Solute Movement in large Soil Columns under different Water Flow Velocities

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Bodenlösungsbewegung in großen Bodensäulen bei verschiedenen Wasserfließgeschwindigkeiten

1. Introduction

Soil-water flow velocity can be a major factor affecting ion movement in the soil matrix. The transport of both cations and anions and their interactions with soil surface affect many aspects of soil management such as wastewater disposal, saline soil reclamation, remediation of sodic soils, and soil decontamination (HENG et al., 1999a). Therefore it is important to understand the processes that govern downward and upward solute movement through soil, and the influence of flow velocity on the concentration of different cations and anions.

The reclamation of saline soils depends upon the leaching of excess salt from the root zone. Insufficient leaching may cause extensive crop loss, while, excessive leaching, besides wasting water, may create some drainage problems, and, possibly, subsequent resalinization of the soil. The effects of slow and fast flow velocities on ion transport have also significant impacts on ion behaviours that allow to avoid these problems. Downward moving soil-water enters and leaches salt from smaller soil pores to a greater extent at lower moisture contents. TERKELTOUB and BABCOCK (1971) reported that slower rates of irrigation leached salt more efficiently than higher rates.

Solute movement experiments have shown that a readily soluble salt moves at a different rate through the soil than the water in which it is dissolved (BIGGAR and NIELSEN, 1962). This behaviour can be explained by anion repulsion or negative adsorption of salt on soil particle surfaces. Most studies on solute transport have been performed assuming that the distribution of ion concentration within a soil pore is uniform, and that the mixing of salt primarily takes place as a result of variations in the water velocity within and between soil pores (KNUPP et al., 1972).

Zusammenfassung

Untersucht wurde der Lösungstransport während überstauter Versickerung in großen Bodensäulen. Um langsame und schnelle Wasserfließgeschwindigkeiten zu erzeugen, wurde ein Wasserstand von 3 cm und 6 cm während der Versickerung an der Oberfläche von sandigtonigen Lehm- und von tonigen Lehm-Boden-Säulen konstant gehalten. Obwohl die benötigte Wassermenge bei der 3 cm Wasseranwendung bei beiden Böden geringer war als im Falle der 6 cm Wasseranwendung, war bei den 3 cm Anwendungen mehr Zeit notwendig, um die elektrische Leitfähigkeit auf ein spezifisches Niveau zu senken.

Die Leitfähigkeit des Abwassers stieg anfänglich von 11.9 dS m^{-1} auf 39.6 dS m^{-1} und begann erst auf 6.2 dS m^{-1} zu sinken bei 16 cm Wasser und dann auf 2 dS m^{-1} bei 11.2 cm Wasser für den tonigen Lehm.

Langsame Änderungen bei der Ca^{+2}- und Mg^{+2}-Konzentration gegen Ende der Versickerung wurden speziell bei tonigem Lehm festgestellt. Eine leichte K^{+1}- und Cl^{-1}-Auswaschung war bei beiden Wasseranwendungsgeschwindigkeiten zu beobachten, während die Na^{+}-Bewegung mäßig aber stetig bis zum Ende des Auswaschungsversuches war. Die Bor-Konzentration wurde in allen Versuchen bei den drei Auswaschungsereignissen nicht auf das gewünschte spezifische Niveau gesenkt. Dennoch wurde bei einem vierten Auswaschungsversuch die Bor-Konzentration von 4.8–4.5 auf 1.1 bis 1.0 mg kg^{-1} gesenkt. Die Versuchsergebnisse zeigten, daß die verschiedenen Wassergeschwindigkeiten keinen Einfluß auf den Bortransport hatten.

Schlagworte: Lösungstransport, intermittierende Flutung, Wasserfließgeschwindigkeit, Ionenbewegung.

Summary

Solute transport during ponding infiltration was investigated in large soil columns. In order to create slow and fast water flow velocities, 3 cm and 6 cm of water were ponded constantly during the leaching on the surface of a sandy clay loam (SCL) and a clay loam (CL) soil column. Although the amount of water used in the 3 cm water applications for both soils was lower than in the case of the 6 cm water applications, more time was necessary to lower the electrical conductivity (EC) of soils to a specific level in the 3 cm applications. The EC of effluent initially increased from 11.9 dS m^{-1} to 39.6 dS m^{-1} and later began first to reduce to 6.2 dS m^{-1} by 16 cm of water, and then to 2 dS m^{-1} by 11.2 cm of water for the CL soil. Slow changes in the concentrations of Ca^{+2}, and Mg^{+2} through the end of the leaching were assessed especially in the CL soil. K^{+1} and Cl^{-1} leached easily in both water application rates, and Na^{+} movement was moderate but steady until the end of leaching events. Boron concentration was not reduced to the specific desired level in all experiments by three leaching events. However, in a fourth leaching event the boron concentration was lowered from 4.8-4.5 to 1.1-1.0 mg kg^{-1}. Experimental results showed that the different water flow velocities had no effect on the boron transport.

Key words: Solute transport, intermittent ponding, water flow velocity, ion movement.

Field scale transport is typically difficult to model due to the complexity and heterogeneity of the flow and transport in natural soils (TORIDE and LEJI, 1996). Moreover, preferential flow caused by high water flow velocity in the disturbed areas can be a problem in leaching experiments. Field studies of solute transport have shown that water flow velocity may tremendously vary across a field. BIGGAR and NIELSEN (1976) also showed that flow and transport processes in most field soils are heterogeneous. All these research and studies of JURY et al. (1990) showed that it is not easy to estimate and model solute movement due to the local water flow variations.

SHUKLA et al. (2000) studied displacement experiments at constant temperatures in loam and sandy loam soil columns of different depths using anions (chloride and bromide). It was clearly demonstrated that incomplete mixing of both anions occurs at slow pore water velocities. Moreover, it was concluded that this limited mixing was also revealed by lack of interconnection between major pore networks. In addition, increasing the pore water velocity decreases the amount of immobile water in the column. HENG et al. (1999b) also reported that preferential flow of water at very high flow velocities have a profound effect on the ion concentration in the effluent and could override the effect of cation exchange in the soil.

The flow velocity can be critical in the leaching process and can determine how effectively water leaches through the soil profile. This study aims to charecterize the transport of various ions during leaching events and to determine the amount of leaching water required to reduce the salinity through the soil profile to a specific value under slow and fast flow velocities. This research quantifies slow and fast water velocities (preferential flow or bypass flow phenomena) and provides insights on the role and efficiency of this bypass on the leaching process of salt through soil. To assess these effects of flow velocity on solute transport, experiments were conducted in soil columns of large depths in laboratory.

2. Materials and methods

2.1 Soils

The saline leaching experiment was conducted in large soil columns of 0.6 m depth. Soil materials were collected from the research field of Ankara University. The texture of the surface soil is clay loam (CL) and the one of the subsurface soil taken from 1.2 m below the surface is sandy clay loam (SCL). The bulk densities of these soils are 1.24 and 1.32 g cm^{-3}, and the saturated hydraulic conductivity values are 0.96 and 1.62 cm h^{-1}, respectively for the surface and subsurface soil. The field samples were air-dried and sieved.

2.2 Salinization

The soils were treated with mixtures of chloride, carbonate, sulfate of calcium, magnesium, sodium, potassium, and boric acid to establish an approximate salinity level of 12 dS m^{-1} in term of electrical conductivity (EC). To obtain a uniform salt concentration throughout the whole soil

Table 1: Selected chemical characteristics of salinized soil
Tabelle 1: Ausgewählte chemische Merkmale der versalzten Böden

Soil	CEC $cmol_c\ kg^{-1}$	pH	$EC_{25°C}$ $dS\ m^{-1}$	$Ca^{2+}+Mg^{2+}$ $me\ L^{-1}$	Na^+ $me\ L^{-1}$	Cl^- $me\ L^{-1}$	Boron $mg\ kg^{-1}$
SCL	13.1	7.62	13.1	6.28	6.01	10.4	4.85
CL	20.2	7.86	11.9	7.32	6.26	12.8	4.51

material, these salts were dissolved in 100 liter of water. The salinization treatment was performed by spraying the salt solution on the 100 kg of soil uniformly spread on a nylon sheet. After spraying, soils were ground and sieved twice. Selected chemical characteristics of salinized soils are given in Table 1. The electrical conductivity and solute concentration were determined in 1:5 (w/w) soil: water extracts, pH and EC were measured in the soil-water saturation extract.

2.3 Leaching experiments

The experiment was carried out using large plexy-glass containers, 0.35 m × 0.4 m × 0.6 m (w × l × h) (outer dimensions) equipped with four tensiometers. The salinized, and air dried soils were moistened stepwise to 18 % (v/v) for SCL and to 22 % (v/v) for CL (pre-wetted) and then stored in polyvinyl containers for more than 3 days to achieve uniform moisture distribution. The soil columns were uniformly packed following the original bulk densities of undisturbed soils. Columns were filled by 0.05 m increments in order to provide a uniform compaction along the whole column length. A filter paper, 3-4 mm washed sand, and a nylon texture were inserted in the base of the container. Effluents were collected at fixed time intervals and analyzed for pH, EC, Na^+, Ca^{+2}, Mg^{+2}, K^+, Cl^-, and boron.

Each column was leached four times and left for evaporation processes after each leaching event. Saturated leaching was conducted by maintaining constant heads of 3 and 6 cm of water on the soil surface using a Mariotte flask apparatus with distilled water. To decide on the leaching event intervals, the EC values of the effluent were measured continuously and when a desired level of EC was reached during leaching, a siphon system was inactived to cease the water supply. Soil surface was then covered by a polyethylene plastic for few days to allow the soil column to reach an equilibrium state. After reaching this equilibrium the first evaporation event was performed by exposing the soil surface to artificial light radiation for 8 hours a day, lasting 10 days. A 100 W lamp was used to simulate artificial light radiation and was placed above the soil column to provide a constant 25 °C monitored by a thermometer.

Soil samples were taken out of the soil columns after each leaching and evaporation event. Each horizontal 0.05 m layer of soil to a depth of 0.5 m was divided into 10 samples and all ion analysis was performed on these samples. Soil water contents were determined gravimetrically for every soil portion. The amount of water evaporated during the drying period was calculated.

2.4 Analysis

Moisture content of each soil sample was measured on an oven-dry basis analysis. EC of the effluents were measured with a YSE 3200 model EC-meter, YSE Instruments Inc., USA, and pH was measured with a WTW-inolab model pH-meter, Germany. Ca^{+2} and Mg^{+2} concentrations were determined by the ETDA titration method (HEALD, 1965), Na^+ and K^+ concentrations were obtained with a flamefotometre, Cl^- concentration was assessed by the $AgNO_3$ titration method (RICHARDS, 1954). Finally boron concentration was determined by a spectrophotometer after coloration with azomethine-H (JOHN et al., 1975).

Table 2: Amount of water used for leaching
Tabelle 2: Für die Versickerung aufgewendete Wassermenge

Soil	Treatment	Water used for leaching (cm of water)				
		Event I	Event II	Event III	Event IV	Total
SCL	3 cm	16.0	12.3	15.8	22.6	66.7
	6 cm	20.2	13.0	19.4	26.9	79.5
CL	3 cm	21.1	18.4	20.2	27.4	87.1
	6 cm	22.1	20.9	22.4	31.3	96.7

3. Results and discussion

The amount of water used for every leaching event for both soils is given in Table 2. The quantity of water used in the 6 cm water applications was always higher than in the case of the 3 cm applications, and much more water was used for CL than for SCL to lower the EC value to a same specific level.

At the beginning of leaching, the EC of effluent increased sharply to 36-39 dS m^{-1} for both soils and then remained stagnant for approximately 1.5 to 2 hours, and after 2-2.5 hours of leaching EC decreased rapidly to a level of 6-9 dS m^{-1} in all experiments. To reduce the EC of both soils from 6-9 dS m^{-1} to 1 dS m^{-1}, the same amount of water used for lowering the EC from 36-39 to 6-9 dS m^{-1} was approximately required, however it required more time. For example, 16 cm of water was used to lower the highest measured level of EC 39.6 to 6 dS m^{-1} in the 3 cm water application for the CL soil. However, an additional amount of 11.9 cm of water was necessary to lower the EC of the effluent from 6 dS m^{-1} to 2 dS m^{-1} in the same experiment.

The removal of salt from soil can be characterized during three stages of the water application. The process of salt removal associated to these three stages can be characterized as fast removal rate, medium removal rate, and relatively slow removal rate (Figure 1). The salt removal rate can be defined by the slope of the graph representing EC vs. Leaching Water (Figure 1). In the first stage, in the case of fast salt removal rate, very fast concentration changes were observed. In the second stage, where medium salt removal rate are observed, medium concentration changes were detected due to the low amount of salts retained on the surfaces of flow channels. In the third stage, when the salt removal rate is slow, salt leaching continued at a very slow and relatively constant rate.

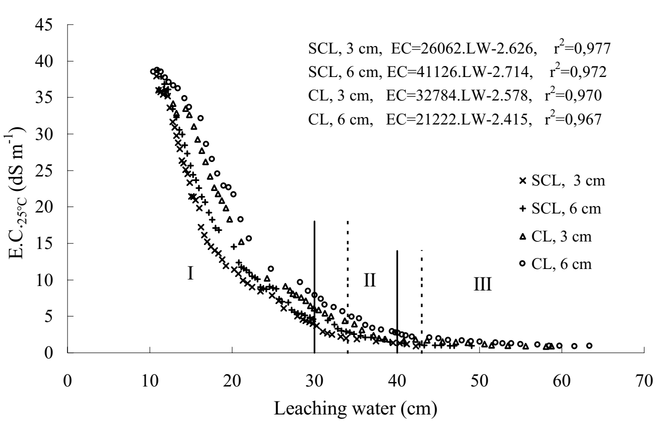

Figure 1: Changes in EC of soils with leaching for SCL and the CL soils (LW: Leaching Water)

Abbildung 1: Veränderungen der elektrischen Bodenleitfähigkeit in Abhängigkeit von der Versickerung bei tonigem Lehm- und sandig-tonigem Lehmboden (LW: Versickerungswasser)

In the case of the SCL, the first stage occurred between 0 and 30 cm of water application, the second stage took place between 30 and 40 cm of water application and the third stage occurred after 40 cm of water application until the end of the leaching event. These values for first, second and third stages are respectively 0-34 cm, 34-43 cm and from 43 cm to the end of the leaching event, for water application in the case of the CL. These values are shown using solid lines for SCL and dash lines for CL in Figure 1.

Generally the effect of coarse textured soil on the ion movement is less than in the case of fine textured soil. SHUKLA et al. (2000) reported that solute arrival in effluent solution is ahead when soil texture is finer. The type and amount of clay minerals play an important role for retaining and ions removal from soil. SELASSIE et al. (1992) attributed the difference between the amounts of irrigation water needed for salinity and sodium removal to the texture of soils. The transport of many ions through soil is strongly affected by their reactions with the solid constitutes. BOND and PHILLIPS (1990) stated that one of the most common of such reactions is cation exchange.

It was found for both soils that less water was used in the 3 cm water application than in the 6 cm water application. For example, to lower the EC value of effluent to less than 2 dS m^{-1}, 34.2 cm of water was used for the 3 cm application, while 37.1 cm of water was necessary for the 6 cm water application experiment in the SCL soil. The difference in the amount of water in both treatments for the CL soil was 4.7 cm (39.2 and 43.9 cm). Water flow traveling at high velocity through macropores has less opportunity than water moving at slow velocity to leach the salts from the root zone. Therefore, PRENDERGAST (1995) concluded that bypass is best defined by hydraulic terms, rather than in terms of salt leaching.

The amount of water used to reduce the EC of soil to any given value with different ponding conditions can be computed by the equations given in Figure 1, which were derived using the regression analysis with EC as the dependent variable and amount of leaching water as the independent variable. The leaching efficiency (LE) was calculated at the end of each leaching event using the following equation;

$$LE = \frac{EC_0 - EC_1}{EC_0}$$

EC_0 is the electrical conductivity of the pre-leaching event and EC_1 is the electrical conductivity of the effluent at the end of a particular leaching event. In the first leaching event, the EC value for the SCL soil in the 3 cm water application ranged from 39 dS m^{-1} to 3.8 dS m^{-1} and in the 6 cm application, EC values ranged from 38.8 to 4.6 dS m^{-1}. From this results the leaching efficiencies were computed as 0.90 and 0.88, respectively for 3 cm and 6 cm applications. The other calculated leaching efficiencies are given in Table 3. It was determined that the leaching efficiencies in the case of the 3 cm water application in both soils were higher than those calculated in the case of the 6 cm water applications. The highest leaching efficiencies were obtained during the first stages of all experiments. The leaching efficiency decreased as the number of leaching events increased. Relatively high leaching efficiency coefficients in the third stage for the case of the CL soil, when compared with the SCL soil, were due to the salt in the soil and indicated the continuation of the salt transport process.

Table 3: Leaching efficiencies of the leaching events
Tabelle 3: Auswaschungseffizienz der Versickerungsversuche

Soil	Treatment	Event I	Event II	Event III
SCL	3 cm	0.90	0.68	0.31
	6 cm	0.88	0.67	0.25
CL	3 cm	0.88	0.62	0.42
	6 cm	0.86	0.58	0.49

TERKELTOUB and BABCOCK (1971) reported that slow rates of irrigation leached the salt more efficiently than high rates; and that increase in salt leaching efficiency associated with decreased rate of the water application was much more pronounced with the Yolo Soil, which contains 32 % clay, than in the case of the Hanford soil, which contains 12 % clay. KNUPP et al. (1972) found that Cl^- and H^+ concentrations in the effluent increased as the flow velocity decreased, and that these changes were related to the total ion concentration, the thickness of the diffuse double layer and the zones of mobile and immobile solution. KELLER and ALFARO (1966) studied the effect of the water application rate on the leaching efficiency using a single soil with different salt and initial soil moisture levels, and claimed that the leaching efficiency was improved by decreasing the water application rate.

Transport of Ca^{+2} and Mg^{+2} through the soil column especially for CL was slow but continued until the end of the leaching experiment, and Na^+ movement in soil was slower than in the case of Ca^{+2} and Mg^{+2}. To reduce Na^+ concentration from 153.8 me L^{-1} to 8.7 me L^{-1} at the end of the third event, 44.1 cm of water was used in the 3 cm water application, and 52.6 cm of water was used in the 6 cm application to achieve to 6.7 me L^{-1} for the SCL soil. It was determined for the CL soil that Na^+ concentration decreased from 160.7 me L^{-1} to 6.0 me L^{-1} using 59.8 cm of water in the 3 cm application, and from 160.7 me L^{-1} to 8.5 me L^{-1} by 65.4 cm of water in the 6 cm application.

The effect of different water flow velocities on the movement of K^+ for both soils was not significant. However, slight changes were found in the Cl^- concentration with regard to the different water flow velocities. By calculating the skewness of the travel time distribution and the efficiency of macropore flow on the solute transport, DYSON and WHITE (1987) concluded that not all the pore water participated effectively in chloride transport and confirmed that Cl^- dispersion increased as the flow velocity increased. BUCHTER et al. (1995) studied the effects of flow heterogeneity on solute transport in stony subsoil in a large undisturbed gravel monolith. Two consecutive pulses (runs) of a Cl^- solution were used for leaching in the monolith. It was reported that the flow paths of water remained invariant and might be an intrinsic feature of a soil medium for any given water content.

The results of the boron movement through the soil columns are given in Figure 2. The boron leaching through the soil is much more difficult than in the case of the chlorine or sulfate. A fourth leaching event was applied to remove boron from the soil column since the previous 3

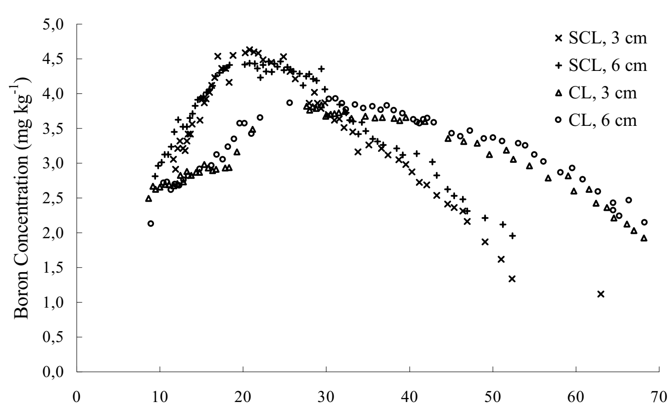

Figure 2: Changes in boron concentrations in soils with leaching for SCL and CL soils
Abbildung 2: Veränderungen der Bodenborkonzentrationen durch Versickerung bei sandig-tonigem Lehm- und bei tonigem Lehmboden

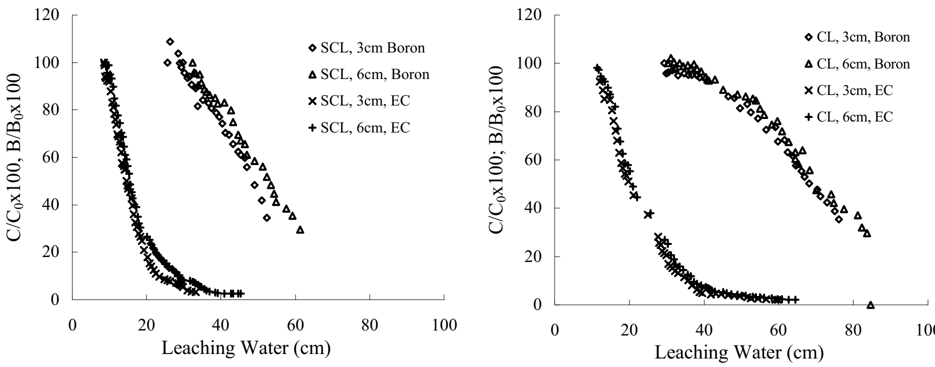

Figure 3: Comparison of the changes in EC and the boron concentration in SCL and CL soils
Abbildung 3: Vergleich der Veränderungen der Leitfähigkeit und der Borkonzentration bei sandig-tonigem Lehm- und bei tonigem Lehmboden

leaching did not reduce the boron concentration to the desired level. Moreover, the experimental results showed that leaching the soil column with 3 and the 6 cm constant ponding did not make any differences in removing the boron from the soil profiles. Slow and fast water flow velocity through the soil pores did not affect the boron transport.

JURINAK (1998) found that the amount of water used for removing the boron from a soil with continuous ponding of water was two times greater than the one of other salts. OMAR et al. (1998) also reported that the required amount of water for boron leaching with 5 cm intermittent ponding irrigation was 4-5 times as much as the salt leaching.

The boron concentrations for both soils steadily increased in the effluent at the beginning of the leaching. From Figure 2, it can be observed that the boron concentration for the SCL soil increased more sharply and decreased faster than the one for the CL soil. By using 57.9 and 68.8 cm of water in the 3 cm and the 6 cm water ponding applications, the boron concentration reduced to 1.12 and 1.01 mg kg^{-1} for the SCL soil, respectively.

For the CL soil, 72.2 cm of water in the 3 cm water application was used to reduce the boron concentration to 0.84 mg kg^{-1}, and 83.7 cm of water in the 6 cm water application were necessary to reduce it to 1.14 mg kg^{-1}.

The comparative changes in the EC and boron concentrations are shown together in Figure 3. Approximately, 75% of the boron was not leached in both experiments – 3 and 6 cm – for the SCL soil. In the case of CL soil, 85 % of the boron was not leached in the similar experimental conditions. These founding indicates that boron removal from soil profiles is limited, particular in heavy soils.

4. Conclusion

Solute transport under different water flow velocities was studied in large soil columns. To create different water flow velocities through the soil profile, 3 and 6 cm of overlaying water depth were constantly maintained during the leaching events. We found that a low water flow velocity caused a high leaching efficiency in both the SCL and the CL soils. This is very important especially in dry regions, in particular if saline soil reclamation is attempted. Another finding was the very fast concentration change at the beginning of salt leaching in both soils, followed by, smaller changes, although the same amount of leaching water was provided. However, this was not true for the boron transport. Still most of the boron remained in the soil profiles when the salt concentration was reduced to an acceptable level, with no significant effect of the water flow velocity on the boron transport.

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