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Effects of Seasonality upon Water and Solute Movement in The Unsaturated Zone

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Abstract

Change of solute concentration and depth to peak with time are frequently used to estimate annual recharge rates from tracers in unsaturated soils. It is hypothesized that seasonality (directionally varying flow) will have an effect upon tracer solute profile shape and position. A lab-column study, with a TDR system and a KCl tracer was setup to investigate this. The solute profile shape and position clearly changed under repeated regimes; upward water flow of equal volume as downward water flow, downward flow was greater than upward flow and upward was greater than downward flow.

Introduction

For soils of semi-arid to sub-humid climates, vertical water movement may seasonally vary in direction due to climate conditions and vegetative demands. Canadian prairies, with its long cold winters, wet spring snowmelts and warm dry summers with intense convective storms, can have distinct seasonal effects on water movement in the vadose zone between the bottom of the root zone (1.2 m depth) and a deep water table (>3 m depth) (Maule et al. 1993). Upward movement of vadose zone water can occur due to winter freezing (during the winter, the ground may be frozen up to two meters in depth) (Maclean 1974) or due to summer drying caused by evaporation and plant transpiration. On the other hand, wet rain periods and/or spring snowmelt, will result in excess water moving downward through the soil and into the vadose zone. Due to low precipitation and high evaporative conditions of the Canadian prairies, downward water flow, past the root zone, on agricultural fields is low, between 2 and 20 mm/yr (Christie et al. 1985; Zebarth and de Jong 1989; Joshi and Maule 2000). One approach towards the quantification of unsaturated flow and solute transport in dry regions is the use of tracer profiles (Allison et al. 1994; Scanlon et al. 1997). The rate of downward movement is determined by the position of the tracer peak relative to time, concentration, and depth. As the Canadian prairies have distinctly upward and downward flow regimes that vary with seasons and annual climate variation (Maule et al. 1993), it is hypothesized that this will affect not only the net transport rate of tracers, but also the shape and concentration of the tracer profile. To date no literature has considered the effect of flow, seasonally varying in direction, upon tracer profiles. As this might not only affect correct calculations of recharge rates but could perhaps enable further interpretation of tracer profiles, the study here is focused upon seasonality and the shape of tracer profiles. The primary focus of this study is thus the seasonality of flow amount and direction and its affect upon solute concentration with depth.

Both physical and chemical methods have been used to determine and study the groundwater and soil water fluxes; however, chemical methods are recommended especially in arid and semiarid environments (Gee and Hillel 1988; Allison et al. 1994; Scanlon et al. 1997) because the soil water fluxes are low, very variable and chemical methods are easier to use (Gaye and Edmunds 1996; Salle et al. 2001). Other advantages of using tracer methods are that natural tracers can represent a spatially uniform input to the soil water and groundwater systems and some tracers are form a part of the water molecule (Deuterium, tritium and oxygen-18).

Studying the seasonal effects on deep soil water movement will improve understanding about the contribution and loss of water and solutes from the root zone, the process of soil salinization, and potential long term pollution movement from prairie soils to the groundwater zone. Groundwater inflow and outflow can strongly affect the water quality of wetlands. As tracer profiles have become a more common way of studying recharge in deep unsaturated regimes (Allison et al. 1994; Scanlon et al. 1997; Dyck et al. 2003; Si and Kachanoski 2003), it is hoped that such a study will enable greater interpretation of field cores. Also, understanding the relationship between the seasonal effects and soil water movement gives an opportunity to better determine the seasonal contribution of precipitation and snowmelt to the soil water and ground water systems and to understand the effects of long-term climate on the ground water recharge and discharge.

The primary purpose for this paper was to study the effect of different seasonal flow regimes upon the solute concentration of the vadose portion of the groundwater zone under controlled laboratory conditions. Although a laboratory study cannot simulate all field conditions, it does offer the advantage of isolating a few important parameters and changing a complex system into something that can be easily studied. As an initial study we proposed to focus upon a sandy soil (no preferential flow paths) of homogeneous density with depth and under controlled conditions of upward and downward fluxes that would enable 20 years of seasonal effects to be simulated within four months. The specific objective of this study is to investigate the effect of repeated cycles (15-20) of directionally-varying flow upon solute profile shape and position used by tracer methods. To meet this objective three different seasonal flow regimes were studied: downward seasonal flow = upward seasonal flow, downward seasonal flow > upward seasonal flow, and downward seasonal flow < upward seasonal flow.

Materials and Methods

Three techniques have been suggested (Allison et al., 1994) for estimating recharge rate from tracer profiles in the unsaturated zone: 1) from the total amount of tracer stored in the profile; 2) from the shape of the tracer profile in the soil; and 3) from the position of the tracer peak (the peak migration method). For column studies it is not possible to determine the soil water fluxes using the first technique, the second technique there is insufficient information within the literature, and thus just the peak migration method was used in our column study.

Three soil columns were used for this study. Each column, constructed of PVC, was 1.2 m length, and 0.25 m in diameter (Fig. 1). The sand at the upper end was exposed to allow water addition by a sprinkler system or evaporative losses. Fifty pairs of TDR probes were installed in each column spaced at 20 mm intervals with depth. The horizontal distance between each rod in a pair was 12 mm. The TDR probes were installed slightly offset from each other in a helical form to avoid the influence of each other with regards to vertical water and solute flow.

Beaver Creek sand was chosen for this study. Beaver Creek sand is located southeast of Saskatoon, Saskatchewan and has been extensively researched in other column studies (Wilson 1990; Bruch 1993). A grain size analyses showed that 95.5% of the material is sand size (0.074 to 2.0 mm) with only 3.5% silt and less than 1% clay. After column packing, column 1 had a lower bulk density and a higher saturated hydraulic conductivity (K_{sat}) than the other two columns (Table 1).

To 'rain' water, a tube pump was used to supply the water to a rain cap. The rain cap was designed to add the water equally distributed to the sand surface of the column. The rain cap was 0.25 m in diameter with water received in a top inlet and water outflow through numerous equally spaced 0.5 mm (i.d.) needles. Evaporation was used to cause upward movement of soil water. To evaporate the water from the sand surface, a 90 mm diameter fan placed within a 0.25 m in diameter plastic dish was located on top of each column. A tygon tube of 9.5 mm in diameter was used for draining the water from the columns. The tube outlet was maintained in a container of water located beside the sand column. This tube was used to initially saturate the sand from the bottom, and to control the water level in the sand columns. Four soil temperature probes were located at depths of 15, 50, 200 and 500 mm. The soil temperature was recorded every hour, and average monthly soil temperature at the depth 0.02 m varied between 20.9 and

22.7 ºC during the study period. Later these values were used to correct TDR measurements and to aid evaporation interpretation.

TDR has been used widely in laboratory and field studies to measure the soil water content, electrical conductivity and other soil hydraulic properties (Ward et al. 1994; Buttle and Leigh 1995; Wang et al. 1998; Ferre et al. 1998; Amente et al. 2000; Vogeler, et al. 2000; Ritter et al. 2005; Ebrahimi-Birang et al. 2006). TDR has the advantage of allowing for continuous and simultaneous measurements of the soil water content and the electrical conductivity (Robinson et al. 2003), and it usually does not require site-specific calibration (Wraith and Baker 1991). We used a MP917 Moisture Point TDR instrument. The length of the TDR probes were 210 mm with approximately 190 mm of the probe inserted into the sand in the column. Thirteen mm of each probe was left out side the column for the TDR's cable connection. Glue was used to seal the gap between each probe and the column's wall. Methods described by Ebrahimi-Birang et al. (2006) were used to calculate soil moisture and solute concentration. The method described by Rhoades et al. (1999) was used to expressing EC data at a reference temperature (25 ºC).

The objectives were studied with three 1.05 m deep sand columns with KCl used as a tracer. The columns were maintained at moisture contents between saturation and field capacity. Seasons involved small amounts of water added or removed over short periods of time; e.g. 60 mm depth in soil of rain (distilled water) added over several hours was the 'wet' season and 60 mm depth in soil of evaporation (over several days) was the dry season. Thus one cycle (of the two seasons) took between three to four days. Three different regimes (one for each column) were studied (Table 2); upward flow was equal to downward flow, upward flow was greater, and upward flow was less than downward. The first regime, with equal downward and upward flow amounts involved moving the peak down by about a distance of about 60 mm by raining water for several hours then evaporate the same amount of water for 3-4 days, so the peak returned to the same location and the end of each cycle. The second regime, where the season of downward water flux was greater than that of upward water flux involved adding enough rain to move the peak down by 60 mm then using evaporation to move the peak up by 40 mm. The third regime used a season of upward water flux greater than that of downward water flux. It was by moving the peak down for about 40 mm by adding water for several hours then moving it up for about 60 mm by evaporation for three to four days, so the peak will move up by 20 mm each cycle.

To evaluate the change of the concentration profile shape and position, several parameters were considered. The comparison between profiles within one regime was done in term of depth and concentration of a rising point, peak, and falling point for each profile. The rising point is the point where the concentration profile starts to rise up from the baseline; and the falling point is the point where the concentration profile falls down and meets the baseline. Various basic statistical parameters were also used such as: mean, standard deviation, skewness, and kurtosis. These parameters were developed to compare profiles (cycles) within and between the three regimes of upward and downward flows. Positive skewness indicates a distribution with an asymmetric tail extending towards more positive values (values of high concentration are in the shallow (top) part of the column with more low concentrations in deeper parts), and negative skewness indicates a distribution with an asymmetric tail extending towards upward in the column. Kurtosis represents how flat or peaked the distribution is with 'platykurtic' has a flatter peak (negative kurtosis values) and leptokurtic referring to peaked distributions (positive values).

Results and Discussion

Change of dissolved salt concentration under cycling conditions

The total mass of dissolved salts increased in the three columns because of dissolution of calcium carbonate salts from the sand to the solution (Fig. 2). This was despite some loss of salts in the drainage waters during the downward movement seasons. As column 2 had a greater loss of drainage waters for the three columns it would be expected that a greater amount of salts would have been lost from column 2, however this was not the case. These variations in total mass of salts might be due to differences of initial concentration and mass of salts between column 3 and the other columns.

Tests were done to account for the contribution of calcium carbonate precipitates present in the sand, to the dissolved salt concentration as measured by TDR. These tests (not described here) showed that the contribution of dissolved salts from the sand was similar 0.84, 1.12, and 0.85 mg d^{-1} per column for columns C1, C2, and C3 respectively. The contribution rate changed with depth. A general equation (model) was developed using SPSS to describe the change in EC for each column as a function of time and depth. This model enabled the subtraction of the soil contribution to EC for the experiments done under the cycling conditions of upward and downward seasonal flows.

Changes of concentration profile shape and position under cycling conditions

1. Downward flow = upward flow

In column 1, the profile shape changed under the cycling conditions of downward flow being equal to upward flow. Any changes occurred beneath the depth of 0.265 m and after the first five cycles. The distance between the rising and falling points was 0.32 m before starting the cycles and it increased to 0.76 m after 20 cycles (Table 3, Fig. 3). The mean, standard deviation and skewness values decreased with cycles (Table 3). The decrease of the standard deviation and the kurtosis with cycling indicates that the concentration values were getting closer to the mean with cycling and the profile shape became flatter (platykurtic). The skewness values indicate that the distribution started with an asymmetric tail extending downward and with cycling conditions it tended towards a normal distribution (-0.09) in the end of the cycling period.

2. Downward flow > upward flow

Under conditions of downward flow being greater than upward flow (column 2) the concentration profile shape changed with cycles. In the depth between the sand surface and 0.235 m there were no changes in the concentration profile shape with cycles (Table 4, Fig. 4). The rising point changed after 5 cycles in term of depth and concentration. The peak depth and falling point depth and concentration increased with cycles; however, the peak concentration decreased with cycles. The increase of depths and increase in rising and falling points' concentrations were a result of the downward net movement in column 2. Skewness values show that the concentration profile before starting cycling was skewed downward and after 16 cycles it was normally distributed. Kurtosis values show that profile shape changed and became flatter (platykurtic) up to 16 cycles. The calculations of skewness and kurtosis might be effected because the lower part of the profile was lost out of the column as a result of the downward net movement.

3. Upward flow > downward flow

The third regime had a season of upward water flux greater than a season of downward water flux. The concentration profile shape changed under the repeated cycles of this regime. The rapid changes of the rising point depth and concentration during the last five cycles were because the peak got closer to the sand surface and the rising point was unobserved (Table 5, Fig. 5). The distance between the rising and falling points became wider with cycling, starting at 0.66 m and ending at 0.94 m after 20 cycles. These changes of the concentration are a result of the upward movement, so distilled water entered from the bottom of the column and salts concentrated in the top part of the column due to evaporation. The calculations of skewness indicate that the profile began relatively normal (between 0.14 and -0.08) and after ten cycles it was skewed upward in the column. Kurtosis values varied between -1.24 and +1.14, and they show that the profile shape changed under the cycling conditions in term of peakedness and flatness, respectively.

Summary and Conclusions

The aim of this study was to investigate the effects of repeated cycles of directionally-varying flow (seasonality) upon solute profile shape and position used by tracer methods. A TDR system within three sand columns with a KCl tracer was used. Seasonality can affect the solute profile shape and position used by tracer methods to estimate water and solute fluxes. To investigate the effect of seasonality on the concentration profile shape and position three different regimes of upward and downward flow were done. These regimes are: downward seasonal flow being equal to upward seasonal flow, downward seasonal flow is greater than upward seasonal flow, and upward seasonal flow is greater than downward seasonal flow.

The solute profile shape and position clearly changed under the three repeated regimes of downward and upward seasonal flows. Several parameters were calculated and considered to compare the percentage of change of the concentration profile shape under the cycling conditions among the three regimes (Table 6). The distance between the rising and falling points got wider for columns 1 and 3 respectively after 20 cycles, and there was no change in column 2 up to 16 cycles. The regimes that had the greatest change in depth of rising point, peak, and falling point were those whose net movement was dominantly downward or upward (columns 2 and 3). The change of skewness shows that the profile in the three columns became skewed upward in the column under the cycling conditions. The change of kurtosis shows that the profile in columns 1 and 2 got flatter (platykurtic) under the cycling conditions, but it was peaked (leptokurtic) in column 3 after 20 cycles (it changed by 88% after 15 cycles). The profile for column 3 became leptokurtic at the end of the cycling period in column 3 because the peak was closer to the sand surface and salts concentrated in the top of the column.

Recommendations towards improving methods and thus confirming our results would be increasing the length of the sand column such that the rising or falling points are not affected by column ends, having sand with no precipitated salts, having replicate regimes within different columns, and being able to verify packing homogeneity with depth.

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Table 1: Comparing the physical and hydraulic sand properties among the three sand columns.

Columns	Bulk density (kg m^{-3})	Porosity (m^3 m^{-3})	K_{sat} (mm min^{-1})
C1	1588	0.37	0.973
C2	1650	0.36	0.605
C3	1650	0.36	0.551

Notes: Bulk density was determined from mass of empty column and column filled with dry packed sand.
Porosity was determined using soil moisture data measured by TDR under the water table depth.
K_{sat} was measured on entire column using Darcy law under downward flow conditions.

Table 2: The variations of scenario, number of cycles, experiment time and average evaporation rate during the study period among the three columns.

Columns	regimes (total flow volume)	Water table depth (m)	Number of cycles	Study period (day)
C1	Upward = downward	0.325	20	77
C2	Downward > upward	0.335	16	51
C3	Upward > downward	0.375	20	78

Table 3: The change of the concentration profile shape under cycling conditions of upward seasonal flow = downward seasonal flow (column 1).

Parameters		Number of cycles				
		0	5	10	15	20
Rising point	depth (m)	0.39	0.27	0.27	0.27	0.27
	conc. (g L^{-1})	*0.28*	*0.30*	*0.29*	*0.30*	*0.29*
Peak	depth (m)	0.61	0.55	0.63	0.67	0.67
	conc. (g L^{-1})	*1.58*	*1.13*	*1.03*	*0.91*	*0.83*
Falling point	depth (m)	0.71	0.75	1.03	1.03	1.03
	conc. (g L^{-1})	*0.43*	*0.42*	*0.39*	*0.37*	*0.37*
Mean (g L^{-1})		0.61	0.59	0.56	0.53	0.50
SD (g L^{-1})		0.44	0.31	0.25	0.22	0.20
Skewness		1.06	0.45	0.35	0.02	-0.09
Kurtosis		-0.33	-1.46	-1.18	-1.35	-1.45

conc. = concentration, SD = standard deviation,

Table 4: The change of the concentration profile shape under cycling conditions of downward seasonal flow > upward seasonal flow (column 2).

Parameters		Number of cycles			
		0	5	10	16
Rising point	depth (m)	0.12	0.12	0.34	0.56
	conc. (g L^{-1})	*0.25*	*0.26*	*0.32*	*0.35*
Peak	depth (m)	0.44	0.50	0.68	0.80
	conc. (g L^{-1})	*1.02*	*0.86*	*0.84*	*0.74*
Falling point	depth (m)	0.56	0.64	0.76	0.96
	conc. (g L^{-1})	*0.35*	*0.52*	*0.56*	*0.59*
Mean (g L^{-1})		0.50	0.52	0.50	0.48
SD (g L^{-1})		0.24	0.17	0.17	0.18
Skewness		1.02	0.29	0.43	0.08
Kurtosis		-0.48	-0.61	-0.45	-1.65

Table 5: The change of the concentration profile shape under cycling conditions of upward seasonal flow > downward seasonal flow (column 3).

Parameters		Number of cycles				
		0	5	10	15	20
Rising point	depth (m)	0.34	0.34	0.32	0.34	0.04
	conc. (g L^{-1})	*0.34*	*0.41*	*0.46*	*0.60*	*0.24*
Peak	depth (m)	0.68	0.68	0.50	0.40	0.16
	conc. (g L^{-1})	*0.89*	*0.88*	*0.82*	*0.81*	*0.96*
Falling point	depth (m)	1.00	1.06	1.06	1.06	0.98
	conc. (g L^{-1})	*0.53*	*0.39*	*0.27*	*0.19*	*0.11*
Mean (g L^{-1})		0.58	0.62	0.63	0.62	0.52
SD (g L^{-1})		0.18	0.16	0.16	0.18	0.25
Skewness		0.14	-0.08	-0.76	-1.36	-0.34
Kurtosis		-1.16	-1.24	-0.18	1.14	-0.83

Table 6: Comparison of relative change in profile shape between start and finish of test cycles among the three different regimes.

Parameters		Total change %		
		C1	C2	C3
Rising point	depth (m)	-11	38	-29
	conc. (g L^{-1})	*2*	*18*	*-18*
Peak	depth (m)	6	34	-50
	conc. (g L^{-1})	*-136*	*-50*	*11*
Falling point	depth (m)	31	38	-2
	conc. (g L^{-1})	*-11*	*43*	*-77*
Wideness (m)		42	0	27
Mean (g L^{-1})		18	3	11
SD (g L^{-1})		82	23	23
Skewness		-47	-39	-20
Kurtosis		-40	-42	12

Total change refers to changes calculated using the profiles before starting cycles and after the cycles were done.
Wideness refers to the distance between the rising point and the falling point depths.
The percentage of change of depths and wideness was calculated relative to the total sand column depth (1.05 m).
The percentage of change of concentrations was calculated relative to the average concentration among the three columns (0.55 g L^{-1}).
The percentages of change of mean, SD, skew., and kurt. were calculated relative to the highest change among the three columns.

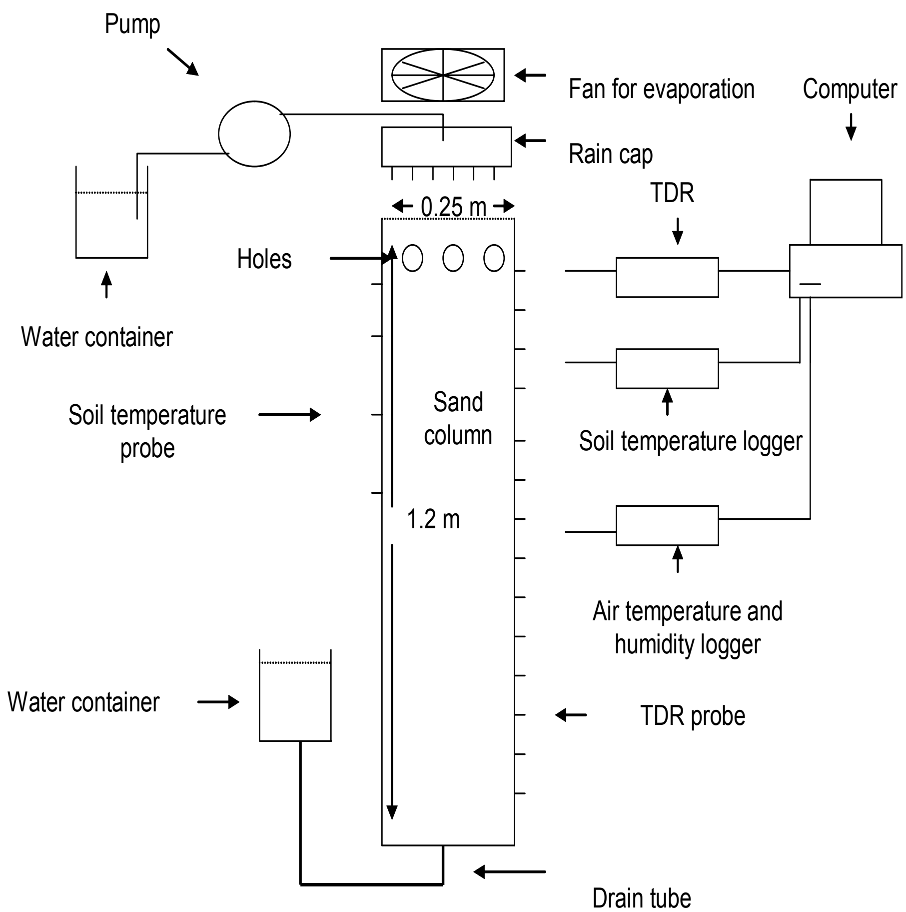

Figure 1: Soil column with instrumentation and the rain, evaporation, and the drainage systems

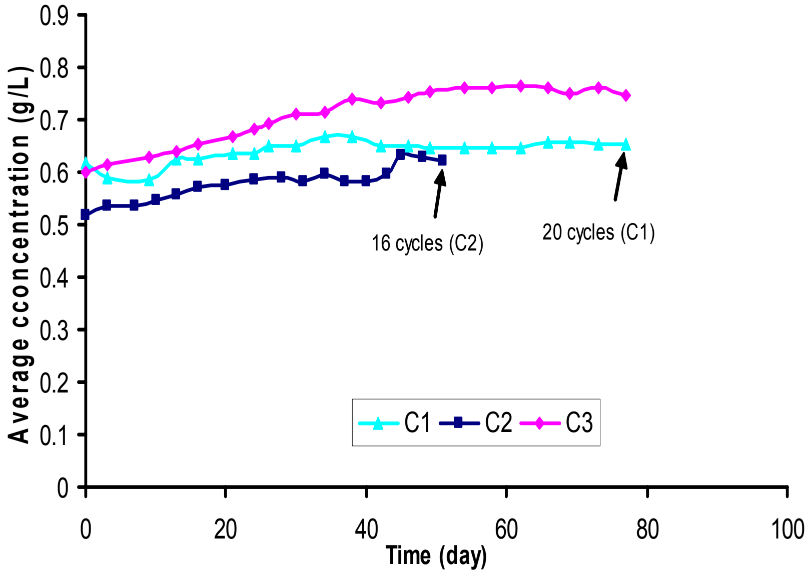

Figure 2: The average concentration as a function of time for the three columns.

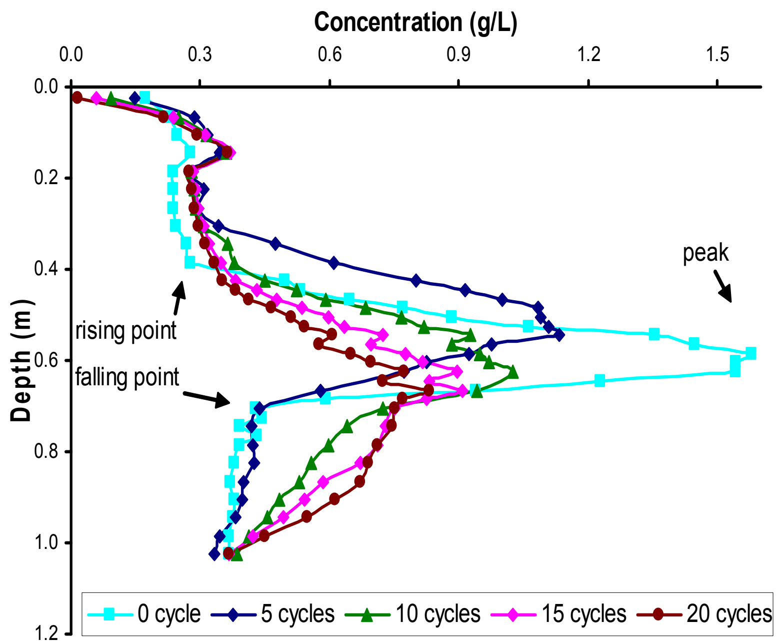

Figure 3: Shape of concentration profiles, corrected by subtracting the dissolved salts from soil, at different cycles for the regime of upward flow = downward flow (column 1).

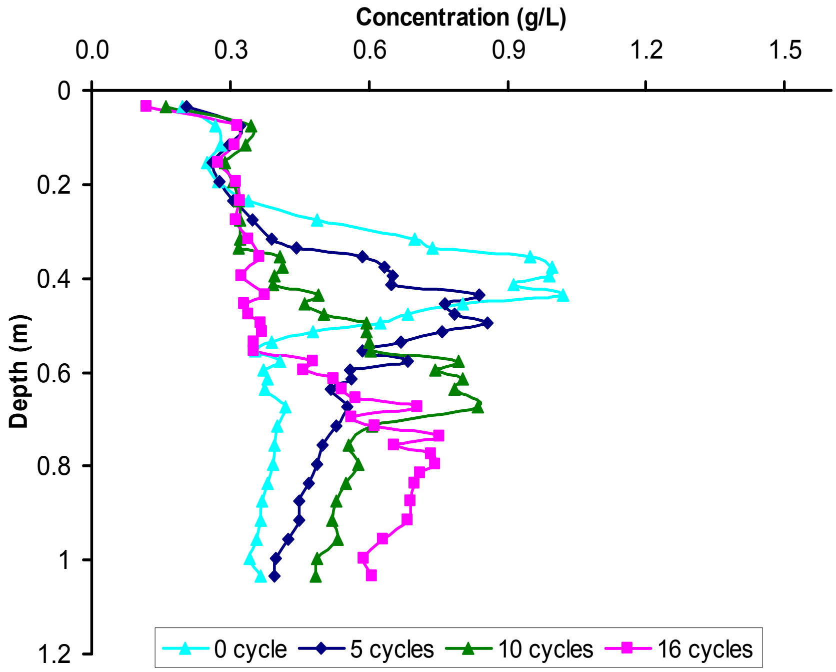

Figure 4: The change of the concentration profile shape under the cycling condition of upward flow >downward flow (column 2).

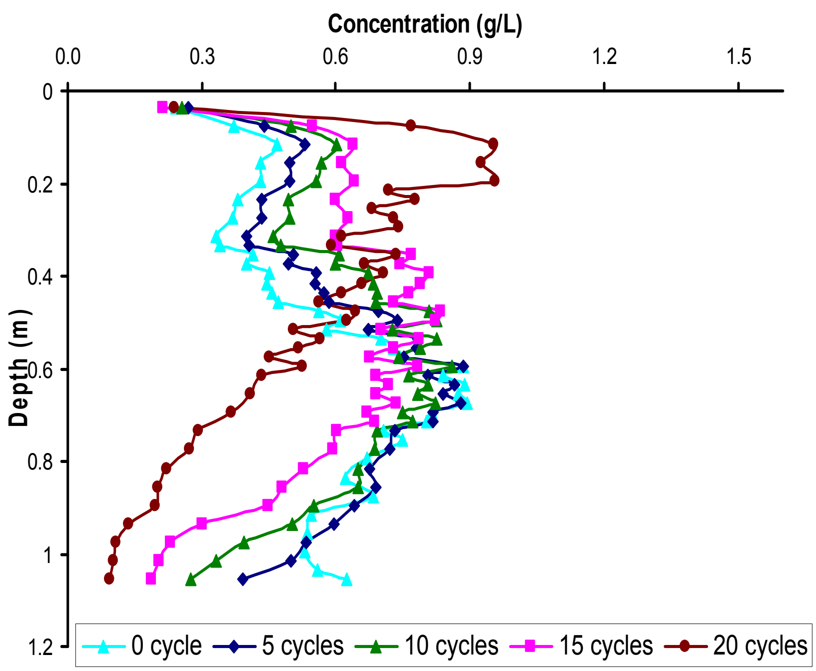

Figure 5: The change of the concentration profile shape under the cycling condition of upward flow > downward flow (column 3).