

Benefaction of Saline water Irrigation in Desert Soils: II. Mathematical Modeling of the Distribution of Salts in Soil Macro and Micro-Pores during Wetting and Drying Cycles

Nabil M. Anwar¹ and Mostafa H. Hilal²

¹Environment and Climate Research Institute; National Water Research Centre, Cairo, Egypt

nabilmamwar@hotmail.com

²Department of Soil and Water; National Research Center; Cairo, Egypt

mostafa@gizatec.com

Abstract: Laboratory tests such as salt concentration, salt activity, salt diffusion and salt balance were conducted to evaluate their effects on the pattern of salt accumulation and distribution in soils. Field trials, including surface soil management, irrigation systems; tree cover and their effect on salt distribution in the root zone were also evaluated. Corrective techniques for saline water irrigation and improvement of salt affected soils were discussed. The obtained empirical results proved to be very beneficial. However, to obtain such results is time consuming, tedious and expensive. That necessitates developing of a mathematical simulation model dealing with preferential salt distribution. Such model, when mature, is expected to facilitate obtaining beneficial results in short time. Computations concerning the building up of the above mentioned mathematical- model is a must. Soil porosity was subdivided into five equal portions. Each portion comprises 20% of the total soil porosity. When a saturated soil column is drained, gradually, larger pores that hold water with a suction head between the saturation point and field capacity (from 0.0 to 1/3rd atmosphere), will drain first. Next to drain is another 20 % which is also large gravitational pores. When downward gravitational flow ends, upward capillary flow due to evaporation will dominate and start transporting salts in the finer pores. At the soil saturation saline soil solution reaches equilibrium. At equilibrium, total pressure in all five pore portions will be equal. **"Total pore pressure can be defined as the resultant sum of pore wall + double layer pressures"**. In addition to salt osmotic pressure in pores and water hydrostatic pressure, there is larger contribution from pore wall pressure, in finer micropores as compared to larger macropores. In this work salts in soil pores were arranged according to their specific osmotic pressures (π_s ; osmotic pressure per unit concentration). Soluble K, Ca and Mg salts have more tendencies for being retained in the soil system as compared to Na salts. Salts with lower π_s (weak base) occupy finer pores, while salts with higher π_s (strong base) occupy larger pores. Examples of some salts as arranged from weaker to stronger are: $MgSO_4 < K_2SO_4 < KNO_3 < Mg(NO_3)_2 < Na_2SO_4 < (NH_4)_2SO_4 < NH_4NO_3 < MgCl_2 < NaCl$. Distribution of these salts in different pore sizes will follow such arrangement from finer to larger pores, following their π_s , in resemblance to densities in the case of buoyancy law. When a saturated soil is drained, solutes with higher π_s that reside in larger pores will move downwards with gravitational water flow, while solutes in finer pores will stay, and thereafter will move upwards with capillary water flow. This makes NaCl the fastest salt to leach from the soil, followed by $MgCl_2$, and then NH_4NO_3 . Meanwhile, $MgSO_4$ tend to stay in the soil. However, K_2SO_4 and KNO_3 are slightly less retained. Equilibrium distribution of solutes in larger and finer pores as mentioned above may not be attained under transient water flow. Simulation model dealing with reactive solute transport should include preferential ion distribution in macro and micro-pores in addition to other physical and chemical processes. It is thought that less moist soils is capable of developing water suction head which changes the double layer thickness, which will in turn alter salt distribution in the remaining pores. Further work is needed to upgrade this simulating model and to test its applicability in the soil-water-plant systems.

[Nabil M. Anwar and Mostafa H. Hilal. **Benefaction of Saline water Irrigation in Desert Soils: II. Mathematical Modeling of the Distribution of Salts in Soil Macro and Micro-Pores during Wetting and Drying Cycles.** *J Am Sci* 2015;11(11):12-23]. (ISSN: 1545-1003). <http://www.jofamericanscience.org>. 2

Key words: Salt activity, salt diffusion, salt balance, saline water irrigation, tree cover, pore wall pressure, Double layer, specific osmotic pressure.

1. Introduction

Saline water irrigation is well known to cause variable hazards to plants; even to the relatively salt tolerant plants which can be seriously affected at excessive salt levels. However, the degree of crop damage is, more or less, related to salt accumulation and distribution around root zone, rather than to

salinity level of irrigation water. The instability of desert agro-system is mainly related to salt accumulation in root zone.

Excessive salt concentration in soils and in underground water has been considered a serious problem in arid and semi-arid regions for centuries. Removal of excess salts or decreasing their activity is

necessary for optimum crop production and for soil conservation.

Macropores are gravitational pores which retain and carry down irrigation and leaching water. Filled macropores hold water at tension value from the point of saturation down to the point of field capacity. Micropores hold water at tension head of $1/3^{\text{rd}}$ atmosphere up to 15 atmosphere or above. Water movement carrying salts in macropores is mainly downwards under the effect of gravity. Meanwhile, movement of moisture and nutrients in capillary pores is horizontal (e.g. under drip irrigation) and upwards by capillary forces and the effect of evaporation from surface as shown by Anwar, (1988) and Hilal (2015).

In the first part of this study, concerning Benefaction of Saline water Irrigation in Desert Soils **as reported by Hilal (2012)**, removal of excess salts or decreasing their activity is necessary for attaining optimum crop production and preventing the formation of salt affected soil. He added that decreasing the activity of soluble salts in irrigation water proved to correct excessive water salinity. Besides, the realization of proper ionic and nutrients balance in soil solution lead to more successful utilization of saline water irrigation.

Benefaction of saline water irrigation in desert soils was the main goal of this program. Set of corrective techniques such as magnetic treatment of irrigation water, application of NF (as a soil amendment) and the choice of proper fertilization program were evaluated on different field scales.

In short, the distribution of salts and ions alike depend on salt type and salt concentration in soil-water-plant system, through irrigation process and drying process (by evaporation or evapo-transpiration) to field capacity or slightly lower. In such condition, salts may move downward through leaching, or accumulate in the surface, through evaporation, and move horizontally to certain distances in case of drip irrigation system.

Surface soil management, induced soil stratification, proper drying cycle and application of Nile Fertile (a natural sulfur fertilizer mixture) and irrigation scheduling, as reported by Hilal and Shata (2000), have been suggested as effective means for promoting saline water irrigation.

Hilal and Shata (2000) have shown that changes in salts and moisture distribution during a drying cycle of stratified soil columns, i.e. 15 cm sand over 15 cm sandy loam (S/SL) and the opposite stratification (SL/S), were evaluated. Results revealed that S/SL system has decreased capillary rise and evaporation loss and consequently limited the upward movement of salts. On the other hand, the system SL/S greatly increased evaporation but slightly increased the upward movement of salts. However, such movement

in homogenous S or SL soils was much greater than that of stratified systems. Besides, longer drying cycle decreased salt accumulation in root zone and activated upward and downward salt movement, under all conditions of study.

Applying MgSO_4 to high concentrations of NaCl in solution is capable of causing significant (EC) reduction.

In such work, magnetic treatment of Saline water (ranging in salinity between

6 to 11 $\text{mS}\cdot\text{cm}^{-1}$), fertilization program, farm management and application of Nile-Fertile[®] (NF) were evaluated, as effective means for improving salt affected regions,

In a semi pilot scale experiment that was conducted at Wadi El-Molak, Fertilization with NPK was compared with NF application. Test crops were wheat, sorghum and sesame. Effect of NF applications on the performance of the relatively salt tolerant crops: wheat, barley, beats and onions.

Effects of applying Nile Fertile (NF) and NPK fertilizer, to selected fields, on salts and nutrients mobilization and distribution around the active root zone (Rhisosphere) were also determined, Hilal and Korkor (1993) and Hilal (2015).

"Nile Fertile is a bio-mineral sulfur fertilizer; produced by Giza Tec Co., Egypt".

Salt, moisture and nutrients distribution in root zone, being the key for good plant performance, were monitored.

A series of field experiments were carried out to evaluate the following:

1- The effect of salt type and salt activity, in irrigation water, on soil salinity and plant growth.

2- The Corrective techniques: Ionic balance (Cl/ SO_4 ratio); induced soil stratification; furrow and strip system of cultivation.

3- Optimizing the roll of the sulfur fertilizer mixture (Nile Fertile) and magnetic treated irrigation water (**Hilal, (2015)** and **Hilal and Abd-Elfattah (1987)**).

Salt, moisture and ions distribution in root zone, being the key for good plant performance, were monitored. Response of salt tolerant plants such as Olives, Barley, Wheat, Beets and Onion, to such set of corrective techniques, has been studied by Hilal et al., (1997) and Hilal and Helal, (2000).

Hilal and Helal (2000) added that magnetizing saline irrigation water through a proper magnetic field has been introduced as an effective mean for soil desalination. Magnetic field causes the hydration of salt ions and colloids to slide down, leading to better salt solubility and accelerated coagulation and salt crystallization. The effectiveness of magnetizing water of different salinity, on soil salinity and alkalinity, on

ionic balance and ion uptake by plant, was evaluated in a series of pot and field experiments.

Hilal (2015) compared upward diffusion of different salts and fertilizers, in normal and magnetized tap water. Magnetized water increased NaCl diffusion by 50% or more; while that of KCl reached 20%. On the other hand, magnetized water has lowered the diffusion of KH_2PO_4 , super phosphate and ZnSO_4 .

Hilal (2015) emphasized that under all these cases, salt diffusion from higher salt concentration to lower ones, depending on ionic balance (Ca^{2+} , Mg^{2+} , Na^+ , Cl^- , SO_4^{2-} , NO_3^-) rather than total salinity (expressed as osmotic pressure). Besides, plant active root zones (rhizospheres) have different powers to mobilize salts and fertilizers from their place of application (e.g. under the dripper) towards the rhizospheres.

Beneficial results can be only obtained through complex work: fields trials, pots and irrigation water sources, experiments and analyses are tedious and time consuming.

Anwar and Hilal (2014) studied Evaporation Barriers as Micro Climate Control to Save Water. However, physical and chemical processes related to soil water salinity and salt affected soils were not well explained by previous studies. Thus, the goal of this work is developing a mathematical simulation model for physical and chemical changes in (soil-plant-water-system) to reach fast and sound results depending on empirical data.

Preferential retention of solutes in the soil profile has long been attributed to adsorption of adjacent pore-walls, because of the negatively charged clay surfaces. As explained elsewhere by the double layer theory. However, as the adsorption sites of soil particles are always occupied, retention of ions in the soil is treated as "ion exchange"; which accounts for the replacement of adsorbed ions by other ions from the pore solution. Hofmeister Series indicates the preferential tendency of some ions to remain longer within the soil profile, and resist downward movement or leaching. The order of ion retention is as follows: $\text{Al}^{3+} > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{NH}_4^+ > \text{K}^+ > \text{Na}^+$ for cations, and $\text{F}^- > \text{Cl}^- > \text{Br}^- > \text{NO}_3^-$ for anions.

The objective of this work is to develop a new mathematical model for the visualization of preferential distribution and retention of salts in soil pores. Retention of salts in Macro pores and finer micro pores, is based on differences in osmotic pressures of each salt, together with differences in pore wall pressures. Pore wall pressures are generated by Diffuse Double Layers which are controlled by charge to mass ratio of clay surfaces.

As reported by **Salisbury et al. (2004)**, osmotic pressure of each salt is determined by Van't Hoff

empirical relation that is similar to the universal gas law. π_s is defined as the specific osmotic pressure of a solute, which is osmotic pressure per unit concentration (atm/g/l), and stronger solutes have higher π_s values, while weaker solutes have smaller π_s values. Buoyancy law indicates that equilibrium is attained when objects in a fluid are ordered vertically with higher density objects are located deeper and lower density objects are shallower. Similarly, solutes with higher Specific Osmotic Pressures (π_s – or osmotic pressure per unit concentration) are 'stronger' in competition and move to larger pores. Meanwhile, 'weaker' solutes with lower π_s move to smaller pores where pore wall pressures are higher and osmotic pressures from solutes are lower.

2. Methodology

I) Laboratory Tests

Within a complete program for the beneficiation of saline water irrigation and the amendment of salt affected soils. Laboratory tests were conducted to study several salinity aspects of soil water systems: Salt concentration as determined by electric conductivity, Salt activities, and Salt diffusivity. Salt accumulation and distribution in fields and forms of applied fertilizers and their role in soil salinization were investigated.

Salt activity: Mixing a saline solution of 6 g NaCl /L with different levels of MgSO_4 have clearly increased the growth of wheat tillers; maximum growth was obtained when mixing 2g MgSO_4 with 6g NaCl with a total salinity of 8 g /L. MgSO_4 solution tripled seedling and increased plant growth as compared to MgCl_2 solution.

In other words increasing salinity of irrigation water can give better growth conditions once a proper salt mix is added.

Salt Diffusion: A set of one liter cylinders were prepared by placing 5 gm salt in the bottom of each cylinder then filled with tap water. The effects on a group of salts were tested by measuring EC at the top 5 cm of the cylinder, which is the electrode thickness, every few minutes. At each time the electrode is dipped to the same depth.

II) Field Trials

Three field sites in Egypt were selected: a sandy soil at Wadi El-Molak and Serabiom (Ismailia); a calcareous sandy loam soil at Ras-Sidre (South Sinai); an alkaline clay loam soil at Shalakan (South Delta).

The effect of Furrow Irrigation; saline water irrigation; drip irrigation with moderately saline water; type of crop and/or tree cover, on salt distribution and accumulation around plants, were overviewed.

Effect of soil surface management on salt distribution in a selected field adapted a split plot design. The main plots were the surface field

management which included two types of management, were conducted. Deep rows of 25 cm depth (ditchers) were installed and drip lines were placed inside them. In the other treatment drip lines were extended on the soil surface (shallow row).

As far as irrigation treatments, 4 treatments were given the same amount of irrigation- water. However the scheduling of their application differed:

- 1) Half an hour daily. (2 One hour/ 2 days.
- 3) One and half hour/ 3 days (4 2 hours/ 4 days

III Mathematical Modeling

Solute Distribution in Saturated Soil Pores

Solution movement in soil pores is known to occur from higher to lower pressure head. Soil-water potentials are controlled by 3 factors: 1) water hydrostatic matrix head; 2) salt osmotic head; and 3) gravitational head. Equilibrium is reached when the net pressure head difference is zero. In a saturated soil where all the pores are filled with water, there is no hydrostatic suction head. In larger pores, pore walls are distant and pore wall effect is minimal. Meanwhile, the closer pore walls in finer pores make the wall effect proportionally larger as part of total pressure in the pore.

Role of Diffuse Double Layer

Wall pressure as will be explained later, has important impact on salt distribution in soil larger and finer pores. Gouy-Chapman theory (Hillel, 1998) describes the characteristic "thickness" of the diffuse double layer at pore walls as dependent on valence of adsorbed ion and proportional to solute concentration in the pore solution (which occur in the soil above field capacity), as:

$$z = \frac{1}{ev} \left[\frac{\epsilon kT}{8\pi n_0} \right]^{0.5} \quad (1)$$

where z is the characteristic length (or 'thickness'); v is the valence of the ions in solution; e is the elementary charge of an electron; ϵ is the dielectric constant; k is the Boltzmann constant; n_0 is the concentration of the ions in the pore solution; and T is absolute temperature.

In larger gravitational pores, pore walls are distant from each other and the double layer 'thickness' compared to pore size is smaller than that in finer pores, and thus relative pressure from pore walls is smaller as compared to pressure of solutes in the pore solution. This makes solutes with higher specific osmotic pressures move to larger pores, and solutes with lower specific osmotic pressures move to finer pores to attain equilibrium.

Role of Pore Wall Pressure

Diffuse double layers of adjacent pore walls exert pore wall pressure on pore solution. The amount of pore water varies according to pore diameter, with less amount of water in each pore at smaller diameters. Pore sizes also vary according to soil type,

with finer pores in soils with higher clay contents. Double layer thickness is variable, and is affected by total solute concentration in pore solution (Hillel, 1998). When the soil is drained, pore water in gravitational pores moves downwards together with its salts. Meanwhile, water in finer capillary pores will move upwards with its salts when the soil further dries by evaporation from the surface.

3. Results and Discussion

Within a complete program for the beneficiation of saline water irrigation and the amendment of salt affected soils, laboratory tests were conducted to study several salinity aspects of soil water systems. Salt activities, Salt diffusivity, Salt accumulation and distribution in fields and forms of applied fertilizers and their role in soil salinization were investigated.

Salt activity

Irrigation solutions, containing 10 g/ L of Cl^- salts of Na^+ , Mg^{+2} or Ca^{+2} , differed greatly in their EC values; NaCl solution gave an EC value above 14 mS.cm^{-1} while.

MgCl_2 gave a value of only 4.3 mS. /cm^{-1} . However all Cl^- salts have caused a great damage to wheat seedlings, while the SO_4^{-2} salts of Na^+ or Mg^{+2} caused no harm.

Actually the irrigation of wheat with 10 g /L of MgSO_4 solution tripled the seedling emergence and growth, as compared to MgCl_2 solution.

Besides, mixing a saline solution of 6 g/L of NaCl with different levels of MgSO_4 have clearly increased the growth of wheat tillers; maximum growth was obtained when mixing 2g/L MgSO_4 with 6g/L NaCl with a total salinity of 8 g /L. MgSO_4 solution tripled seedling growth as compared to MgCl_2 solution.

In other words increasing salinity of irrigation water can give better growth conditions once a proper anion balance is maintained, table (1).

Response of wheat to irrigation with saline solution of Cl^- and $\text{SO}_4^{=}$ is presented. Soil pots, irrigated with 10000 ppm sulfate solution showed a plant growth comparable to non saline water irrigation. Cl^- solution on the other hand initiated a little or no growth.

Salt Diffusion:

A set of one liter cylinders were prepared by placing 5 gm salt in the bottom of each cylinder then filled with Tap Water.

A group of salts were tested by measuring EC at the top of the cylinder every few minutes.

Data in table (2) indicate that diffusion of certain salts and its upward movement in graduated cylinders filled with water, were enhanced while others were inhibited. NaCl diffusion increased from 8.5 to 11 in only 25 minutes. Upward movement of Na NO_3

increased from 10 to 14 in 20 minutes. Its diffusion continued to increase to 30 minutes. Sodium sulfate – diffusion reached a high value in 5 minutes but remained constant thereafter. On the other hand, diffusion of Super phosphate, Zn Sulfate and Mg Sulfate was not affected.

Field Trials:

Field sites were selected to represent wide range of irrigation water salinity and field conditions,

changes in salt activity, salt accumulation, salt distribution, nutrient balance, plant growth, yield, nutrient availability and uptake were monitored in some or all of the selected sites.

Salt Distribution under Drip Irrigation System:

The pattern of salt distribution in fields depends on the initial soil salinity, inlet water, dripper discharge and hydraulic characteristics of the soil are important, in order to control soil salinity.

Table (1): Effect of salt type and salt balance on EC values of irrigation water and of topsoil and on yield of wheat seedlings:

(a) Type of salt.

Added soluble salts	Type of Cations	Cl ⁻ salts			SO ₄ ⁻² salts		
		EC (mS.cm ⁻¹)		Yield of wheat seedling (g)	EC (mS.cm ⁻¹)		Yield-of wheat seedling (g)
		Irrig. water	Top soil		Irrig. Water	Topsoil	
Non	several	0.35	1.5	20.8	-	-	20.8
10 g.l ⁻¹	Na ⁺	14.8	6.0	6.5	11.3	4.2	15.3
	Mg ⁺²	4.3	2.6	6.0	2.9	2.5	16.5
	Ca ⁺²	4.8	2.8	5.5	-	-	-
10 g.l⁻¹	Salt mixture of 1:1; NaCl: MgSO ₄				7.89	3.37	15.9

(b) Balance of Salt mixtures

Total salts (g.l ⁻¹)	Salt balance NaCl + MgSO ₄	EC (mS.cm ⁻¹)			Yield of wheat tillers(g)	Cl ⁻ uptake (mg/100g leaves)
		Irrig. Water	Top soil	Root Zone		
6	6 + 0	9.0	9.5	4.4	70	154
7	6 + 1	8.6	8.6	3.5	89	107
8	6 + 2	8.3	8.4	3.1	105	72
9	6 + 3	9.1	9.0	3.9	93	84
10	6 + 4	9.4	9.2	4.3	84	90

Table (2): Upward diffusion of different salts and fertilizers in Water

Salt type	E.C. (m. mohs / cm) at different minutes after adding water		
	5 minutes	20 minutes	30 minutes
Na Cl	8.5	9.3	11.2
Na NO ₃	10.0	14.0	15.3
Na ₂ SO ₄	17.0	16.7	17.0
K Cl	17.5	20.1	19.2
K H ₂ PO ₄	2.3	2.8	3.6
Super phosphate	1.5	--	2.1
Zn Sulfate	3.5	3.6	3.6
Cu Sulfate	1.6	1.6	1.7
Mg Sulfate	2.0	2.1	2.1

An orchard farm at Regwa area (Cairo – Alexandria road) which is irrigated by 2 wells having salinity of 1000 and 1500 ppm, was evaluated with respect to salt accumulation at different depths below drippers. Data in table (3) show the effect of soil surface management on salt distribution in soil profiles below the drippers. Salts accumulate in the surface layer, 0 to 15 cm. Salinity decreased sharply in the lower layers. Salinity of surface samples from

spots in between trees differed, depending on the rate of salt diffusion and water permeability.

Likewise, Drip irrigation with saline water or of saline soil produces different salt distribution patterns in the root zone. As shown in table (4) the lowest concentration of salts occurred below the dripper outlet and this was also the zone of highest root growth. Salt concentration increased towards the edge of wetting zone. However, several factors such as drippers spacing, irrigation rate, irrigation frequency,

evaporation and water uptake by roots have their effect on salt distribution patterns. Isolated pockets of salts were formed midway between drippers. Meanwhile, the effects of irrigation water salinity, the type of tree cover and subsurface irrigation on salt accumulation around trees are presented in table (5).

In case of irrigation with low saline water of 2 to 2.5 m. mhos/cm; apricot was the most able tree to

push salts out of the root zone while grapes allowed for the highest salt accumulation at the wetting edge. Drip irrigation of olives with highly saline water of 8.3 m. mhos/cm; reached dangerous levels of salinity at the surface sites. On the other hand, subsurface irrigation was able to cut down surface salinity sharply and provided much better conditions for plant growth.

Table (3): Salt concentration in 2 soil profiles and surface samples in between trees, under mango.

Soil Sample Depth (cm)	Field I			Field II		
	% Moisture	pH	Dissolved Salts (g/kg)	% Moisture	pH	Dissolved Salts (g/kg)
Surface Sample Between Trees	20	8.3	27.0	27	8.33	9.8
0 - 15	18	8.1	22.5	31	8.69	19.8
15 - 30	33	8.2	10.1	42	8.82	7.6
30 - 80	35	8.4	6.2	30	8.39	6.5

Table (4) Effect of Field Management and Irrigation Scheduling on Salt Distribution around Plants.

Time after irrigation hours	Deep Row			Shallow Row.		
	½ h/d	1 h/2 d	2 h/4d	½ h/d	1 h/2 d	2 h/4d
Top Layer						
1	1.65	1.5	1.53	1.93	1.77	1.60
8	2.03	2.63	1.74	2.56	1.88	2.10
24	2.30	3.04	1.86	2.86	3.00	2.20
48	2.62	3.32	2.00	3.01	3.85	2.40
72	2.82	2.28	2.30	2.27	2.65	2.56
96	3.2	2.37	2.35	3.62	3.00	2.76
Root Zone						
1	1.14	1.04	0.66	1.63	1.36	1.25
8	1.35	1.18	0.69	2.38	1.66	1.45
24	2.12	1.25	0.78	3.40	1.84	1.800
48	2.03	1.34	0.90	3.22	2.86	1.90
72	2.16	0.96	1.13	3.46	2.18	2.20
96	2.00	1.24	1.22	3.23	2.64	2.60
Mid- way between drippers						
1	4.80	3.20	2.00	6.40	5.40	4.50
8	7.4	4.80	2.40	8.40	6.60	5.40
24	8.80	5.10	2.70	10.20	7.9	6.50
48	8.40	5.6	3.10	11.20	8.20	7.40
72	9.30	5.80	3.50	11.70	7.70	8.60
96	9.00	6.1	3.8	12,7	8.8	9.6
Wetting front.						
1	5.30	4.70	4.80	7.80	6.20	7.00
8	7.40	7.80	6.00	9.90	6.90	8.70
24	9.60	6.80	6.70	14.30	9.50	11.40
48	10.50	7.30	7.60	15.00	11.20	13.30
72	10.80	7.20	8.80	15.80	9.80	14.70
96	11.70	7.60	9.70	17.00	11.4	15.8

Salt distribution under furrow-irrigation:

At moderately saline conditions, the system of furrow irrigation, result in salt accumulation to a dangerous level on the top of the furrow; the EC value

on the top reaches about 60 (mS.cm⁻¹). On the other hand, the EC value at the bottom reaches only 2 to 3 (mS.cm⁻¹) which is completely safe for cultivating

seeds at the bottom of the furrow, as shown in figure (1).

Table (5): Effect of irrigation water salinity and tree cover on salt accumulation around trees.

Site	EC of Irrigation water (mS.cm ⁻¹)	Tree cover	Sample depth (cm)	Soil EC (mS.cm ⁻¹)		
				Under drippers	Wetting edge	Between rows
1 Sadat City	2 to 2.5 mS.cm ⁻¹	Grapes	0-30	2.6	17.5	38
		Peaches	0-30	3.5	14.8	58
		Apricot	0-30	2.4	10.7	70
2 Serabiom	4.2 to 5.6 mS.cm ⁻¹	3 surface samples of olive farm	0-30	3.1	21.5	29
			0-30	5.1	19.8	48
			0-30	3.4	20.4	61
3 Serabiom drip irrigation	8.3 mS.cm ⁻¹	profile of olives farm	0-30	15.7	39.0	113
			30-60	6.1	9.1	33.4
			60-90	7.1	18.0	51.0
3 Serabiom subsurface vertical irrigation	8.3 mS.cm ⁻¹	profile of olives farm	0-30	5.6	10.8	17.6
			30-60	6.6	6.5	13.9
			60-90	7.4	6.7	11.5

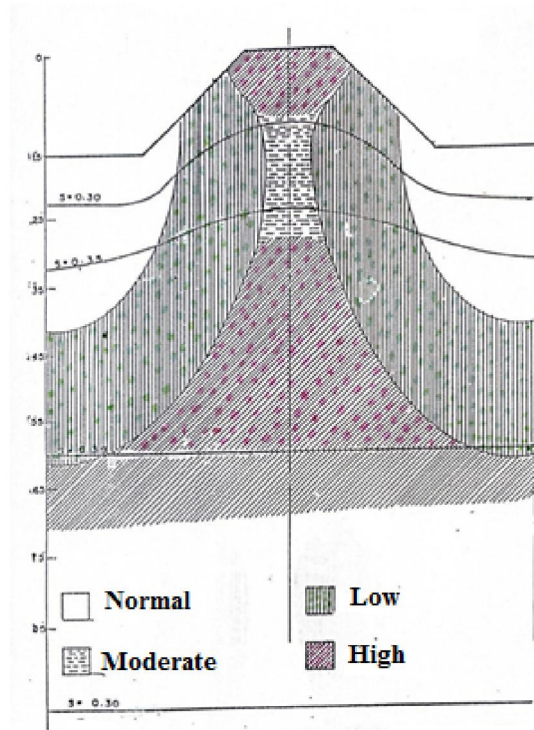


Figure (1): Salt distribution under furrow irrigation for a saline Sandy Loam soil at the end of evaporation (irrigation 2).

After United States Salinity Laboratory Staff (1954).

Theoretical Role of Diffuse Double Layer

Total pore pressure can be defined as the resultant of pore wall double layer pressure in addition to pore osmotic pressure and water hydrostatic pressure.

In larger gravitational pores, pore walls are distant from each other and the double layer 'thickness' compared to pore size is smaller than that in finer pores. Thus relative pressure from pore walls is smaller as compared to pressure of solutes in the pore solution. This makes solutes with higher specific osmotic pressures move to larger pores, and solutes with lower specific osmotic pressures move to finer pores to attain equilibrium.

Wall pressure can be explained as has important impact on salt distribution in soil larger and finer pores. Gouy-Chapman theory (Hillel, 1998) describes the characteristic "thickness" of the diffuse double layer at pore walls as dependent on valence of adsorbed ion and proportional to solute concentration in the pore solution (which occur in the soil above field capacity), as:

$$z = \frac{1}{ev} \left[\frac{ekT}{8\pi n_0} \right]^{0.5} \quad (1)$$

where z is the characteristic length (or 'thickness'); v is the valence of the ions in solution; e is the elementary charge of an electron; ϵ is the dielectric constant; k is the Boltzmann constant; n_0 is the concentration of the ions in the pore solution; and T is absolute temperature.

According to the above remarks related to pores and diffuse double layer, diagrammatical presentation of the total pore pressure components is developed theoretically as shown in Figure (2).

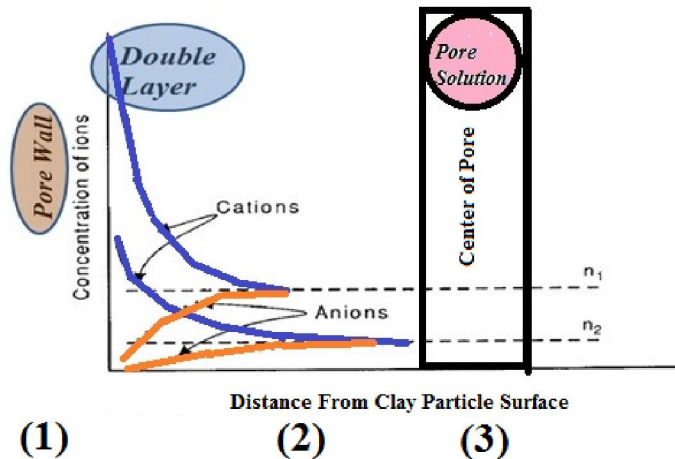


Figure (2): Schematic diagram of double layer in soil pores (1) Pore wall, (2) diffuse layer, and (3) pore free solution.

Estimation of Salts' Osmotic Pressures

Salts' Osmotic pressure as estimated by Van't Hoff's Equation (as reported by Salisbury et al., 2004 in their textbook "Plant Physiology"):

$$\pi = -iCRT \quad (2)$$

Where π is osmotic pressure of a certain salt (atm), i is Van't Hoff factor (equals the number of parts resulting from dissolution of one molecule), C is solute molar concentration (mol/l), R is the universal gas constant and T is absolute temperature. Thus, osmotic pressure of a salt is a function of its concentration and its molecular weight.

Thus, the Specific Osmotic Pressure; π_s (atm g^{-1} l) = π / C , can be defined as Osmotic pressure per unit concentration (1.0 g/l). It is used to determine a certain salt 'strength' in competition with other salts in a solution which is similar to the role of density in buoyancy law, as will be explained below.

Salt Competition in Soil Pores

Buoyancy law indicates that equilibrium is attained when objects in a solution are ordered vertically with higher density objects (Al) are located deeper, and lower density objects (wax) are shallower (figure 3). Similarly, solutes with higher Specific Osmotic Pressures (π_s ; atm g^{-1} l) are 'stronger' in competition and move to larger pores (macropores), while 'weaker' solutes with lower π_s move to smaller pores (micropores).

The specific osmotic pressure (π_s), which was defined earlier, for some soluble salts are arranged from 'weaker' salts (lower π_s) that will move in the competition to finer pores, to 'stronger' salts (higher π_s) that will move to larger pores are shown in figure (4).

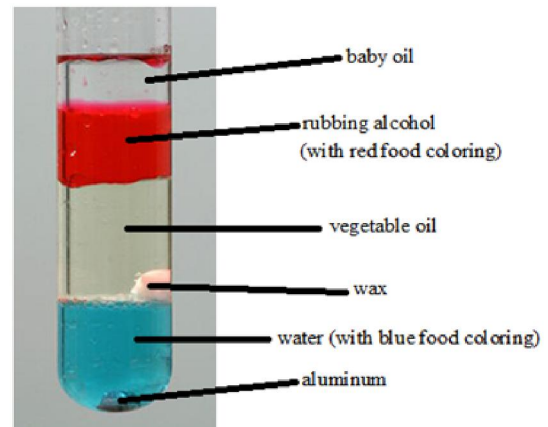


Figure (3): A density column containing some common liquids and solids as Quoted from (<http://en.wikipedia.org/wiki/Buoyancy>).

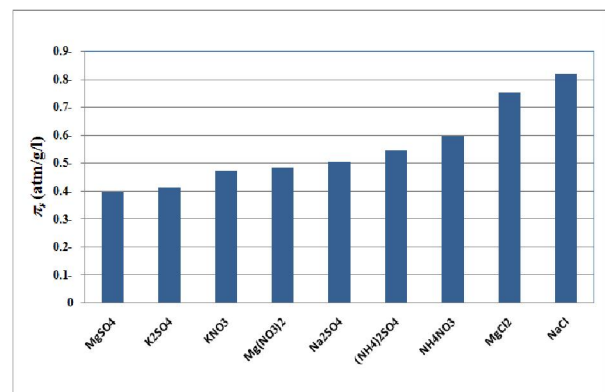


Figure (4): Specific osmotic pressures (π_s , atm g^{-1} l) for some soluble salts, arranged from 'weaker' (lower π_s) that move to finer pores, to 'stronger' (higher π_s) that move to larger pores of the soil.

Salts shown in figure (4) are arranged from weaker to stronger salts as: $\text{MgSO}_4 < \text{K}_2\text{SO}_4 < \text{KNO}_3 < \text{Mg}(\text{NO}_3)_2 < \text{Na}_2\text{SO}_4 < (\text{NH}_4)_2\text{SO}_4 < \text{NH}_4\text{NO}_3 < \text{MgCl}_2 < \text{NaCl}$. Distribution of these salts in different pore sizes will follow this arrangement from finer to larger pores. This is in resemblance to buoyancy law.

Subdivision of Saturated Soil Porosity (free solution).

Soil-water characteristic curve of a sandy clay-loam soil is shown in figure (5).

For computational consideration to build up the simulation model, soil porosity of "0.36 cm³/cm³" was subdivided into five equal portions. Zero moisture is defined at air dry soil, while complete saturation is defined at zero tension (soil paste). Each portion comprises 20% of the total soil porosity. When saturated soil column is drained gradually, larger pores that hold water with suction head between 0.0 and 1/3rd atmosphere (which is the field capacity) will first be drained (i.e. degree of saturation; $S = 0.8$ to 1), followed by next larger pores (i.e. at $S = 0.6$ to 0.8), and salts in these pores will move downwards with gravitational water. When downward gravitational flow ends, upward capillary flow will transport salts in the finer pores towards the soil surface under the effect of evaporation and diffusion. Thus, the distribution of salts in different pore sizes is very important in predicting preferential movement of different salts in the soil profile.

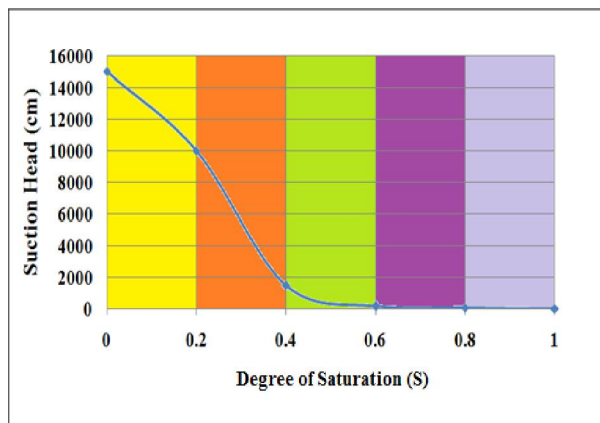


Figure (5): Soil-water characteristic curve, where soil porosity is subdivided into five equal portions, for computational purposes.

Relationship between Soil Salinity and Pore Wall Pressure

As discussed above, double layer thickness, and consequently pore wall pressure, varies with total solute concentration in pore solution. Thus, pore wall pressure (π_{wj}) in each of the pore size portions of figure (6) is assumed as:

$$\pi_{wj} = a_j C_T \quad (3)$$

where $j = 1$ to 5 for each of the pore portions of figure (5); respectively, and C_T is the total salt concentration in the soil solution (herein equals 9 g/l). The coefficients (a_j 's) in equation (3) are assumed as 0, 0.10, 0.20, 0.40 and 0.80, and they comprise corresponding pore wall pressure as part of total pore pressure as shown in figure (6). These constants will be studied further in a future work. Besides, correlation relation will be developed for these constants as function of the soil cation exchange capacity (CEC), for each portion of the soil-water characteristic curve shown in figure (5).

Total osmotic pressure in the pore is the sum of pore wall pressure and osmotic pressure of pore solution and can be expressed as;

$$\pi_j = \sum \pi_{si} + \pi_{wj} \quad (4)$$

Where π_j is the total osmotic pressure in pore segment j , $\sum \pi_{si}$ is the summation of osmotic pressures of all salts in the pore (herein, $i=1$ to 9 salts), and π_{wj} is the pore wall pressure in the pore j (equation 3). After sufficiently long time for a sealed saturated soil sample, total osmotic pressures (π_j) in all pore segments ($j=1$ to $j=5$) will approach equilibrium. Soil pore sizes are expressed on the scale of the degree of soil saturation; $S =$ volumetric soil water content θ /saturation volumetric soil water content θ_s as shown in figure (6).

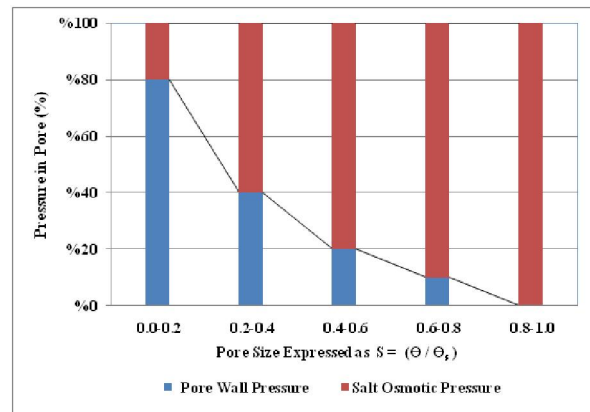


Figure (6): Contribution of solutes and pore-wall-pressure in the total pore pressure of a saturated soil, at equilibrium.

Preferential Salt Distribution in Soil Macro and Micropores

As shown in figure (6), for a saline solution in a saturated soil at equilibrium, total pressure in all five pore portions is equal. There is larger contribution from pore wall pressure in finer pores as compared to larger ones. As an example, considering a solution # 1 of different 9 salts: MgSO_4 , K_2SO_4 , KNO_3 , $\text{Mg}(\text{NO}_3)_2$, Na_2SO_4 , $(\text{NH}_4)_2\text{SO}_4$, NH_4NO_3 , MgCl_2 , NaCl . This solution is comprised of 3 g/l NaCl and

0.75 g/l for each of the other 8 salts; with the total concentration of 9 g/l (table 6).

Arrangement of salts with 'weaker' (lower) specific osmotic pressure (π_s) in finer pores and 'stronger' (higher π_s) salts in larger pores will result in the distribution shown in table (6). According to the charge to mass ratio and Van't Hoff factor ($\pi = -i C R T$), Such order of arrangement, from finer pores to larger pores, is " $\text{MgSO}_4 < \text{K}_2\text{SO}_4 < \text{KNO}_3 < \text{Mg}(\text{NO}_3)_2 < \text{Na}_2\text{SO}_4 < (\text{NH}_4)_2\text{SO}_4 < \text{NH}_4\text{NO}_3 < \text{MgCl}_2 < \text{NaCl}$ ", with π_s values of **-0.4, -0.411, -**

0.473, -0.483, -0.505, -0.54, -0.597, -0.753, -0.818 atm g⁻¹ l; respectively.

It is important to note that total salt concentration in finer pores of table (6) is higher than that in larger pores. This explains the salt build-up and leaching resistance due to higher ('stronger') specific osmotic pressure of NaCl at lower concentrations in the gravitational pores. It is also important to note that NH_4NO_3 is third after NaCl and MgCl_2 , which explains its tendency for leaching with gravitational water to drainage.

Table (6): Distribution of different added salts, in a saturated soil, among pores of different sizes (fine to large pores).

Pore Size	Salts Concentration in each pore portion (g/l)					Net Average in soil (g/l)
	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	
NaCl	0.0	0.0	0.0	5.26	9.74	3
MgCl_2	0.0	0.0	0.0	3.75	0.0	0.75
NH_4NO_3	0.0	0.0	3.68	0.07	0.0	0.75
$(\text{NH}_4)_2\text{SO}_4$	0.0	0.0	3.75	0.0	0.0	0.75
Na_2SO_4	0.0	0.0	3.75	0.0	0.0	0.75
$\text{Mg}(\text{NO}_3)_2$	0.0	3.24	0.51	0.0	0.0	0.75
KNO_3	0.0	3.75	0.0	0.0	0.0	0.75
K_2SO_4	0.25	3.50	0.0	0.0	0.0	0.75
MgSO_4	3.75	0.0	0.0	0.0	0.0	0.75
Total	4.01	10.49	11.7	9.08	9.74	9.00

Table (7) shows contents of salts added to the saturated soil solution, and net salts in the remaining soil solution after its step removal. 40% of soil solution were step removed (portion I and portion II, where suction head is almost equal as in figure 4), and their dissolved salts were also removed. NaCl and MgCl_2 , and part of NH_4NO_3 were removed in this step. The removal of portion III (down to 40%

moisture, where suction head is slightly higher than portions I & II), 5 of the 9 added salts were removed as shown in table (7) (NaCl , MgCl_2 , NH_4NO_3 , $(\text{NH}_4)_2\text{SO}_4$ & Na_2SO_4). Further removal of portion IV (down to 20% moisture, where suction head is much higher to -10000 cm), only 2 salts remained in the soil solution (K_2SO_4 & MgSO_4). This is other than native salts in the double layer.

Table (7): Content of added salts (g/l of saturated soil solution), and net salt concentrations in remaining soil moisture after the soil solution is step removed.

Retained soil solution		100% moisture	60% moisture	40% moisture	20% moisture
Salinity (g/l of saturated soil)*	NaCl	3.0	0.0	0.0	0.0
	MgCl_2	0.75	0.0	0.0	0.0
	NH_4NO_3	0.75	0.74	0.0	0.0
	$(\text{NH}_4)_2\text{SO}_4$	0.75	0.75	0.0	0.0
	Na_2SO_4	0.75	0.75	0.0	0.0
	$\text{Mg}(\text{NO}_3)_2$	0.75	0.75	0.65	0.0
	KNO_3	0.75	0.75	0.75	0.0
	K_2SO_4	0.75	0.75	0.75	0.05
	MgSO_4	0.75	0.75	0.75	0.75
Net Conc. (g/l) in retained soil solution		9.0	8.73	7.25	4.07

* Native salts within the double layer are not regarded.

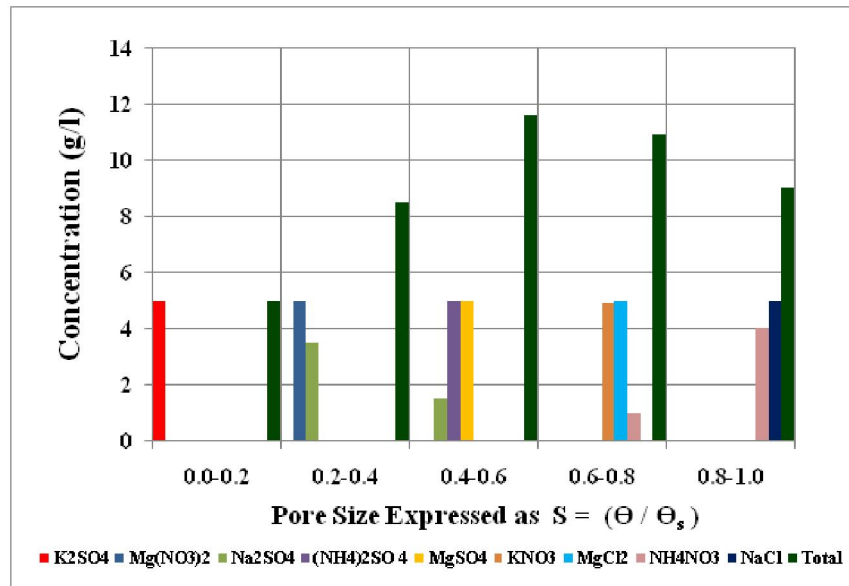


Figure (7). Distribution of 9.0 g/l of solute # II in pores of a saturated soil, at equilibrium. Each of the 9 salts is 1.0 g/l.

In figure (7), each of the 9 salts shown in table (6) is added at the equal concentration of 1.0 g/l (instead of higher contribution from NaCl of case I). It is realized in figure (7) that NH_4NO_3 is moved towards larger gravitational pores as compared to table (6) due to less competition from NaCl. This is useful in managing fertilizer application with saline water when we use variable salinities of irrigation water.

It is also important to note that individual ions behave differently when associated in different salts. Sodium Chloride (NaCl) has a molecular weight of 58.5 and π_s of -0.82 (atm g^{-1} l), which is higher than Ammonium Sulfate ($(\text{NH}_4)_2\text{SO}_4$) with π_s of -0.54 (atm g^{-1} l) and molecular weight of 132. Meanwhile, Sodium Sulfate (Na_2SO_4) has molecular weight of 142 and π_s of -0.505 (atm g^{-1} l), which is lower than that of $(\text{NH}_4)_2\text{SO}_4$. This makes NaCl more likely to move with leaching than $(\text{NH}_4)_2\text{SO}_4$, while Na_2SO_4 is more likely to stay in finer pores than $(\text{NH}_4)_2\text{SO}_4$. This should be considered in understanding reactive solute transport in the soil, and in leaching specific ions to reduce their hazards.

For the soil solution in table (6), NaCl concentration in the two largest pore portions is around 9.74 8.4 g/l (0.8-1.0 pores) and 5.26 6.6 g/l (0.6-0.8 pores), respectively. Meanwhile, MgCl_2 concentration is 3.75 g/l (0.6-0.8 pores), and NH_4NO_3 is about 0.07 (0.6-0.8 pores) and 3.68 g/l in 0.4-0.6 pore portion. When 40% of soil water is drained (table 7), water in the largest two pore portions will be removed with their content of salts, and 0.6 of soil water will remain. The amounts of MgCl_2 and

NH_4NO_3 in the 0.4-0.6 pore portion will remain unchanged. Meanwhile, these salts will be dissolved in only 60% of the soil water. Thus, concentrations of remaining salts will increase in less moist soils, and in our case MgCl_2 and NH_4NO_3 concentrations that were input at 0.75 g/l of the total soil solution will be 1.23 and 1.25 g/l of the total soil solution in all pore portions; respectively. As the soil is loses more moisture to 20% saturation, K_2SO_4 concentration that was input at 0.75 g/l of the total soil solution will become 3.75 g/l of the total soil solution. This will affect availability of nutrients to plant root uptake. It is important to note that less moist soil is capable of developing water suction head which changes the double layer thickness and concentration, which will in turn alter salt distribution in the remaining pores.

Further research is needed to determine how such changes will occur.

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9/28/2015