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A Parametric Desalinization Model for Large Scale Saline Soil Reclamation

Safoora Asadi Kapourchal[1*], Mehdi Homaee[2] and Ebrahim Pazira[3]

[1]PhD student, Department of soil science, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2] Professor of Soil Science, Tarbiat Modares University, Tehran, Iran
[3]Department of soil science, Science and Research Branch, Islamic Azad University, Tehran, Iran

ABSTRACT

Accumulation of soluble salts within the root zone in arid and semi-arid irrigated soils is a dominant problem after water scarcity. Soil salinity adversely affects the plant stand, plant growth and yield production. To reduce soil salinity, the first practical requirement is to reduce salinity by leaching to a level at which plants can grow up with minimum yield reduction. The objective of this study was to develop and verify a simple practical model to account for reclamation water requirement at large scale. Consequently, a large area of 1375 ha with S_4A_3 (extreme salinity and sodicity) salinity/sodicity class was selected to obtain the required data. Several mathematical models were applied to the collected data to obtain the suitable empirical model. The results for large scale applications indicated that the proposed logarithmic model can provide reasonable estimates for leaching process compares to the available models, in a large scale practices. This finding is more important particularly when fresh water resources are limited within a saline region.
KEYWORDS: Leaching requirement; Modeling; Saline–Sodic soils; Salt leaching.

1. INTRODUCTION

Soil salinity and sodicity are two important environmental tasks in the world. Almost 1000 million ha of lands are affected in several degrees by soil salinity [25].

Salinity is also a major limiting factor for agricultural crop production in soils with inadequate natural drainage. In those areas that are affected by salinity, it is quite difficult to monitor the required ground information[1].

Soil salinity and soil sodicity are quantitatively expressed by electrical conductivity of saturation extract (EC_{se}) and exchangeable sodium percentage (ESP), respectively. Saline soils have EC_{se} of larger than 4 dS m^{-1}, ESP of less than 15% and their pH is usually less than 8.5. If the exchangeable sodium percentage of a soil is more than 15, the soil is categorized as saline-sodic soil. Soils are called sodic when their EC_{se} is less than 4 dS m^{-1} with ESP of larger than 15%.

Dominant salts in soils are generally consisted of NaCl, $MgCl_2$, $CaCl_2$, Na_2So_4, and $MgSo_4$. These salts are originally present in soil parent materials and released within soils as result of bedrock weathering. Salts are usually moved into the soil subsurface horizons and may either remain in the soil solutions or precipitate within the root zone. When the origins of accumulated salts belong to weathering process, the salinity is called primary or residual salinity.

The most important and common problem of high soil salinity in agricultural lands is the tendency of salt to accumulate in topsoils where the roots should be grow in. Soil salinization process can be either natural or may be imposed by human activities. The latter is usually arises from irrigation in areas with low rainfall and high evaporation. In such conditions, the necessary steps are conducting leaching practices and/or performing a desirable drainage system [1, 11, 21].

Saline, sodic and saline-sodic soil reclamation requires applying leaching practices but prerequisite of any leaching practice is the improvement of soil drainage conditions. Without installing a proper drainage system, removal of soluble salts from the root zone of saline-sodic soils would not be successful.

In saline-sodic soils, plants are directly affected by the existing salts within the root zone as well as by the shallow saline water table. Consequently, the first step for soil reclamation in such conditions is to reduce soil salinity to an optimal level through leaching process. In practical, removal of the accumulated salts from saline soils can be conducted by three methods including scrapping, flushing and leaching. The leaching practice is the most reasonable and feasible method for reclamation of saline soils at field scales.

The issue of salinity is widely studied by several investigators [e.g. 7, 8, 9, 10, 11, 21] from different point of views. In two independent investigations conducted by Du Plessis (1986) and Moolman (1993), the concept of salt leaching with every irrigation event has been studied to verify the salt removal from the root zone. However, the most recent irrigation technology has mainly focused on reducing the volume and salinity of

Corresponding Author: Safoora Asadi Kapourchal, Science and Research Branch, Islamic Azad University, Soil Science Department, Tehran, Iran; Phone: ++989126873367, E-mail: safoora.asadi@yahoo.com

leaching waters [5]. This way, the so-called periodic leaching is recommended where soil salinity reaches the threshold salinity level capable of interfering with crop yield [16]. Leaching efficiency depends on several factors, but usually increases at higher soil salinity contents [4].

Soil properties are major factors to control the amount of water required for leaching. Leaching curves have been used to determine the amount of water required to leach a soil to a predetermined salinity level (22, 2, 13, 12, 24, 21].

The objective of this study was to quantitatively assess the experimental leaching curves that were developed to quantify the pore volume of required water for efficient salt leaching in large scale. Further, it was aimed to investigate the accuracy and validity of the previously proposed models and to propose a new model for estimating water requirements for capital leaching to desalinize these soils. Additionally, the effect of gypsum application in the flushing solution was examined for soil reclamation purposes.

MATERIALS AND METHODS

Intensive sets of large scale experiments were conducted in Mouran soil series of Khuzestan plains, Iran. The study area was located at south Khuzestan province which covers an area of 22500 ha. This area is located between 48°, 20' and 48°, 38' East longitude, and 31°, 51' and 31°, 55' North latitude. The average long term annual temperature and rainfall are 24.9 °C and 252.1 mm, respectively. The soil temperature regime is Hypertermic and the soil moisture regime is Aridic (Torric). The soil order was categorized as Entisols, with the texture varied from silty clay to silty clay loam and clay loam, having massive structure. According to soil survey and land classification studies, the salinity (S) and sodicity (A) of this area were classified as S_4A_3 (extreme salinity and sodicity). Over 96 percent of the study area imposed by salinity and sodicity limitations. To conduct the experiments, a large saline-sodic area of 1375 ha (6.11% of the total area) was selected by primary investigation of soil salinity maps. Some physical properties of the experimental soil profile before applying any leaching water is presented in Tables 1 and 2.

Table 1. Some major properties of the experimental site

Salinity/Sodicity Class	Depth of Water Table (m)	Hydraulic Conductivity (m day^{-1})	Depth of Impervious Layer (m)	Basic Infiltration Rate Before Leaching (cm hr^{-1})		
				First rep.	Second rep.	average
S_4A_3	2.65	1.23	5.50	0.49	0.92	0.71

Table 2. Some physical properties of the soil layers before leaching

depth (cm)	Soil texture	Water content (%)			Bulk density	Particle density	Total Porosity (%)	Permeability	Moisture deficit (cm)	
		Y	FC	PWP	g cm^{-3}			Rate (mm h^{-1})	Layers	Cumulative
0-25	CL	7.10	22.23	15.14	1.44	2.73	47.26	0.49	5.45	5.45
25-50	SiCL	13.10	24.32	15.87	1.46	2.71	46.13	3.20	4.10	9.54
50-75	SiCL	14.33	23.27	4.00	1.65	2.66	38.00	5.00	3.22	7.34
75-100	SiCL	15.70	22.23	15.14	1.44	2.73	47.26	2.87	2.35	10.68
100-125	SiC	14.60	25.70	19.64	1.56	2.72	42.65	0.40	4.33	14.02
125-150	SiC	14.85	25.70	19.64	1.56	2.72	42.65	0.40	4.23	18.25

Y: initial soil water content

According to Table 2, the soil profile contained heavy to very heavy texture and the cumulative soil moisture deficit was between 5.45 cm and 18.25 cm in the first and last layers of the soil profile, respectively. Ranges of soil permeability were between 0.49 to 0.40 mm h^{-1} and the total porosity varied from 47.26% in first layer to 42.65% in the last one.

All experiments were conducted with two replicates. In the first replicate, the experiment was conducted by applying only 100 cm water in four-25cm intervals. In the second replicate, 10000 Kg ha^{-1} gypsum (78% purity rate) was applied prior to salt leaching together with leaching water. The required water for leaching was supplied from Karun river. The intermittent pounding method [14] was conducted with six double rings infilterometer in a circular array with 10 m in diameter. The total applied water depth was 100 cm (four-25cm depths). Soil samples were taken from 0-25, 25-50, 50-75, 75-100, 100-125 and 125-150 cm soil depths, each in three replicates. These replicates reflect the samples that were taken before, during and after each leaching water application interval. The collected soil samples were then analyzed in the laboratory and their EC_e, pH, CEC, $ExNa^+$, $CaSO_4$, $CaCO_3$, total anions and total cations were measured. The mean chemical properties of different soil layers for the first and second experimental replicates are respectively given in Tables 3 and 4. The equilibrated salinity was also measured after fourth leaching water interval application from 0-5 cm soil depths in three replicates.

Table 3. Some chemical properties of different soil layers before and after applying leaching for the first replicate

Sampling time	Soil depth	EC_e	pH	T.N.V	Gypsum	CEC	$Ex.Na^+$	Mg^{2+}	Ca^{2+}	Na^+	SAR	ESP*
	(cm)	(dS m^{-1})		%		Cml kg^{-1}		Meq L^{-1}				
Before leaching	0-25	58.30	7.60	46.50	0.50	14.10	5.80	168.0	234.00	509.00	35.90	41.13
	25-50	43.00	7.70	45.00	0.34	15.50	9.30	98.00	133.00	360.00	33.50	60.00
	50-75	42.50	7.70	44.00	0.10	14.60	8.50	89.00	115.00	372.00	36.83	58.22
	75-100	40.20	7.70	45.00	0.27	13.80	10.40	84.00	97.00	386.00	40.58	75.36
	100-125	32.50	7.80	44.00	0.15	14.80	9.10	56.00	69.50	319.00	40.27	61.49
	125-150	29.70	7.90	45.00	0.09	16.50	8.00	44.00	60.00	292.00	40.49	48.48
After applying 100 cm leaching water	0-25	5.40	8.10	42.00	0.43	12.50	8.00	11.00	33.00	10.60	2.26	64.00
	25-50	5.00	8.10	43.00	0.00	16.00	11.86	14.00	20.00	16.00	3.88	74.13
	50-75	5.80	8.30	44.00	0.00	10.50	5.70	5.00	10.00	46.20	16.87	54.29
	75-100	12.20	8.20	48.90	0.04	18.00	0.74	34.00	39.00	157.00	25.99	4.11
	100-125	25.40	7.80	47.80	0.04	13.20	4.00	46.00	44.00	165.00	24.60	30.30
	125-150	30.00	8.00	45.00	0.64	12.00	5.80	60.00	41.00	258.00	36.31	48.33
Mean	Before	41.03	7.73	44.92	0.24	14.88	8.52	89.83	118.08	373.00	37.93	57.45
	After	13.97	8.08	45.12	0.19	13.70	6.02	28.33	31.17	108.80	18.32	45.86
difference	Decrease	27.06	-	-	0.05	1.18	2.50	61.50	86.91	264.20	19.61	11.59
	Increase	-	0.35	0.20	-	-	-	-	-	-	-	-

*(ESP=Ex.Na^+×100/CEC)

Table 4. Some chemical properties of different soil layers before and after applying leaching for the second replicate

Sampling time	Soil depth	EC_e	pH	T.N.V	Gypsum	CEC	$Ex.Na^+$	Mg^{2+}	Ca^{2+}	Na^+	SAR	ESP*
	(cm)	(dS m^{-1})		%		Cml kg^{-1}		Meq L^{-1}				
Before leaching	0-25	58.30	7.60	46.50	0.50	14.10	5.80	168.0	234.00	509.00	35.90	41.13
	25-50	43.00	7.70	45.00	0.34	15.50	9.30	98.00	133.00	360.00	33.50	60.00
	50-75	42.50	7.70	44.00	0.10	14.60	8.50	89.00	115.00	372.00	36.83	58.22
	75-100	40.20	7.70	45.00	0.27	13.80	10.40	84.00	97.00	386.00	40.58	75.36
	100-125	32.50	7.80	44.00	0.15	14.80	9.10	56.00	69.50	319.00	40.27	61.49
	125-150	29.70	7.90	45.00	0.09	16.50	8.00	44.00	60.00	292.00	40.49	48.48
After applying 100 cm leaching water	0-25	4.20	8.00	46.00	0.04	12.40	0.85	14.00	29.00	12.00	2.59	6.85
	25-50	4.20	8.20	43.50	0.16	12.40	0.94	11.00	24.00	21.50	5.14	7.58
	50-75	4.60	8.00	44.00	0.00	15.00	3.11	4.00	8.00	34.20	13.96	20.73
	75-100	15.90	7.80	47.50	0.00	16.00	5.80	14.00	28.00	111.20	24.27	36.25
	100-125	32.20	7.70	47.50	0.02	8.92	4.55	58.00	58.00	237.00	31.12	51.01
	125-150	26.50	7.80	44.50	0.00	15.00	6.00	34.00	48.00	200.00	31.23	40.00
Mean	Before	41.03	7.73	44.92	0.24	14.88	8.52	89.83	118.08	373.00	37.93	57.45
	After	14.60	7.92	45.50	0.07	13.29	3.54	22.50	32.50	102.65	18.05	27.07
Difference	Decrease	26.43	-	-	0.17	1.59	4.98	67.33	85.58	270.35	19.88	30.38
	Increase	-	0.19	0.58	-	-	-	-	-	-	-	-

*(ESP=Ex.Na^+×100/CEC)

The data presented in Tables 3 and 4 indicate that soil pH before leaching was varied between 7.60 to 7.90. The soil salinity has demonstrated decreasing trend with respect to soil depth. The ESP value varied between 41.13 to 75.36. This variation for gypsum was between 0.50% and 0.09%. The lime content (T.N.V) varied between 46.5 and 44.0 % in the soil profile. Using the data presented in Tables 2, 3 and 4, the desalinization values were obtained from

$$X = \frac{D_{lw}}{D_s} \tag{1}$$

$$Y = \frac{(EC_f - EC_{eq})}{(EC_i - EC_{eq})} \tag{2}$$

Where D_{lw} is depth of applied leaching water, D_s is depth of soil, EC_i and EC_f are electrical conductivity (dS m^{-1}) of saturated extract before and after leaching, respectively, and EC_{eq} is electrical conductivity of soil water at equilibrium.

The value of EC_{eq} is considered to be EC_e of the soil upper layer after leaching was stopped and D_{lw}/D_s is the ratio of net depth of leaching water (D_{lw}) to unit depth of soil (D_s). The quality of water used in this study is given in Table 5. This is classified as C_4-S_2 based on the Willcox diagram [23].

Table 5. Chemical properties of the applied water for soil desalinization

EC_w	TDS	pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	Sum of Cations	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}	Sum of anions	SAR	$adjR_{Na}$
(dS m^{-1})	(mg L^{-1})		(Meq L^{-1})					(Meq L^{-1})					(Meq $L^{-1})^{0.5}$	
2.362	1512.0	8.2	15.0	2.0	10.0	-	27.0	13.0	11.0	3.0	-	27.0	6.10	6.19

Four mathematical models including exponential, power, inverse and logarithmic functions were fitted to the obtained experimental data using curve estimation technique. Then, regression coefficients and standard errors at significance level of 1% were obtained and the functions were compared accordingly. The best fitted model with the highest significance level was then selected. Similar procedure was conducted for those replications that have received chemical amendment. The water needed for leaching to reduce soil salinity was determined, using the best fitted model. The analysis of residual errors, differences between measured and predicted values were performed to evaluate model performance [7, 27]. These statistics consisted of the so-called Root Mean Square Error (*RMSE*), Modeling Efficiency (*EF*), Coefficient of Residual Mass (*CRM*), Coefficient of Determination (*CD*) and Maximum Error (*ME*). In mathematical form, these can be presented as [27]:

$$ME = max|Pi - Oi|_{i=1}^{n} \tag{3}$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{\frac{1}{2}} \tag{4}$$

$$CD = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2}{\sum_{i=1}^{n}(P_i - \bar{O})^2} \tag{5}$$

$$EF = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(P_i - \bar{O})^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{6}$$

$$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \tag{7}$$

Where P_i and O_i are the predicted and measured data, respectively, $\bar{O}$ is the mean of observed data, and n is the number of samples.

Descriptions of these statistics are thoroughly discussed by Homaee et al. (2002b).

As the prerequisite of soil desalinization and land reclamation in large scale is to equip the field with a drainage system (open or subsurface), for this reason based on available data obtained during the field studies, efforts were made to calculate the optimal depths and spacing of tile drains based on Glover-Dumm equation:

$$L = \pi \frac{\left[\frac{K(d_e + 0.5Y_0)*t}{S}\right]^{\frac{1}{2}}}{\left[ln 1.16\frac{Y_0}{Y_t}\right]^{\frac{1}{2}}} \tag{8}$$

where K is saturated hydraulics conductivity, d_e is equivalent depth, Y_0 is maximum water table depth at upper part of drains, Y_t is variable height of water table depth as function of time, S is drainable porosity and t is irrigation interval.

Using these data, the spacing of 50 m was obtained which seems to be practically and economically acceptable.

RESULTS

Based on data presented in Table 2, from 100 cm applied water for both leaching and total water deficit of entire 150 cm soil depth, 18.25 cm belongs to water deficit. Thus, the net depth of applied leaching water was about 81.75 cm.

In order to develop a desalinization model, the data presented in Tables 6, 7, 8 and 9 were employed by making use of Eqs. 1 and 2. The obtained results and the derived empirical models are also represented in Tables 10 and 11, respectively.

Table 6. Initial and final weighted mean EC_e before and after leaching for the first replicate

Soil depth (cm)	ECe (dS m^{-1}) before leaching	ECe (dS m^{-1}) after leaching				
		D_w=25cm	D_w=50cm	D_w=75cm	D_w=100cm	Mean of EC_f
		EC_f (25)	EC_f (50)	EC_f (75)	EC_f (100)	
0-25	58.30	5.00	6.00	5.70	5.4	5.53
0-50	50.65	16.40	7.00	5.85	5.2	8.61
0-75	47.93	25.32	9.33	6.57	5.40	11.65
0-100	46.00	30.49	14.25	9.33	7.10	15.29
0-125	43.30	-	18.30	14.32	10.76	16.94
0-150	41.03	-	-	16.73	13.97	16.57

Based on data presented in Table 3   - Data were not reliable

Table 7. Initial and final weighted mean EC_e before and after leaching for the second replicate

Soil depth (cm)	ECe (dS m^{-1}) before leaching	ECe (dS m^{-1}) after leaching				
		D_w=25cm EC_f (25)	D_w=50cm EC_f (50)	D_w=75cm EC_f (75)	D_w=100cm EC_f (100)	Mean of EC_f
0-25	58.30	6.20	2.20	4.80	4.20	4.35
0-50	50.65	15.35	4.60	5.45	4.20	7.40
0-75	47.93	25.57	9.23	6.23	4.33	11.34
0-100	46.00	29.93	12.68	11.68	7.22	15.38
0-125	43.30	-	16.02	16.34	12.22	17.13
0-150	41.03	-		18.75	14.60	16.66

Based on data presented in Table 4 - Data were not reliable

Table 8. The obtained desalinization values for the experimental soils for first replicate

Soil depth (cm)	Net depth of leaching water applied and related ratios of applied water to unit depth of soil (X,Y)				
0-25	Dlw (cm)	19.55	44.55	69.55	94.55
	X=dlw/Ds	0.78	1.78	2.78	3.78
	Y=ECf-ECeq/ECi-ECeq	0.01	0.03	0.02	0.02
0-50	Dlw (cm)	15.46	40.46	65.46	90.46
	X=dlw/Ds	0.31	0.81	1.31	1.81
	Y=ECf-ECeq/ECi-ECeq	0.26	0.05	0.03	0.02
0-75	Dlw (cm)	17.66	42.66	67.66	92.66
	X=dlw/Ds	0.24	0.57	0.90	1.24
	Y=ECf-ECeq/ECi-ECeq	0.48	0.11	0.05	0.02
0-100	Dlw (cm)	10.25	35.25	60.25	85.25
	X=dlw/Ds	0.10	0.35	0.60	0.85
	Y=ECf-ECeq/ECi-ECeq	0.63	0.24	0.12	0.06
0-125	Dlw (cm)	10.98	35.98	60.98	85.98
	X=dlw/Ds	0.09	0.29	0.49	0.69
	Y=ECf-ECeq/ECi-ECeq	-	0.36	0.25	0.16
0-150	Dlw (cm)	6.75	31.75	56.75	81.75
	X=dlw/Ds	0.04	0.21	0.38	0.54
	Y=ECf-ECeq/ECi-ECeq	-	-	0.34	0.26

EC_{eq}= 4.48 dS m^{-1}

Table 9. The obtained desalinization values for the experimental soils for second replicate

Soil depth (cm)	Net depth of leaching water applied and related ratios of applied water to unit depth of soil (X,Y)				
0-25	Dlw (cm)	19.55	44.55	69.55	94.55
	X=dlw/Ds	0.78	1.78	2.78	3.78
	Y=ECf-ECeq/ECi-ECeq	0.07	-	0.05	0.03
0-50	Dlw (cm)	15.46	40.46	65.46	90.46
	X=dlw/Ds	0.31	0.81	1.31	1.81
	Y=ECf-ECeq/ECi-ECeq	0.27	0.05	0.07	0.04
0-75	Dlw (cm)	17.66	42.66	67.66	92.66
	X=dlw/Ds	0.24	0.57	0.90	1.24
	Y=ECf-ECeq/ECi-ECeq	0.51	0.15	0.09	0.05
0-100	Dlw (cm)	10.25	35.25	60.25	85.25
	X=dlw/Ds	0.10	0.35	0.60	0.85
	Y=ECf-ECeq/ECi-ECeq	0.63	0.24	0.22	0.11
0-125	Dlw (cm)	10.98	35.98	60.98	85.98
	X=dlw/Ds	0.09	0.29	0.49	0.69
	Y=ECf-ECeq/ECi-ECeq	-	0.34	0.34	0.24
0-150	Dlw (cm)	6.75	31.75	56.75	81.75
	X=dlw/Ds	0.04	0.21	0.38	0.54
	Y=ECf-ECeq/ECi-ECeq	-	-	0.43	0.32

EC_{eq}=2.26 dS dS m^{-1}

Table 10. The calculated model parameters and related statistics for evaluating different desalinization models performance for first replicate

mathematical expression	related coefficients		statistics parameters		
	a	b	r	SE	Sig F
$Y=a.e^{b.x}$	0.20	-1.06	0.90	0.04	0.001
$Y=a.x^b$	0.04	-1.15	0.68	0.07	0.001
Y=a+blnx	0.07	-0.16	0.92	0.04	0.001
Y=a+b/x	0.02	0.04	0.70	0.07	0.001

Table 11. The calculated model parameters and related statistics for evaluating different desalinization models performance for second replicate

mathematical expression	related coefficients		statistics parameters		
	a	b	r	SE	Sig F
$Y=a.e^{b.x}$	0.27	-0.99	0.91	0.08	0.001
$Y=a.x^{b}$	0.06	-1.22	0.68	0.08	0.001
Y=a+blnx	0.11	-0.16	0.92	0.06	0.001
Y=a+b/x	0.02	0.07	0.72	0.09	0.001

For the first replicate, the logarithmic model with maximum correlation coefficient (r) of 0.92 and minimum standard error (SE) of 0.04 was selected. This was significant at 1% of significancey level. The best fitted empirical model obtained to be:

$$Y = 0.07\text{-}0.16 \ln x \quad (9)$$

For the second replicate, the logarithmic model was also provided the best results, having maximum correlation coefficient (r) of 0.92 and minimum SE of 0.06 at 1% significancey level. The obtained relation can be written as:

$$Y = 0.11\text{-}0.16 \ln x \quad (10)$$

By substituting Eqs.1 and 2 into Eq.9 the latter can be written as:

$$\left[\frac{(EC_f - EC_{eq})}{(EC_i - EC_{eq})}\right] = 0.07\text{-}0.16 \ln x \quad (11)$$

By making use of Eq.11, the net water depth (D_{lw}) needed for reducing soil salinity after applying leaching water and final soil salinity can be determined by:

$$D_{lw} = D_s \, exp[(y - 0.07)/(-0.16)] \quad (12)$$

$$EC_f = [(0.07 - 0.16 \, ln(D_{lw}/D_s)) \times EC_i - EC_{eq}] + EC_{eq} \quad (13)$$

Substituting Eqs.1 and 2 into Eq.10, the latter leads to:

$$\left[\frac{(EC_f - EC_{eq})}{(EC_i - EC_{eq})}\right] = 0.11 - 0.16 \, ln(D_{lw}/D_s) \quad (14)$$

By using Eq.14, the net water depth (D_{lw}) needed for reducing soil salinity after applying leaching water and final soil salinity can be determined by:

$$D_{lw} = D_s \exp[(y - 0.11)/(-0.16)] \quad (15)$$

$$EC_f = [(0.11 - 0.16 \, ln(D_{lw}/D_s)) \times EC_i - EC_{eq}] + EC_{eq} \quad (16)$$

Based on the data presented in Tables 6 and 7, the remaining initial salts as well as the leached out initial salts percentage were calculated and presented in Tables 12 and 13.

Table 12. The relation between depths of applied leaching water and remaining initial salts and initial removed salts in soil for first replicate

D_w (cm)	Initial salinity (%)	D_s (cm)				Means EC_e
		0-25	0-50	0-75	0-100	
25	+	8.58	32.38	52.82	66.28	40.01
	-	91.42	67.62	47.18	33.72	59.99
50	+	10.29	13.82	19.47	30.98	18.64
	-	89.71	86.18	80.53	69.02	81.36
75	+	9.78	11.55	13.70	20.27	13.82
	-	90.22	88.45	86.30	79.73	86.18
100	+	9.26	10.27	11.27	15.43	11.56
	-	90.74	89.73	88.73	84.57	88.44
Average	+	9.48	17.00	24.31	33.24	21.01
	-	90.52	83.00	75.69	66.76	78.99

+: Remained -: Removed

Table 13. The relation between depths of applied leaching water and remaining initial salts and initial removed salts in soil for second replicate

D_w (cm)	Initial salinity (%)	D_s (cm)				Means EC_e
		0-25	0-50	0-75	0-100	
25	+	10.63	30.31	53.39	65.05	39.83
	-	89.37	69.69	46.66	34.95	60.17
50	+	3.77	9.08	19.26	27.55	14.92
	-	96.23	90.92	80.74	72.45	85.08
75	+	8.23	10.76	13.01	25.38	14.34
	-	91.77	89.24	86.99	74.62	85.66
100	+	7.20	8.29	9.04	15.71	10.06
	-	92.80	91.71	90.96	84.29	89.94
Average	+	7.46	14.61	23.66	33.42	19.79
	-	92.54	85.39	76.34	66.58	80.21

+: Remained -: Removed

The data given in Table 12 indicate that by applying 100 cm leaching water, 90.52, 83.00, 75.69 and 66.76 percents of the initial salts were leached out from corresponding depths, respectively. The used leaching water for these depths corresponds to 8.46, 4.34, 3.51 and 2.12 pore volumes, respectively.

The data given in Table 13 indicate that by applying 100 cm leaching water, 92.54, 85.39, 76.34 and 66.58 percents of the initial salts were leached out from the corresponding depths. The applied leaching water for these depths corresponds to 8.46, 4.34, 3.51 and 2.12 pore volumes, respectively.

Calculated values of the five statistics for measured and predicted data for two replicates of experimental soils are given in Table 14.

Table 14. The calculated statistics to evaluate the mathematical models

Models	Replicate	RMSE	CRM	CD	EF	ME
Exponential	1	0.08	0.18	4.15	0.29	0.17
	2	0.09	0.23	3.51	0.48	0.26
Power	1	0.003	0.27	2.17	0.47	0.19
	2	0.003	0.18	1.47	0.70	0.19
Logarithmic	1	0.08	-0.11	0.72	0.37	0.17
	2	0.07	0.002	1.14	0.68	0.12
Inverse	1	0.07	0.03	3.67	0.49	0.19
	2	0.07	0.05	2.55	0.69	0.17

According to this table, the calculated *RMSE* values (0.08 for exponential, 0.003 for power, 0.08 for logarithmic and 0.07 for inverse models) indicate that the estimates of logarithmic model are more reasonable than other models for the first replicate. The tendency to underestimate or overestimate is also similar to that of *RMSE* statistics, but these tendencies are not very strong because all *CRM* values are around zero. Also, there is significant difference in calculated *CD* statistics among models. The lowest maximum error (*ME*) in logarithmic model indicates the reasonable performance of this model. In general, these five statistics show that the models perform almost similar prediction trend, but the logarithmic model provides more accurate estimates than other models for desalinization of saline soils in the first replicate.

For the second replicate, the *RMSE* values of 0.09 for exponential, 0.003 for power, 0.07 for logarithmic and 0.07 for inverse models indicate that the result of logarithmic model is more reasonable than inverse, power and exponential models, respectively.

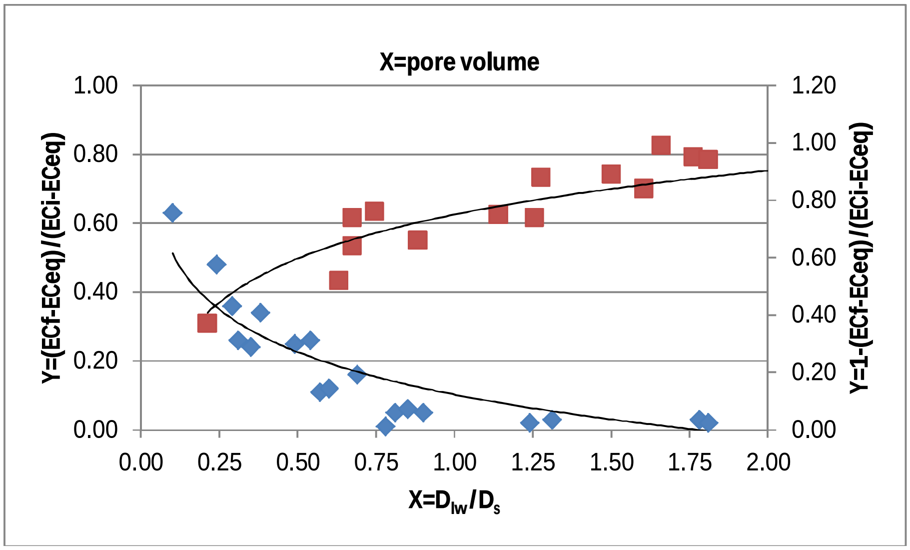
The positive *CRM* values show that the model tends to underestimate, but this tendency is not very strong because all *CRM* values are around zero. There is significant difference in calculated *CD* statistics among models. The lowest maximum errors (*ME*) in logarithmic model indicate the reasonable performance of this model. These statistics indicate that the logarithmic model provided better estimates than three other models for desalinization purpose.

By using Eqs. 9 and 10, that have provided best empirical outputs for the entire study area, the leaching curves were obtained. These results are presented in Figs. 1 and 2, respectively.

Using these curves, the net required leaching water (D_{lw}) can be calculated for practical purposes. It is obvious that for calculating the total leaching water (D_w), the water deficit in soil profile, evaporation from soil and water surface, and the amount of precipitation should be considered. It should be noted that the calculations drawn from the desalinization leaching curves are valid for the study area conditions. Also, those salts that were removed until an equilibrium *ECeq* is reached under specific soil-irrigation-water-drainage conditions were referred to as excess salts. Under ideal conditions, this equilibrium will be 1.5-2.0 times of irrigation water salinity. In this study, this proportion was obtained to be 3.37 dS m^{-1}, which is the average of 4.48 and 2.26 dS m^{-1} that were obtained from first and second replications, respectively. Also, Figs. 1 and 2 show the fraction of excess salts removed from both replications, expressed by $Y=1- ((EC_f-EC_{eq}) / (EC_i-EC_{eq}))$ as function of pore volumes.

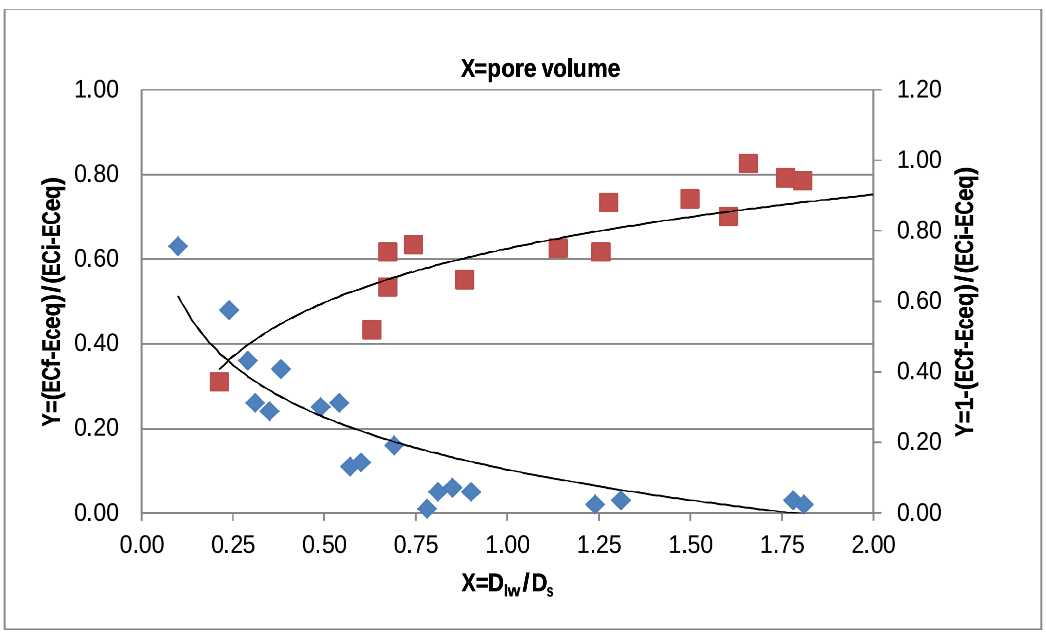
By subtracting EC_{eq} from the actual and initial EC_e values, leaching curves are obtained that are independent of the salinity of leaching water, existing drainage and evaporation conditions. Therefore, the shape of leaching curves was governed solely by soil characteristics.

Since the salt leaching follows the miscible displacement concept, based on the Nielsen and Biggar (1961) approach, for each pore volume, 50% and for two pore volumes about 80% of the initial salts should be removed from the soil profile. However, Fig. 1 indicates that about 75% and 90% of the initial salts are leached out for one and two pore volume water application for the first replicate, respectively. Also, Fig. 2 indicates that about 71% and 84% of the initial salts are leached out for 1 and 2 pore volume, respectively, water application for the second replicate.



*pore volume was obtained from X = (D_{lw})/(D_s*n)

Figure 1. Soil desalinization curve and fraction of excess salts removed from replication 1 (leaching water without amendment).



*pore volume was obtained from X = (D_{lw})/(D_s*n)

Figure 2. Soil desalinization curve and fraction of excess salts removed from replication 2 (leaching water + gypsum).

To evaluate the obtained desalinization data, these data were compared to some other previously proposed empirical models to assess the predictability of capital leaching water requirements. The related results are presented in Table 15. For this comparison the initial, final and equilibrated soil salinities were considered to be 45.0, 8.0 and 3.54 dS m^{-1} (1.5 times of leaching water salinity), respectively, in 150 cm depth.

Table 15. Comparison of required desalinization water for different available models and the newly proposed model

Model	year	Water required for desalinization(m)				Needed water (weighted mean) (m)	Rank
		Soil depth increment (D_s) (m)					
		0.25	0.50	0.75	1.00		
Reeve	1957	0.41	0.83	1.22	1.63	1.50	8
Dielman	1963	0.50	1.00	1.50	2.00	1.67	9
Leffelaar &Sharma	1977	0.15	0.30	0.46	0.61	0.54	4
Hoffman	1980	0.18	0.37	0.55	0.74	0.69	7
Pazira & Kawachi	1981	0.17	0.34	0.51	0.67	0.66	5
Verma & Gupta	1989	0.19	0.39	0.58	0.78	0.67	6
Pazira & Keshavarez	1998	0.13	0.26	0.39	0.51	0.50	3
Mohsenifar	2006	0.02	0.11	0.26	0.47	0.41	2
Proposed model	2012	0.02	0.08	0.18	0.33	0.24	1

The results indicated that the models proposed by Mohsenifar (2006) and Pazira and Keshawarz (1998) can provide second and third best perditions fallowing the newly proposed model. Some other empirical models (e.g. Reeve 1957; Dieleman 1963; Hoffman 1980) did not provide a reasonable prediction. This can be related to different soil physical and chemical properties, and to desalinization experimental performances.

It should be mentioned that the soil desodification process (method of data generation, analysis, comparison and results) is rather the same as desalinization process and for this reason did not presented in this article.

DISCUSSION

The collected data from the extensive experiments indicates that by applying 100 cm leaching water, the soil salinity reduces to 83.00 and 66.76 percents of initial NaCl dominant salts in the first replicate. This was 85.39 and 66.58 percents of the initial salts for the second replicate at 0.5 and 1.0 m of soil profile, respectively. The soil water deep percolation itself can leach out about 80% of the initial salts when only 100 cm water applied. The results of correlation mathematical models indicate that logarithmic model can well describe the collected experimental data at large scale. The newly proposed empirical model with minimum weighted mean of required leaching water (0.24) presents best performance from water saving point of view compares to other models. Also from the data presented in Tables 3 and 4, it is obvious that desalinization process simultaneously lead to desodification because the dominant salt is NaCl. Then one may draw a conclusion that when NaCl is the dominant salt in the system, there is no need to apply any further amendments than water for soil reclamation.

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