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Effect of Water Application Methods on Salinity Leaching Efficiency in Soils of Different Textures

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Effect of Water Application Methods on Salinity Leaching Efficiency in Soils of Different Textures

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in

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by

Setrag Christopher Cherchian

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ABSTRACT OF THE THESIS

Effect of Water Application Methods on Salinity Leaching Efficiency in Soils of Different Textures

by

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Master of Science, Graduate Program in Environmental Sciences
University of California, Riverside, June 2019
Dr. Laosheng Wu Chairperson

Irrigated agriculture has been in a quandary of sustaining its productivity for centuries while attempting to cope with soil and water salinity issues that continue to devastate crop yields. Several of the research gaps associated with current irrigation methods include how to assess leaching requirements and efficiency for different soils, crops, and irrigation regimes. The objective of this project was to test water application methods on salinity leaching efficacy. Three soils of different textures (clay, loam, and sandy soils) were collected from fields. The soils were air-dried and sieved (1.7 mm) and were used to pack the soil columns (10-cm dia. and 30-cm height) for the leaching experiments. Treatments of the column experiments included continuous ponding, intermittent ponding, and unsaturated water application with three replicates per treatment using the three soils. Furthermore, the HYDRUS 1D model was used to analyze the experimental data and to evaluate the leaching efficiency under different irrigation schemes. Our results showed that intermittent ponding was the most effective water application method for salinity leaching in the loamy soil, and that the unsaturated water application was the most effective water

application method for salinity leaching in the clay soil by achieving 75% salt removal out of the columns using the least amount of water. The sandy soil had no difference in leaching efficiency among water application methods, therefore continuous ponding is recommended if time is not a limiting factor in water supply. The findings from this research will allow farmers to improve their water management practices and reduce groundwater contamination from excessive irrigation.

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1. Introduction

Irrigated agriculture has been in a quandary of sustaining its productivity for centuries, while also attempting to cope with soil and water salinity issues that continue to devastate crop yields. The formation of salinized soil is not only related to soil parent materials, climate, and topography, but also induced by anthropogenic activities such as improper irrigation practices. Improper quantity and quality of irrigation water and poor soil internal drainage conditions often lead to soil salinization (Kitamura et al., 2006).

The surge in human population has increased the water demand for urban and agricultural uses. Unfortunately, according to the United Nations Department of Economic and Social Affairs (UNDESA), approximately 1.6 billion people live in areas where they face water scarcity, and agriculture accounts for about 80 percent of the nation's consumptive water use in 2018 (USDA, 2019). Thus, increase water use efficiency in agriculture is critical to sustaining water resources and improving agricultural water management practices, especially in arid and semiarid regions where soils are most affected by salts.

Salinity refers to the presence of dissolved inorganic solutes in aqueous samples, such as Na^+, Ca^{2+}, Mg^{2+}, and K^+ for the cations and Cl^-, SO_4^{-2}, and HCO_3^- for the anions. Salinity concentrations have direct effects on plants and soil physical properties. Excess salinity within the rootzone reduces plant growth rate because it increases the energy that the plant must expend to acquire water from the soil by depressing external water potential and it causes ion toxicity and nutrient imbalance (Bernstein, 1975). Sodic soils are characterized by a disproportionately high concentration of sodium in their cation exchange complex relative to magnesium and calcium. Sodicity degrades the soil structure due to the swelling, slaking, and dispersion of soil particles (Quirk and Schofield, 1955) leading to reduced air and water permeability in soils (Oster and Shainberg, 2001) and poor aggregate stability and tilth (Goldberg et al., 1988). Agriculture induced salinity and sodicity not only influence the chemical and physical characteristics of soils but also greatly affect soil microbial and biochemical properties (Haynes and Rietz, 2003) Unfortunately, according to ASCE (American Society of Civil Engineers), all irrigated water contains salts, and are concentrated in the crop rootzone because crops take up pure water and leave them behind to accumulate from evapotranspiration.

Thus, repeated leaching, the net downward movement of water, is required to remove salts to prevent it from concentrating in the rootzone beyond the crop's salt-tolerance level to not interfere with crop yield (Monteleone et al., 2004). Leaching involves the dissolution of soluble salts in the soil, the passage of the resulting solution through the soil profile, and the consequent removal of salt from the root zone, where its efficiency can be defined as the quantity of soluble salts leached per unit volume of water applied (Tanji, 1990). Proper irrigation restores the soil's water deficit without using excess amount of water and establishes sustainable water management criteria. California and many other regions around the world are geographically located in drought-stress regions which are essential in managing the use of water with efficiency to sustain its resources.

Excess leaching causes a progressive rise to the water table, which can result in groundwater capillary rise into the root zone and infusing the soil with salts. Thus, attempting to leach the soil without the establishment of suitable drainage can further exacerbate the salinity problem. In many regions where natural drainage is slow, it can become impractical to sustain irrigation and as a result can degrade soil quality and force farmers to abandon large areas of land.

Disproportionate leaching not only wastes tons of water but also tends to remove essential nutrients and impedes aeration by waterlogging the soil (Hillel, 2003). Nutrients such as nitrogen and phosphorous that are leached out to the groundwater can contaminate surface waters from runoff by causing eutrophication (Carpenter et al., 1998). Thus, the application of excessive water during leaching can be detrimental for the environment and crop production, making it imperative to assess the optimum quantity of water that must be applied for leaching purposes.

Hoffman and van Genuchten (1983) developed a steady state model that determined the linearly averaged, mean rootzone salinity by solving the continuity equation for the one-dimensional vertical flow of water through soil. The fraction of the amount of water that drains beyond the root zone relative to the amount of applied irrigation water is defined as the leaching fraction (LF). When the crop root zone has become too saline for the existing plants, it requires extra water to leach out the accumulated salts by increasing the LF. Maintenance leaching is necessary to keep the average rootzone salinity below the plant threshold EC levels. The U.S. Salinity Laboratory (Smith and Hancock, 1986) developed the concept of leaching requirement (LR), the minimum LF that is required over a growing season for a quality of water to achieve maximum yield of a given crop, and it has been utilized as an irrigation management tool to control salinity affecting plant growth and has become a vital component in water conservation (Hoffman and van Genuchten

1983). Rhoades (1974) introduced an equation (Eq. 1) to estimate LR by correlating crop salt tolerance (EC_t) and irrigation water salinity (EC_{iw}):

$$LR = EC_{iw} / (5EC_t - ECiw) \qquad (1)$$

However, the conventional LR models only assume steady-state conditions. Mathematically, a steady-state flow analysis does not include a time variable; whereas, a transient-flow analysis does, i.e., in a leaching experiment the water content and solute concentration at a given point remains constant with time in a steady-state system and can vary in a transient-state system.

There are many factors that can violate the steady-state assumption, such as variations in irrigation water quality, soil profile water content, water application method and rate, precipitation/dissolution of mineral phases, and rainfall. The present guidelines based on steady-state analyses were found overestimated the leaching requirements under field conditions (Letey et al., 2007). Furthermore, drip and micro-spray irrigation systems usually wet only a section of the rootzone, and thus water and salt movement are not one-dimensional. Applying water as recommended by the normal LR based on the assumption of one-dimensional flow and transport under drip irrigation can result in excessive leaching (Wallender, et al., 2011). This further justifies the reasoning behind progressing from the conventional one-value LR and adopting a comprehensive approach to determine the leaching requirement by considering the relationships among water salinity, water application rate, soil texture, and the amount of leaching.

Intermittent Application

Flow and mixing of the solutes are dominated by the larger pores, while the smaller pores within the aggregates act as a sink or source of solute. During leaching, water does not always flow uniformly through the soil, but may preferentially through macropores (Tanji, 1990; Jury et al., 1991). Preferential flow decreases the effectiveness of leaching (Seyfried et al., 1987).

Water application can change the soil water flow regimes. Intermittent leaching is described by Al-Sibai et al. (1997) as successive cycles, each consisting of two periods: a water-application period and a rest period. During the application period water is continuously ponded on the surface. The column is saturated, and the flow is steady. This is a case of miscible displacement, and this period is termed the 'displacement period' or 'on time'. During the rest period the column is saturated, but flow is interrupted for a predetermined time. No convective transport will occur, and it is assumed that the solute transfers only by radial diffusion from the immobile-water region within the spheres to the mobile-water region between them. Therefore, this period is termed the 'diffusion period' or 'off time'. For this reason, intermittent ponding can be more efficient because it allows time for solutes to diffuse to the surfaces of aggregates during the rest period and subsequently be removed in macropore flow. During the rest period flow stops, and solute reallocates within the aggregates by diffusion.

With the application of the pulse (intermittent) method, solutes can diffuse to the surface of aggregates without flow of irrigated water during the rest period. While in the subsequent irrigation, such solutes at the interface of the large pores would be leached without hesitation (Al-Sibai et al., 1997). Several experiments have shown that leaching efficiency increased under intermittent flow (Oster et al., 1972; Dahiya et al., 1981; Meiri & Plaut, 1985). The differences in leaching efficiency among the leaching methods are caused by differences in hydrodynamic dispersion and molecular diffusion (Gardner et al., 1957). Dahiya et al. (1981) also indicated that leaching intermittently allows more time for movement of water through small pores by allowing solutes to diffuse from the non-mobile to the mobile water regions, thus improving the leaching efficiency. Solute is leached at a slower rate through macropore flow because a decreasing proportion of the flow occurs through micropores (Oster et al., 1972). Thus, intermittent leaching allows more time for solutes to diffuse from the micropores between applications, and consequently it improves the leaching efficiency by decreasing the proportion of flow in large pores.

Many field studies have shown that intermittent leaching is more efficient in terms of water usage and solute movement than continuous leaching (Miller et al., 1965; Oster et al., 1972; Addiscott and Rose, 1978; Dahiya et al., 1981), which was attributed to the fact that soil is drier under pulse application, resulting in water flowing through the finer pores more effectively and allowing more efficient displacement of the saline solution (Hoffman, 1980). The pulse water application principle can be used effectively to control the wetting of the soil profile during the infiltration process (Zur, 1976). According to (Cote et al. 2000), leaching can be enhanced at the field scale by making use of the intermittent dry periods by assessing the amount of water saved to leach a given number of solutes.

Solute Transport under Unsaturated Conditions

Several researchers have concluded through laboratory procedure (Nielsen and Biggar, 1961) and field experiments (Nielsen 1966) that leaching salts will be more efficient under unsaturated conditions where more salts can be removed per unit depth of water leached because the degree of saturation and the rate of water movement in each soil can affect the transport of salts. Previous soil column experiments have shown that a small reduction in soil water content during leaching can increase the efficiency of chloride removal from the soil by decreasing the water application rate (Keller and Alfaro, 1965). Unsaturated conditions allow enough time for solutes to diffuse to the surface of aggregates so that it can subsequently be removed by the main convective dispersion transport stream through larger pores (Barnard et al., 2010) and minimize the effects of bypass flow (Hoffman et al., 1980).

Most of the irrigation water in the field flows into the cracks in the topsoil by the form of preferential flow or finger flow when the infiltration rate exceeds the soil matrix intake rate (Topp and Davis 1981; Kosmas et al. 1991; Mitchell and van Genuchten, 1993). Under unsaturated conditions, a large portion of the applied water flows through the soil matrix, thereby reducing the amount of preferential or macro pore flow to allow the salts to leach more effectively. In partially saturated soil, irrigation and rainfall infiltrating along macropores can permeate into the soil matrix and effectively displace the saline water that is stored within the soil matrix and transport it down along the macropore network. In contrast, under saturated matrix conditions, the infiltration of water from the macropores to the matrix is limited because the lack of advective water transfer between the macropores and matrix limits the salt transfer from the matrix to the macropores from molecular diffusion (Callaghan et al. 2017). This results in greater amounts of irrigation water required to leach the salts out of the rootzone and reach a desired salt concentration in the soil to be reclaimed. Thus, less irrigation water is required when applying the water under unsaturated conditions when leaching salinized soil.

The application of irrigated water using micro-sprinkler irrigation is an effective method for reclaiming the highly saline soils that are widely distributed (Chu et al., 2016). However, sprinklers must have an application rate less than the maximum percolation rate of the saturated soil to maintain unsaturated conditions and provide efficient leaching capabilities (Oster et al., 1972). The percent saturation of the soil under the sprinkling application decreases exponentially with the application rate (Keller 1964.) Since previous research has proven that leaching efficiency is expected to decrease with water content, the benefit of utilizing the sprinkling method is to create continuously unsaturated soil conditions while removing surface ponding. Ponding can cause a loss of efficiency due to inefficient salt displacement by water flow in larger pores and soil cracks during the initial stages of infiltration and to nonuniform infiltration resulting from overland flow to the more permeable areas of a ponded field (Oster et al., 1972). This leads to a significant waste in irrigated water.

In sprinkler irrigation, solute transport is governed by the combined processes of convection and diffusion, while only convection is the main governing process in continuously ponding irrigation (Qadir et al., 2000). Hoffman (2009) proposed the leaching coefficient for ponding and sprinkling to be 0.3 and 0.15 respectively, where the smaller leaching coefficient value corresponds to a greater leaching efficiency based on application rate.

Effect of Soil Texture on Leaching Efficiency

Further research needs to be conducted to evaluate the leaching efficiency of irrigation methods in reclaiming degraded soil of various soil types (Dai et al., 2015; Xu et al., 2015). The difference between the amount of irrigation water required for transporting and removing salts from the soil profile is attributed to the soil texture (Hosseini et al., 2015) due to their difference in hydraulic conductivity (Shat et al., 2011). Ajdary et al. (2007) applied the Hydrus-2D model to nitrate leaching in soils under drip irrigation using different emitter discharge rates and fertigation strategies. They discovered that soil texture had a significant effect in leaching, course textured sandy loam soils having the most leaching while silt clay soils did not result in any leaching. However, the reverse is true under unsaturated conditions, where soils with larger particles have poorer soil water infiltration and experience decreased desalination in comparison with fine soils (Huang et al., 1995).

Finer soil textures can store more water and solutes within their aggregates compared with coarse textured soils (Xu et al., 2015). Hoffman proposed an equation (1980) for the salt transport efficiency under one-dimensional leaching (Eq. 2):

$$k = (C/C_o)\ (D/D_s) \qquad (2)$$

where C is the salt concentration in the soil, C_o is the initial salt concentration in the soil, D is the depth of leaching water applied, D_s is the depth of the soil to be leached, and k is an empirical coefficient that reflects the differences in saturated volumetric water content and leaching efficiency among soil types. Coarse textured soils have a low water content and high leaching efficiency under continuous ponding with k = 0.1, whereas the reverse is true for finer textured soils (k = 0.3).

Structured clay soils benefit mostly from leaching under unsaturated flow conditions (Tanton et al., 1995; Armstrong et al., 1998) and intermittent applications (Tagar et al., 2010; Hoffman, 1980). Under saturated conditions, fine soils such as clay retain some of the original soil solution during continuous leaching; whereas drier soils with intermittent or sprinkling leaching methods allow a larger percentage of water flowing through the fine pores and displacing the saline solution more efficiently (Hoffman et al., 1980). Thus, smaller k values were found under intermittent ponding irrespective of soil type (Hoffman et al., 1980). However, Phogat et al. (2012) determined that intermittent water application has a smaller impact on leaching fraction and salt removal in light textured soils. This is because sandy soils mostly have larger pores that predominate the convective transport processes due to the lack of finer pores present in coarse textured soils. Thus, soil texture can play a significant role in leaching requirement that must be taken into consideration.

The hydraulic properties, especially those of fine textured soils, are greatly affected by the total concentration and ionic composition of the soil solution (Nielsen et al., 1986.) Single positively charged cations, such as sodium, harmfully affect the hydraulic properties of fine textured soils because they cause the swelling between individual platelets of clay particles and the detachment of small clay particles from larger units that restricts their transport processes, thereby decreasing the hydraulic conductivity at any given water content. The leaching process in cracking clay soils is not limited by diffusion, but rather by its insufficient flow through large pores (Tanton et al., 1988). Despite the bypassing that takes place under macropore flow, leaching is very efficient when clay soils are not fully saturated and results in the deflocculation of the sodic clay soil (Tanton et al., 1994).

The above discussion illustrates the importance of water application on salinity leaching. However, most of the studies were conducted in field conditions, and inconsistent reports were observed under different environmental conditions. Thus, investigations are still needed to further evaluate leaching efficiency of irrigation methods in reclaiming degraded soil of various soil types under laboratory conditions that have better control of influence factors. Our goal is to narrow the knowledge gap between the leaching requirement and the leaching efficiency on irrigated cropland with the overall objective to test water application methods on salinity leaching efficacy in three soils of different textures (clay, loam, and sandy soils). Specifically, this experiment aims to (1) evaluate the salinity leaching efficiency of the intermittent ponding application utilized over sandy, loamy, and clay soil textures; and (2) test the effect of the water application rate on salinity leaching efficiency to reduce the amount of water used for leaching and determine whether unsaturated conditions play a significant role in leaching efficiency under various soil textures.

2. Materials and Methods

Sample Preparation

Disturbed surface soil samples (0-20 cm) were collected from three on-going research projects. The field sites included the University of California Desert Research &

Extension Center (DREC) in Holtville, CA, the South Coast Research & Extension Center (SCREC) in Irvine, CA, and an almond orchard in Kern County, CA. The field sites were chosen based on their different soil textures ranging from clay (DREC), sandy (SCREC), and loamy soil (Kern County) respectively. The collected bulk soils were air-dried, gently crumbled to pass through a 1.7 mm sieve and mixed thoroughly before packing.

Particle size analysis was performed to verify soil texture using the Beckman-Coulter LS 13-320 (Beckman-Coulter, California) laser particle size analyzer. The porosity of each soil type was estimated indirectly from measurements of the particle density and dry soil bulk density using standard methods (Klute and Dinauer, 1986). The porosities of the packed soil columns were approximately 0.54 for the clay, 0.44 for the sandy, and 0.37 for the loamy soils.

Column Setup

Nine plex-glass cylinders were used in this experiment with 37-cm length and 9.5-cm internal diameter. In each column, a cellulose sheet was placed on the bottom of the column, followed by 1 cm of homogeneous grain sized sand to facilitate the free vertical drainage ensuring one dimensional movement of water and to act as a filter. The air-dried soils were then packed tightly in 5cm increments uniformly by continuous tapping of the side walls and auguring and pressing the soil during the soil filling procedure to obtain approximate field soil bulk density.

After packing, the vertically placed soil columns were slowly saturated from the bottom up with a saline solution (created by mixing 0.90g/L of $CaCl_2$ and 0.48 g/L of NaCl in distilled water with EC = 3 dS/m, SAR = 16 and pH = 7.55) applied by Mariotte bottles.

After water appeared at the surface for 24 hr., the columns drained from the outlets installed at the bottom for three days to ensure stabilization of the soils (Figure 1). The wetting and drying cycle further promotes the compaction of the soils similarly to field conditions.

Figure 1. The soil columns were saturated by saline solution from the bottom to the top using Mariotte bottles to establish initial distribution of soil salinity for the leaching experiments.

Finer textured soils retain water and salts more effectively than coarse textured soils because finer soils have a higher surface area that allow them to hold more available water. Thus, it is important to evaluate and compare the initial soil salinity concentrations of each respective soil texture before proceeding to the leaching experiment. The salinity concentrations of the soils were measured every three centimeters from the 30-cm soil columns using the 1:5 soil/water extraction ratio method (Rhoades, 1982) with four replicates each. The Accumet Research AR50 Conductivity Meter (Artisan Technology Group, Illinois) was used to measure the electrical conductivity (EC) of the soils and leachate for this experiment. The electrical conductivity of the saturated paste extract (EC_e) was estimated from the EC of a 1:5 soil/water suspension ($EC_{1:5}$) (Khorsandi and Yazdi, 2011):

$$EC_e = 5.60 EC_{1:5} - 4.37 \qquad (3)$$

and the concentration of the soil water (EC_{sw}) was estimated from the concentration of the saturated paste extract (EC_e) by multiplying EC_e by 2.06 (Benes, 2014).

The salinity distribution in the soil columns illustrates the relationship between soil texture and salinity concentration with respect to depth (Figure 2). The finest clay textured soil appeared to have the highest initial EC among the saturated soil columns, where most of the salts were retained in the top half of the soil column. The loamy textured soil had high initial EC, but experienced decline after the 5 cm mark in the soil column. The coarsest textured sandy soil appeared to have the lowest initial EC in the saturated soil columns, where the salts were retained poorly due to the low water holding capacity.

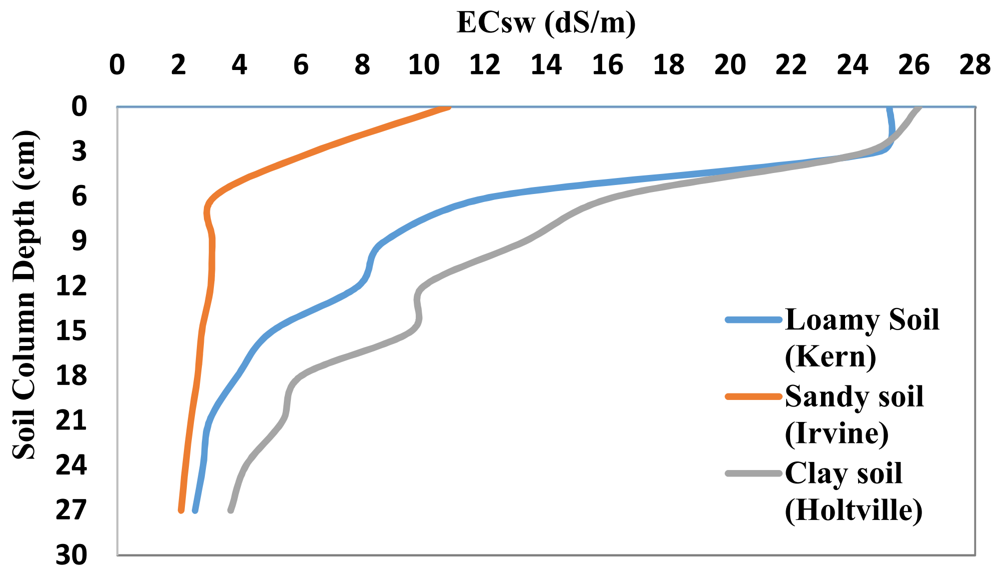

Figure 2. Depth profile of the soil columns demonstrate the relationship between soil texture and salinity concentration. The finer textured soils retain more salts compared to coarser textured soils.

Leaching Experiment

To assess the salinity leaching efficiency, we tested three different soil textures (sandy soil, loamy soil, and clay soil) and applied three treatments each (continuous ponding, intermittent ponding, and unsaturated water application) using tap water (400 µS/cm and 5 SAR) to leach the soils. We evaluated three replications for each treatment, which resulted in a total of 27 soil columns.

Mariotte bottles were used to maintain constant water supply at the top of each column. For continuous and intermittent ponding application, the ponding head for the soil columns was maintained at one cm. Drainage tubes were connected to the bottom outlets of the soil columns to collect the leachate, which was collected continuously in successive aliquots to measure the EC concentration throughout the leaching experiment (Figures 3 and 4). Matric suction from vacuum of approximately 100 cm was applied from the bottom of the columns to facilitate the collection of leachates for the clay soils. A vacuum regulator was utilized to maintain the desired vacuum pressure. For the sandy and loamy soil, the outlets were kept in free drainage.

Volume of the leachate was also measured to assess the salinity leaching efficiency (e.g., pore volume necessary to achieve 75% salt removal). The total leachate was approximately two pore volumes for each of the 30 cm soil columns to develop a breakthrough curve for each respective leaching treatment. Pore volume [V/V_o] was used as a dimensionless time to evaluate the leaching efficacy since we were more interested how much water is required to leach certain amount of salinity. It was calculated by multiplying the porosity of the respective soil texture with the volume of the soil column (1790.7 cm^3). Time was recorded as well for modeling purposes.

For the continuously ponded application, the water was continuously applied to the soil surface at a constant ponding head until the desired amount (~ 2 pore volumes) of leachate was collected. For the intermittent ponded (pulse) application, the water was turned on for about 8 hours and turned off for about 16 hours every day until the desired amount (~2 pore volumes) of leachate was collected. This method of pulse application allowed the flow of leachate to be interrupted for a predetermined time and let for both convective flow and diffusive flow to be attained during the leaching process.

Figure 3. Illustration of the Mariotte bottles applying water to the soil columns at a constant head under gravimetric flow and collection of leachates from the drainage outlets. Ponding is present given saturated conditions. The water valve in the figure is used to turn the water application on and off for the intermittent treatment.

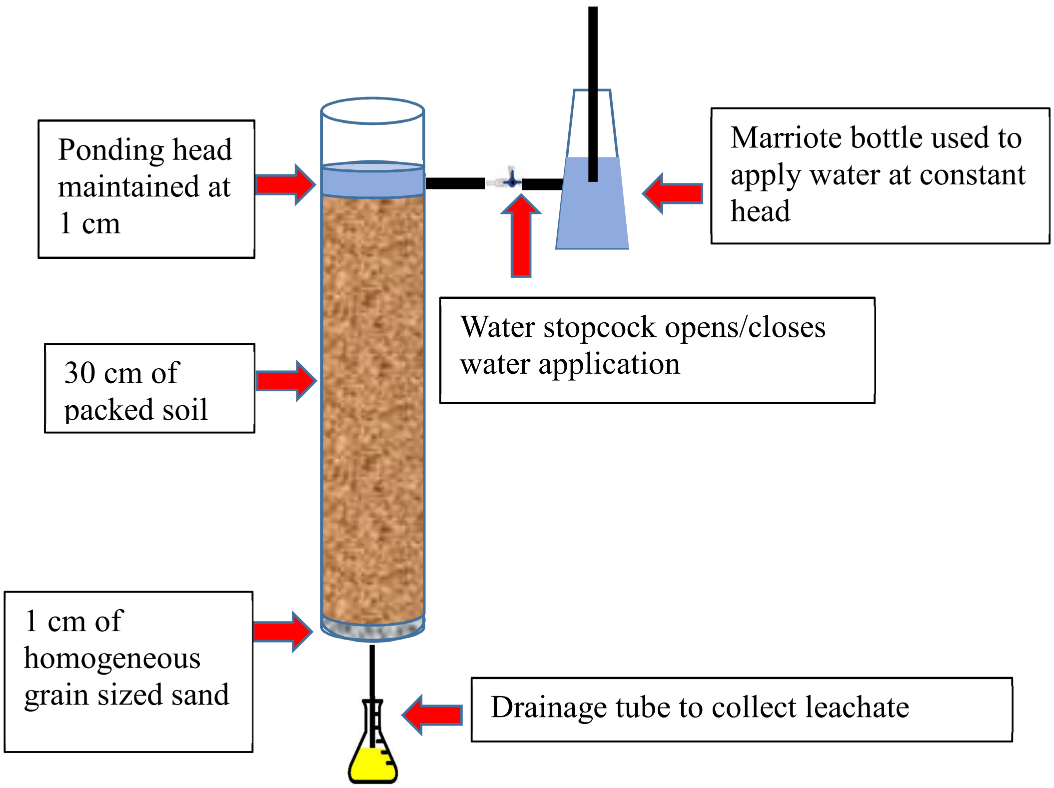

Figure 4. Schematic of leaching experiment under continuous and intermittent ponding.

Unsaturated Water Application

The procedure for the soil column experiments treated under continuously unsaturated application was like the other water application methods with a few adjustments. White fine-grained sandy glass beads were applied 2 cm on the bottom and on the top of the packed soil in the columns, which acted as porous plates with sufficiently high air entry suction of about 100 cm and high hydraulic conductivity without limiting soil water movement. The glass beads provided the hydraulic connection between the head- and tail-water reservoirs and the pore fluid in the unsaturated soil (Benson and Gribb 1997). A 5-mm diameter and 9 cm long plastic tube with three small holes drilled were attached to the brass fitting of the soil columns located on top of the packed soils underneath the sandy glass beads to ensure the low application necessary for unsaturated flow. They were attached tightly to make certain that no air escaped in the tubing. The opposite end of the tubes was covered to only allow water to flow from the small holes. The Marriote bottles applied water to the surface of the white glass beads below the soil surface via capillary flow to provide a pressure of -2 cm (-0.2 kPa) at the soil surface (Figures 5 and 6) until equilibrium was reached for each respective soil type to provide uniform and low application rates. Aluminum foil was used to cover the soil columns to prevent water loss from evaporation.

Figure 5. Illustration of a Marriote bottle applying water to clay soil under unsaturated conditions. The hydraulic head of the bottle is underneath the soil column demonstrating capillary flow. Vacuum matric suction of approximately 100 cm was applied underneath the columns to facilitate leachate collection for the clay soil.

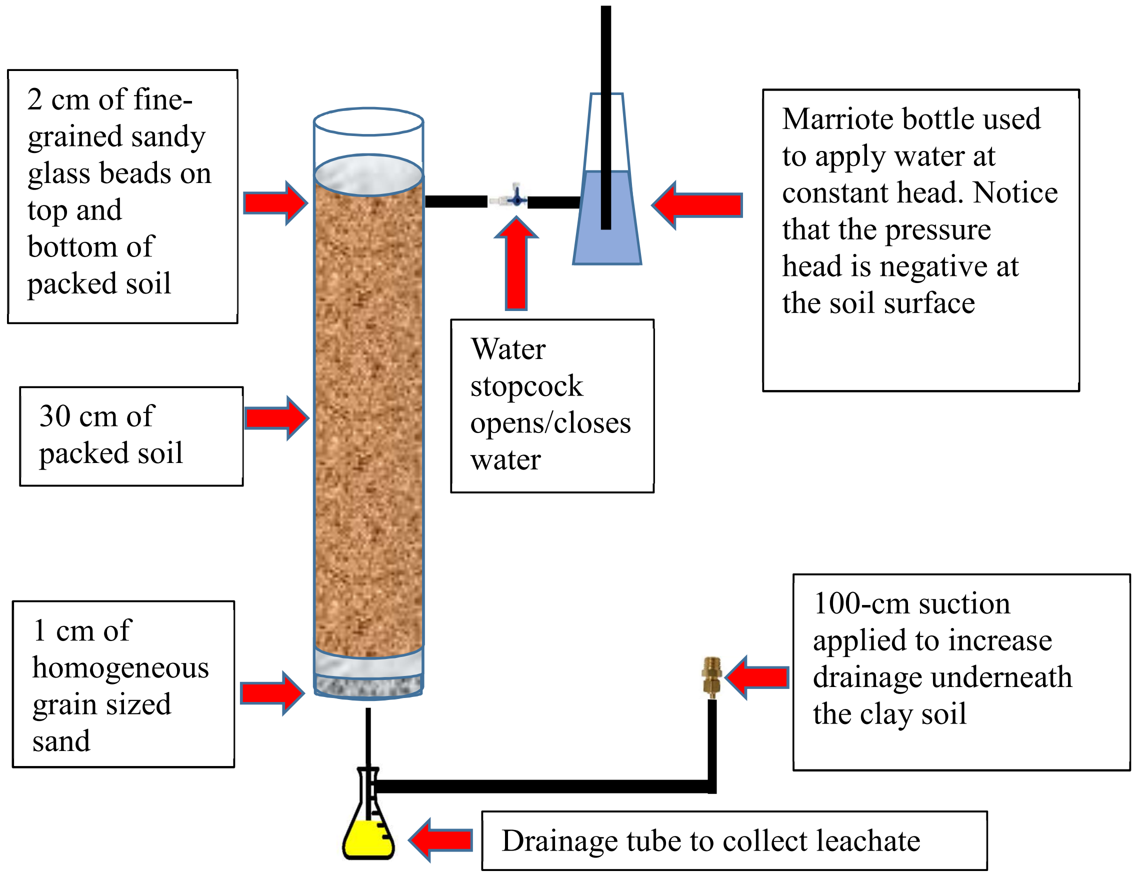

Figure 6. Schematic of leaching clay soil under unsaturated water application.

3. Statistical Analysis of the Salinity Leaching Efficiency Experiments

To evaluate the leaching efficiency, we were more interested in the amount of salinity leaching when certain amount of water was applied. Thus, we used the dimensionless time variable of pore volume (PV) in the X-axis for the breakthrough curves, i.e., the simulated and observed concentrations were plotted against the drainage amount expressed as PV [V/V_o] from each soil column to evaluate their respective leaching effectiveness. 75% salt removal was used as an indicator for evaluating salt leaching efficiency (Ahmed et al., 1999; Barnard et al., 2010). Removing the remaining 25% of excess salts is not efficient in terms of the amount of water required (Barnard et al., 2010). Thus, the three cumulative TDS (total dissolved solids) curves for each experimental treatment were plotted onto the same chart to integrate 75% of the total area under the curve and assess the mean pore volume of water necessary to achieve 75% removal of the total amount of salts in the columns. TDS was converted from EC to evaluate the total amount of salts drained from the soil columns (Walton, 1989). Figure 7 displays an example of the cumulative TDS curves for leaching the sandy soil with the continuous ponded application.

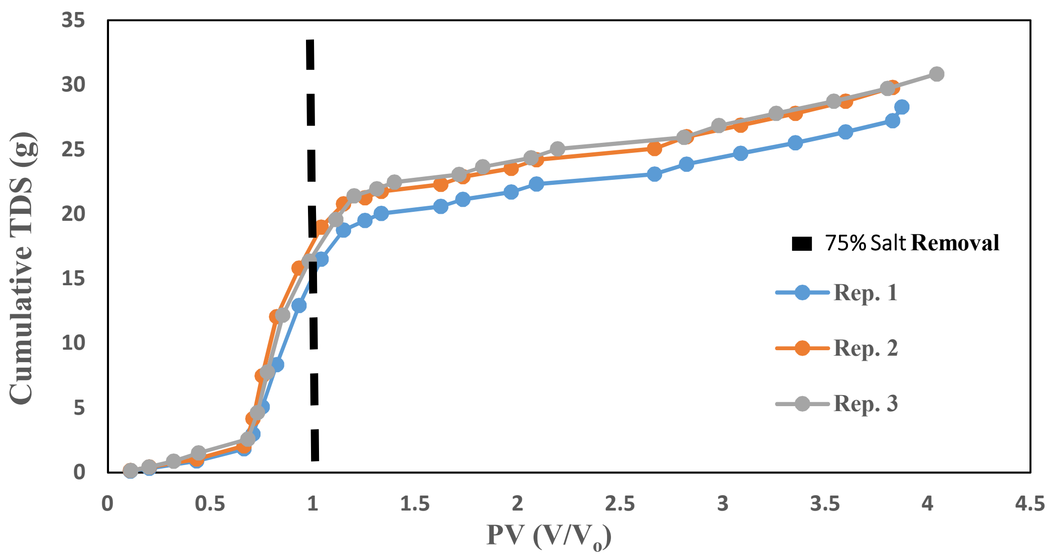

Figure 7. Cumulative TDS curves of three replicates for leaching the sandy soil with the continuous ponded application to assess pore volume for removing 75% of salts.

MATLAB, a numerical computing software, was used for data analysis and statistical computation. The three replicates for each water application treatment were interpolated onto the same X-axis (pore volume) and normalized with respect to the peak values. Given the small number of replicates (3) for each treatment, 1000 random samples were bootstrapped from each treatment dataset (3 replicates) to statistically test the pore volume requirements necessary to reach the 75% salt removal mark after two pore volumes were leached from the 30 cm soil columns. The bootstrap method is a resampling technique used to estimate population statistics by sampling a dataset with replacement. Samples were constructed by drawing observations from the original sample of three replicates and generating 27 different configurations (3^3) one at a time and returning them to the data sample after they have been chosen (Hesterberg, 2015). A 1000 samples were bootstrapped for sampling to ensure all 27 configurations were covered and randomized. Since the 75% pore volume is an integration of the area under the cumulative TDS curve, shuffling the pore volume is equivalent to shuffling the curve as a whole. This allowed statistical conclusions to be made from a small sample size without assuming Gaussian distribution of the samples.

A 95% confidence interval test was also performed after bootstrapping to determine any significant differences between the water application methods on leaching efficiency among soil types by assessing the differences from the means of the pore volumes that were required to achieve 75% salt removal for each treatment. This will determine which water application method is the efficient practice for salinity leaching purposes among soil types.

4. Model Simulation

Physical-process based computer models can help to explore the mechanisms that influence the salinity leaching efficiency. In this study, the HYDRUS 1D software was used to simulate the one-dimensional variably saturated water flow and solute transport in the 30-cm vertical soil columns for each soil texture to analyze the soil column experimental results. The software uses linear finite elements to numerically solve the Richards equation (Eq. 4) for saturated-unsaturated water flow and the Fickian-based advection-dispersion equations (Eq. 5) for solute transport in the liquid phase (Šimunek et al., 2005).

$$\frac{\partial\theta(h)}{\partial t}=\frac{\partial}{\partial z}\left[\mathrm{K}(h)\left(\frac{\partial(h)}{\partial z}+1\right)\right]-S \qquad (4)$$

$$\frac{\partial\theta c}{\partial t}+\rho\frac{\partial s}{\partial t}=\frac{\partial}{\partial z}\left(\theta D\frac{\partial c}{\partial z}\right)-\frac{\partial qc}{\partial z}-\Phi \qquad (5)$$

In Eq. (4), z is the vertical coordinate upward [L], t is time [T], h is the pressure head [L], θ is the water content [L^3 L^{-3}], S is the sink term [T^{-1}], and K(h) is the unsaturated hydraulic conductivity function. In (Eq. 5), c is the solution concentration [M L^{-3}], s is the sorbed concentration [M M^{-1}], D is the dispersion coefficient accounting for both molecular diffusion and hydrodynamic dispersion [L^2 T^{-1}], q is the volumetric fluid flux density [L T^{-1}] evaluated using the Buckingham Darcy law, and Φ is a sink-source term.

However, the standard advection-dispersion equation for solute transport was only applied for the sandy textured soil that mostly contain larger pores in its medium. The dual-porosity flow model equations (Eq. 6a-6c) were used to simulate the solute transport in the loamy and clay textured soils because the equations consider a fraction of the water content to be immobile, which is practical for soil textures containing finer pores in their medium (Šimunek and van Genuchten, 2008). The governing solute transport equations of the dual-porosity model are as follows:

$$\frac{\partial \theta_{mo} c_{mo}}{\partial t} + f_{mo} \rho \frac{\partial s_{mo}}{\partial t} = \frac{\partial}{\partial z}\left(\theta_{mo} D_{mo} \frac{\partial c_{mo}}{\partial z} \right) - \frac{\partial q_{mo} c_{mo}}{\partial z} - \phi_{mo} - \Gamma_s \quad (6a)$$

$$\frac{\partial \theta_{im} c_{im}}{\partial t} + (1 - f_{mo}) \rho \frac{\partial s_{im}}{\partial t} = \Gamma_s - \phi_{im} \quad (6b)$$

$$\Gamma_s = \omega_{mim} (c_{mo} - c_{im}) + \Gamma_w c^* \quad (6c)$$

in which solute exchange between the two liquid regions is modeled as the sum of an evident first-order diffusion process and advective transport (where suitable). In (Eq. 6), c_{mo} and c_{im} are concentrations of the mobile and immobile regions [M L^{-3}], respectively; s_{m0} and s_{im} are sorbed concentrations of the mobile and immobile regions [M M^{-1}], respectively; D_{mo} is the dispersion coefficient in the mobile region [L^2 T^{-1}], q_{m0} is the volumetric fluid flux density in the mobile region [L T^{-1}], Φ_{mo} and Φ_{im} are sink-source terms that account for various zero- and first-order or other reactions in both regions [M L^{-3} T^{-1}]; f_{mo} is the fraction of sorption sites in contact with the mobile water content (dimensionless), ω_{mim} is the mass transfer coefficient [T^{-1}], and Γ_s is the mass transfer term for the solutes between the mobile and immobile regions [M L^{-3} T^{-1}]. Equation (6a) describes solute transport in the mobile (macropore) zone, Eq. (6b) is a mass balance for the immobile (micropore) domain, while (Γ_s) in Eq. (8c) describes the rate of mass transfer between the mobile and immobile domains. The second advective term (Γ_s) in Eq. (6) is equal to zero for the mobile-immobile model since that model does not account for water flow between the two regions. In the dual-porosity model, c^* is equal to c_{mo} when $\Gamma_w > 0$, and c_{im} when $\Gamma_w < 0$.

The upper boundary condition for water flow for the continuously ponded and unsaturated water applications were set at a constant pressure head (Marriote bottle), where pressure heads (h) were fixed to be positive (ponding) and negative (unsaturated), respectively. The upper boundary condition for water flow for the intermittent application was set at a variable pressure head due to the time-variable pressure head that was entered as a time series. For the sandy and loamy soils, a lower boundary condition of 'seepage face' was imposed on all three treatments because water freely drained through the soil column exposed to the outer atmosphere. The clay soil columns utilized a pressure head of h = -100 cm at the seepage face due to a vacuum suction was imposed at the bottom of the soil columns.

Concentration flux was set for the upper boundary conditions for solute transport because the concentration of the infiltrating water was specified (3 dS/m). A zero-concentration gradient was established at the lower boundary condition for solute transport due to the free drainage from the bottom outlets of the soil columns for all leaching treatments as well.

Hydraulic parameters (Table 1) were estimated using the water retention and hydraulic conductivity functions (1980) described by van Genuchten's equations (Eqs. 7-8):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m}; \text{ h} < 0 \qquad (7a)$$

$$\theta(h) = \theta_s; \text{ h} \geq 0 \qquad (7b)$$

$$K(h) = K_s S_e^{\lambda}\left[1 - (1 - S_e^{1/m})^m\right]^2 \qquad (8)$$

where θ_s is the saturated volumetric water content [L^3 L^{-3}], θ_r is the residual water content [L^3 L^{-3}], h is the pressure head [L], m, α, n, and I are empirical factors where m = 1 – 1/n, K_s is the saturated hydraulic conductivity [L T^{-1}], and λ is the shape factor. S_e is the relative saturation, and is defined (Eq. 9):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_m} \qquad (9)$$

The parameters θ_r, θ_s, α, n, and l used in the HYDRUS-1D model were obtained from the measured θ (h) by fitting the soil water retention model (Phogat et al., 2010). Particle size distribution and bulk density of the soils were estimated using the Rosetta model (Schaap et al., 2001) applied in HYDRUS 1D. An air-entry value of -2 cm in the Mualem-van Genuchten function was used for the clay soil because it improves the description of the hydraulic conductivity near saturation by introducing a small correction in the water retention function. Dispersivity [L], and immobile water content (ThImob) from the dual porosity model were specified in the solute transport parameters (Table 2). Dimensionless fraction of adsorption sites (Frac.) is equal to 1 because all absorption sites are in contact with mobile water.

Table 1. Soil hydraulic parameters used in HYDRUS 1D simulations for the three test soils under ponding, intermittent, and unsaturated water applications.

Leaching treatments	Qr	Qs	Alpha	n	Ks	I
Sandy Cont.	0.02	0.5	0.064	1.38	3.2	0.5
Sandy Inter.	0.02	0.5	0.064	2.5	1.6	0.5
Sandy Unsat.	0.02	0.5	0.064	1.16	2.2	0.5
Loamy Cont.	0.048	0.45	0.11	1.25	1.6	0.5
Loamy Inter.	0.048	0.45	0.11	1.18	0.375	0.5
Loamy Unsat.	0.048	0.45	0.08	1.15	1	0.5
Clay Cont.	0.068	0.38	1.15	1.15	0.0115	0.5
Clay Inter.	0.04	0.38	0.03	1.2	0.05	0.5
Clay Unsat.	0.068	0.38	0.009	1.2	0.0029	0.5

Table 2. Solute transport parameters used in HYDRUS 1D simulations for the three test soils under ponding, intermittent, and unsaturated water applications.

Leaching treatments	Disp.	Frac.	ThImob. *
Sandy Cont.	0.18	1	0
Sandy Inter.	0.22	1	0
Sandy Unsat.	1	1	0
Loamy Cont.	0.15	1	0.3
Loamy Inter.	0.2	1	0.2
Loamy Unsat.	1.23	1	0.1
Clay Cont.	3	1	0.05
Clay Inter.	0.5	1	0.03
Clay Unsat.	5	1	0.02

*Thlmob = 0 for sandy soils because physical nonequilibrium not considered since dual porosity model not used.

R^2 (regression of predicted vs observed) and RMSE (root mean squared error) were used to assess the model simulation results with respect to the experimental data with time as the variable in the X-axis:

$$R^2 = 1 - \frac{SS_R}{SS_T} \qquad (10)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad (11)$$

where SS_R is the regression sum of squares, SS_T is the total sum of squares, P_i is the simulated value, O_i is the observed value, and n is the total number of samples.

5. Results

The observed and simulated data were plotted onto the same breakthrough curve for each respective treatment to evaluate leaching efficiency under different water application methods using the statistics defined in the previous section. The observed data represent the average of the three replicates from the experiments.

Salinity Leaching in the Sandy Soil

Figures 8A, 8B, and 8C illustrate the breakthrough curves for the observed and simulated data under continuously ponding, intermittent ponding, and unsaturated water applications, respectively, for the sandy soil columns. Table 3 displays the simulation and experimental results for the leaching of the sandy soil columns. All data points represent the mean EC concentrations of the three replicates for each treatment.

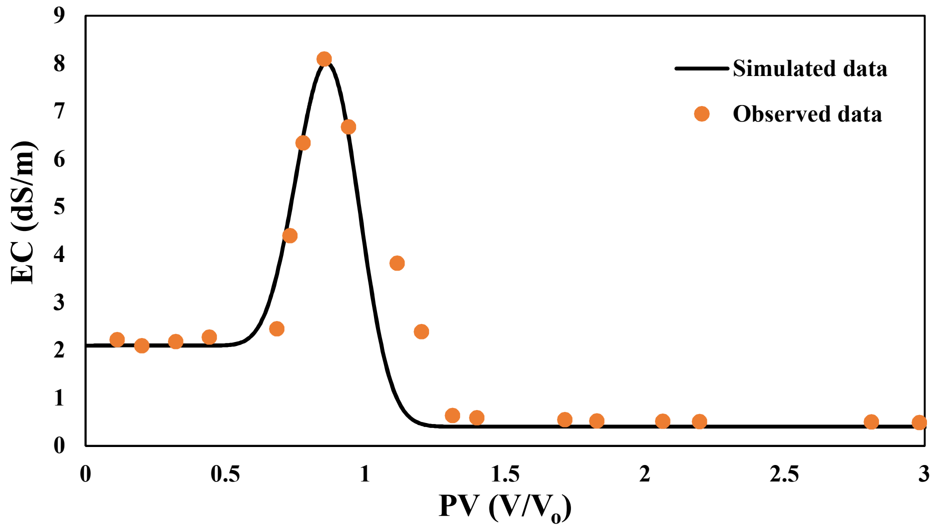

Figure 8A. Salinity leaching breakthrough curve in the sandy soil under continuously ponding.

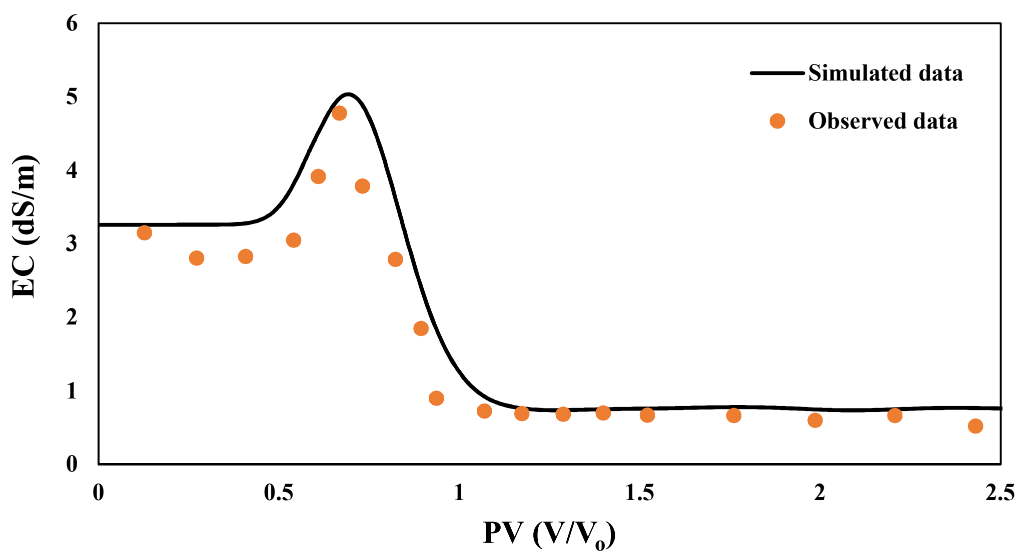

Figure 8B. Salinity leaching breakthrough curve in the sandy soil under intermittent ponding.

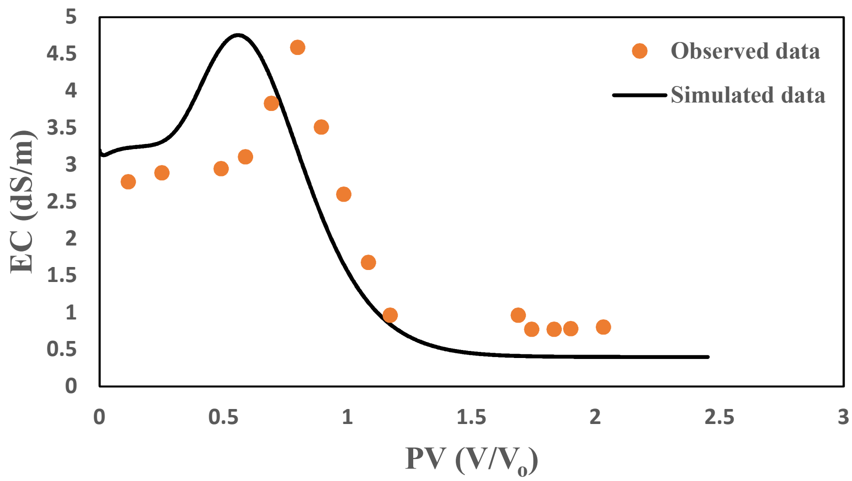

Figure 8C. Salinity leaching breakthrough curve in the sandy soil under unsaturated water application.

Table 3. Simulated and experimental results for salinity leaching in the sandy soil.

Water application method	**R^2**	**RMSE (dS/m)**	**75% salt removal PV (V/V_o)**
Cont. ponding	0.942	0.0723	1.02
Inter. Ponding	0.955	0.0642	0.984
Unsat. application	0.983	0.0907	1.02

The simulation results appear to fit the experimental data successfully, achieving high R^2 and low RMSE values. The continuosly ponding application appeared to leach the highest maximum EC concentration 8.68 dS/m at 0.839 PV. The intermittent ponding application achived the lowest peak EC concentration of 4.78 dS/m at 0.683 PV. The unsaturated water application had a similar breakthrough curve as the intermittent ponding water application, achieving approximate peak value concentrations.

Distribution of the 1000 bootstrapped samples of pore volumes necessary to achieve 75% salt removal are shown in Figures 9A- 9C. Because of the presence of 0 in the 95% confidence intervals displayed by the histograms, there was enough evidence to conclude that none of the three water application treatments were the most efficient in leaching the sandy soil columns and no significant difference existed among the treatments. All three leaching methods used approximately 1 pore volume to leach 75% of the salts out of the sandy soil columns.

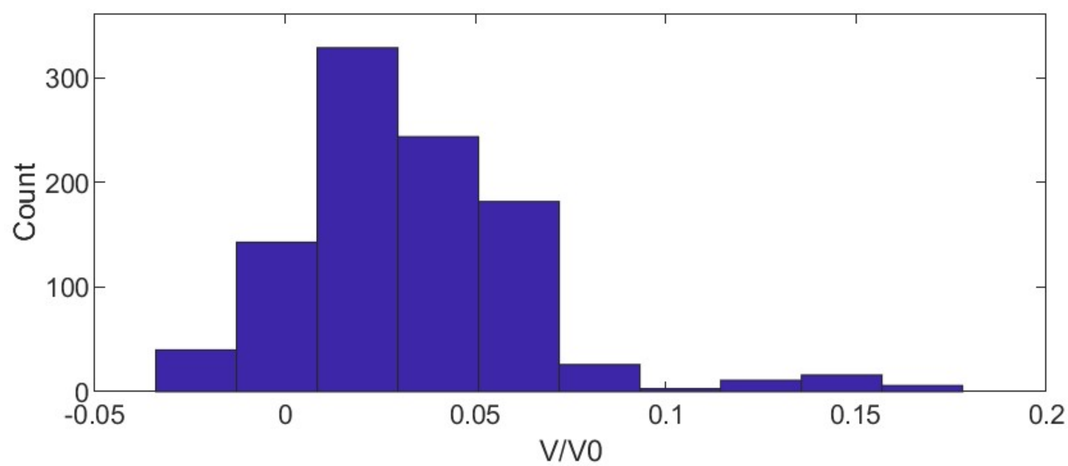

Figure 9A. Histogram displays 95% confidence interval that shows no significant difference in salt leaching efficiency for a 75% salt removal among continuous ponding and intermittent ponding applications under the sandy soil columns.

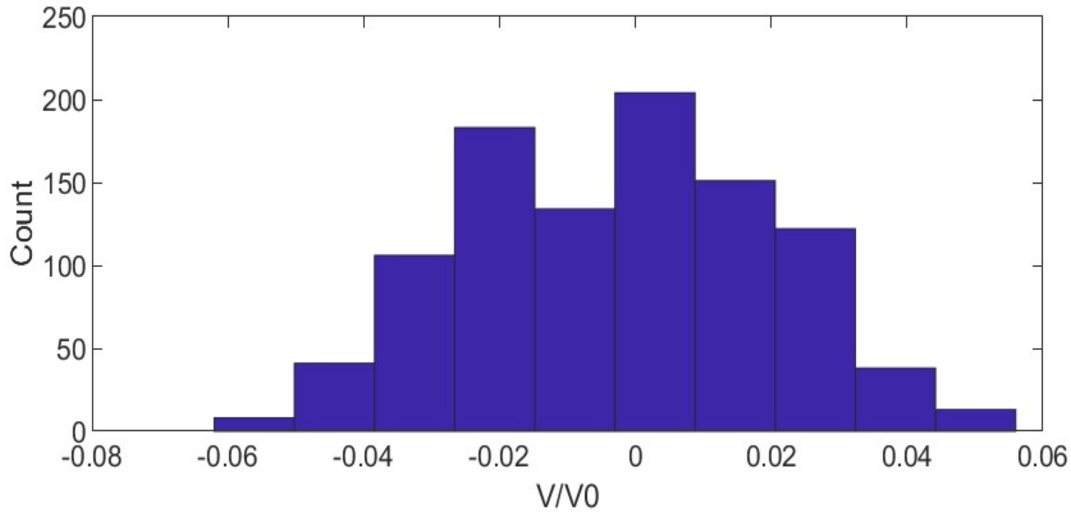

Figure 9B. Histogram displays 95% confidence interval that shows no significant difference in salt leaching efficiency for a 75% salt removal among continuous ponding and unsaturated water applications under the sandy soil column.

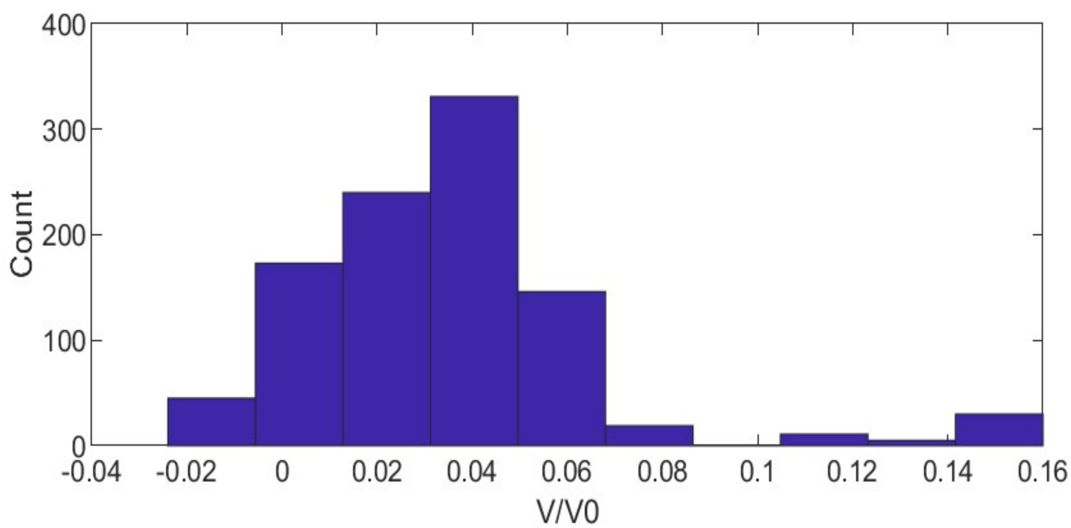

Figure 9C. Histogram displays 95% confidence interval that shows no significant difference in salt leaching efficiency for a 75% salt removal among unsaturated and intermittent ponding water applications under the sandy soil columns.

Salinity Leaching in the Loamy Soil

Figures 10A, 10B, and 10C illustrate the breakthrough curves for the observed and simulated data under continuously ponding, intermittent ponding, and unsaturated water applications, respectively, for the loamy soil columns. Table 4 displays the simulation and experimental results for the leaching of the loamy soil columns.

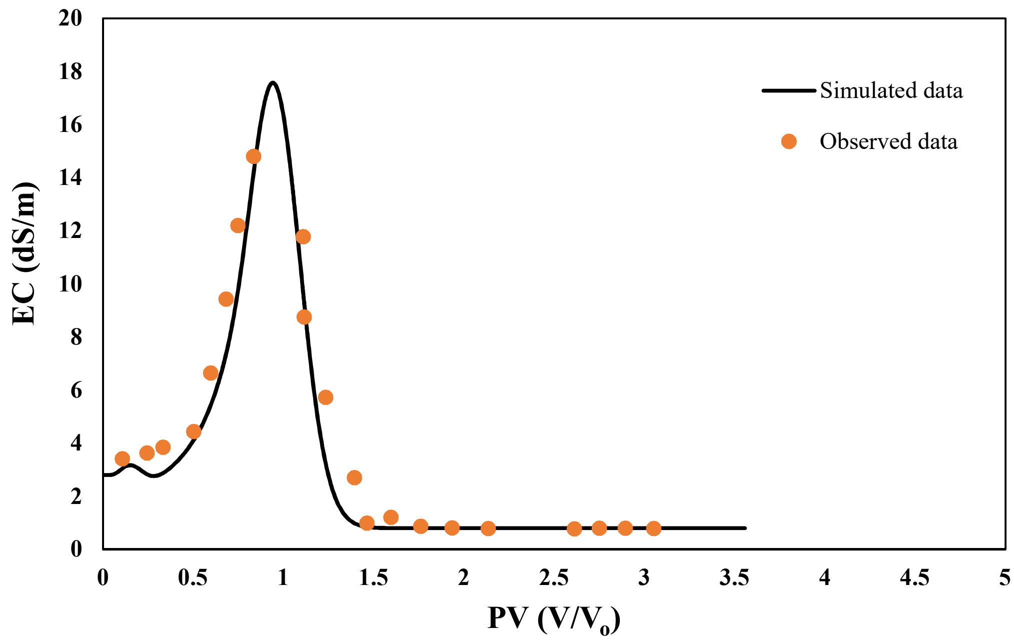

Figure 10A. Salinity leaching breakthrough curve in the loamy soil under continuous ponding.

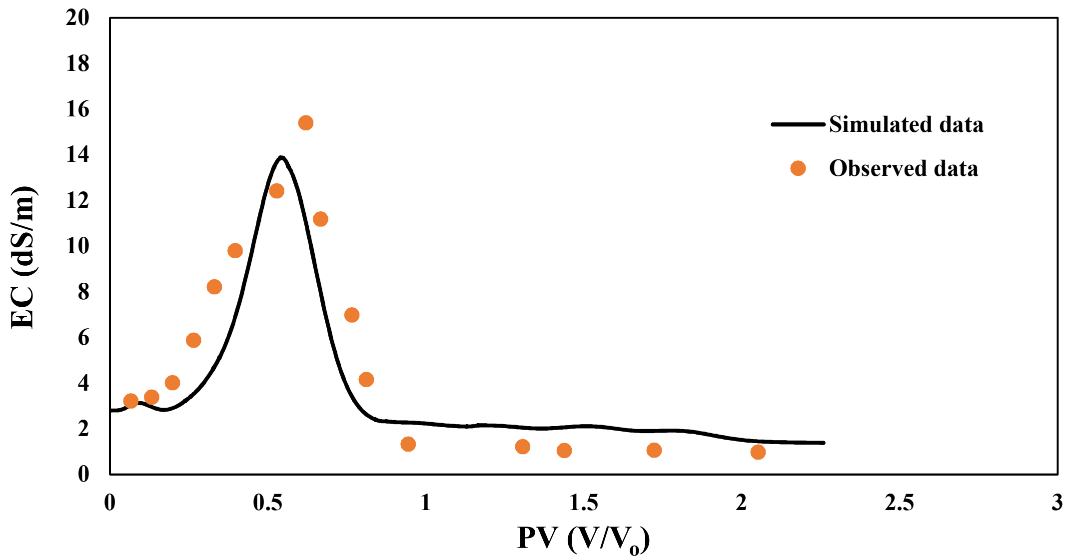

Figure 10B. Salinity leaching breakthrough curve in the loamy soil under intermittent ponding.

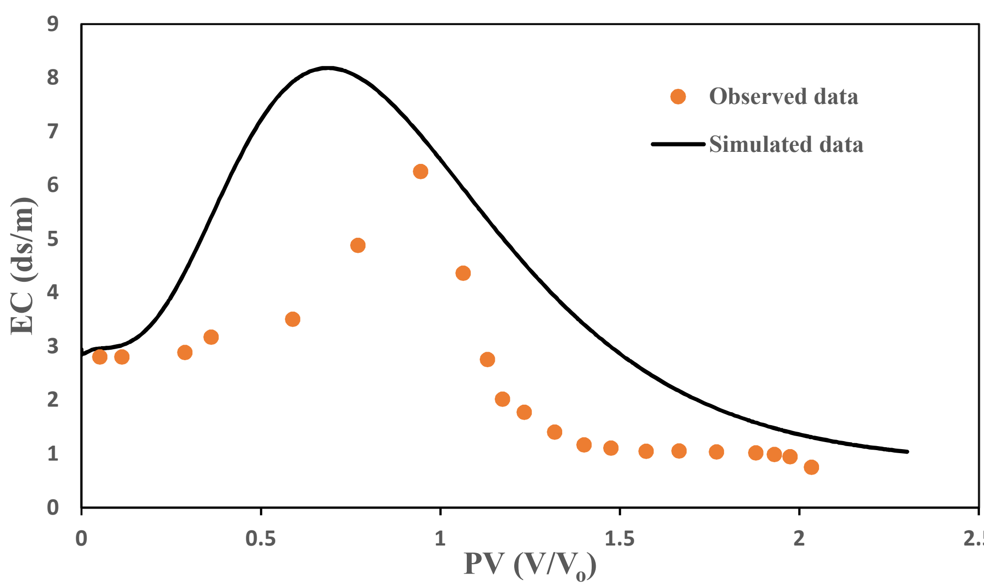

Figure 10C. Salinity leaching breakthrough curve in the loamy soil under unsaturated water application.

Table 4. Simulated and experimental results for salinity leaching in the loamy soil.

Water application method	**R^2**	**RMSE (dS/m)**	**75% salt removal PV (V/V_o)**
Cont. ponding	0.956	0.192	1.08
Inter. ponding	0.954	0.105	0.739
Unsat. application	0.833	0.231	1.14

The simulation results for the continuous and intermittent ponding fited the experimental data successfully, achieving high R^2 and low RMSE values. However, the unsaturated water application simulation was not as precise compared to the other treatments. There could have been potential clogging in the column that could have explained this. Nevertheless, an R^2 value of 0.833 is still acceptable for simulation purposes. The continuosly and intermittent ponding applications appeared to leach signifcantly higher maximum EC concentration of approximamtely 17 dS/m at 0.863 and 0.581 pore volumes respectively, compared to the peak EC concentration of the unsatured flow treatment of 6.27 dS/m at 0.942 pore volume which could also have explained the clogging in the soil columns (see further discussions in Figure 14 in Results Section 5).

Distribution of the 1000 bootstrapped samples of pore volumes necessary to achieve 75% salt removal are shown in Figures 11A- 11C. There was enough evidence to conclude from the experimental results that intermittent ponding was the most efficient water application method in leaching the loamy soil because there was not a 0 present in the confidence intervals displayed by the histograms, which indicates a significant difference in mean pore volume. Intermittent ponding achieved 75% salt removal out of the loamy soil columns with 0.739 pore volume of water, which was significantly lower than those for the other two water application methods. The continuously ponding and unsaturated water application methods had no significant difference between each other in leaching efficiency (Fig. 11B), using 1.08 and 1.14 pore volumes respectively to displace 75% of the salts out of the loamy soil columns.

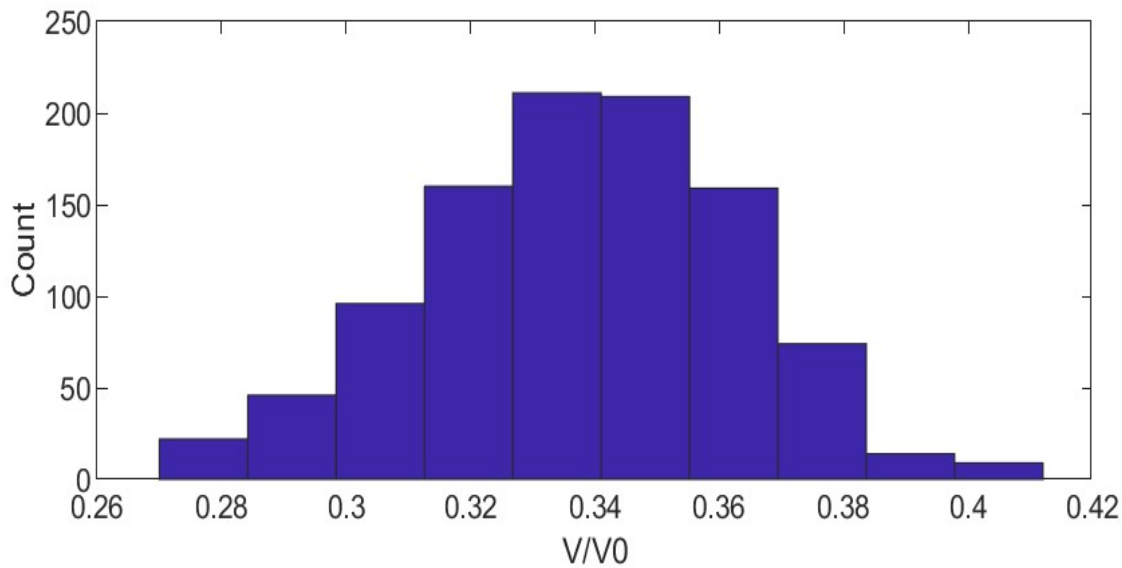

Figure 11A. Histogram displays 95% confidence interval that shows a significant difference in salt leaching efficiency for a 75% salt removal under the loamy soil. Intermittent ponding proved to be more efficient in salinity leaching compared to continuously ponding.

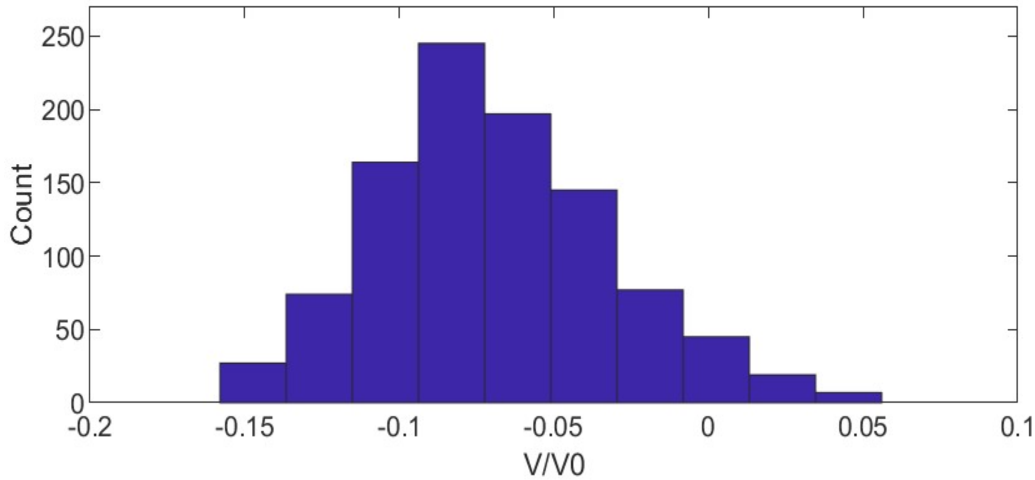

Figure 11B. Histogram displays 95% confidence interval that shows no significant difference in salt leaching efficiency for a 75% salt removal among continuous ponding and unsaturated applications under the loamy soil.

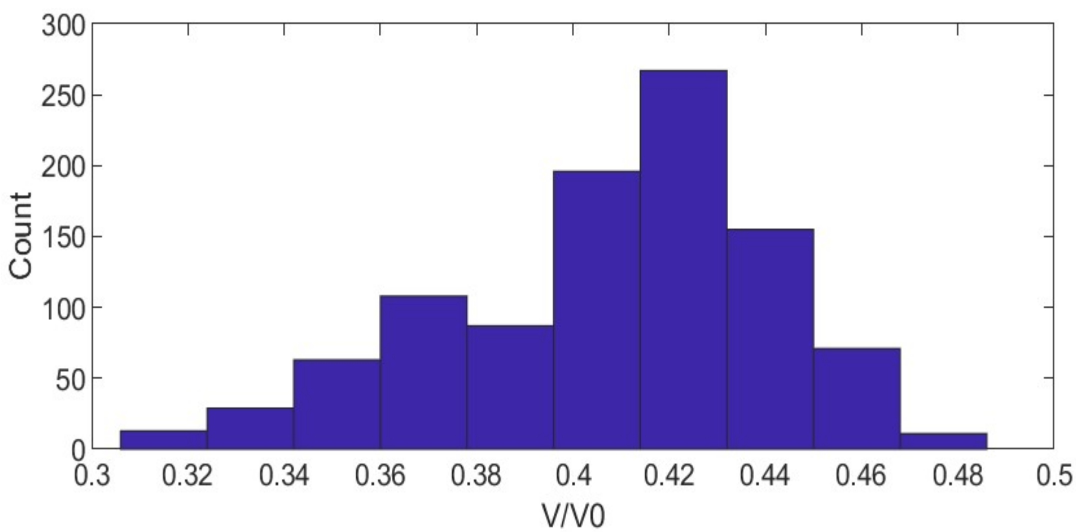

Figure 11C. Histogram displays 95% confidence interval that shows a significant difference in salt leaching efficiency for a 75% salt removal under the loamy soil. Intermittent ponding proved to be more efficient in salinity leaching compared to unsaturated water application.

Salinity Leaching in the Clay Soil

Figures 12A, 12B, and 12C illustrate the breakthrough curves for the observed and simulated data under continuously ponding, intermittent ponding, and unsaturated water applications, respectively, for the clay soil columns. Table 5 displays the simulation and experimental results for the column leaching of the clay soil.

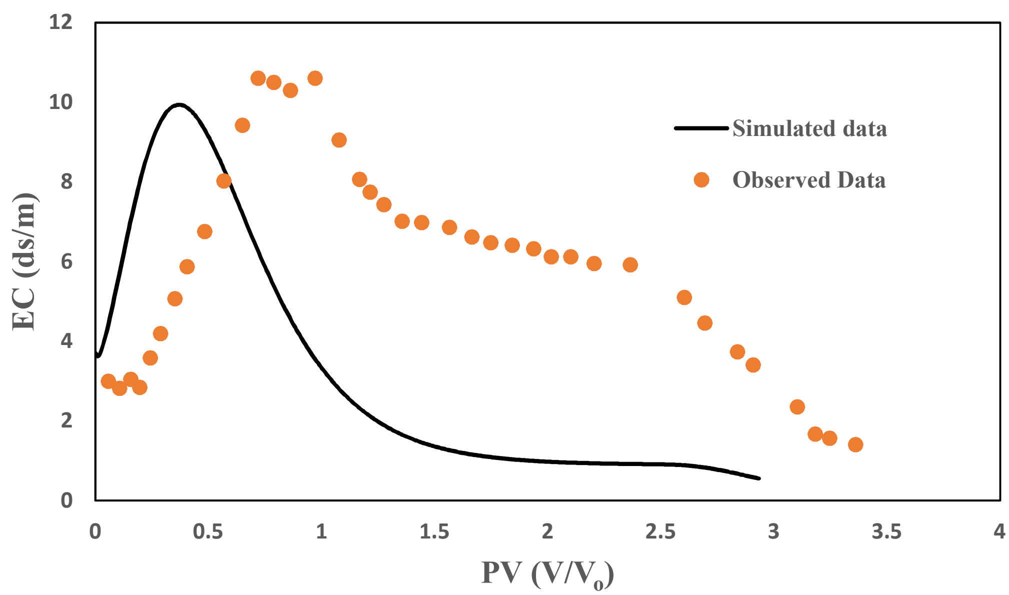

Figure 12A. Salinity leaching breakthrough curve in the clay soil under continuously ponding.

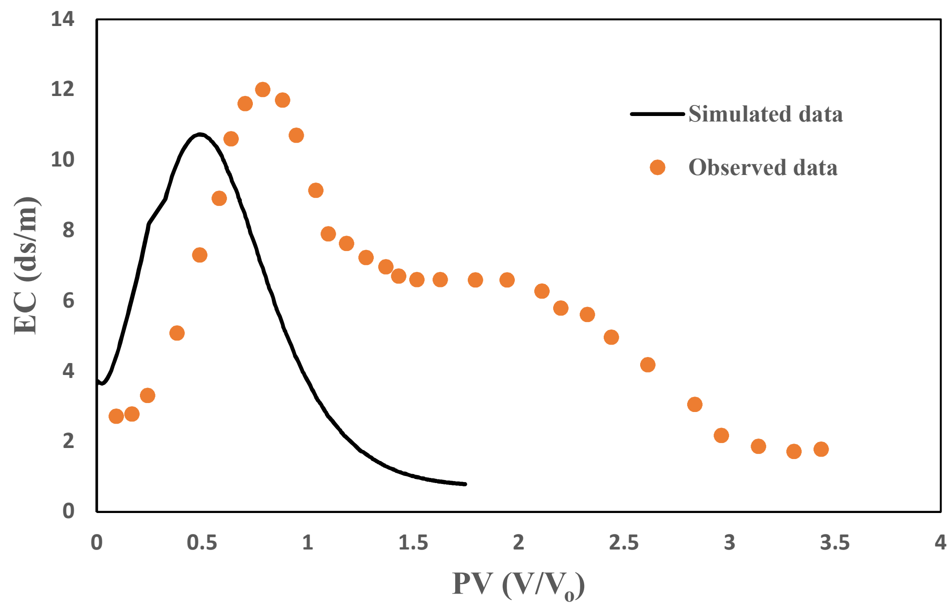

Figure 12B. Salinity leaching breakthrough curve in the clay soil under intermittent ponding.

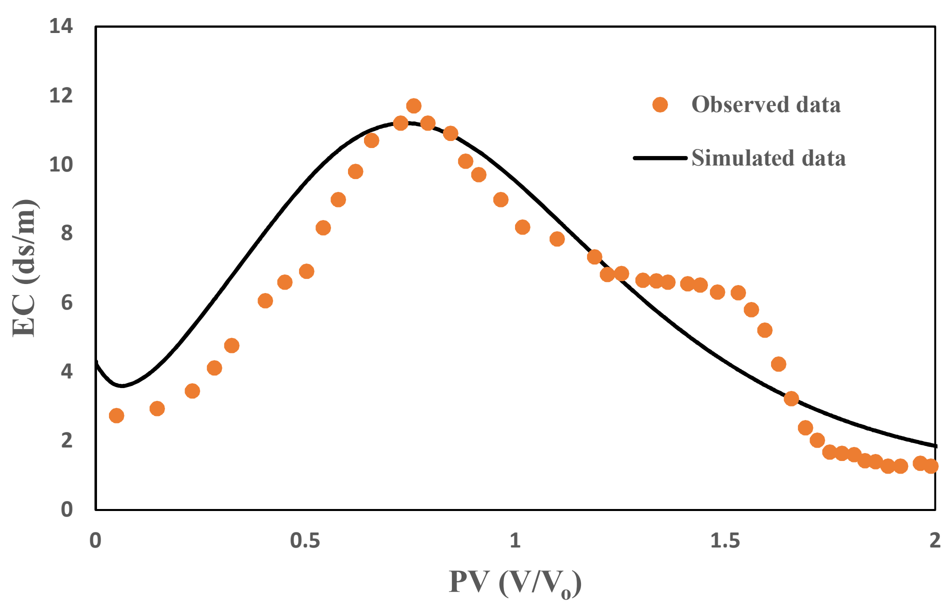

Figure 12C. Salinity leaching breakthrough curve in the clay soil under unsaturated water application.

Table 5. Simulated and experimental results for salinity leaching in the clay soil

Water application method	$\mathbf{R^2}$	**RMSE (dS/m)**	**75% salt removal PV (V/V_o)**
Cont. ponding	0.896	0.157	1.60
Inter. Ponding	0.881	0.134	1.58
Unsat. application	0.990	0.032	1.34

The simulation results for unsaturated water application appear to fit the experimental data successfully, achieving high R^2 and low RMSE values. However, the continuously ponding and intermittent ponding simulations were not as precise. There could have been potential swelling in the clay soil due to particle dispersion, which was evidenced by reduction in drainage rate, even under constant ponding head (further discussed in the Discussion Section 6). However, both treatments have an R^2 value of about 0.89 that is is still acceptable for simulation purposes. It is interesting to note that the unsaturated water application did not experience this reduced drainage rate. All three treatments leached a maximum EC concentration of approximamtely 12 dS/m at about 0.8 pore volume.

Distribution of the 1000 bootstrapped samples of pore volumes necessary to achieve 75% salt removal are shown in Figures 13A- 13C. There was enough evidence to conclude from the experimental results that unsaturated water application was the most efficient method in leaching the clay soil because there was not a 0 present in the confidence intervals displayed by the histograms that indicates a significant difference in mean pore volume. Unsaturated water application achieved 75% salt removal out of the loamy soil columns under 1.34 pore volumes of water, which was significantly lower than the other two water application methods. The continuously ponding and intermittent ponding water applications had no significant difference between them in leaching efficiency (Fig. 13A), using about 1.6 pore volumes respectively to displace 75% of the salinity out of the clay soil columns.

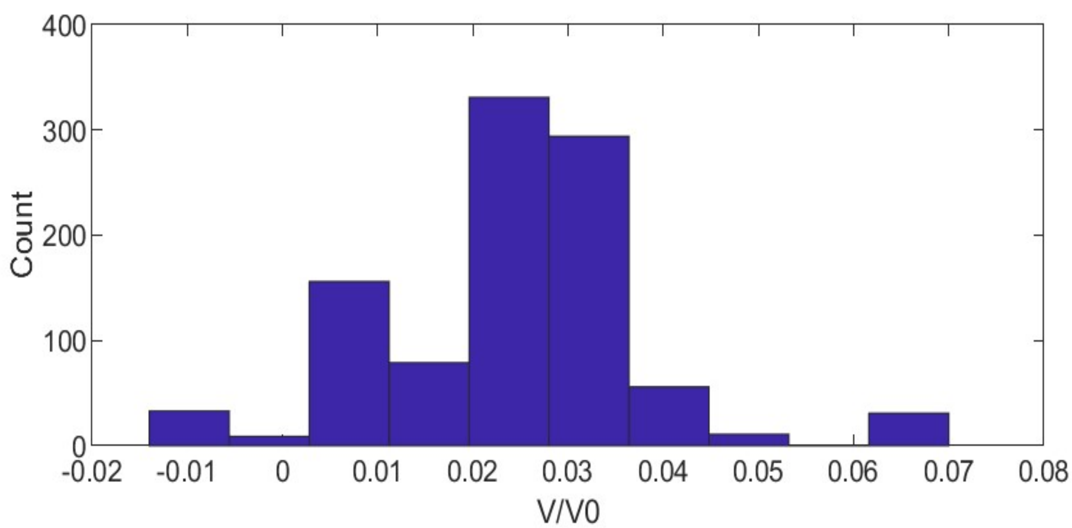

Figure 13A. Histogram displays 95% confidence interval that shows no significant difference in salt leaching efficiency for a 75% salt removal among continuously ponding and intermittent ponding applications under the clay soil.

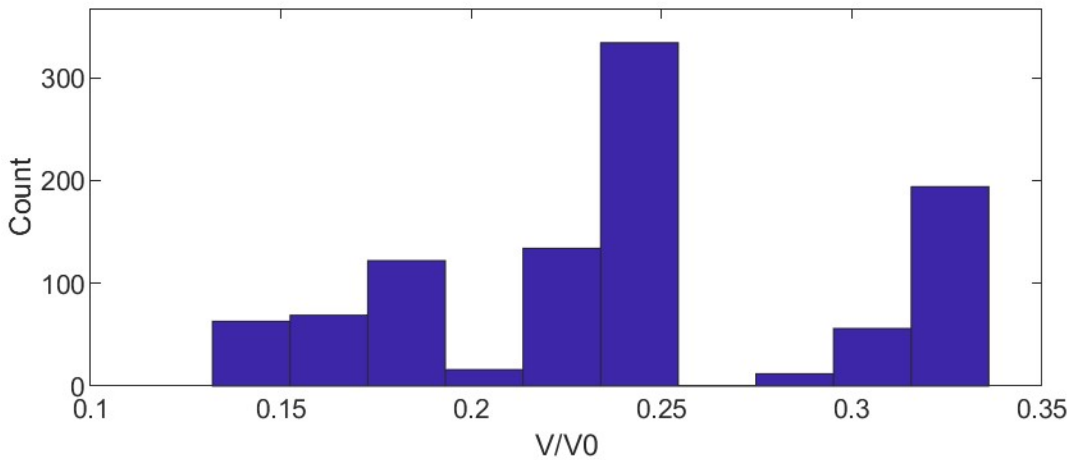

Figure 13B. Histogram displays 95% confidence interval that shows a significant difference in salt leaching efficiency for a 75% salt removal under the clay soil. Unsaturated water application proved to be more efficient in salinity leaching compared to continuously ponding.

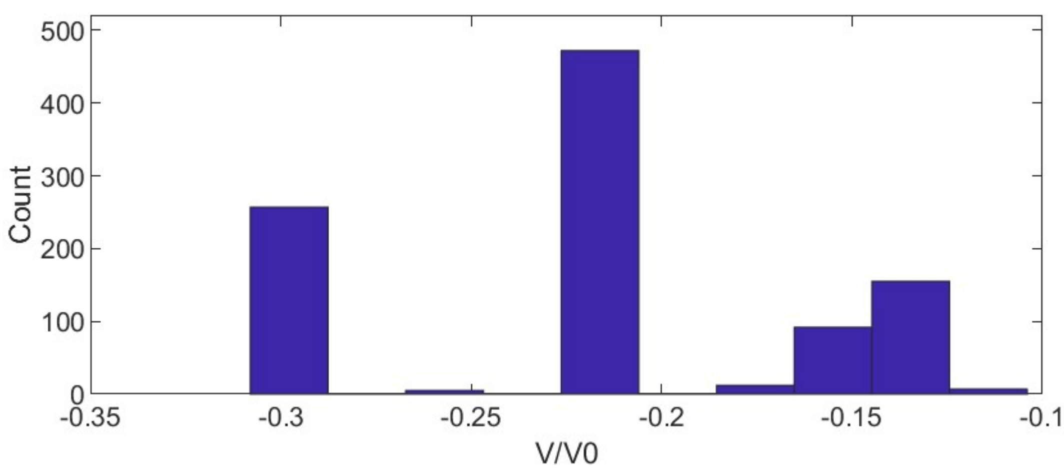

Figure 13C. Histogram displays 95% confidence interval that shows a significant difference in salt leaching efficiency for a 75% salt removal under the clay soil. Unsaturated water application proved to be more efficient in salinity leaching compared to intermittent ponding.

Simulation Hindrances

Some treatments experienced hindrances when simulating the column leaching experiments using the HYDRUS 1D software. This was showcased when converting the simulation results with time as the independent variable to cumulative flux out of the columns to measure pore volume. This could potentially be attributed to the fact that the saturated hydraulic conductivity was constant for the entire simulation period for all the soils.

It was observed that the HYDRUS 1D simulation can represent the experimentally observed data very well (R^2 = 0.983 and RMSE = 0.0907 dS/m) in the sandy soil with unsaturated water application (Fig. 14). However, when the dimensionless scale of pore volume was used in the X-axis to plot against the concentration in the Y-axis, the simulated data shifted to the left (Fig. 8C) in comparison to that in Figure 14 when real time was used. This phenomenon was a result of the change in drainage rate during the leaching, even though the ponding head was held constant. Figure 15 shows that the cumulative drainage volume of the soil column was initially faster than the simulation, then slowed down after the 100-hr. mark.

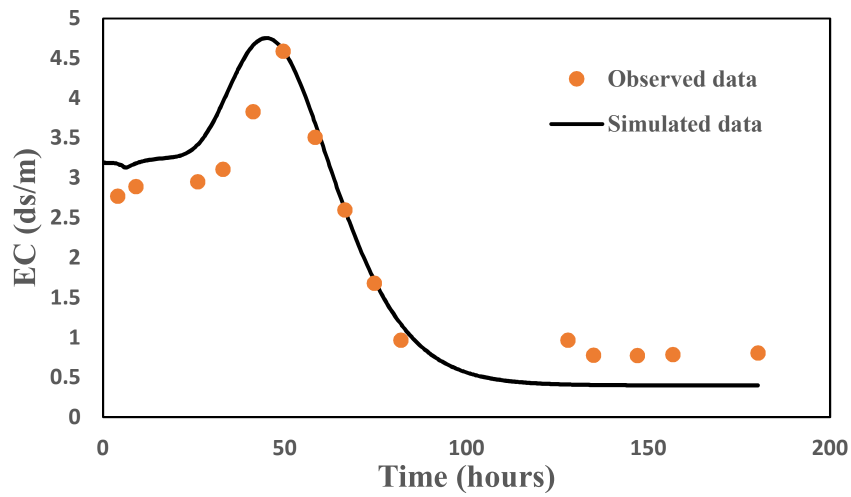

Figure 14. Breakthrough curve for salinity leaching in the sandy soil under unsaturated water application with time as independent variable.

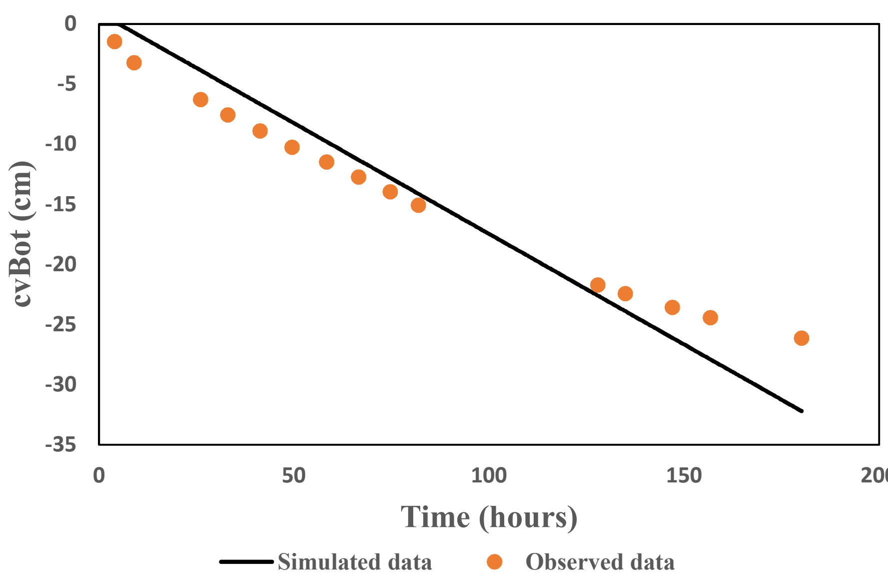

Figure 15. Cumulative bottom flux of the sandy soil under unsaturated water application. Notice that water flow is faster than the simulated data at the beggining of the leaching experiment, then slows down after 100 hrs.

This similar occurrence of the simulation data shifting to the left when the cumulative drainage was plotted against the real time was also observed for the unsaturated water application for the loamy soil. The drainage rate change in the loamy soil under unsaturated water application was even more dramatic (Fig. 16). During the entire leaching process, the measured drainage decreased with time (open circles), while the simulation assumed no change in hydraulic conductivity and drainage rate, resulting in a constant drainage flux (straight line) in Fig. 16. As a result, low R^2 values between observed and simulated data were observed. Again, the decrease in drainage rate under constant head water application is attributed to the possible clogging in the soil columns due to ions and soil particle interactions (Nielsen et al., 1986).

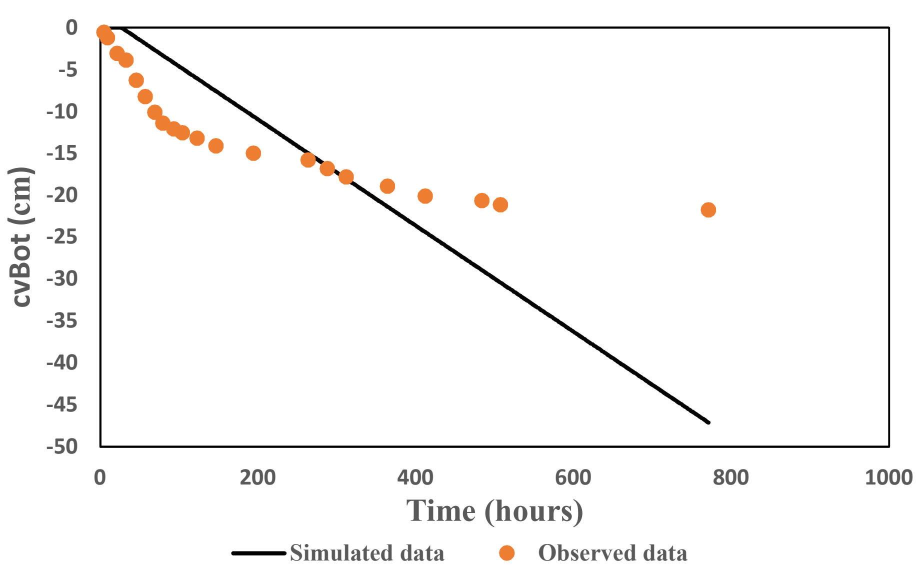

Figure 16. Cumulative bottom flux in the loamy soil under unsaturated water application. Notice that water flow is faster than the simulated data at the beginning of the leaching experiment, then slows down significantly after 100 hrs.

There were also some examples of a reversed trend that was observed under transient conditions when leachate concentration was plotted as a function of real time. For example, Fig. 17 shows that the peak leachate concentration appeared much earlier in the simulation than that in the observed data (Fig. 12A). The shift occurred because the initial water flow was significantly slower than the simulation, which was possibly from the hydraulic conductivity used in the model did not representing the column well. It was also observed that when most of the salts were displaced out of the column at the 1500-hr., water flow rate increased significantly (Fig. 18) towards the later part of the leaching experiment, resulting in a faster drainage flux than that of the simulation data. Similar occurrences were observed from the intermittent ponding application in the clay soil.

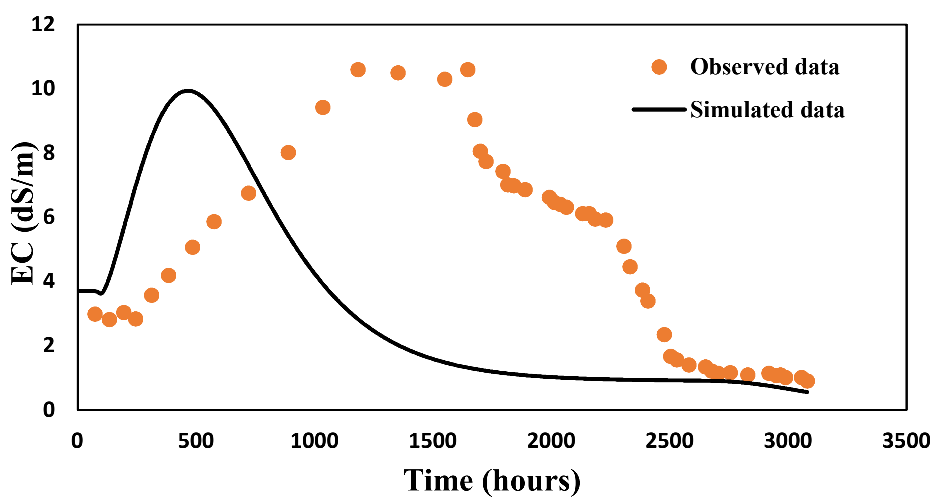

Figure 17. Breakthrough curve in the clay soil under continuously ponding with time as independent variable.

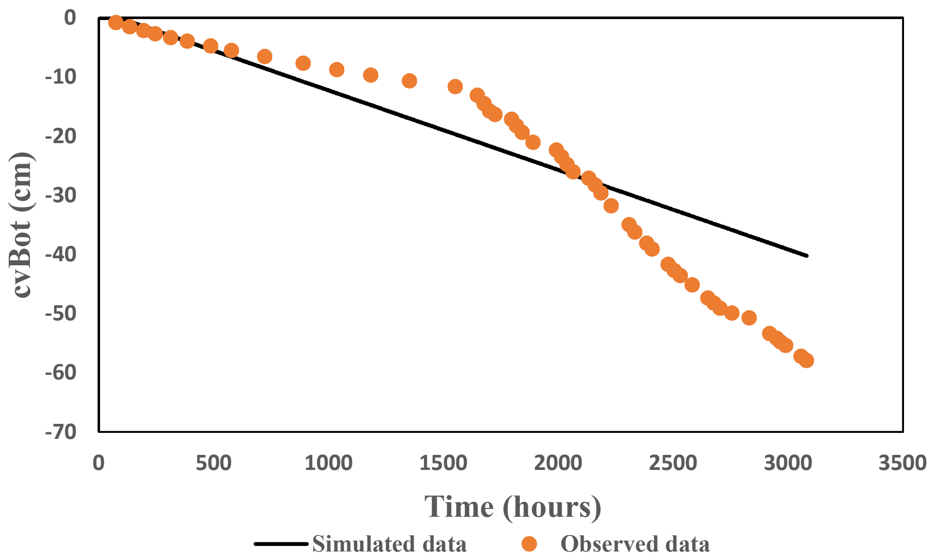

Figure 18. Cumulative bottom flux of the clay soil under continuously ponding application. Notice that the observed water flux was slower than the simulation data at the beginning of the leaching experiment, then speeded up significantly after 1500 hrs.

The rest of the treatments showed a somewhat steady state hydraulic conductivity throughout the duration of the leaching experiments. For example, the simulated and measured drainage EC for the same treatment of unsaturated water application in the clay soil matched very well when either time (Fig. 19) or pore volume (Fig. 12C) was used as the independent variable, as indicated by high R^2 (0.99) and low RMSE (0.032 dS/m). In the clay soil, unsaturated water application was the only treatment that did not experience drainage rate change that was possibly caused by interaction of particles and ions (Fig. 20).

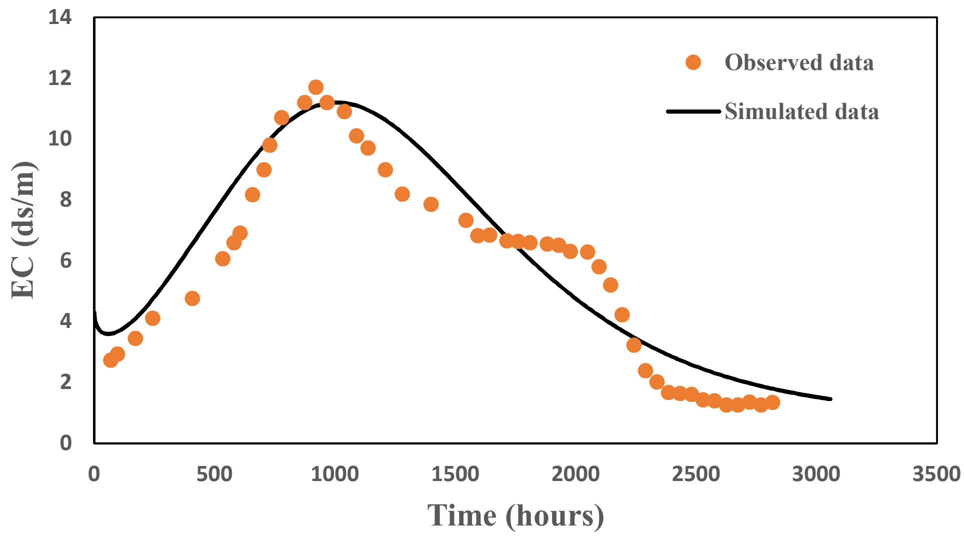

Figure 19. Breakthrough curve for salinity leaching in the clay soil under unsaturated water application with time as independent variable.

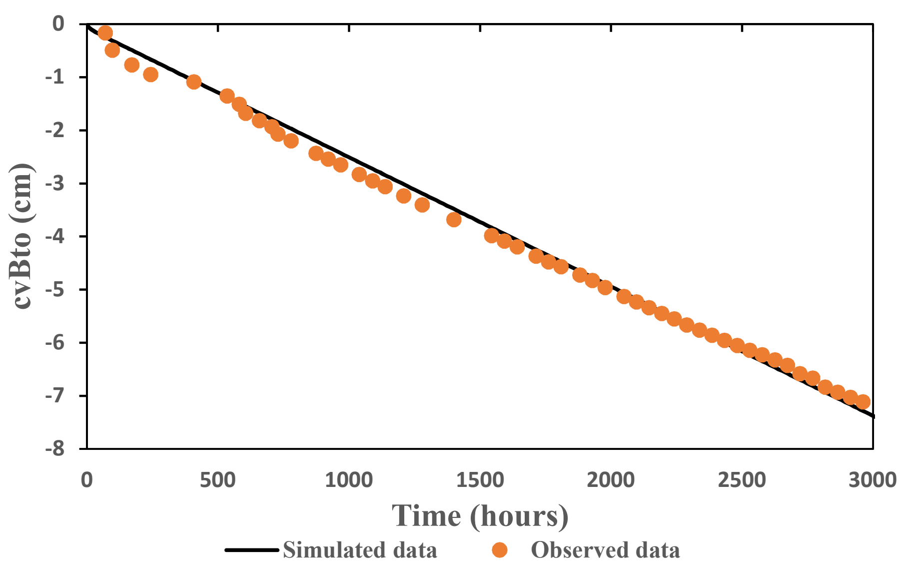

Figure 20. Cumulative bottom flux of clay soil column under unsaturated water application. Notice that the water flux was constant under steady state, and the simulated and observed data matched very well.

6. Discussion

The soil column leaching experiment showed the difference in salinity leaching efficiency among soil textures and water application methods. According to the results, salt removal in coarse textured soils was more effective than in fine textured soils. The presence of larger pores in the sandy soils allowed the entry of most solute into the effluent rapidly regardless of water application rate because of their ability to drain quickly, which resulted in a higher volume of leachate and salt removal. In these soils, the majority of solute was transported through large pores (mobile-water region) by convection and hydrodynamic dispersion (Al-Sibai et al., 1997). Intermittent and unsaturated water application methods had no significant impact on leaching efficiency in the coarse-textured sandy soil because there were few to no smaller pores present that rely on diffusive flow within the aggregates (immobile-water region), as indicated that similar amount of water was needed to achieve 75% salt removal in the sandy soil columns in this study. This observation also agrees with Hoffman's concept of salt transport efficiency for one-dimensional leaching (1980), in which the empirical coefficient (k) in Eq. (2) for coarse-textured soils under continuous ponding is 0.1, but 0.3 for finer textured soils.

Under intermittent ponding, the empirical coefficient was about 0.1 irrespective of soil type, the same value as the continuous ponding for coarse textured soils. Thus, continuous ponding is recommended for leaching coarse textured soils only when time is not a limiting factor in water supply (Tagar et al., 2010).

The loamy soil typically contains a mixture of larger and small pores, which affects the transport mechanism of water and solute in the porous medium because they must rely on transport through the interaggregate (mobile-water region) and within the aggregates (immobile-water region). Our measurement results indicated that intermittent ponding application proved to be the most effective leaching technique in removing 75% of the salts out of the loamy soil columns. This is because the off period during the intermittent water application allowed the solutes to diffuse to the surface of aggregates while there was no water flow. Leaching intermittently allowed more time for water exchange between large and small pores, and for solute to diffuse from the immobile to the mobile water regions following the next water application period (Al-Sibai et al., 1997). Thus, intermittent ponding is recommended for leaching loamy soils because it improves the leaching efficiency by allowing enough time for solutes to diffuse from the micropores to large pores between water applications.

Clay soils are comprised of mostly finer micropores and are highly inefficient in displacing salts out of the soil column due to their large surface area and slow drainage rate. This is because most soluble salts in saline clay soils are contained in micropores within aggregates in the immobile region that are all impermeable in terms of gravitationally induced flow (Armstrong et al., 1988). Solute transport in the clay soil depends on the molecular diffusion of salts that spread out from the interior of the aggregates to the larger pores which contain the water capable of leaching salts under hydrodynamic dispersion (Tanton et al., 1995). According to the results, the unsaturated water application proved to be the most effective leaching technique in removing 75% of the salts out of the clay soil columns. This is because a reduction in soil water content proportionally increases diffusion in the solute transport process that increases chloride removal in finer textured soils (Nielsen and Biggar. 1962).

Clay soil is sensitive to the sodium absorption ratio in the soil-water solution. Sodium harmfully affect the hydraulic properties of fine textured soils because they cause swelling between individual platelets of clay particles and the detachment of small clay particles from larger units, which can significantly alter the leaching effectiveness. The applied tap water used in the soil column leaching experiment had a moderate to severe sodium absorption ratio relative to the EC concentration (400 µS/cm and 5 SAR) that could have potentially altered the hydraulic conductivity and decreased the ability to displace the salts out of the clay soil columns. However, unsaturated water application proved to be the most significant water application method in leaching efficiency. There is a possibility that leaching under unsaturated conditions could have resulted in the deflocculation of the sodic clay soils (Tanton et al., 1995). However, more research is needed in a laboratory setting to prove this phenomenon.

7. Conclusion

The US Department of Agriculture reports that agriculture accounts for about 80 percent of the nation's consumptive water use in 2018., and improper irrigation practices such as improper quantity and quality of irrigation water and poor soil internal drainage conditions can cause and exacerbate salinity issues in irrigated croplands. All irrigation water contains salts and the salts can accumulate in the crop rootzone because crops take up pure water for evapotranspiration. Salt accumulation in the rootzone can have direct effects on plants and soil physical and hydraulic properties. Thus, repeated leaching, the net downward movement of water, is required to remove salts to prevent it from concentrating in the rootzone beyond the crop's salt-tolerance level to not interfere with crop yield. However, disproportionate leaching not only wastes water but also tends to remove essential nutrients, impedes aeration and contaminates surface- and ground-waters. Thus, the application of excessive water during leaching can be detrimental for cropland, making it imperative to assess the optimum quantity of water that must be applied for leaching purposes.

The present salinity leaching guidelines based on steady-state analyses overestimate the leaching requirements under field conditions (Letey et al., 2011). The objective of this soil column leaching study was to assess water application methods including continuous ponding, intermittent ponding, and unsaturated water application on salinity leaching efficacy under soils of different textures (clay, loam, and sandy soils). The HYDRUS 1D model was used to simulate the experimental results to further analyze the data. Some discrepancy between measured and the simulated data was observed, and the differences were potentially from unstable soil properties such as swelling and pore clogging, while in simulation we assumed that hydraulic properties remain constant during the leaching process. Nevertheless, the simulations were acceptable for all the leaching treatments achieving a R^2 value over 0.8.

Our results demonstrated that intermittent ponding was the most effective water application method for leaching the loamy soil because it allowed enough time for allowing solutes to diffuse from the non-mobile small pores to the mobile large pores that facilitate solute transport. Unsaturated water application was the most effective water application method for leaching the clay soil because the reduction in soil water content proportionally increased diffusion in the solute transport process that increased salt removal. It was also the only water application treatment in the clay soil that showed no signs of soil property change during the leaching process. Leaching under unsaturated conditions could have resulted in the deflocculation of the sodic clay soils, but more research is needed to investigate this phenomenon.

The sandy soil had no difference in leaching efficiency among the water application methods, therefore continuous ponding is recommended if time is not a limiting factor for water supply.

The findings from this research will allow farmers to improve their water management practices and reduce groundwater contamination from excessive irrigation by considering soil type and their different leaching characteristics. However, more research is need in a field setting to further investigate salinity leaching efficiency and improve water use efficiencies.

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