastic tubes were inserted through the rubber stopper. One tube extended just below the bottom of the rubber stopper and was used as an air entry tube. The other tube extended into the ceramic cup at the bottom of the solution sampler and served as a solution extraction tube.

Installation of the solution samplers consisted of removing a soil core to a depth of 150 cm and setting the soil aside. A slurry was made from the soil material from the 150-cm depth and poured back into the hole. Using a 3-m length of PVC pipe, a solution sampler was pushed into the hole so that the ceramic cup was at a depth of 150 cm and seated in the soil slurry. The procedure was repeated at 90 and 30 cm. The remaining soil was used to fill the hole to the surface, leaving only the plastic tubing extending out of the soil. This procedure was repeated twice at all three sites (E7.2, E7.6, and E7.8), resulting in replicate samplers at each depth at each site. All plastic vacuum lines for each site were run through a section of plywood to hold the lines off the ground and keep the lines in order. A small length of silicon tubing was attached to the end of the plastic tubing so that a hose clamp could be used as a valve to close off the system and hold a partial vacuum in the samplers.

A Campbell Scientific (Logan, UT) CR10 datalogger was installed at E7.6 to log soil moisture, soil temperature, and precipitation on an hourly basis. Soil liquid water was measured via TDR at depths of 15, 30, 60, and 90 cm with a Tektronix (Beaverton, OR) 1502B cable tester. Waveguides consisted of two 45-cm-long, 3.2-mm-diam. stainless steel rods soldered to a 75/300-ohm transforming balun. A narrow pit was excavated with a tiling spade to a depth of approximately 1 m. The waveguides were pushed horizontally into the undisturbed soil profile, and the pit was filled with the excavated soil.

Soil temperature was measured with copper/constantan thermocouples at depths of 15, 30, 60, 90, 120, and 150 cm below soil surface. Thermocouples were housed in a Teflon rod. A core was removed with a 5-cm-diam. soil probe, leaving a hole to accept the thermocouple rod. The rod was inserted into the hole and pushed against a sidewall to bring the thermocouple ends in contact with undisturbed soil. The hole was carefully refilled to assure no openings to the surface.

The instrumentation at the depressional site (G2) and level site (G6) consisted of previously installed drain lines and automated water samplers at access manholes. The subsurface drains are constructed of 15-cm-diam. corrugated plastic drain line. The drain under the depressional site at G2 is 2.4 m below ground surface and flows from south to north. The drain under the level plot at G6 is 3 m below ground surface and also flows from south to north. Access manholes (T03 and T04) are located at 420 m north, 120 m east and 400 m north, 520 m east; approximately 200 m downgradient (north) from the plots at G6 and G2, respectively. These manholes are at the junction of two drain runs and allow access to the drains for sampling. An automated wastewater sampler was installed at each manhole to sample drain effluent at 6-h intervals during periods of expected recharge.

Tracer Application

Granular potassium chloride (KCl) as 0–0–60 bulk fertilizer was surface broadcast-applied at a rate of 448 kg ha^{-1} along the E transect between E7 and E8 and at the G2 and G6 plots on 10 Nov. 1993. Tracer was applied in November to simulate a fall fertilizer application and to assure that the initial spring recharge event was not missed. The 0.06-ha area at the E transect receiving tracer was 6.1 m wide and 100 m long, encompassing the six ground water observation wells and the solution samplers. The two other plots were each 30.5 m wide by 30.5 m long or 0.09 ha. The KCl was mechanically incorporated with a disk immediately after application to a depth of approximately 10 cm. Total material (0–0–60) applied to the 0.06-ha strip and the 0.09-ha plots was 27 and 42 kg, respectively, resulting in application of 213 kg ha^{-1} of Cl^{-}. Final tracer concentrations in the top 15 cm of the soil after application approximated 95 mg kg^{-1} of Cl^{-}, assuming a bulk density of 1.45 g cm^{-3}. This is a safe assumption as near-surface bulk densities measured in 1989 ranged from 1.32 to 1.54 with a mean of 1.45 g cm^{-3} in soil series similar to the tracer plot locations (Knighton et al., 1990).

Water Sampling

Soil solution samples were taken before tracer application and approximately weekly the following spring. During an expected recharge event such as precipitation or infiltration of ponded snowmelt, samples were taken more frequently. The method of sample extraction involved creating a partial vacuum (70 kPa) in the solution sampler with a vacuum pump and allowing extraction of soil solution for a few hours or up to 1 d, depending on the soil moisture status. When the soil solution was to be extracted from the samplers, a vacuum pump was used to remove the water that had collected in the ceramic cup directly into a sample collection vessel attached in-line with the vacuum pump.

Wastewater samples from the subsurface drains were taken automatically at 6-h intervals during recharge events. Samples were removed from the automatic sampler at the end of its 4 d cycle. During periods of no recharge, samples were taken manually with a stainless steel bucket.

The monitoring wells were sampled at the same time as the solution samplers. Sample collection was done by lowering a tube into the well and extracting water with a peristaltic pump. All subsamples were refrigerated and later analyzed by USBR personnel for chloride via colorimetric, automated ferricyanide AAII analysis (USEPA Method 325.2).

RESULTS AND DISCUSSION

Water Movement

Figure 3 is a three-dimensional view of the water table with time at the E7.6 depressional recharge site. The ground surface elevation line has been imposed on the vertical axis. The *x*-axis labels are at 20-d intervals. Similar to the observations of Baker and Spaans (1997), Knuteson et al. (1989), and Lissey (1971), a dramatic rise in water table was measured after the spring thaw of 1994. On 19 Mar. 1994, water from snowmelt runoff was ponded in the bottom of the depression. A slight ground water mound indicated that some water was infiltrating at this time and recharging the ground water. Two days later on 21 Mar. 1994, the ground water mound is much higher and is focused tightly at the bottom of the depression, indicating that the recharge from the snowmelt was very localized. The water table was also very responsive to rainfall and irrigation events throughout the year. In all instances, a ground water mound was formed under the depression at E7.6 after a water application. In a matter of days, the mound would recede, resulting in an increase in water table elevation in the adjacent wells.

The most dramatic indication of ground water recharge is seen after a 90-mm rainfall event in early July 1994. Cumulative rainfall and irrigation amounts are shown in Fig. 4. The *x*-axis labels are at 8-wk intervals with 1 wk between minor tick marks. After this event, the water table rose to the soil surface in the depression at E7.6. The greater lateral extent of this mound relative to the tightly focused mound observed on 21 March indicates that some infiltration and recharge was also occurring near the top and along the sides of the depression.

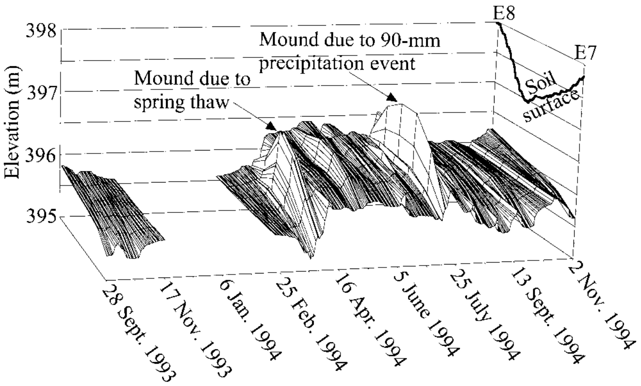

Fig. 3. Three-dimensional plot of water table over time measured at the E7.6 depressional site.

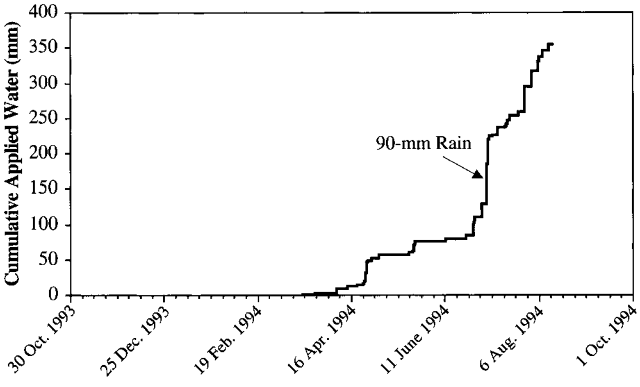

Fig. 4. Cumulative rainfall and/or irrigation measured at the E7.6 depressional area.

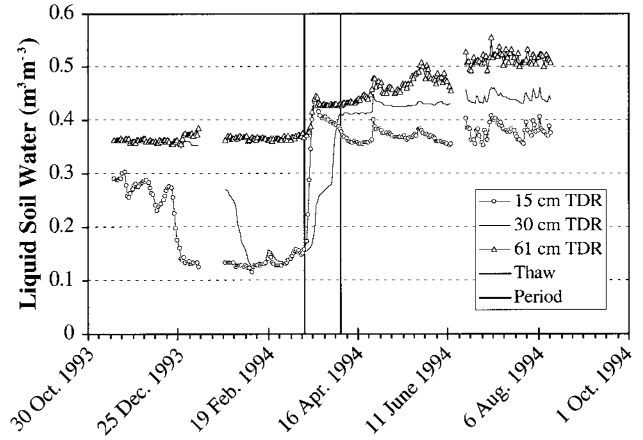

Fig. 5. Soil liquid water content at 15, 30, and 61 cm in the bottom of the depression at E7.6. Vertical lines at 14 Mar. 1994 and 3 Apr. 1994 enclose the period of thaw. TDR = time domain reflectometry.

Liquid Soil Water and Soil Temperature

Liquid soil water and soil temperature were measured to discover if ground water recharge is occurring at the bottom of the E7.6 depression while the soil is still partially frozen in the spring.

The trace of liquid soil water as measured by TDR in the bottom of the depression at E7.6 for the study period is shown in Fig. 5. Soil temperature for the same site and depths is shown in Fig. 6. Also included in Fig. 6 is the water table elevation measured at E7.6. The two vertical lines in each figure at 14 Mar. 1994 and 3 Apr. 1994 indicate the period of thaw. The *x*-axis labels for Fig. 5 and 6 are 8-wk intervals with minor tick marks at 1-wk intervals. The liquid soil water measured at 15 and 30 cm is relatively low prior to the thaw period, indicating that the soil is mostly frozen. On 14 Mar. 1994, the percent liquid water begins to increase dramatically to a maximum of 0.43 m^3 m^{-3} 5 d later on 19 Mar. 1994. This peak in liquid water content at 15 cm occurs concurrently with the marked rise of the water table as shown in Fig. 6, indicating that infiltration and ground water recharge is occurring. During this same time period, the liquid soil water measured at 30 cm has increased very slightly from its initial frozen moisture content of 0.15 to 0.17 m^3 m^{-3}. On 19 Mar. 1994 the liquid soil water at 30 cm increases almost immediately from 0.17 to 0.23 m^3 m^{-3}. From 20 March through 30 March, there is a leveling out of the increase of soil water at the 30-cm depth as a decrease is measured at 15 cm and the water table is receding. On 30 Mar. 1994 the liquid soil moisture at 30 cm begins to increase sharply again to its maximum of 0.41 m^3 m^{-3} on 3 Apr. 1994. This indicates the point at which the soil at 30 cm is now completely thawed.

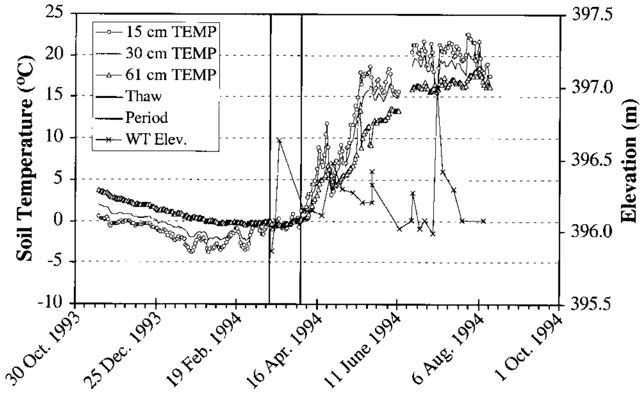

Fig. 6. Soil temperature at 15, 30, and 61 cm and water table elevation measured in the bottom of the depression at E7.6. Ground surface elevation is 397 m and vertical lines at 14 Mar. 1994 and 3 Apr. 1994 enclose the period of thaw.

During the period of thaw indicated in Fig. 5 and 6, the soil temperature stays relatively constant around 0°C. This is consistent with an isothermal period associated with the phase change from solid to liquid water. The fact that the liquid soil water at 30 cm does not increase immediately to its maximum, but levels out for a time, suggests that there is still ice present at that depth and infiltrating water is starting to refreeze as it reaches 30 cm, similar to that observed by Baker and Spaans (1997).

The liquid soil water content measured at 61 cm was initially high (approximately 0.37 m^3 m^{-3}), which indicates that the soil was not frozen at this depth. The 61-cm liquid soil water content did however increase sharply to a maximum at the same time as the large peak in the 15-cm liquid soil water and the first spike in the 30-cm liquid soil water. This is due to the recharge event raising the water table to a level very near the 61-cm TDR waveguide.

These data indicate that ground water recharge was occurring from ponded snowmelt in the depression even as the underlying soil was partially frozen.

Chemical Movement

The spatial and temporal distribution of the applied chloride tracer material in the soil solution was highly variable at the E7.6 recharge site. Chloride in the soil solution prior to tracer application was relatively low. During the following spring, chloride concentrations varied greatly.

Solution sampler and observation well chloride data for E7.2, E7.6, and E7.8 are shown as time series contours in Fig. 7a, 7b, and 7c, respectively. Included in each of the figures is the concentration contour by date, the sampling locations for each date, water table elevation, and date of tracer application. The *x*-axis labels are 40-d intervals. The data represented at the solution sampler locations are average values from the two samplers at each depth. Small circles in the figures indicate the sample locations. For each of the three time series contours, the data from pre-tracer application through the winter are missing as no samples were taken during the winter.

Figure 7a is the time series contour for chloride concentration at E7.2. As indicated by the plot, chloride tracer was transported to the top solution sampler (30 cm) early in the year and then was moved to the 91-cm depth following a 90-mm rainfall event in early July 1994. No chloride fluctuations were observed deeper

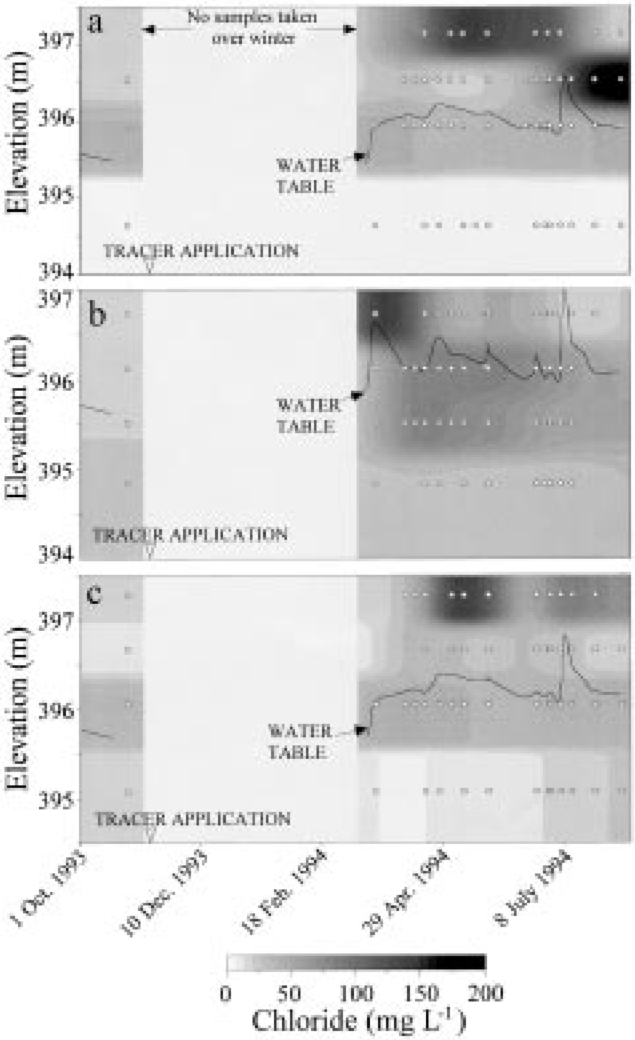

Fig. 7. Time series contours of chloride concentration and water table elevation at E7.2 (*a*), E7.6 (*b*), and E7.8 (*c*). Circles indicate spatial and temporal sample location.

than 91 cm or in the ground water at any time during the study at E7.2. This site does not exhibit focused recharge solute transport characteristics, as is indicated by the lack of chloride movement during the period of spring thaw.

The time series chloride data for E7.6 are shown in Fig. 7b. The chloride at E7.6 is seen to move rapidly to 30 cm, very near to the water table at the time, and then dissipates to deeper into the ground water as time progresses. The initial rapid transport of chloride corresponded to the previously mentioned increases in liquid soil water during spring thaw, when snowmelt accumulations are infiltrating at the bottom of the small depression. The large rainfall event in July did not result in an increase in chloride at the 30-cm sampler. This would indicate that the majority of the applied tracer had already been moved past that depth. The close proximity of the water table to the soil surface in the depression is also a major factor in the rapid movement of chloride to the ground water.

Chloride at E7.8 is seen to move only to the 30-cm depth midway through the study. Another smaller increase in chloride is observed in July (Fig. 7c). These data suggest that the majority of the tracer chloride was moved past 30 cm by slower flow processes such as piston or Darcian flow and remained between 30 and 91 cm for the duration of the study. The intense rainfall then moved remaining chloride in a second pulse.

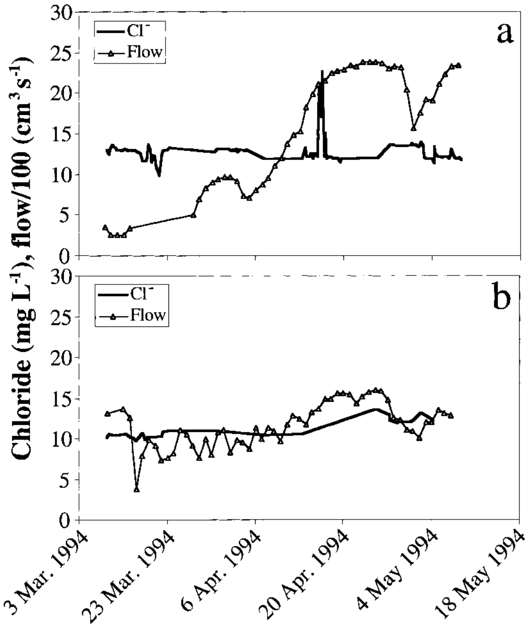

Fig. 8. Chloride concentration in subsurface drain effluent and drain flow measured at (*a*) Manhole T04 downstream from the depressional plot (G2) and (*b*) Manhole T03 downstream from the level plot (G6).

The collection and subsequent infiltration of snowmelt is the main factor influencing the travel time of surface-applied chloride to greater depths. As Sites E7.2 and E7.8 are on the sides or near the ridge of the depression, they receive less water for recharge than E7.6, which is at the bottom of the depression. In the bottom of the depression, the tracer is seen to move rapidly to the shallow ground water while on the ridges, the tracer remains near the surface. Only after several months and an extremely large rainfall event does some tracer move to an intermediate depth on one of the ridges.

Chloride concentration measured in water samples taken at the subsurface drain manholes downstream from the tracer plots (G2 and G6) is shown in Fig. 8. Also shown is the corresponding drain flows. The *x*-axis labels are at 14-d intervals. No corrections were made for dilution effects as only travel times were of interest for this study. Figure 8a shows the chloride measured at T04, downstream from G2, the depressional tracer plot. A spike in Cl^- was measured on 16 Apr. 1994. Note that this corresponds to a period of increasing drain flow rates, indicating that the soil had thawed and ground water recharge was occurring. In contrast, the chloride measured in T03 downstream from the level tracer plot (G6) shows little or no increase. These data indicate that ground water recharge and chemical movement was focused under the depression due to rapid infiltration of ponded snowmelt, as was seen at the E7.6 site.

CONCLUSIONS

Very localized depression-focused recharge was shown to have a marked effect on the movement of water and surface-applied chemicals to shallow ground water. When snowmelt infiltration was partially inhibited by frozen soil and the majority of the melt-water was collected in these small depressions, the effect was much more dramatic. We observed ground water recharge and rapid movement of chloride tracer to the ground water, focused at small depressions after spring snowmelt and after large rains. Technologies such as variable rate chemical application are now readily available. They may be employed to adjust the amount of chemicals applied in areas such as depressions, where nutrients may be leached out of the crop root zone, or the near-surface ground water contaminated by this field scale preferential flow. Further work should be done to address the total load of pollutants added to the ground water from this phenomenon.

ACKNOWLEDGMENTS

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