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Assessment of salt leaching management in saline soils with MACRO model

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Abstract

Today, in many parts of the world, water and soil resources are facing the threat of salinization. Several researches has been done for the desalination of water and soil resources. One of these proposed solutions is leaching. There are several leaching methods which should be studied for each area. The present paper studies the saline soil of Nazarabad area, Iran using two types of saline and conventional water of the region and three different volumes of water (one, three, and five times the pore volume) in both continuous and alternate modes under frozen and non-frozen conditions with three replications. Then, the movement of salt was simulated by the MACRO model. The amount of salinity in drain water was measured during the experiments. The results showed that the conventional water managed to reduce soil salinity and solute concentration in the leaching experiments. Accordingly, the frozen treatments continuously irrigated with conventional water outperformed other treatments in terms of achieving minimum soil salinity (ECe<1 dS/m). Similarly, less water can be used in these treatments to reach the minimum ECe according to the irrigation scheduling predicted by the MACRO model i.e. 3.5 pore volume. At last, it was found that these soils did not require $CaCl_2$ for correction.

Introduction

Recent studies state that more than 50% of arable land will be affected by salinity by 2050 (Shrivastava and Kumar, 2015; Wang et al., 2020). On a global scale, salinity causes the loss of arable land, which is about 2000 hectares per day, which leads to 1-2% loss of agricultural land worldwide every year (Sahab et al., 2021). Situated in dry and semi-arid geographic regions that are subject to uneven spatial and temporal distribution patterns of rainfall, Iran is exposed to risks of drought, water scarcity, and soil salinity. The use of saline water facilitates salt accumulation in the root zone, leading to reduced crop production and low soil fertility (Ayars et al., 1993; Tedeschi and Dell'Aquila 2005; Mostafazadeh-Fard, 2008). High soil salinity threatens not only the growth of plants but also the functioning of the soil ecosystem (Hou et al., 2022). Fresh water resources available for saline soil reclamation and agricultural production are becoming more limited with rapid economic development. Therefore, the investigation of scientific and suitable methods for rehabilitating saline soils has become the research focus of agricultural development in saline soils (Yin et al., 2022).

Water scarcity in arid and semi-arid areas may aggravate the risk of soil salinity in these areas due to the insufficient amount of water for salt leaching. The low quality of water and wastewater available in these areas will further increase the risk of soil salinity (Beltran, 1999).

To correct saline soils through proper irrigation and efficient drainage systems, leaching is one of the best and most practical methods for salt leaching (Anapali et al., 2001; Amezketa et al., 2005; Ammari et al., 2008). Increasing sodium salinity in the soil solution leads to destruction of colloids, spreading, swelling and scattering of soil particles, trapping and reducing porosity, low soil permeability and low soil hydraulic conductivity (Bennett et al., 2019). The basis for modifying sodic soils is to replace exchangeable sodium with calcium (Qadir et al., 1996; Sadiq et al., 2007; Fa-Hu and Keren, 2009). The common source of calcium is a substance that contains calcium itself and can dissolve in a soil solution after use (Mitchell et al., 2000). Therefore, there are two methods for correcting such soils: 1) adding a source of calcium to non-calcareous soils and 2) increasing the solubility of calcium in calcareous soils. Since the solubility of lime is too low to provide calcium, it is usually used as an acidic or anti-acidic substance (Mojalali, 1994).

Today, models are considered to be the most important tools for conducting empirical and developmental studies in order to have a better understanding of a phenomenon or a combination of phenomena. Estimation is the outcome of a process that requires simulation. In other words, the existence of a model is a prerequisite for estimation. A model is used to examine a phenomenon in the simplest way possible and, if successful, it can be generalized to a more complicated one (Refahi 2003). MACRO is a one-dimensional dual-permeability model of variably saturated water flow and reactive solute transport in soil that has been used since the early 1990s as a research tool to investigate the effects of macropore flow on soil hydrology and contaminant transport under transient field conditions (Jarvis and Larsbo, 2012). MACRO model is also used to simulate the movement of salts in the soil, which is a double-field, one-dimensional model of unsaturated water flow and salt transfer in soil macropores. This model is widely used as a physical model with a numerical solution for all types of soils, even for simulating long periods of time. As one of its advantage, the MACRO model is characterized by its relative ease and simplicity in implementing this model and its minimum number of required parameters (Jarvis and Larsbo, 2012). One of the features of MACRO model is the ability to simulate flow in micropores or that in both micropores and macropores domains (Merdan and Quisenberry (2005), Jarvis and Lasbo, 2012). This feature makes it able to quantitatively evaluate the effects of the preferential water flow and salt transfer onto the surface and into underground water in soils with a structure on top. In the two-dimention flow, the total porosity of the soil profile in each layer is divided into two regions of macropores and micropores flows. Each of these two regions is characterized by its own humidity, hydraulic conductivity, and flow. Macropores play an important role for soil hydrology as they improve infiltration capacity and drainage rates, thereby minimizing risks of waterlogging, surface runoff and flooding (Bronstert et al., 2023).

The aim of the present study is the evaluation of MACRO model to find appropriate management scenarios for soil leaching. This study was accomplished to compare and evaluate the reclamation potential of different leaching methods.

Materials and methods

The soil samples were gathered from a orchard in Nazarabad, Iran, having salinity issue. The samples were prepared from a depth of 0 to 30 cm. Soil texture was determined by the hydrometric method, being clay loam. Dry bulk density and particle density of the soil were also measured (Table 1). The amount of ECe was measured by an extractor, and K_s in soil was determined by the falling head test according to soil sampling and methods of analysis (Carter and Gregorich, 2008).

Table 1- some physicochemical characteristics of soil at sampling location, Nazarabad city

Sand (%)	29
Silt (%)	43
Caly (%)	28
Porosity (%)	43
ρ_b (gr/cm^3)	1.34
ρ_s (gr/cm^3)	2.39
Ks (cm/hr)	2.8
Water EC (dS/m)	0.8
Soil ECe (dS/m)	3.45

In this research, columns made of PVC pipes characterized by a height of 0.3 m and an inner diameter of 0.1 m along with a funnel attached to the end of the column to convey drain water into a sample container for leaching were constructed. To fill the columns, the 0.3 m height of the soil column was divided into three 0.1 m sections, and each 0.1 m section reached the soil bulk density equivalent to field conditions by two shots with a weight of 326 g. After filling the soil columns, irrigation and the leaching process were carried out according to the type of treatments, at the lower end of which an appropriate filter was inserted to prevent fine particles from passing through. A container was designed and installed at the end of the column to observe and direct drainage and collect drains. A filter paper was placed on the soil surface to prevent soil compaction and structure disturbance of soil surface while adding water. It should be noted that any upward movement of water (evaporation) during the experiment was prevented by covering the soil surface (Wong et al., 2009; Delbari et al., 2012).

This study was carried out with two types of water, three different volumes of water, and continuous and alternate modes with frozen and non-frozen waters. Saline water and conventional water were the typical types of water in the region, which contained an equivalent amount of salinity at the time of leaching. Three different volumes of water included one, three, and five times the soil pore volume. The experiment was done in continuous and alternate modes in frozen and non-frozen water conditions. In the continuous mode, irrigation in the non-frozen water condition was applied continuously and, in the frozen water mode, the water required for all three volumes and the soil column froze simultaneously. In the alternate mode, irrigation in the non-frozen mode was applied through several steps: in the case of the volume one time the soil pore volume, irrigation was done similar to that in the continuous mode; however, for the volume three and five times the soil pore volume, irrigation interval lasted 48 hours.

Furthermore, in the alternate mode under the frozen condition, in the case of the volume one time the soil pore volume, water and soil column froze together, whereas, for the volume three and five times the soil pore volume, the first water volume and the soil column froze together and the rest of water volumes froze separately. Further, a day after the drainage of water from the bottom of the soil column, the other water volumes that froze separately in the freezer were applied to the soil surface at an interval of 48 hours. All treatments were replicated three times. At the end of each treatment, soil salinity was measured. It should be noted that the ambient temperature of the laboratory was kept almost constant during the experiment using the heating/cooling system. During the experiment, the amount and electrical conductivity of the drain water (EC) from the soil column were also measured (Office of Standard and Technical Criteria 2002). The irrigation during the experiment was done in the following manner; first, initial irrigation began to increase the soil moisture content by saturation using saline water and conventional water of the region, used for leaching in both modes of frozen and non-frozen waters. Saline water was prepared using laboratory-based $CaCl_2$ to reach EC=3.45 dS/m, equal to soil ECe before leaching. $CaCl_2$ was used to replace Na with Ca in soil. Then, the freezing phenomenon occurred in frozen treatments, which was followed by the occurrence of the melting phenomenon and water drainage. Finally, after initial irrigation, another irrigation was carried out with conventional water in the region for three to five pore water treatments in the continuous and alternate modes for both frozen and non-frozen treatments. For the sake of the purpose of this study, aiming to perform soil leaching, in order to reach the salinity level of water in the area, laboratory-based NaCl was used; in addition, to supply water for irrigation, distilled water was used. Considering that all the events that occurred during the experiment resulted from the presence of sodium salt and not anything else, distilled water was used in this study to simplify the problem. A total of 72 experimental units (72 = two types of water × two continuous and intermittent modes × two frozen and non-frozen conditions × three volumes of water × three replications) were considered according to available options. However, since the alternate and continuous modes of irrigation water treatments are similar in form, the number of treatments decreased to 60 units to expedite the experiment and reduce the cost. Abbreviations for each treatment are given in Tables (2) and (3). Statistical analysis was done using SPSS software.

After the laboratory observations, basic information related to some soil characteristics and hydraulic elements were measured and introduced to the MACRO model, and with its help, the movement of solutes along the soil profile was simulated (Jarvis, 2007). Results from laboratory observations with simulated results based on statistical indicators RMSE (Root Mean Squared Error), NRSME (Normalized Root Mean Squared Error), and mean comparison were compared. Finally, the efficiency of the model was checked with respect to the studied soil. The model was used to evaluate different leaching management scenarios and introduce the appropriate leaching method.

RMSE and NRMSE were calculated according to relations 1 and 2, respectively:

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

$$NRMSE = \frac{RMSE}{\bar{O}} \times 100 \quad (2)$$

where Pi: the simulated values, Oi: the observed values, Ōi: the mean observed values, and n: the total number of observations. The RMSE shows the difference between the observed and simulated values, and the lower this value is, the better the simulation will be. Of note, NRMSE is a method for reporting errors in which the mean squared error represents a percentage of the averaged observations. If the NRMSE is less than 10%, then excellent model simulation is achieved. Very good performance is observed in the range of 10 to 20%, average performance in the range of 20 to 30%, and poor model performance at a value above 30% (Khaledian et al., 2009).

Results and discussion

Before conducting the experiments, soil salinity level was determined and, then, during the experiments, the salt concentration in the drain water was measured using an EC meter. At the end of the experiments, the EC_e and the salt concentration of NaCl in all treatments were measured at the water-quality laboratory of University of Guilan, Iran. Table (4) represents some soil and water characteristics in the studied region.

Table 2- Introducing non-frozen (NF) treatments

Alternate (A)				Continuous (C)			
Common (C)		Salty (S)		Common (C)		Salty (S)	
NFAC		NFAS		NFCC		NFCS	
NF1AC	1PV	NF1AS	1PV	NF1CC	1PV	NF1CS	1PV(Pore volume)
NF3AC	3PV	NF3AS	3PV	NF3CC	3PV	NF3CS	3PV
NF5AC	5PV	NF5AS	5PV	NF5CC	5PV	NF5CS	5PV

Table 3- Introducing frozen (F) treatments

Alternate (A)				Continuous (C)			
Common (C)		Salty (S)		Common (C)		Salty (S)	
FAC	FAC	FAS		FCC		FCS	
F1AC	1PV	F1AS	1PV	1PV	1PV	F1CS	1PV
F3AC	3PV	F3AS	3PV	3PV	3PV	F3CS	3PV
F5AC	5PV	F5AS	5PV	5PV	5PV	F5CS	5PV

Table 4- Some characteristics of soil and irrigation water in the study area

Head of irrigation water	one volume of water	Salt concentration in irrigation water
cm	cm^3	gr/lit
16.99	1470	0.512

Table 5- The amount of measured ECe (mS/cm) and simulated with MACRO model in continuous treatments

Treatments	Measured ECe	ECe simulation by MACRO model
F5CS	0.58	0.58
F5CC	0.48	0.43
F3CS	0.59	0.70
F3CC	0.57	0.52
F1CS	0.75	0.83
F1CC	0.63	0.61
NF5CS	0.62	0.50
NF5CC	0.60	0.41
NF3CS	0.80	0.61
NF3CC	0.59	0.50
NF1CC	0.80	0.61

F: frozen; C: continuous; C: common, S: salty; A: alternate; N: non-frozen

Soil texture was determined by the hydrometric method in the laboratory so that clay, silt, and sand percentages of the considered soil texture were 28%, 43%, and 29% classified as clay loam.

MACRO model evaluation for comparing the average leached salinity in reality and estimation of the MACRO model

According to the values of the RMSE and NRMSE indices for continuous treatments (0.12 and 16.34, respectively) shown in Table (5), it can be concluded that the MACRO model has made satisfactory predictions for the continuously irrigated treatments. However, in the case of treatments with alternate irrigation Table (6), given the values of the RMSE and NRMSE indices (0.35 and 48.68, respectively), the model did not meet our expectations adequately for three reasons: first, the studied soil did not have a good structure (dispersed because of the high value of ECe); second, the leaching process was done in the laboratory conditions; third, internal drainage did not take place in practice (Beltran, 1999). These reasons seem quite definitive despite the fact that the MACRO model, by default, performs internal drainage, which is the reason why the MACRO model has underestimated the amount of salt in the soil after leaching under alternate treatments. Moreover, according to the calculated p-value of 0.19 by SPSS software, it is clear that there is no significant difference between the proposed model and the reality in estimating salt concentrations in soil after leaching under all treatments, indicating that the model has shown fairly good estimates.

Electrical conductivity variations of soil saturation extract with increasing irrigation water volume

As the amount of irrigation water increased, the amount of salt released from the soil column also increased nonlinearly as in a downward trend. That is, the amount of the extracted salt in the treatment with the 5 pore volumes of water was higher than that in the 3 pore volumes of water treatment, but not directly, since, in the early stages of leaching, the salts available in the macropores were removed and, then, the salts were slowly taken out of the micropores by the addition of the irrigation water. The salt in the micropores was not entirely leached as it was stuck at the bottom of the aggregates, which is the reason why the salt cannot be entirely removed by simply increasing irrigation water. Paired sample t test was used for comparing the treatments. First, saline treatments were compared in frozen and non-frozen treatments. Table (6) reports the significance or insignificance of the existing differences. According to Fig (1), it is clear that frozen continuous saline treatment (FCS) showed better performance. Then, continuous conventional treatments (FCC) were compared. According to Fig (2) and with regard to lower values of soil ECe in FCC, a comparison between this treatment and FCS treatment is made, as shown in Fig (3).

According to Fig (3), it was determined that, under frozen treatments, continuously irrigated treatments with conventional water showed better performance. In the next comparison, frozen and non-frozen alternate saline treatments were compared in accordance with Fig. (4), which revealed that frozen alternate saline irrigation treatments (FAS) had a better yield than non-frozen saline irrigation treatments (NFAS). The occurrence of this situation is completely consistent with the physical principles of water in liquid state, freezing and melting of ice. Freezing saline water and melting saline ice are potential desalination processes. In the freezing process of saline water, water molecules first crystallize to form ice crystals, while salts and other impurities remain in the salt water. Then, the ice crystals gradually increase as the temperature decreases further, and salts and impurities are concentrated and trapped inside the ice (Gu et al., 2012). Therefore, salt ice consists of ice crystals, salt water holes, air holes, and other solid impurities, and salt in salt ice is mainly in the form of salt water holes. When the temperature rises above the melting point of the salt ice, the interface between the salt water voids and the ice crystals begins to melt, and the salt water expands and joins to form channels. Then the salty water quickly leaves the salt ice through these channels due to gravity (Gu et al., 2013). In addition, a greater sweetening effect can be obtained by melting salt ice than by freezing salt water (Xie et al., 2009).

Table 6- The amount of measured ECe (mS/cm) and simulated with MACRO model in intermittent irrigation treatments

Treatments	Measured ECe	ECe simulation by MACRO model
F5AS	0.69	0.32
F5AC	0.77	0.25
F3AS	0.74	0.53
F3AC	0.66	0.38
NF5AS	0.75	0.40
NF5AC	0.70	0.33
NF3AS	0.60	0.57
NF3AC	0.90	0.46

F: frozen; C: continuous; C: common, S: salty; A: alternate; N: non-frozen

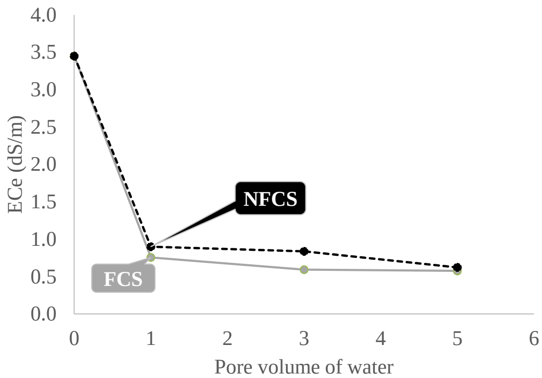

Fig. 1- Comparison of changes in salt content in soil with increasing irrigation water between FCS and NFCS

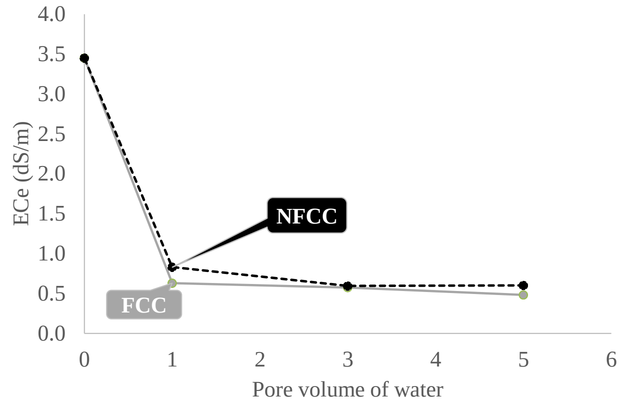

Fig. 2- Comparison of changes in salt content in soil with increasing irrigation water between FCC and NFCC

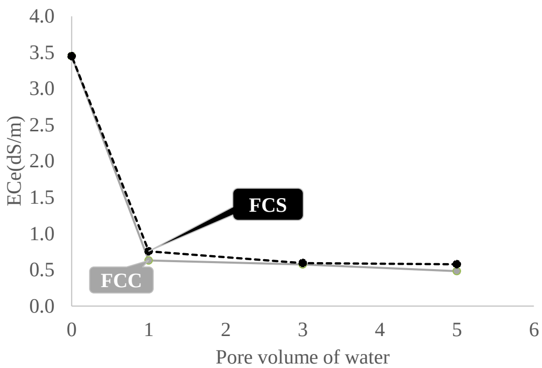

Fig. 3- Comparison of changes in salt content in soil with increasing irrigation water between FCS and FCC

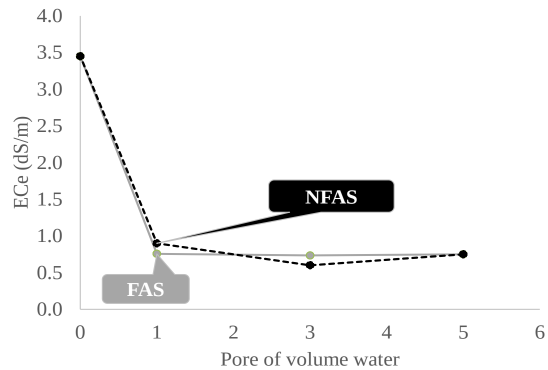

Fig. 4- Comparison of changes in salt content in soil with increasing irrigation water between FAS and NFAS

According to Fig. (5), the FAC treatment performed better. Figure (6) shows the comparison results of the treatments that demonstrated good performance in both Figures (4) and (5). Accordingly, the treatments had almost the same function; however, given that the conventional alternate freezing treatment (FAC) in 3 and 1 pore volumes of water had a lower salt content in the soil, this treatment was selected to make a general comparison with the type of frozen treatment that received continuous conventional irrigation (FCC) (see Fig. 7). The comparison of the graphs showed that frozen treatments outperformed non-frozen treatments. Further to that, it is evident that the treatments that were tested continuously performed better than the alternate treatments. Zare et al. (2022) used two types of saline and normal water in the same region as in the present study and three different volumes of water in continuous and intermittent states under frozen and non-frozen conditions. They concluded that the frozen treatments that were continuously irrigated with normal water of the area, performed better than other studied treatments and can be applied in winter in the studied area.

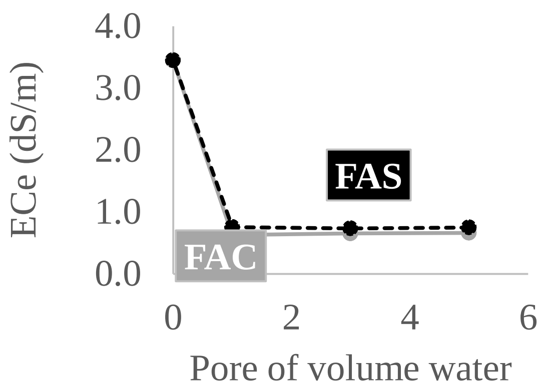

Fig. 5- Comparison of changes in salt content in soil with increasing irrigation water between FAS and FAC

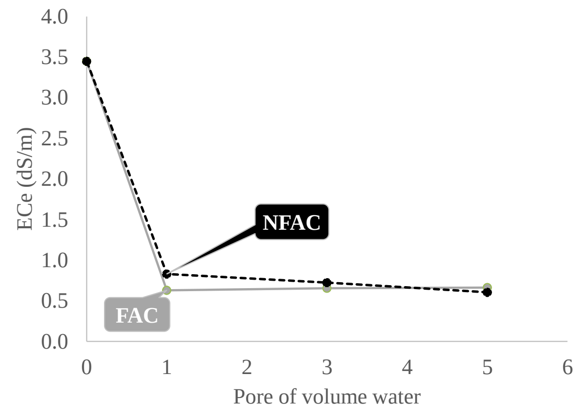

Fig. 6- Comparison of changes in salt content in soil with increasing irrigation water between FAC and NFAC

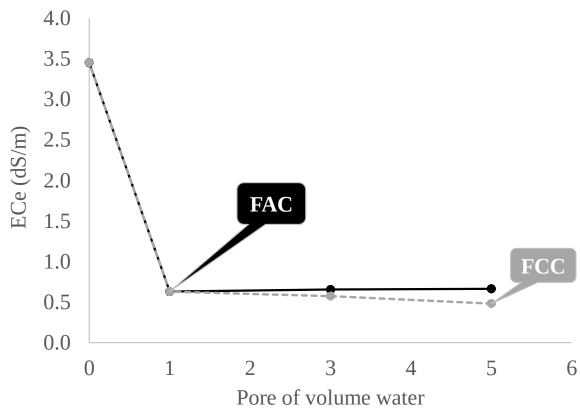

Fig. 7- Comparison of changes in salt content in soil with increasing irrigation water between FAC and FCC

Simulation of the amount of salt concentration in the soil by MACRO model

Due to the incorrect estimation of the MACRO model for the alternate treatments, the MACRO-based predictions of the salt concentration in the leached soil at various depths under continuous treatments are presented in Figures (8-10). In all three figures, it is clear that the level of leaching in the upper parts of the soil column is higher than that in the lower parts of the column. Furthermore, treatments with more pore volumes of water showed better performance, which is consistent with the reality. According to the MACRO model, the FCC and NFCC treatments showed almost identical performance and, thus, are considered to be the most appropriate options. Perhaps the reason for this is that due to the high salinity of the soil, the structure of the soil has been destroyed and due to the lack of separation of macropores and micropores, internal drainage (Beltran, 1999) has not occurred, therefore there is no difference between continuous and intermittent management.

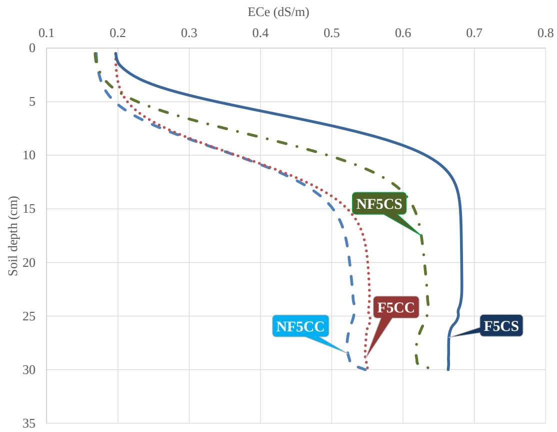

Fig. 8- Salt concentration profiles in soil after leaching by MACRO model for continuous treatments with 5 pore volumes of water

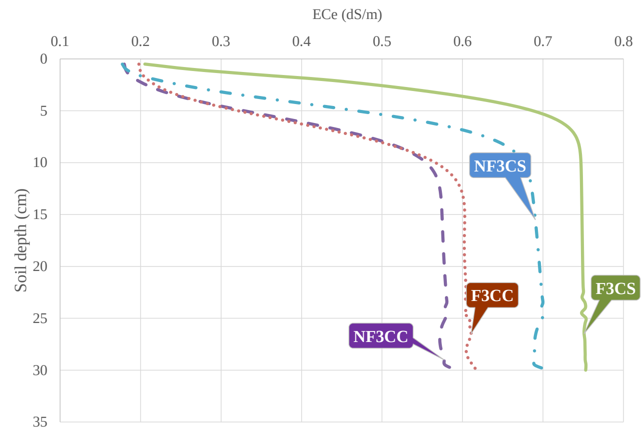

Fig. 9- Salt concentration profiles in soil after leaching by MACRO model for continuous treatments with 3 pore volumes of water

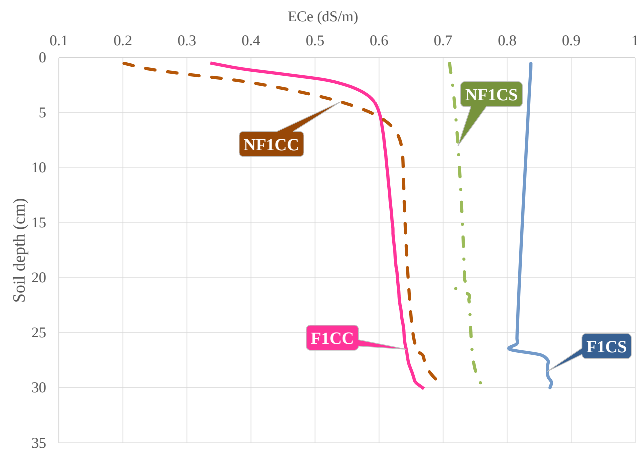

Fig. 10- Salt concentration profiles in soil after leaching by MACRO model for continuous treatments with 1 pore volume of water

The irrigation scenarios predicted by the MACRO model to achieve the minimum amount of soil salinity

One of the important measures in leaching saline and alkaline soils is the correct and appropriate calculation of water volume required for leaching so as to ensure less water consumption, time-saving, and energy efficiency. In fact (the laboratory), three quantities of irrigation water were considered for leaching, whereby each amount of leachate extracted a quantity of salt from the soil; however, this amount of removed salt has an inverse relation with the amount of irrigation water, such that the salt leached from the soil is initially exhausted at a greater amount, which decreases over time and with an increase in irrigation water. Such a decrease in the amount of extracted salt continues until the salt in the micropores and macropores is almost completely exhausted in the soil. Achieving the objective of minimum soil salinity may be possible through a treatment with a pore volume of 3.5 (3.5PV), provided that the amount of irrigation water set for the same treatment in this study be five pore volumes of water (5PV). For this reason, all treatments were evaluated by using MACRO model in terms of the exact amount of irrigation water required for achieving minimum salinity. It was found that F5CS, F5CC, and NF5CC treatments required 3.5, 4, and 4.5 pore volumes of water, respectively, to reach the minimum amount of salinity after leaching. Guo and Liu (2020), in their study on salinity, evaluated the effect of freezing saline water irrigation on salt leaching in saline soil, and a clear desalination effect was observed as a result of the saline ice melting process. During the process of melting and infiltration of saline ice, soil ECe first increased and then decreased drastically under this treatment.

Conclusion

An increase in the volume of irrigation water results in an increase in the leached salt, and the amount of salt leaching from the whole soil profile in the frozen treatments is higher than that of the non-frozen treatments. The amount of salt leaching from the whole soil profile in continuous treatments is more than that in alternate treatments. According to ECe, the treatments that were irrigated with saline water did not perform well. Therefore, the addition of calcium salt ($CaCl_2$) did not have effect on leaching. In brief, it can be concluded that frozen treatments that were irrigated continuously with conventional water of the region (FCC) showed better performance than other treatments. The management which is feasible during winter in the region. Due to irrigation scheduling predicted by the MACRO model, frozen treatments that were irrigated continuously with conventional water (FCC) required less leaching water than other treatments to reach the minimum amount of salinity. It was reportedly made clear that the MACRO model satisfactorily estimated the necessary amount of leaching for continuous irrigation treatments. In addition, in the case of alternate irrigation treatments, the model did not meet our expectations and performed rather poorly for a number of reasons: first, internal drainage was not implemented in practice, while the MACRO model was preconditioned to do so. Therefore, the amount of salt concentration in the soil after leaching in the alternate mode was higher than that predicted by the MACRO model. In the end, it should be noted that the addition of $CaCl_2$ in the soil is not recommended for correcting the studied soil. The finding of this research can be generalized in regions with the same conditions of soil. Motivated by the experience gained throughout this research and given the importance of leaching in regions with saline and alkaline soils, this study recommends conducting salt leaching a year at a proper temperature in the winter.

Conflict of interest

There is not any conflict of interest.

Funding Declaration

This research received no funding.

Availability of Data and Materials Declaration

The data that support the findings of this study are available on request from the corresponding author.

References

1- Amezketa E, Aragues R, Gazol R. 2005. Efficiency of sulfuric acid, mined gypsum and two gypsum byproducts in soil crusting prevention and sodic soil reclamation. Agronomy Journal. 97: 983-989. DOI: 10.2134/agronj2004.0236

2- Ammari TG, Tahboub AB, Saoub HM, Hattar BI, Al-Zubi YA. 2008. Salt removal efficiency as influenced by phyto-amelioration of salt-affected soils. Journal of Food Agriculture and Environment. 6(3/4): 456-460.

3- Anapali Ö, Şahin Ü, Öztaş T, Hanay A. 2001. Defining effective salt leaching regions between drains. Turkish Journal of Agriculture and Forestry. 25(1): 51-56.

4- Ayars JE, Hutmacher RB, Schoneman RA, Vail SS, Pflaum T. 1993. Long term use of saline water for irrigation. Irrigation Science. 14(1): 27-34. Doi: 10.1007/BF00195003

5- Bennett JM, Marchuk A, Marchuk S, Raine S. 2019. Towards predicting the soil-specific threshold electrolyte concentration of soil as a reduction in saturated hydraulic conductivity: The role of clay net negative charge. Geoderma. 337: 122-131. DOI: 10.1016/j.geoderma.2018.08.030

6- Bronstert A, Niehoff D, Schiffler G. 2023. Modelling infiltration and infiltration excess: the importance of fast and local processes. Hydrological Processes. 37: 14875. DOI: 10.1002/hyp.14875

7- Carter MR, Gregorich EG. 2008. Soil sampling and methods of analysis. Second edition. CRC Press. DOI: 10.1017/s0014479708006546

8- Delbari M, Talebzadeh M, Naghavii H, Gholamalizadeh A. 2012. Salt leaching process in saline soils through disturbed soil columns. Irrigation and Water Engineering. 2(8): 54-65.

9- Beltran JM. 1999. Irrigation with saline water: benefits and environmental impact. Agricultural Water Management. 40(2): 183-194. DOI: 10.1016/s0378-3774(98)00120-6

10- Fa-Hu LI, Keren R. 2009. Calcareous sodic soil reclamation as affected by corn stalk application and incubation: A laboratory study. Pedosphere. 19(4): 465-475. DOI: 10.1016/s1002-0160(09)60139-9

11- Gu W, Lin YB, Xu YJ, Chen WB, Tao J, Yuan S. 2013. Gravity-induced sea ice desalination under low temperature. Cold Regions Science and Technology. 86: 133-141. DOI: 10.1016/j.coldregions.2012.10.004

12- Gu W, Lin YB, Xu Y, Yuan S, Tao J, Li L, Liu C. 2012. Sea ice desalination under the force of gravity in low temperature environments. Desalination. 295: 11-15. DOI: 0.1016/j.desal.2012.03.017

13- Guo K, Liu, X. 2020. Salt leaching process in coastal saline soil by infiltration of melting saline ice under field conditions. Journal of Soil and Water Conservation. 75(4): 549-562. DOI: 10.2489/jswc.2020.00161

14- Hou R, Qi Z, Li T, Fu Q, Meng F, Liu D, Li Q, Zhao H, Yu P. 2022. Mechanism of snowmelt infiltration coupled with salt transport in soil amended with carbon-based materials in seasonally frozen areas. Geoderma. 420: 115882. DOI: 10.1016/j.geoderma.2022.115882

15- Jarvis N. 2007. Review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. European Journal of Soil Science. 58: 523–546. DOI: 10.1111/j.1365-2389.2007.00915.x

16- Jarvis N, Larsbo M. 2012. MACRO (v5.2): model use, calibration, and validation. Transactions of the ASABE. 55(4): 1413-1423. DOI: 10.13031/2013.42251

17- Khaledian, M.R., Mailhol, J.C., Ruelle, P., Rosique, P. 2009. Adapting PILOTE model for water and yield management under direct seeding system: The case of corn and durum wheat in a Mediterranean context. Agricultural Water Management 96: 757-770. 10.1016/j.agwat.2008.10.011

18- Merdan H, Quisenberry VL. 2005. Evaluation of MACRO model by short-term water and solute transport simulation in Maury silt loam soil. Plant, Soil and Environment. 51: 110-123. DOI: 10.17221/3563-pse

19- Mitchell JP, Shennan C, Singer MJ, Peters DW, Miller RO, Prichard T, Grattan SR, Rhoades JD, May DM, Munk DS. 2000. Impacts of gypsum and winter cover crops on soil physical properties and crop productivity when irrigated with saline water. Agricultural Water Management. 45: 55-71. DOI: 10.1016/s0378-3774(99)00070-0

20- Mojalali H. 1994. Soil chemistry. Nashr Press. Tehran, Iran. 341 pages.

21- Mostafazadeh-Fard B. 2008. Effect of leaching on soil desalinization for wheat crop in an arid region. Plant, Soil and Environment. 54(1): 20-29. DOI: 10.17221/2780-pse

22- Office of standard and technical criteria. 2002. Manual for leaching experiments for saline and sodic soil in Iran. No 255.

23- Refahi H. 2003. Water erosion and its control. Tehran University Press. Fourth Edition.

24- Qadir M, Qureshi RH, Ahmad N. 1996. Reclamation of a saline-sodic soil by gypsum and Leptochloa fusca. Geoderma. 74: 207-217. 10.1016/s0016-7061(96)00061-4

25- Sadiq M, Hassan G, Mehdi SM, Hussain N, Jamil M. 2007. Amelioration of saline-sodic soils with tillage implements and sulfuric acid application. Pedosphere. 17: 182-190. DOI: 10.1016/s1002-0160(07)60024-1

26- Sahab S, Suhani I, Srivastava V, Chauhan PS, Singh RP, Prasad V. 2021. Potential risk assessment of soil salinity to agroecosystem sustainability: Current status and management strategies. Science of the Total Environment. 764: 144164. DOI: 10.1016/j.scitotenv.2020.144164

27- Shrivastava P, Kumar R. 2015. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi Journal of Biological Sciences. 22(2): 123-131. DOI: 10.1016/j.sjbs.2014.12.001

28- Tedeschi A, Dell'Aquila R. 2005. Effects of irrigation with saline waters, at different concentrations, on soil physical and chemical characteristics.Agricultural Water Management. 77(1): 308-322. DOI: 10.1016/j.agwat.2004.09.036

29- Wang F, Shi Z, Biswas A, Yang S, Ding J. 2020. Multi-algorithm comparison for predicting soil salinity. Geoderma. 365: 114211. DOI: 10.1016/j.geoderma.2020.114211

30- Wong VNL, Dalal RC, Greene RSB. 2009. Carbon dynamics of sodic and saline soils following gypsum and organic material additions: A laboratory incubation. Applied Soil Ecology. 41: 29-40. DOI: 10.1016/j.apsoil.2008.08.006

31- Xie L, Ma J, Cheng F, Li P, Liu J, Chen W, Wang S. 2009. Study on sea ice desalination technology. Desalination. 245(1-3): 146-154. DOI: 10.1016/j.desal.2008.06.016

32- Yin CY, Zhao J, Chen XB, Li LJ, Liu H, Hu QL. 2022. Desalination characteristics and efficiency of high saline soil leached by brackish water and Yellow River water. Agricultural Water Management. 263: 107461. DOI: 10.1016/j.agwat.2022.107461

33- Zare H, Khaledian MR, Shabanpour M, Malekpour A. 2022. Evaluating the Performance of salt Leaching in Frozen Saline Soils. Journal of Irrigation and Sciences and Engineering. 45(2): 99-108. DOI: 10.22055/jise.2021.37483.1975