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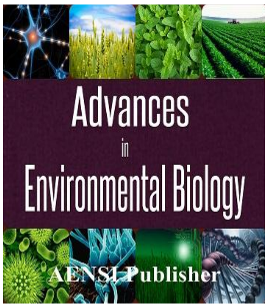

Leaching Mathematical Modeling for Salt Leaching of Saline-Sodic Soils of Ahvaz North Plains of Khuzestan Province

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ABSTRACT

The most important task in leaching practices is assessment of water quantity required for leaching of saline and saline-sodic soils. Therefore, reliable estimation of the required leaching water quantity is vital for reducing soil salinity to a desirable level. The objectives of this study were to introduce an empirical model to account for reclamation water and to compare the obtained results with some available models. Consequently, a large area of 3898 ha with S_4A_4 salinity/sodicity class in Khuzestan, Iran, was selected to obtain the required data. This experiment was conducted with two treatments and tree replicates. In the first treatment, the experiment was conducted by applying just 100 cm water depth in four-25 cm intervals. In the second treatment, 5000 kg/ha Sulfuric Acid was applied prior to salt leaching together with leaching water. The intermittent ponding method was conducted with double rings in a rectangular array. Soil samples were taken from 0-25, 25-50, 50-75, 75-100, 100-125, 125-150 cm soil depths before, during and after each leaching water application interval. The required physical and chemical analyses were performed on the collected data. The leaching water was supplied from Karun river. Four mathematical models were applied to the collected experimental data to derive a suitable empirical model. The results indicated that the logarithmic models can estimate the capital leaching requirement much than other models.

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INTRODUCTION

Salt concentration and accumulation in a soil profile affects soil physical and chemical properties such as osmotic pressure, infiltrability, and hydraulic conductivity and leaves behind such effects as to disrupt or completely stop growth and development of most crop and horticultural plants. The consequence of extreme solubility of sodium (Na) salts and precipitation of calcium carbonate (CaCo3) at high pH values (that happens usually and naturally) increases salt concentration or salinity (the process of salinization) and raises the pH value of soil solution (the alkalinization process) leading to accelerated soil sodication (the alkalization or sodication process). Therefore, in agricultural plans for areas under irrigation, soil salinity and sodication must be reduced to desirable levels in order to achieve economic efficiency in agricultural and horticultural production. From the practical and empirical points of view, the only definitive and long-term solution for amending saline and sodic soils is to remove soluble salts from soil profile through leaching with water of suitable quality. Field tests are recommended to determine the quantity of water needed for leaching salts from salt-affected soil profiles. Results of such tests make it possible to prepare and present curves of leaching salts from soil profiles and to use these curves for determining the quantity of water needed to reduce salinity to the desirable level. Conducting such research and field tests requires substantial time and funds to take many soil samples and perform physical and chemical analyses. However, theoretic models and leaching equations, which

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have been developed based on empirical and mathematical relationships, use the technology of computer simulation models to analyze the leaching process of salts from soil profiles (after various quantities of water have been applied) with acceptable approximation and accuracy. Empirical models are the product of observational data and empirical measurements fitted to mathematical relations (and, therefore, no physical and mathematical preconditions are involved in their derivation). Although used in a specific location or for a specific problem, empirical models of this type can be an important part of a complex numerical model, and their application for making preliminary and approximate estimates can prove useful in achieving information needed for soil improvement.

Empirical relationships and leaching curves can be used for a specific soil depth with respect to the soil type, degree of salinity, or exchangeable sodium percentage. Researchers have developed many empirical models including those introduced by Reeve [27], Dieleman [9], Hoffman [13], Kawachi, and Gupta and Verma [12]. In Iran, leaching experiments have been carried out in most provinces facing salinity problems [22]. Based on numerous research and experiments conducted in the central part of the Khuzestan Province during the course of many years, an empirical relation has been introduced in the form of a hyperbola. Moreover, Pazira and Keshavarz [22] introduced an exponential model for estimating the quantity of water required in leaching saline and sodic areas in the southeastern part of Khuzestan Province. Rajabzadeh *et al*. [26] conducted a study in the central part of Khuzestan Province and found that the logarithmic model with the one meter depth of leaching water application in four 0.25 m intervals was the most efficient among the common methods used [1,2]. In another study in the Jufeir region of the southwestern part of Khuzestan Province, an exponential empirical model was introduced for determining the depth of water required for leaching to desalinize saline and sodic soils [16].

The purpose of this research was to conduct field tests in a part of the lands located in the south plain of Ahvaz in Khuzestan Province to desalinize soil profiles, and to find a suitable model for estimating the depth of leaching water needed for improving soils in the region. To do this, various mathematical models were fitted to field data and results were compared with those of available empirical models.

Table 1: Some experimental models of soil leaching.

No. of equation	Name of empirical model	Type of mathematical model	Mathematical model relationship
1	Reeve (1957)	Hyperbolic function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = \frac{1}{5[\frac{Dlw}{Ds} - 0.15]}$
2	Dieleman (1963)	Exponential function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = e^{-[\frac{Dlw}{Ds}]}$
3	Leffelaar & Sharma (1977)	Hyperbolic function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = \frac{0.062}{[\frac{Dlw}{Ds}]} + 0.034$
4	Hoffman (1980)	Hyperbolic function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = \frac{K}{[\frac{Dw}{Ds}]}$
5	Pazira & Kawachi (1998)	Hyperbolic function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = \frac{0.076}{[\frac{Dlw}{Ds}]} + 0.023$
6	Verma and Gupta (1989)	Power function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = 0.099 \frac{Dw}{Ds}^{-1.27}$
7		Power function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = 0.09 \frac{Dw}{Ds}^{-1.63}$
8	Pazira & Keshavarz (1998)	Power function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = 0.0764 \frac{Dlw}{Ds}^{-0.864}$
9	Rajabzadeh (2009)	Exponential function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = 0.8653 e^{-0.4498\frac{Dlw}{Ds}}$
10	Asadi (2011)	Logarithmic function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = -0.035 - 0.22 \, Ln \frac{Dlw}{Ds}$
11	Asadi (2012)	Logarithmic function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = 0.07 - 0.16 \, Ln \frac{Dlw}{Ds}$
12	Mohammadzadeh (2013)	Power function	$\frac{(ECf - ECeq)}{(ECi - ECeq)} = 0.059 \frac{Dlw}{Ds}^{-1.181}$

In the above table, D_w is the gross depth of water (for leaching) in cm, D_s the depth of the soil layer (from ground surface) in cm, and EC_i electrical conductivity of soil saturation extract before applying a specific depth of water in dS/m, and D_{lw} the net depth of water for leaching (that, after deducting the water needed to offset the water deficit in the related soil layer, moves out of the soil layer column by gravity and deep percolation) in cm. Moreover, EC_{eq} is the electrical conductivity of soil saturation extract that reaches chemical equilibrium by the water applied (for leaching) in dS/m, and K the empirical coefficient with no dimensions.

MATERIALS AND METHODS

To collect the required data, intensive sets of large scale experiments were conducted in Abu Boqqal soil series of Khuzestan plains, Iran. The study area is located in the south Khuzestan province which covers an area of 20167 ha. This area is located between 48^o, 40', 50" and 48^o, 51', 50" East longitude and 31^o, 24', 25" and 31^o, 37', 10" North latitudinal. In terms of climate categories it is an arid region with hot and long summers and short and soft winters. Its annual precipitation is 252mm with an average temperature of 24.9^{oc} and annual evaporation rate of 3222 mm.

Since about 19024.5 ha of all studied area have saline-sodic soil, from low to extreme, it can be argued that salinity and sodicity is the main qualitative limitation of more than 94% of the region's soils. Thus, this study was carried out on saline-sodic lands and in the process of land selection and definition of repetition time, it was tried to select an extreme saline-sodic land because according to investigations, if reclamation of these lands (extreme saline-sodic) is practicable, it will be justifiable and practicable to generalize the obtained results to other classes with different degrees of salinity and sodicity in the studied region.

In order to perform required experiments, salinity and sodicity maps were studied and Abu Boqqal soil in Typic Salorthids group and Aridisals order with S_4A_4 salinity-sodicity class (extreme salinity and relative extreme sodicity) before leaching tests was selected as the target soil. In the study zone, the area of Abu Boqqal soil series is 3898 ha (more than 19% of the region's soil). Tables 2 and 3 present the situation, series, and salinity-sodicity classes of the soils in the study area, and some physical characteristics of the various layers in the soil profiles before leaching.

To desalinize soils, leaching of soluble salts from soil profiles was carried out. The experiment had two treatments and was conducted with three replications. Leaching was performed using the intermittent ponding method and the required water was taken from the Karun River. Table 4 lists results obtained from the chemical analysis of the water used in both treatments. In the first treatment, no amendment material was used and the 1 meter depth of water was applied in four 0.25-meter intervals. However, in the second treatment, five tons of 95% sulfuric acid was applied and leaching was then carried out by using irrigation water.

The six double cylinders used in the experiment were arranged 5 meters apart on the perimeter of a circle with a radius of 5 meters. Soil samples were taken from depths of 0-25, 25-50, 50-75, 75-100, 100-125, and 125-150 centimeters of the soil profiles before leaching and after application of 25, 50, 75, and 100 centimeters of water. The samples were sent to the laboratory for analysis. In each experiment, the electrical conductivity, pH, cation exchange capacity, sodium adsorption ratio, exchangeable sodium percentage, saturation percentage, lime, gypsum, and cations and anions (Na, Ca, Mg, Cl, sulfate, carbonate, and bicarbonate) in the soil extract solution were measured. The chemical characteristics of the various soil layers before and after applying 100 cm of water in the related treatments are presented in Table 5 respectively. The salinity values (electrical conductivity of the soil saturation extract) before, during, and after each water application were determined for the desired horizons in the soil profiles (that is, at the depths of 0-25, 0-50, 0-75, 0-100, 0-125, and 0-150 centimeters) relative to the mean weight calculations for different depths of water applied. The results for both treatments are listed in table 6.

Since all the water applied may not be used for leaching soluble salts out of soil profiles and some if it may be used to offset the soil moisture deficit, even applying large volumes of water will not result in a chemical equilibrium of the soil with the water used in leaching. To overcome this problem, desalinization values were determined based on the averages of salinity by weight as follows:

$$X = [D_{lw}/D_s] \quad Y = \left[\left(EC_f - EC_{eq}\right)/\left(EC_i - EC_{eq}\right)\right] \tag{13}$$

EC_i, EC_f are electrical conductivity of soil saturation extract before and after leaching (dS/m), D_{lw} the net depth of water for leaching, and D_s the depth of the soil layer (m). Actually, D_{lw} represents the depth of water that, after offsetting the moisture deficit in the related layer, leaves it by gravity. Deducting EC_{eq} from the numerator and denominator of the mentioned fraction will cause the results obtained from the effects of external factors such as the amount of evaporation, the condition of the internal drainage in the soil, the quality of water used for leaching, and the conditions under which the experiment is conducted, to become independent. In fact, this will convert the function from the explicit to the implicit state. After obtaining all the values of the leaching experiments, the required analysis was performed using SPSS, Curve Expert, and Excel. The four mathematical models including the power, exponential, inverse, and logarithmic models were fitted to the desalinization values, were analyzed using statistical criteria such as coefficient of determination and standard deviation at the one percent level of significance, and the most suitable desalinization model for the tested soils was determined. The ME, RMSE, CD, EF, and CRM statistics were used to evaluate the accuracy, validity, and efficiency of the proposed model.

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Table 2: Series, salinity and sodicity class and some physical characteristics of the studied soil.

series name	salinity and sodicity class (before test)	depth of water table (m)	hydraulic conductivity (m/day)	depth of impervious layer (m)
Abu Boqqal	S_4A_4	2.70	7.54	2.40

Table 3: Some physical characteristics of different layers of soil profile before leaching process in Abu Boqqal soil series.

Row	Sampling depth (m)	Soil Particles (%)			Soil texture	Soil density (gr/cm3)		Total porosity (%)	Permeability (mm/hr)		Humidity (mass percentage)			Soil moisture deficit (cm)	Cumulative Soil moisture deficit (cm)
		sand	silt	clay							Before leaching	Filed capacity	Wilting point		
1	0-25	8.80	48.0	44.0	SiCL	1.60	2.64	39.0	0.70	M.S	8.20	20.50	12.40	4.92	4.92
2	25-50	10.0	52.0	38.0	SiCL	1.69	2.66	36.5	0.60	V.S	16.90	23.20	13.20	2.66	7.58
3	50-75	2.00	48.0	50.0	SiC	1.59	2.64	39.8	0.50	V.S	18.70	24.00	12.30	2.11	9.69
4	75-100	2.00	49.2	48.8	SiC	1.74	2.69	35.0	0.40	V.S	20.70	28.40	17.20	3.35	13.04
5	100-125	2.00	50.0	48.0	SiC	1.75	2.64	33.7	0.40	V.S	19.20	25.00	15.00	2.54	15.58
6	125-150	2.00	50.0	48.0	SiC	1.75	2.71	35.4	0.40	V.S	16.50	22.50	13.10	2.63	18.20

Table 4: Chemical decomposition of the water used to leach out soluble salts from soil profile.

Water source	EC_w (ds/m)	pH	T.D.S (mg/lit)	Na^+	Mg^{2+}	Ca^{2+}	K^+	Sum of cations	Cl^-	So_4^{2-}	Hco_3^{2-}	Sum of anions	SAR	Wilcox category
				(meq/lit)					(meq/lit)					
Karun river	1.42	8.2	850	8.20	5.80		0.0	14.00	7.00	6.00	1.00	14.00	4.81	C3-S1

Table 5: Some chemical characteristics of soil layers before and after leaching.

Sampling time	Soil depth (cm)	ECe (dS/m)	pH	T.N.V (%)	Gypsum	C.E.C	$Ex.Na^+$	SAR	ESP*
						(meq/100gr)			
Before leaching	0-25	111.0	7.4	33.0	8.60	11.0	10.4	114.9	94.5
	25-50	43.0	7.7	31.0	20.0	15.0	6.50	73.6	43.3
	50-75	39.0	7.8	32.0	23.0	15.0	7.60	55.2	50.7
	75-100	33.5	7.8	30.0	46.0	16.0	5.70	48.4	35.6
	100-125	33.0	7.8	30.0	45.0	16.0	5.10	50.1	31.9
	125-150	32.0	7.6	35.0	34.0	11.0	4.60	46.6	41.8
After leaching	0-25	3.4	8.1	33.0	2.90	11.2	1.30	7.30	11.6
		3.3	7.9	33.0	2.00	11.3	0.60	5.60	5.30
	25-50	3.9	8.0	31.5	6.50	14.2	2.00	5.40	14.1
		3.8	7.9	31.0	16.0	15.8	0.70	4.50	4.40
	50-75	6.4	8.1	32.0	25.8	14.5	3.80	16.5	26.2
		5.2	8.0	32.0	21.0	15.0	2.10	8.60	14.0
	75-100	9.5	8.2	32.0	26.6	16.3	5.10	22.2	31.3
		11.5	8.3	31.0	33.0	18.0	5.50	27.5	30.6
	100-125	19.2	8.4	28.2	50.7	17.0	8.00	33.6	47.1
		28.5	8.2	30.0	40.5	17.0	8.20	49.4	48.2
	125-150	41.2	8.3	34.3	31.8	13.0	6.30	49.5	48.5
		30.0	8.1	32.0	34.0	11.0	4.00	46.9	36.4
Avarage	Before leaching	48.58	7.68	31.84	29.44	14.00	6.65	64.80	49.64
	After leaching	13.94	8.18	31.84	24.05	14.37	4.42	22.42	29.80
		13.72	8.07	31.50	24.42	14.68	3.52	23.75	23.15

$$*ESP = \frac{100\ (Ex.Na^+)}{C.E.C}$$

Table 6: Calculated values (weight average) for Initial salinity (EC_i) and Final salinity (EC_f) of saturated soil extract before and after applying different amounts of leaching water (gross) in different soil layers of Abu Boqqal soil series (with and without reclamation substances).

Row	Sampling depth (m)	salinity of saturated soil extract before leaching (dS/m)	salinity of saturated soil extract after different frequencies of leaching water (dS/m)									
			EC_f (25)		EC_f (50)		EC_f (75)		EC_f (100)		EC_f (avarage)	
1	0-25	111.0	5.20	4.50	4.90	3.90	4.50	3.70	3.40	3.30	4.50	3.85
2	0-50	77.00	7.00	6.35	5.10	4.40	4.85	3.80	3.65	3.55	5.15	4.53
3	0-75	64.34	12.47	13.90	6.57	7.27	6.30	5.54	4.57	4.10	7.48	7.70
4	0-100	56.63	18.78	18.68	9.68	12.70	8.95	9.90	5.80	5.95	10.80	11.81
5	0-125	51.90	22.56	21.54	13.74	15.96	14.62	14.12	8.48	10.46	14.85	15.52
6	0-150	48.58	25.08	23.45	16.45	18.14	17.85	16.60	13.94	13.72	18.33	17.98

RESULTS AND DISCUSSION

According to analyses as well as fitting four mathematical models i.e. logarithmic, power, exponential and inverse models to the values extracted from X and Y variables, derived from field desalination experiments in Abu Boqqal soil series, logarithmic model with a determination coefficient of 0.760 and standard error of 0.070 in a significance level of 1% is the best model for treatment 1 which is shown as follows:

$$Y = 0.091 - 0.114 \operatorname{Ln} X \tag{14}$$

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Replacement of related variables results in:

$$\frac{EC_f - EC_{eq}}{EC_i - EC_{eq}} = 0.091 - 0.114\ \mathrm{Ln}\frac{D_{lw}}{D_s} \tag{15}$$

Having relation 15, required depth for removing soluble salts from soil profile with a given thickness and a given final salinity of saturated soil extract is computed as follows:

$$D_{lw} = D_s.\exp\left[\langle(\frac{EC_f - EC_{eq}}{EC_i - EC_{eq}}) - 0.091\rangle/(-0.114)\right] \tag{16}$$

$$EC_f = \left[\left(EC_i - EC_{eq}\right).(0.091 - 0.114\ \mathrm{Ln}\frac{D_{lw}}{D_s}) + EC_{eq}\right] \tag{17}$$

In this study EC_f in 0-100cm layer of soil profile per 100cm of depth of leaching water (D_w), water deficit in 0-100cm layer of soil profile before leaching and salinity of leaching water were estimated as 5.80 dS/m, 18.20 cm and 1.42 dS/m, respectively. Therefore, leaching efficiency coefficient can be derived from the following empirical relations:

$$r = \frac{D_w}{D_p} \tag{18}$$

$$f = \frac{r.EC_w}{EC_{eq}} \tag{19}$$

Where:

r is gross depth of leaching water to net depth of leaching water or deep permeation ratio (D_p=D_{lw}); EC_W is salinity of leaching water in dS/m and EC_{eq} is final salinity of the studied layer after applying a given amount of leaching water in dS/m.

Therefore, we have:

D_w=100 cm $\qquad r = \frac{D_w}{D_p} = \frac{100}{81.80} = 1.223$

D_p=100-18.20=81.80 $\qquad f = \frac{r.EC_w}{EC_{eq}} = \frac{(1.223).(1.42)}{(5.80)} = 0.299$

The calculated leaching efficiency coefficient of soluble salts (f=0.29) agrees with the studied region's soil texture reported in valid literatures and this implies that the obtained results are logic. The numerical value of this coefficient represents the efficiency of applied leaching water for removing soluble salts from soil profile which can be substituted with the water content of soil during leaching process.

According to analyses as well as fitting different empirical models, logarithmic model with a definition coefficient of 0.770 and standard error of 0.067 in a significance level of 1% is the best model for treatment 2 which is shown as following:

$$Y = 0.083 - 0.113\ \mathrm{Ln}\ X \tag{20}$$

By replacing related variables the above relation is written as:

$$\frac{EC_f - EC_{eq}}{EC_i - EC_{eq}} = 0.083 - 0.113\ \mathrm{Ln}\frac{D_{lw}}{D_s} \tag{21}$$

Having the above relation, required depth for removing soluble salts from soil profile with a given thickness and given EC_f of saturated soil extract can be derived from the following relation:

$$D_{lw} = D_s.\exp\left[\langle(\frac{EC_f - EC_{eq}}{EC_i - EC_{eq}}) - 0.083\rangle/(-0.113)\right] \tag{22}$$

$$EC_f = \left[\left(EC_i - EC_{eq}\right).\left(0.083 - 0.113\ \mathrm{Ln}\frac{D_{lw}}{D_s}\right) + EC_{eq}\right] \quad (23)$$

Having relations 14 and 20, desalination curves of Abu Boqqal soil series were obtained. Figure 1 shows the results.

According to figure 1, in the soil series removing salts is easier in treatment 1 compared with treatment 2. Comparison of the curves show that in the case of applying sulfuric acid as reclamation substance, more leaching water is required compared with the case of no use of sulfuric acid.

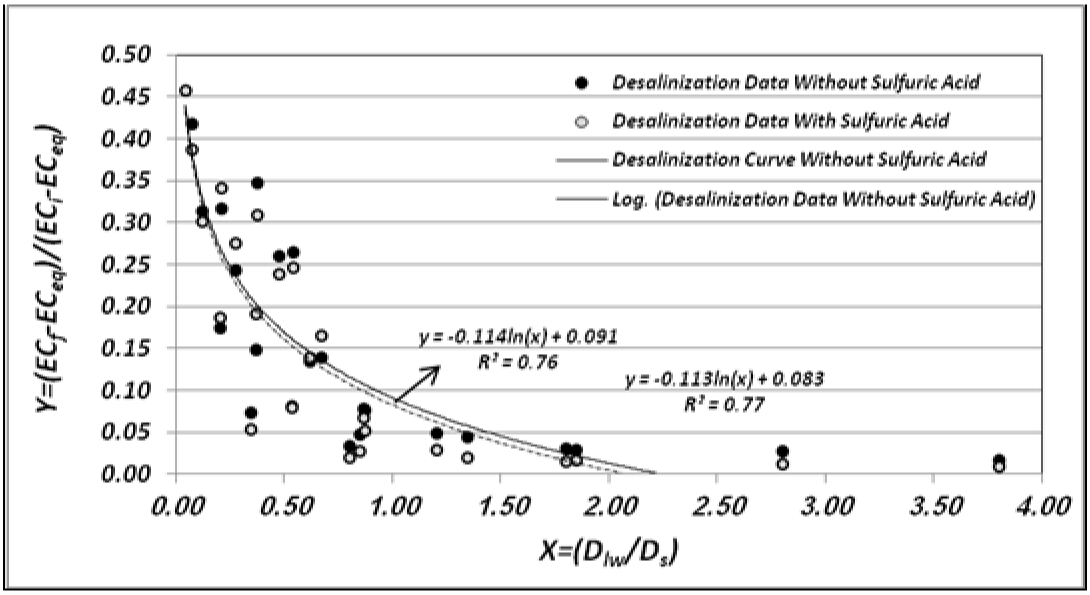

Fig. 1: Soil desalination curves under the influence of two leaching treatments in Abu Boqqal soil series.

From the curves shown in Fig.1, final electrical conductivity of soil (EC_f) and required net depth of water for reclamation (D_{1w}) can be estimated. It should be noted that if one wish to estimate total required depth of leaching water, soil water deficit in the considered soil layer, surface evaporation and precipitation amount should be taken into account in the calculations and planning of leaching process. However, the curves are valid only for the region's soil and within initial electrical conductivity limits of 32.00 dS/m to 111.00 dS/m and exchangeable sodium percentage (ESP) of 31.90 to 94.50.

In treatment 1, 100cm depth of leaching water removed 95.95%, 93.31%, 88.38%, 80.93%, 71.39% and 62.27% (average) of initial salts in the related depths while in treatment 2 the same amount of water removed 96.53%, 94.12%, 88.03%, 79.15%, 70.10% and 63.00% (average) of initial salts in the related depths. The amount of applied water was 10.26, 5.30, 3.47, 2.66, 2.17 and 1.82 units of pore water in the related depths.

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