976

STUDYING NITRATE-N LEACHING WITH A BROMIDE TRACER IN AN IRRIGATED SILT LOAM SOIL

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ABSTRACT

Most of the irrigated land in southern Idaho is Portneuf silt loam varying in depth from 3 to 30 ft over fractured basalt. Leaching of ag-chemicals through this soil is of potential concern though major problems have not yet been generally encountered. We evaluated downward movement of water and the bromide (Br) anion at a sprinkler irrigated field site over a 3-year period to determine the potential for NO_3-N leaching losses. Potassium bromide as a conservative tracer was incorporated into the top 8 in. of soil at the start of the study. Soil solution samples obtained from soil solution suction tubes at six depths above bedrock were used to monitor the downward movement of Br. Soil water drainage was determined by a soil water balance utilizing neutron meter data and evapotranspiration computed from meteorological data and crop coefficients. Depth of sampling varied among eight subplots from 12 to 16 ft. Preferential water flow was evident in the initial downward movement of Br. However, drainage of water sufficient to completely replace the initial soil water (44 in) was necessary to completely flush Br from the profile. With recommended irrigation practices, about seven years would have been required to leach Br and presumably, NO_3-N as well, below 12 ft.

INTRODUCTION

Year-round drainage of water from irrigated lands presents a challenge to irrigators where the goal is to provide sufficient soil water to maintain crop production while minimizing contamination of ground water. Exploratory studies on irrigated silt loam soils in southern Idaho indicated that between 45 and 135 lbs per acre of nitrate nitrogen (NO_3-N) may be lost during the nongrowing season. The cause of the loss, while commonly considered to be due to leaching, was unknown. The soil varies in depth from 3 to 30 ft and lies over fractured basalt. It contains a calcic layer between about 16 and 30 inches which restricts root growth but not water penetration. Appreciable amounts of residual NO_3-N can be found in the soil profile after the cropping season. When fields are irrigated late in the season, there is considerable potential for loss of nitrate by soil drainage during winter months (Wright, 1993). This residual N could impact ground water quality if drainage between October and March is the major mechanism by which NO_3-N is lost from the soil profile. However, long term (+20 yr) monitoring of springs, drainage tunnels, and domestic wells in the irrigation tract near

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Twin Falls, Idaho, shows little increase in NO_3-N concentrations and no evidence of any peak concentrations during the year (D.L. Carter, personal communication).

Transport of solutes in unsaturated soils has been intensely studied during the past 30 years or more. Results indicate that solute transport experiments need to be conducted on a field scale to further the understanding gained from laboratory column studies. It is difficult to quantitatively trace the movement of NO_3-N through soil profile because of the dynamics of its extraction by roots and its transformation by soil chemical and microbial processes. Bromide (Br) is not as subject to the dynamics of NO_3-N change in the soil solution and can be used as a tracer to study solute movement in the soil (Smith and Davis, 1974).

Early theories of water flow through unsaturated soils considered the soil to be a continuous solid matrix with unsaturated water held in pores and films. This flow is often called Darcy flow or matrix flow. Drainage from matrix flow is sometimes also called piston flow drainage; i.e., water flowing in at the top replaces water that drained through the profile. Since the late 1970's considerable research has centered on water flow and solute transport through larger pores (often called macropores) due to the cracks, root holes, and worm burrows existing in field soils (Thomas and Phillips, 1979; Beven and Germann, 1982; Quisenberry et al., 1994; Shipitalo and Edwards, 1996). This flow, called macropore flow or preferential flow, causes faster solute movement than that predicted by Darcy flow. Surface tillage affects the extent and distribution of macropores and, thus, influences paths of water flow in the surface soil (Thomas et al., 1989). Soil water content impacts the proportion of applied water that moves through the soil matrix or macropores, but research results indicate the effects of soil water content are highly variable depending on surface litter, cracking, and soil structure. Shipitalo and Edwards (1996) found that increasing soil water content increased the involvement of the soil matrix in the flow process. In spite of increased understanding about the role of macropore flow in solute movement, it is not yet possible to predict, on a field scale, the combined effect of all the contributing factors.

Izadi et al. (1993) applied a pulse of bromide (Br) in a small furrow-irrigated field near the site of the present study and found evidence of both piston flow and preferential flow, depending on the length of the irrigation and the wetness of the soil. Their measurements were restricted to three irrigations during one summer and traced the solute to a depth of about 3.5 ft. Kessavalon et al. (1996), using bromide and other tracers, found that large amounts of nitrate can be lost by leaching from irrigated corn in central Nebraska on fine to medium-textured soils.

Our objectives were to evaluate downward movement of water and Br from the surface soil of an irrigated silt loam profile, including that occurring during the nongrowing season, to better explain why far less No_3-N is found in drainage water than would be expected given the yearly losses of NO_3-N from the irrigated soils of southern Idaho. While the ultimate goal is to explain NO_3-N losses, Br was selected as a tracer of solute movement because the subject soils have a relatively high rate of mineralizing NO_3-N and because denitrification might occur in some soil horizons if they become water saturated.

EXPERIMENTAL PROCEDURES

Research Site and Management

The research was conducted about one mile northeast of Kimberly, Idaho, at the USDA Agricultural Research Service Northwest Irrigation and Soils Research Laboratory in an irrigated region of southcentral Idaho at 3960 ft elevation, 42°31'N and 114°21'W. The region has an arid temperate climate with a winter precipitation pattern. The soil, a Portneuf silt loam (*Durixerollic Calciorthid*), was more than 14 ft deep and underlain by fractured basalt. Depth to the major aquifer at the site is about 200 ft. Local canal water diverted from the Snake River, classified as low salinity water, was used for irrigation. Irrigation water was available from mid-April until mid-October. Field studies were initiated in the fall of 1993 and continued through February 1997. The drainage of soil water was determined by soil water balance utilizing neutron moisture meter measurements of soil water contents (Wright, 1990) and estimates of the evapotranspiration component obtained from daily meteorological data using reference ET and crop coefficients (Wright, 1981; 1982; 1996; Jensen et al., 1990). Soil solution samples, obtained at varying depths with soil-solution-sampling tubes, were used for Br analysis.

Plots were established in the central portion of a field of 0.7 acres with a slope of about 0.5%. Eight subplots, each 40 x 40 ft, were arranged 4 x 2 with a 10-ft wide alleyway lengthwise between subplots. Thus the plot area was 160 ft long by 90 ft wide with at least 25 ft of border area surrounding the plots. The field was furrow irrigated 21 Sep. 1993 to bring the soil profile water content to field capacity. Potassium bromide (KBr) was applied on 13 October in a spray solution over the entire study area at 200 lbs Br per acre to obtain spatial uniformity. The Br was incorporated by rototilling to 8-inches the same day. The plot areas were roller harrowed a few days later to firm the soil surface for the installation of sampling devices.

After Br incorporation an aluminum, neutron meter access tube (NMAT) was installed in each of the 8 subplots. Six tensiometer-type, ceramic-tipped, soil solution suction tubes (SSST's) were installed in a row about 1 ft apart in each subplot to average depths of 1, 3, 5, 9, 10.5, and 12.5 ft. A diagram of the installation scheme and a description of the soil profile are shown in Fig. 1. The 48 SSST's were connected via plastic tubing manifolds to a laboratory-type high vacuum pump to obtain soil solution samples.

Cropping Management

After Br incorporation in October 1993 the soil surface was bare until June 1994. A crop of pink, dry-edible beans was planted in early June, cultivated in early July, and otherwise

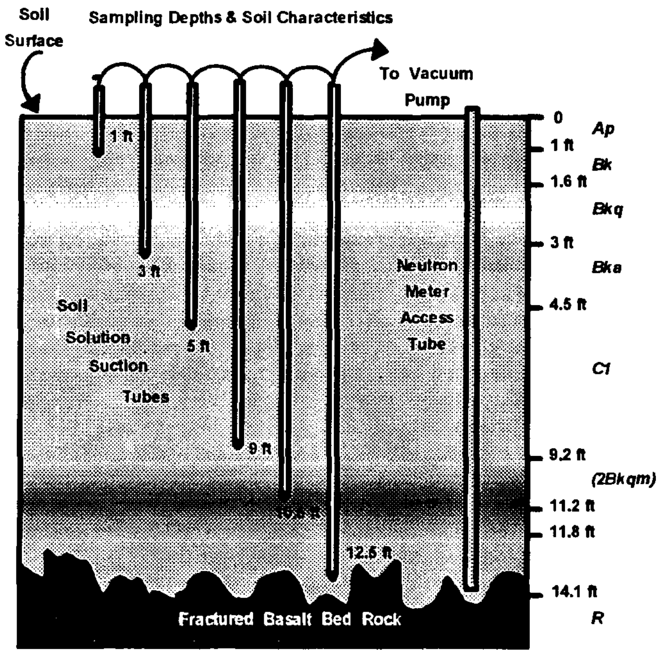

Fig. 1. Diagrammatic Representation of Sampling Tubes and a General Description of the Soil Profile

managed according to conventional practices. The beans were cut for harvest in late August, harvested in September, and the plot area was cultivated to incorporate the bean residue. The field was in this fallow condition through May 1995. A mix of perennial rye and fescue grasses was then cross-seeded with a double disc press wheel drill with a 6 ½-inch row spacing in late May. The grass was allowed to grow throughout its first summer. It was cut in early November 1995 and removed from the plot. The grass cover crop was used for the duration of the study. During the 1996 growing season, the grass was periodically mowed with a rotary lawn mower. The grass clippings were not removed from the plots. Only minimal amounts of nitrogen fertilizer (about 25 lb N per acre per year) were applied to maintain the grass soil cover.

Irrigation Management

The irrigation system was a conventional, solid-set sprinkler system with three laterals spaced 50 ft apart, with the central lateral in the alleyway between subplots. Thirty-inch sprinkler risers were at 40-ft intervals along the laterals with conventional impact, rotating sprinkler heads with 1/8-inch nozzles. This provided a symmetrical sprinkler design for each of the subplots. A four-inch diameter, funnel-type rain gage (RG) was placed near each NMAT, while two more were placed at each end of the banks of SSST's giving 3 RG's per subplot, 24 RG's overall, to measure irrigation amounts. Irrigation intensity averaged about 0.175 inches per hour and irrigation durations varied in length depending on the water content of the soil. The first irrigations were applied in April and May 1994 prior to planting the dry-bean crop. During the first phase of the study from then until July 1995, irrigations were scheduled to provide sufficient water for crop growth with some drainage. In the second phase during the summer of 1995, irrigation amounts were increased to provide a larger drainage component. In the third and final phase, from July 1996 on, irrigation amounts were increased substantially more than phase 2 to hasten the movement of Br through the soil profile. During any irrigation, if water began to pond on the soil surface, irrigation was terminated. Duration of irrigation usually exceeded 10 hr.

Soil Water Sampling

The first soil solution samples were collected in early December 1993 and at approximately monthly intervals thereafter. To obtain samples, the vacuum manifold connected to the SSST's was activated at about 8:00 a.m. each sampling date and operated for approximately six hours to provide enough solution for chemical analysis. Solution samples were extracted from the tip of each SSST with a long, thin nylon tube connected to a 60-ml hand-operated syringe. About 20 ml of extracted solution was saved for analysis. Extracting all 48 solution samples took about 45 minutes. Samples were stabilized with boric acid and analyzed for Br and other anions using an automated, flow-injection chemical analyzer (FIA). Minimum detectable Br concentration was 0.5 ppm or less. (Results of analysis for other ions are not reported here.)

Water Balance Procedures

Neutron meter (NM) measurements began in early November 1993 and continued at monthly or more frequent intervals throughout the study. Measurements were made within 24 hours of collection of solution samples. Neutron meter readings consisted of 30-second counts at 5.9-inch (15-cm) depth increments, starting at the 5.9-inch depth and continuing to the bottom of each access tube. The deepest measurements varied from 11.6 to 13.5 ft depending on the depth of the access tubes in the respective subplots. Volumetric soil water contents were computed from NM count ratios using calibration equations specifically obtained for the experimental site. The gravimetric water content of the surface 3-inch soil layer was measured on samples obtained with a hand-operated soil probe. Total water content of the soil profile was obtained by summing the incremental water contents.

The field soil water balance in terms of drainage can be described as:

$$D = Irr + Ppt - Etc - \Delta SW - R \qquad (1)$$

where D is drainage, Irr is irrigation, Ppt is precipitation, Etc is computed evapotranspiration (described hereafter), and ΔSW is change in soil water content (present minus past), and R is runoff; with all units equivalent to those of precipitation, i.e., volume of water per unit soil surface area, in^3/in^2, or simply depth equivalent, inch. Drainage by Eq. (1) represents net drainage over the time period selected. The terms Irr and Ppt were measured by rain gages, Etc was computed on a daily basis and summed for the appropriate time interval, and ΔSW was calculated from the neutron meter data. The terms in the equation are all positive except D and ΔSW which may be positive or negative. A negative value for ΔSW means the soil is drier at present than in the past. A negative D implies flow of water into the profile, which may occur if hydraulic gradients are appropriate or it may be the result of errors in the other terms. For purposes of this study, R was considered negligible.

The equations used in computing Etc are listed here for clarity, but without discussion for brevity. Detailed definitions and discussions of the principles involved were given by Wright (1981, 1982, 1985, and 1996) and were presented in general by Allen et al. (1989) and Jensen et al. (1990). The approach is based on the equation:

$$\text{Etc} = (\text{Kc})\,(\text{Etr}) \qquad (2)$$

where Etc is daily computed evapotranspiration for a particular crop or cover condition, Kc is a dimensionless crop coefficient, and Etr is a reference daily ET. Units are in depth equivalent, as with precipitation. In this study, all computations were made in SI units with the resulting Etr and Etc values in mm/day, which were then converted to inches per day for presentation of results. Values of Kc must be known from previous research or must be estimated.

A form of the Penman combination equation developed for southern Idaho conditions (Wright 1982, 1996) was used to compute daily Etr from appropriate meteorological data:

$$\text{Etr} = \left[\frac{\Delta}{\Delta + \gamma}(\text{Rn} - \text{G}) + \frac{\gamma}{\Delta + \gamma}\,\text{Wf}\,(\text{es} - \text{ea})\right] \text{L}^{-1} \qquad (3)$$

where Rn is net radiation, G is soil heat storage, Wf is a wind function, (es – ea) is the mean daily saturation vapor pressure deficit, Δ is the slope of the saturation vapor pressure versus temperature curve, γ is the psychrometric constant, and L is the latent heat of evaporation. For these calculations, Rn was computed from measured solar radiation and G was computed from daily average air temperatures, Wf was computed using measured daily average wind speed and previously developed functional relationships, (es – ea) was computed from maximum and minimum air temperatures. The dew point temperature was measured at 7:00 a.m. during daylight savings time and at 8:00 a.m. otherwise. For this study, an alfalfa reference Etr (Wright, 1982) was used for the 1994 growing season with appropriate crop coefficients developed for dry beans (Wright, 1981). For the 1995 and 1996 growing seasons (April through October), a grass-based reference Etr (Wright, 1996) was used with crop coefficients estimated for the specific crop/soil surface conditions (wet, etc.) of the study area. For the nongrowing season (November through March), procedures developed by Wright (1996) for simulating wintertime daily evaporation, based on earlier lysimetrically measured wintertime ET (Wright, 1993), were used to compute Etc. These procedures involve relationships similar to Eq. (3), but compute a reference ET for bare wet soil, frozen or thawed, and include effects of snow cover on daily net radiation and a wind function for wintertime conditions. Daily meteorological data required for computing ET were obtained from instrumentation located at a weather station about 300 ft from the study site. The weather station plot was about 150 x 115 ft and had an irrigated clipped-grass surface. Meteorological data were recorded with a data acquisition system.

All data were imported into a worksheet and initial Etc computations were on a daily basis. For final computation of the drainage component (Eq. 1), a smaller worksheet was developed containing data only from 84 dates when neutron meter measurements were obtained. The respective summed values of Irr, Ppt, and Etc were then used to compute D for the intervals between neutron meter measurements..

RESULTS AND DISCUSSION

Soil Water Profiles

The soil water content profiles of the 8 subplots were relatively consistent each measurement date, so for purposes of this analysis a mean profile water content was used to the 11.5-ft depth, which was the deepest measurement possible in the shallowest NMAT. Two profiles are shown in Fig. 2 representing the driest (29 Aug. 1994) and wettest (6 Aug. 1996) mean profiles measured throughout the study period. Also shown in Fig. 2 is the cumulative water with soil depth for the first neutron meter measurements (3 Nov. 1993). The water content profile on this date was between the dry and wet profiles shown. The beginning profile soil water was 44 in. The standard deviations (SD) at each measurement depth are indicated for the profiles and are representative of the spatial variability between the 8 subplots encountered throughout the study. The dry soil above the 2-ft depth of the dry profile (Fig. 2) reflects the water depletion from the root zone of the bean crop at harvest. Otherwise, the water contents below the 2-ft depth of the dry profile represent the well-drained condition for the soil of the plot area. The average volumetric water contents (averaged across all depths) of the dry and wet profiles were 29.7 and 34.5% and total profile soil water averaged 41.1 and 47.8 in, respectively. Average difference in volumetric water content between the wet and dry profiles was 4.8%, 6.7 in. Based on the difference between the wet and dry profiles (Fig. 2) and accounting for water depletion by the beans, the wet profile contained about 5.5 in of drainable water. The wet profile occurred during the third irrigation phase following relatively heavy irrigations intended to increase the rate of bromide leaching.

Shapes of the water content profiles of Fig. 2 are similar to many obtained near the study site and reflect the soil profile characteristics shown in Fig. 1. The relatively high water contents of the soil above the 2.5-ft depth occur in the calcic (Bkq) horizon. The Bka and C1 horizons (Fig. 1) extending from 3 ft to about 7 ft contain little clay and have a lower water holding capacity than the soil above or below that zone. The pore

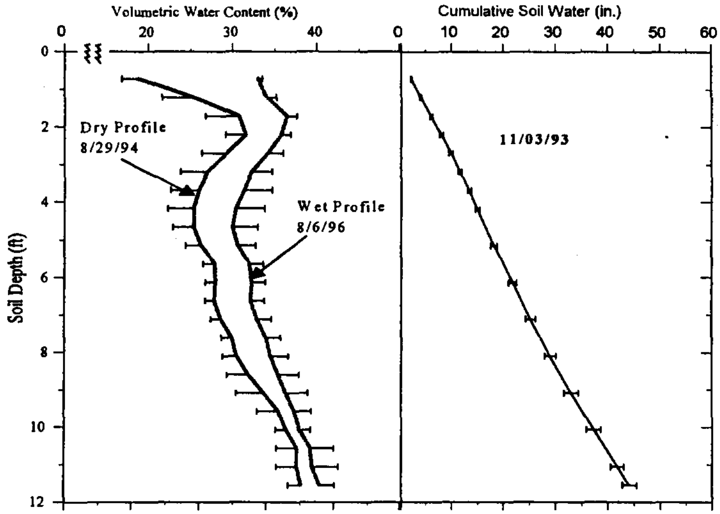

Fig. 2. Neutron Meter, Volumetric Water Content Profiles Representing the Driest and Wettest Profiles Measured (Left) and Cumulative Profile Water at the Start of the Study (Right). (Horizontal Bars are Standard Deviations)

volume of these soils is about 50% (Robbins, 1977), so even the wettest profile was considerably less wet than a saturated profile.

The rapidity of water movement through the soil profile is demonstrated by data obtained in late September 1994 (data not shown) following the harvest of the bean crop. A 4.8-in irrigation was applied during 2 days to the freshly tilled soil. Three days after irrigation ceased, the pulse of water in the previously well-drained soil had descended to about 64 in. Three days later, 6 days after irrigation, the water pulse had descended to 103 in, and the top 3 ft of the profile showed evidence of drainage. Data for the interval between 35 and 48 days after irrigation showed evidence of drainage from all soil depths.

Seasonal Variation in Evapotranspiration and Drainage

Seasonal variation of daily Etc (computed by Eq. (2)) precipitation (Ppt) and irrigations (Irr), and daily drainage are shown in Fig. 3 for the study period. Daily drainage was computed as a function of total profile soil water using an equation derived from the drainage obtained for the intervals between neutron meter measurements. Results show less drainage during the early months of the study than later due to little precipitation the first winter, relatively high ET from the bean crop, and only slightly excessive irrigation. Drainage increased somewhat during 1995 due to increased irrigation levels, and then increased markedly in 1996, initially because of the higher levels of irrigation and subsequently due to end of year precipitation (Fig. 3). Cumulative values of (Ppt + Irr),

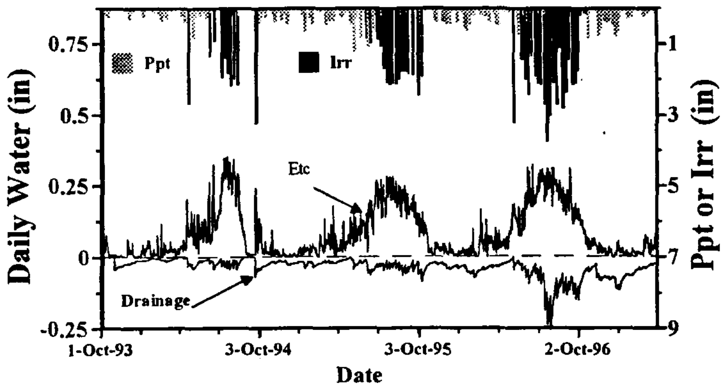

Fig. 3. Daily Values of Ppt and Irr (Right-Hand Axis), Crop Etc, and Drainage

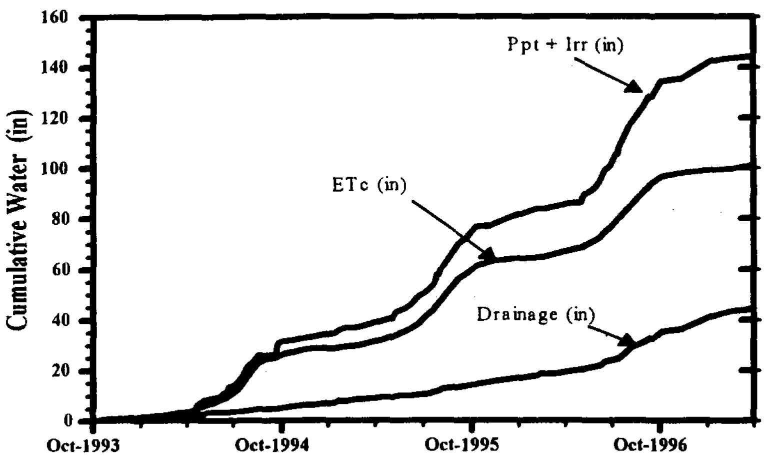

Fig. 4. Cumulative (Ppt + Irr), Etc and Drainage for a Br Leaching Study at Kimberly, Idaho, over a 40-Month Period.

Etc, and drainage summed for each of the neutron meter intervals, are shown in Fig. 4. Totals were for (Ppt + Irr): 144, Etc: 101, and D: 43 inches. Thus, total Etc for the 40-month duration of the study was 70% of (Ppt + Irr) and drainage was 30%.

Drainage during the nonirrigation season, November through March, averaged 4.4 in fo the 5-month period (0.0289 in./day). This compared with 8.9 in for the 7-month irrigation season (0.0417 in./day). Thus nonirrigation season drainage was 33% of the mean annual drainage of 13.3 in.

Bromide Leaching

Soil solution samples obtained 8 and 12 weeks after Br application showed negligible Bı contents. This was consistent with the small amount of water that moved through the soil profile during that time (Figs. 3 and 4). Average Br concentrations for the 8 subplots are shown in Fig. 5 for each of the 6 sampling depths and 33 sampling dates. By the third sampling date (3 Feb. 1994), the leading edge of the Br pulse was detected at the 1-ft depth in 5 of the 8 subplots and in a few samples from the 3-ft depth. By the fourth sampling (2 Mar. 1994, 20 weeks after Br application), some Br had arrived at the 1-ft depth at all 8 sites with concentrations ranging from 6 to 415 ppm. The 415-ppm sample was the highest detected in the study. Some Br was also detected on the fourth sampling at the 3-ft depth (2 sites), but all the 3-ft depths did not indicate Br until the eighth sampling date (30 Jun. 1994). The Br was mostly leached from the 1-ft depth by the eleventh sampling (7 Oct. 1994) about 1 yr after Br application. However, Br was still detectable at the 1-ft depth at some sites until the nineteenth sampling (5 Jul. 1995).

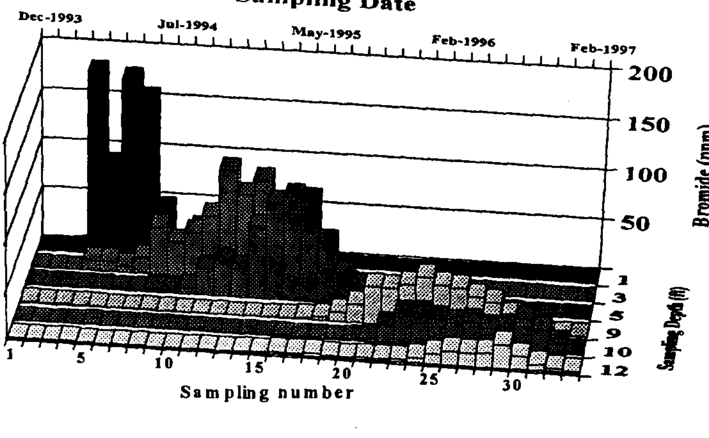

Fig. 5. Mean Br Concentrations of the Soil Solution Samples as a Function of Sampling Number and Sampling Depth.

The Br pulse moved down through the soil profile with a gradual reduction of the peak concentration, and a lengthening of the time interval for passage with depth (Fig. 5). However, even when the Br-pulse was present at any given depth, there was considerable variation in concentration among the 8 sites. For example, at the 5-ft depth on 4 Apr. 1995 (the sixteenth sampling, Fig. 5), Br concentration ranged from 15 to 173 ppm, and averaged 105 ppm with a CV of 55%. The highest mean Br concentrations for the 6 depths were: 1 ft: 182 ppm on 2 Mar. 1994, 3 ft: 109 ppm on 31 Jan. 1995, 5 ft: 105 ppm on 4 Apr. 1995, 9 ft: 48 ppm on 14 Aug. 1995, 10 ft: 31 ppm on 14 Aug. 1995, and 12.5 ft: 24 ppm on 16 Jul. 1996. Bromide was mostly leached from the deepest sampling depth by 13 Nov. 1996 except for one subplot which still showed trace amounts (7.2 ppm) at the 21 Feb. 1997 sampling.

The relationship of depth of Br leaching to total soil profile drainage is shown in Fig. 6 with the arrival, peak concentration, and departure of Br at the given sampling depths shown separately. Dates corresponding to the respective drainage amounts (shown on the upper axis of Fig. 6) are for general reference since cumulative drainage was nonlinear with time (see Fig. 4). The simultaneous detection of Br at some of the 1- and 3-ft depths on 3 Feb. 1994 (fourth sampling, Fig. 5), may have been due to macropore flow following saturation of the soil surface associated with thawing of the soil. Macropore flow also appears to have been responsible for the leading edge of the Br

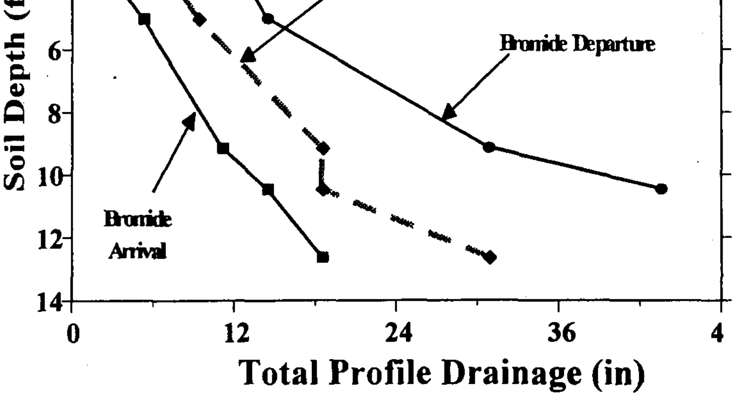

Fig. 6. Arrival, Peak Concentration and Departure of Br
as a Function of Soil Depth and Total Soil Water Drainage

pulse (Br arrival, Fig. 6) reaching particular depths well before "piston flow" would predict its arrival. For example, on average, Br was detected at the 5-ft depth on 31 Oct. 1994 (tenth sampling, Fig. 5) after 5.9 in of drainage (Fig. 6). The initial soil water content to 5 ft was 17.3 in. Thus the leading edge of the Br pulse occurred with drainage equivalent to only 35% of the antecedent water content. The peak concentration of the pulse at that depth (Figs. 5 and 6) occurred with 9.0 in of drainage or 52% of antecedent water content, while 13.1 in of drainage or 76% of antecedent water, was required to flush Br from the 5-ft depth. Thus macropore or preferential flow was effective in initially moving Br into the soil profile; however, matrix flow was essentially required to leach the bulk of the Br below the deepest sampling depth. The arrival of some Br at the 13-ft sampling depth by October 1995 occurred when drainage was only 14.5 in, or 33% of the total of 43.6 in. The relationship of the arrival and peak concentration of Br in the soil solution with soil depth was nearly linear with total drainage (Fig. 6), but the trailing edge of the Br pulse was somewhat exponentially related to drainage. On average, 44 in of drainage was needed to leach the bulk of the Br through the 12.5-ft profile. This was essentially equal to that predicted by piston flow, given the initial profile water content of 44 in (Fig. 2).

Effects of increasing the amount of irrigation to increase movement of water and hasten leaching of Br is also evident from Fig. 6. The first phase of soil wetness extended from initiation of the study until about 5 July 1995. The second phase extended from then until about 15 Jun. 1996 when the third phase started. During the first phase of irrigation management, drainage was about 20% of total applied water. This level of irrigation management produced an average of 0.017 in/day drainage, about 0.52 in/month. At this rate, if 44 in of drainage would be required to leach Br to the 12.5-ft depth, nearly 7 years would pass with desirable irrigation management before all Br was leached from the profile.

Because we applied and incorporated the Br in the surface soil, with some subsequent soil drying before the onset of winter precipitation (Fig. 3), some Br was probably drawn into the smaller pores (micropores) of the soil matrix, where it was positionally slowly available for movement by subsequent macropore flow. Thereafter this Br moved from the micropores by diffusion into the larger pores. Thus considerable leaching was required to move the Br from these pores through the soil matrix to below the 1-ft depth. Water that flowed through any existing macropores would not have displaced the water in the smaller pores. Sufficient water application was necessary to effectively displace all the water originally held in the surface soil. However, once Br had leached from the surface layer, macropore flow was effective in moving Br downward with relatively less soil water flow than required to replace the antecedent soil water. Using the data of Figs. 1 and 6, one can see that the arrival of Br at all depths was considerably more rapid than would be predicted by matrix flow drainage. However, as Br was absorbed into the deeper soil layers, drainage equivalent to the original soil water content to that depth was necessary to flush Br from the layer. Considering that the original concentration of Br in the soil solution of the 8-in surface layer was about 400 ppm, and assuming all the Br was leached from the profile, the overall dilution of Br in the leaching processes was 20:1. On the basis of drainage occurring from time of arrival of the Br pulse at 12.5 ft until its departure, the overall dilution was about 10:1. This dilution may account for the relatively low concentration of NO_3-N in the drainage water. With furrow irrigation even greater dilution may occur since a higher fraction of the drainage could be by macropore flow than with sprinkler irrigation since for, short periods of time, some of the surface soil would be at or near saturation.

CONCLUSIONS

Drainage and bromide movement occurred throughout the year, including wintertime, in the deep irrigated, silt loam soils of southern Idaho. Though macropore flow was evident in hastening the movement of some of the Br tracer downward through the soil, drainage equivalent to total displacement of the antecedent soil water at the time of Br application was necessary to flush the bulk of the Br from the soil profile. Mechanisms that reduced the Br concentration in the soil solution with increasing depth would likely also be effective in reducing NO_3-N concentrations with depth. The data indicate that one mechanism could simply be dilution as progressively more water is required with depth to move Br downward through the soil horizons. With nominal sprinkler irrigation and precipitation levels 20% greater than annual ET, more than 7 years would be required to leach Br, incorporated into the surface soil, 12.5 ft below the soil surface. This would result in about a ten-fold reduction in Br concentration in the soil solution draining below that depth.

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