Study of the moisture and salinity distribution pattern for subsurface drip irrigation in sandy mixed soil using the Hydras 2D program

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Abstract

Water scarcity in arid regions makes saline water a valuable alternative source for irrigation. Trickle irrigation is a method that delivers water directly to the soil through an emitter into the root zone of plants. This study investigates the impact of varying amounts of irrigation water from drip emitters on water and salt distribution. It will use a numerical model (Hydrus 2D) to analyze the two-dimensional flow and solute distribution under subsurface irrigation with different drip settings. Irrigation duration and volume directly influenced solute distribution in all soil types. Salinity volume depended on saline content in irrigation water and discharge duration. In the simulation, when plants are irrigated with water that has a salt concentration of 8 ds m-1, the yield of maize crop grown reduction is 100%. If the plants are irrigated only with salt water, the salt concentration decreases by 17.5%. If they are irrigated with salt water and one-time fresh water, concentration decreases by 25%. In this case, a large quantity of fresh water is required to flush out the amassed salt from the soil. However, when the plants are irrigated with water with a salt concentration of 4 ds m-1, the reduction is 25% to 50%. If the plants are irrigated only with salt water, the salt concentration decreases by 15%. If they are irrigated with salt water and one-time fresh water, the salt concentration decreases by 25%. In this case, only a tiny amount of fresh water is needed to leach the salt.

Keywords : Saline concentration, Drip system, Subsurface irrigation Emitter, Percolation, Moisture content, Wetting patterns, Hydrus-2D.

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دراسة نمط توزيع الرطوبة والملوحة للري بالتنقيط تحت السطحي في التربة الرملية المختلطة باستخدام برنامج(Hydrus 2D)

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الخلاصة

إن ندرة المياه في المناطق القاحلة تجعل المياه المالحة مصدراً بديلاً قيماً للري. الري بالتنقيط هو طريقة توصل المياه مباشرة إلى التربة من خلال باعث إلى منطقة جذور النباتات. تبحث هذه الدراسة في تأثير كميات متفاوتة من مياه الري من باعثات التنقيط على توزيع المياه والملح. وسوف تستخدم نموذجًا رقميًا (Hydrus 2D) لتحليل التدفق ثنائي الأبعاد وتوزيع المواد المذابة تحت الري تحت السطحي بإعدادات تنقيط مختلفة. تؤثر مدة الري والحجم بشكل مباشر على توزيع المواد المذابة في جميع أنواع التربة. يعتمد حجم الملوحة على محتوى الملح في مياه الري ومدة التصريف .في المحاكاة، عندما يتم ري النباتات بمياه تحتوي على تركيز ملح $8\ ds\ m^{-1}$، فإن غلة محصول الذرة المزروعة تنخفض بنسبة 100 % إذا تم ري النباتات بمياه مالحة فقط، فإن تركيز الملح ينخفض بنسبة 17.5 %.إذا تم ريها بمياه مالحة ومياه عذبة لمرة واحدة، فإن التركيز ينخفض بنسبة 25 % في هذه الحالة، هناك حاجة إلى كمية كبيرة من المياه العذبة لطرد الملح المتراكم من التربة. ومع ذلك، عندما يتم ري النباتات بمياه بتركيز ملح $4\ ds\ m^{-1}$، فإن الانخفاض يتراوح بين 25 % إلى 50 %. إذا تم ري النباتات بمياه مالحة فقط، فإن تركيز الملح ينخفض بنسبة 15 %. إذا تم ريها بمياه مالحة ومياه عذبة لمرة واحدة، فإن تركيز الملح ينخفض بنسبة 25 %. في هذه الحالة، هناك حاجة إلى كمية صغيرة فقط من الماء العذب لتصفية الملح.

الكلمات المفتاحية: تركيز المحلول الملحي، نظام التنقيط، الري تحت السطحي، النفاذية، محتوى الرطوبة، أنماط الرطوبة، Hydrus-2D.

1- Introduction

The limited availability of fresh water in arid and semi-arid regions highlights the importance of exploring saline water as an alternative irrigation source (Hussain et al, 2020; Hargrove et al, 2023; Khondoker et al, 2023). Consequently, numerous researchers have been motivated to investigate and evaluate the potential use of poor-quality saline water for crop production (Syed et al, 2021; Hailu & Mehari, 2021; Dotaniya et al, 2023). Subsurface drip irrigation is a highly effective technique for distributing water (YAO et al, 2021; Wang et al, 2021; Cao et al, 2022). It involves delivering water through low-pressure pipes directly to the plant in the soil using a closed network (Gomaa, Y, 2021). The water slowly and consistently leaves the network through emitters, maintaining the moisture of the root zone near field capacity (Bhattacharya & Bhattacharya, 2021; Yang et al, 2023). When designing a subsurface drip irrigation system, it is important to consider the dimensions of the wetted area and soil salinity in order to Subsurface drip irrigation does not cause deep percolation of water. (Cahn & Hutmacher, 2024; Karimzadeh et al, 2024). Drip irrigation is well-suited for using saline water compared to other irrigation methods (Fayed, 2020; Lamm et al, 2021). This is because the moisture content in the root zone remains high, reducing the capillary tensile forces between the water and the soil particles (Li et al, 2021; Yingjun et al, 2022). As a result, plants can meet their water needs despite the high osmotic tension caused by increased salts in irrigation water (Yildiz et al, 2020; Ozturk et al, 2021). Knowledge of the infiltration procedure and salinity distribution around a buried drip emitter can enhance water use efficiency, contributing to the success of drip irrigation systems (Noguchi et al, 2021; Manda et al, 2021). Salt distribution around the dripper reflects the irrigation wetting patterns and redistribution of soil water content (He et al, 2023; Lu et al, 2024). Hydrus-2D software is an effective tool for modelling flow and material distribution movement under drip irrigation in two-dimensional variable media (Jia et al, 2023). The factors that affect the soil salinity of the root zone under a drip irrigation system include the salinity of the irrigation water, the flow rate of the emitters, the depth at which the drip irrigation is installed, and the hydraulic properties of the soil (Bajpai & Kaushal, 2020). Research gap identify by how does the use of saline water affect the long-term soil health and fertility and What are the economic implications of using saline water for irrigation compared to traditional freshwater sources. This study aims to determine the location of subsurface emitters, salt and water distribution patterns, soil types, and their relation to soil solute concentration and water wetting pattern for different emitter depths by using a Hydrus-2D software.

2- Material and Methodology

2.1 Governing Equations (HYDRUS Software)

The governing equation (Richards) of flow from an unmarried point through a saturated soil sample can be expressed in two-dimensional coordinates of finite element method as follows (Mavimbela, 2012) in Equ1:

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

θ = Soil water content ($L^3 . L^{-3}$)

h = Head pressure (L)

t = Irrigation time (T)

$K(h)$ = Hydraulic conductivity (L / T)

x = Horizontal distance (L)

z = Vertical distance (L)

The equation of advection within medium is given as (Zhou & Selim, 2003) in Equ 2:

$$\frac{\partial\theta c}{\partial t} = \frac{\partial}{\partial x}\left[Dxx\frac{\partial c}{\partial x} + Dxx\frac{\partial c}{\partial z} - qxc\right] + \frac{\partial}{\partial z}\left[Dzz\frac{\partial c}{\partial z} + Dzz\frac{\partial c}{\partial x} - qzc\right] \qquad (2)$$

C = Salt concentration in the fluid (ML^{-3})

Dxx, Dzz = Dispersion coefficient (L^2T^{-1})

q = Flux salt solution (LT^{-1}).

Hydraulic conductivity required for soil showed by the van Genuchten–Mualem linkage (de Melo et al, 2021) in Equs 3, 4, 5& 6:

$$\theta(h) = \begin{cases} \theta_r + \frac{(\theta_s - \theta_r)}{(1+|\alpha\, h\,|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (3)$$

$$K(h) = K_s S_e{}^I \left[1 - \left(1 - S_e{}^{1/m}\right)^m\right]^2 \qquad (4)$$

$$m = 1 - \frac{1}{n} \qquad (5)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (6)$$

Where:

θ= moisture content

θs = Saturated moisture (L^3L^{-3})

θr = Residual moisture (L^3L^{-3})

n = Pore- index (dimensionless)

α = Value of air-entry (L^{-1}),

Ks = Saturated conductivity (LT^{-1})

2.2 Boundary Conditions

The domain for all cases was classified about a perpendicular pivot as axisymmetric due to flow from a subsurface emitter (Lazarovitch et al., 2023; Sciandra, 2024). Just half the flow needed to be modeled in HYDRUS-2D. The unmarried subsurface emitter was positioned at the upper left of the field (Dou et al., 2022). This study utilized two emitter depths (10 and 30 cm). The simulation was applied on a rectangular field (80 x 100 cm), which was large sufficiently to evade interference with the water range around the emitters. The boundary requirements assumed that the top domain was exposed to an atmospheric state while the bottom domain was open. The vertical border emitter was considered to have no flux, with a circular emitter of a 1 cm radius site on the perpendicular of the domain. See (Figure 1) for the conditions assumed in this study.

The mensuration of irrigation change in HYDRUS-2D should stay within the dripping conductivity (Morianou et al., 2023; Khashaei et al., 2024) in Equ 7.

$$q = \frac{Q}{2\pi rd} \quad (7)$$

q = Irrigation change (L/T), Q = Rate of emitter flow (L^3/T),

d = distance (L), and r = Radius of emitter (L).

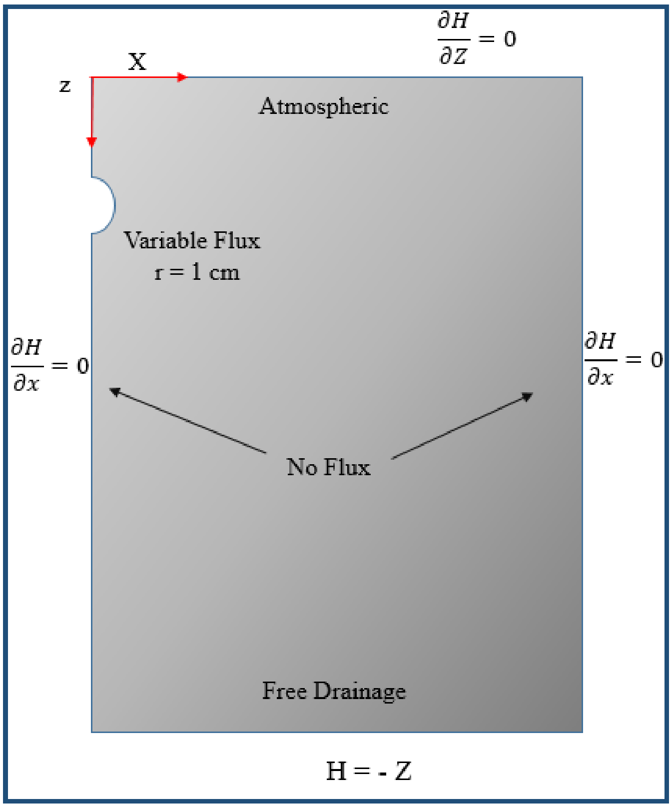

Figure (1): Schematic representation boundary condition

Suppose the soil has zero salinity initially, then raise the salt concentration via the emitter (Ayars & Corwin, 2024). The direction of salt dispersivity involves linear ƸL to match one-tenth of the depth and sideways (lateral) ƸT to set 0.1 times ƸL (Waseen & Abid, 2020). The boundary conditions define the movement of salt via continuous irrigation processes. The model demands driving the soil moisture and hydraulic parameters (Cena, 2020; Zemni et al., 2022). These hydraulic parameters were determined using the Rosetta model (Ružičić et al, 2017; Grecco et al, 2019) and then applied to the Hydrus-2D. Salinity calculates the number of salts in water and soil. It is generally distinguished by electrical conductivity (EC) gauged in decisions (dS/m). The simulation examined salt and wetting designs from an unmarried subsurface emitter using a specific type of sandy loam soil. (Figure 2) displays the properties of the soil, emitter's discharge wilting point and moisture at field capacity.

Ks	5.65 cm/hr	
θr	0.061cm³.cm⁻³	
θs	0.371cm³.cm⁻³	
α	0.027 cm⁻¹	
n	1.41	
Q	0.75 *l/hr*	1 *l/hr*
Initial moisture	0.09 0 cm³. cm⁻³	0.098 cm³. cm⁻³
$\theta_{F.C}$	0.124 cm³. cm⁻³	
$\theta_{W.P}$	0.075 cm³. cm⁻³	

Figure (2): Properties of soil used in study.

2.3 Statistical Measurement

To evaluate accuracy between predict outcomes using the HYDRUS-2D/3D software and real-world observations, statistical measurement such as root mean square error and correlation coefficient are utilized. The optimal value of RMSE approaches zero, while R^2 reaches a maximum of 1 when the predicted values perfectly align with the observed ones (Datta, 2020; Gupta, 2023) in Equ. 8& 9.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{N}} \tag{8}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{9}$$

N = Number of samples

Pi = Predict

Oi = Observed

Ō = Mean

The process of formulas that simulation in the HYDRUS – 2D software showed in (Figure 3).

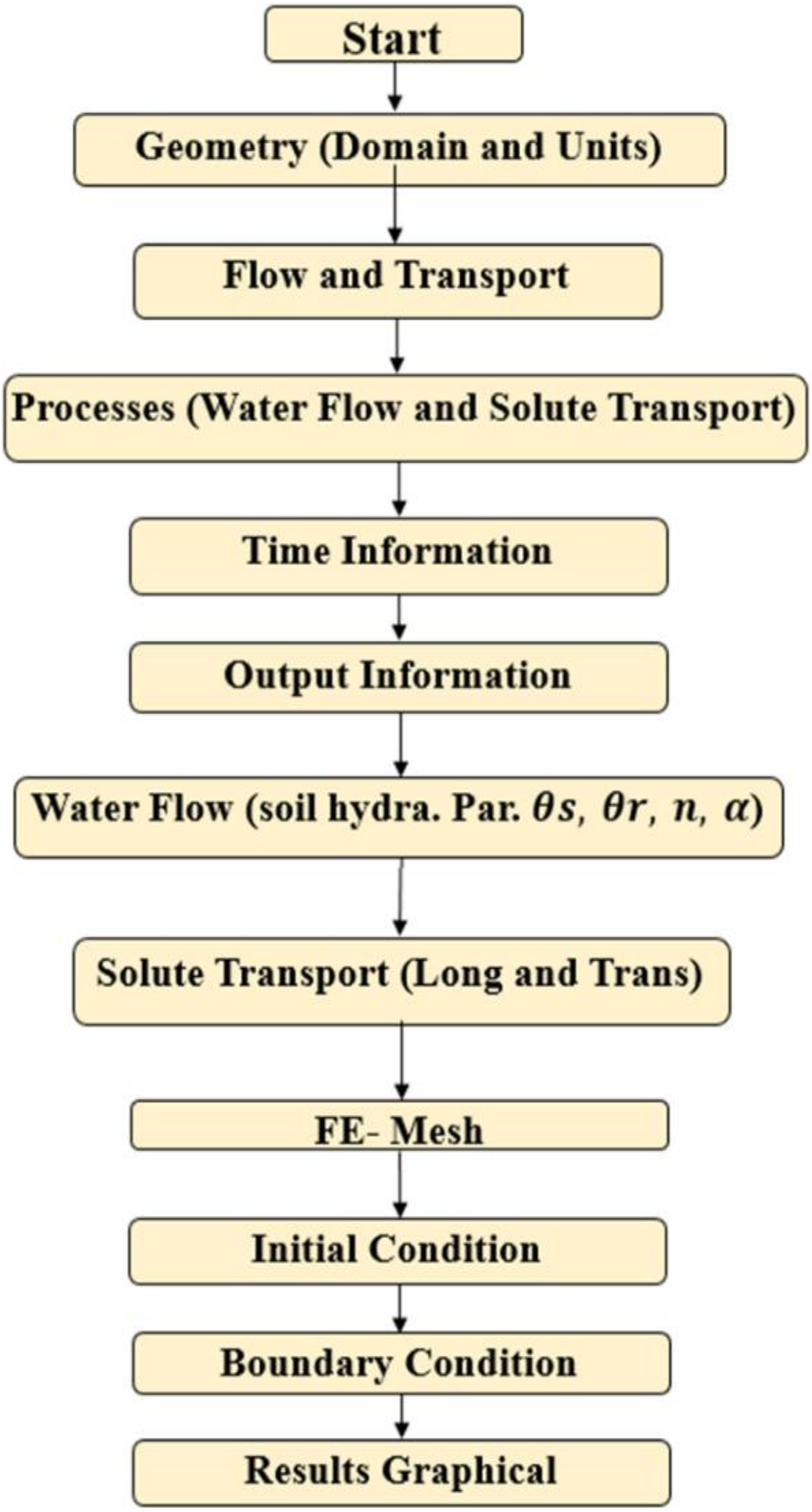

Figure (3): Flow chart of formulas development

3- Results and Discussion

3.1 Model Validation

The transient water movement and distribution of soil salinity through the subsurface emitter of homogeneous soil texture are simulated numerically. The precision of the predicted results is compared to the measured values. This validation is shown in (Figure 4) at 10 cm distance from the junction between emitters. The results show good agreement with field measurements.

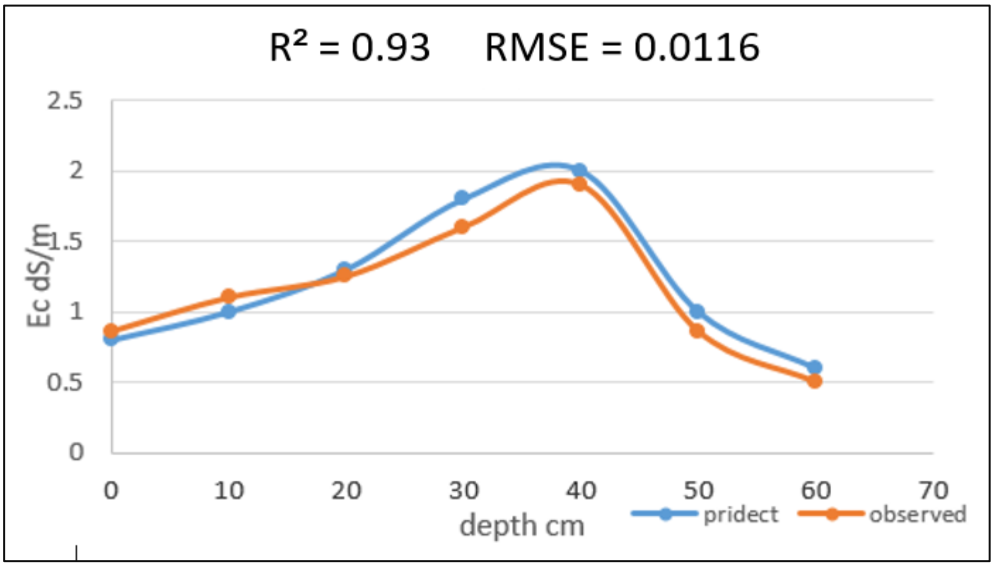

Figure (4): Validation between predict and observed data.

3.2 Water Wetting Pattern

The diagram in (Figure 5) illustrates the wetting pattern at a emitter in soil. The initial moisture (θi) is 0.18 cm^3cm^{-3}, the emitter discharge (Q) is 0.4 Lh^{-1}, the electrical conductivity (EC) is eight ds m^{-1}, and the emitter depth is 20 cm. The simulation time is 12 hours, with 3 hours of irrigation. The changes in water- pattern and initial moisture were minimal. The wetting dimensions in sandy loam soil were more significant due to spreading longitudinally more than laterally due to gravity. The high air-filled pore in coarse-textured soils increased infiltration capacity, causing a laterally moving. Sandy loam soils have high conductivity and a low capacity for water-holding (Suzuki et al, 2004).

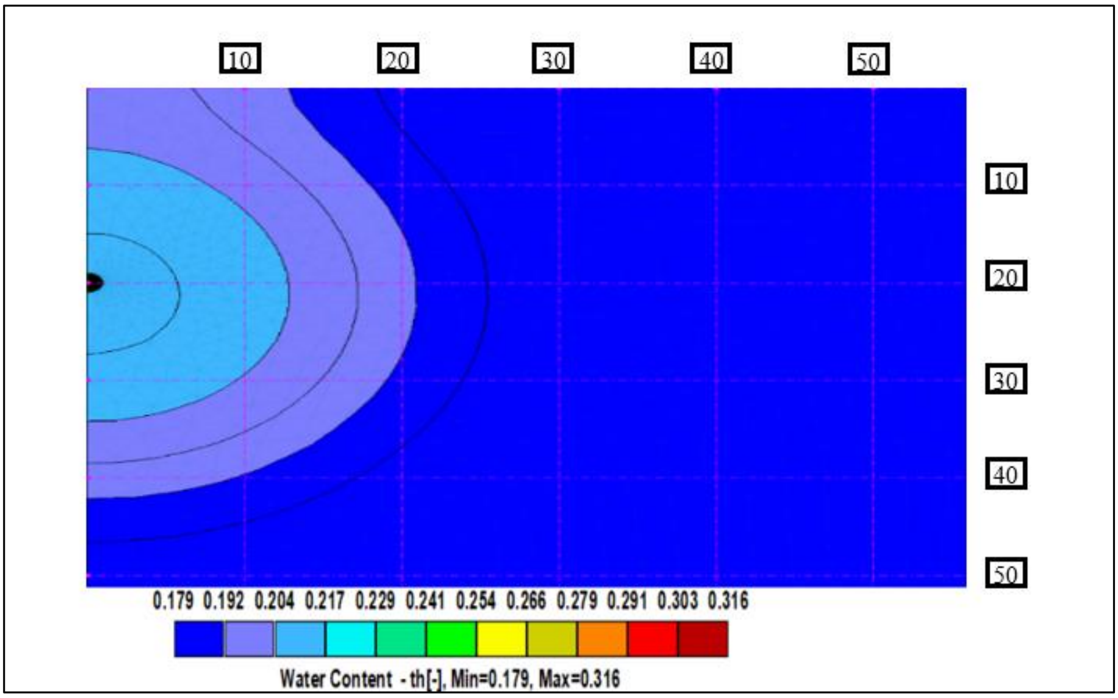

Figure (5): Wetting pattern modeling for a subsurface emitter in soil.

3.3 Salinity Wetting Pattern

Figure (6) depicts the salt diffusion in soil. The soil parameters are θi = 0.18 cm3/cm3, Q= 0.4 Lh^{-1}, EC = 8 ds m^{-1}, and the emitter depth is 20 cm. After the 12-hour modeling (with 3 hours of irrigation), the change in salt quantity and distribution was minimal. Due to the soil's characteristics, the salt dimension, and larger spread 49% longitudinally more than laterally.

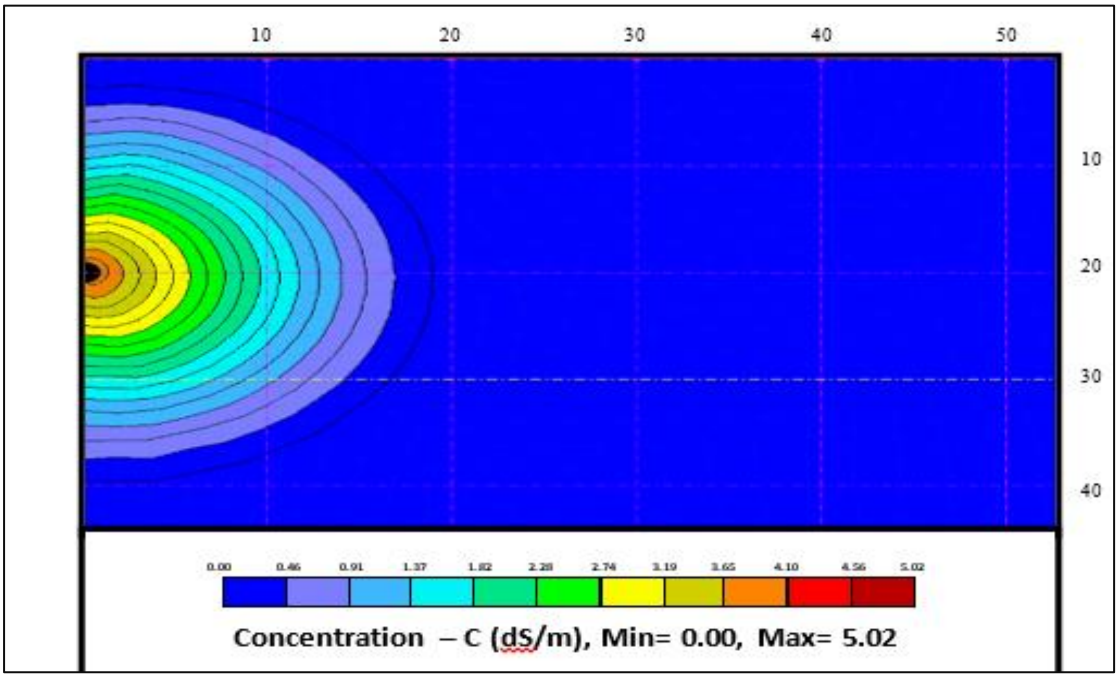

Figure (6): Salt pattern around emitter in soil.

3.4 Emitter Discharge Volume

The salt distribution for an emitter was studied for two soil moisture levels (0.090 and 0.098 cm^3cm^{-3} and two flow rates (0.75 and 1 Lh^{-1}), with an electrical conductivity (EC) of 8.3 ds m^{-1} and depth of 20 cm. After a three-hour simulation (irrigation time 3 hr), the results were plotted in (Figure 7). Water directly influenced the distribution of wetted salt and wetting volume. Higher irrigation amounts resulted in initially higher salt levels and water content. The more lateral extension observed in soil can be explained by the reduced availability of air-filled pore space, decreasing the soil's infiltration capacity.

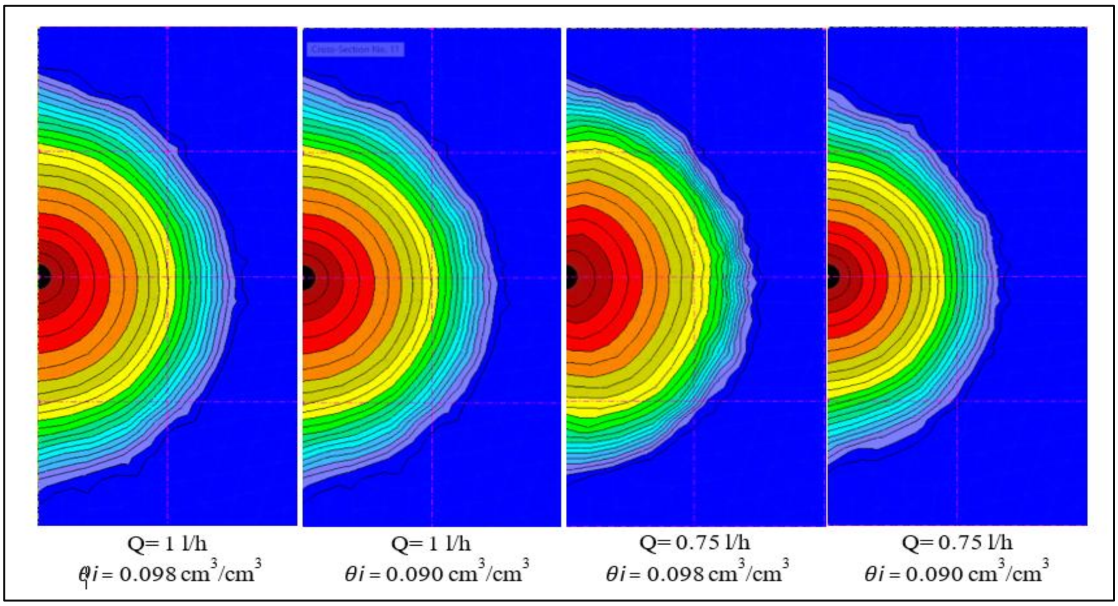

Figure (7): Salt distribution for emitter discharge volume.

3.5 Irrigation Time

As the irrigation duration increases, the dimensions of salt and water distribution also rise significantly. Water allocation aligns with the surface at a depth of 30 cm. The maximum widths were observed at a depth of 10 cm (at 12 and 24 hours), and the greatest depth was reached at 30 cm.

3.6 Crop Yield

In a simulation, at electrical conductivity (EC) levels (8 and 4.2) ds m^{-1}, were planted in soil. The irrigating water containing eight ds m^{-1} of salt led to a 100% reduction in yields and required a large amount of fresh water to flush out the accumulated salt from the soil. On the other hand, irrigation with 4 ds m^{-1} salt led to reductions maize crop grown ranging from 25% to 50% and required less fresh water to leach the salt (Devkota et al, 2022).

4- Conclusions

1. The distribution of salt in sandy loam soil varies slightly, ranging from 0.3% to 2.6%, with salt spreading more longitudinally due to gravity.
2. Salt and water levels depend on irrigation; more water initially increases salt concentration near the emitter.
3. Soil moisture decreases by 46% with distance from the emitter, while salinity rises by 2% due to lower hydraulic conductivity and increased water retention.
4. Emitter placement at 10 cm causes evaporation and higher salt concentration at the surface, while 30 cm depth allows deeper penetration and potential deep percolation.
5. Increasing irrigation from 3 to 12 hours enhances the distribution dimensions, with water width increasing by 48% and salt by 35%; depth rises by 47% for water and 35.6% for salt.
6. Salinity ranges from 1 to 3 ds/m, with moisture decreasing from the emitter.
7. Irrigation with water at 8 dS/m salt results in a 100% yield loss and requires substantial fresh water for leaching; at 4 dS/m, yield reduction is 25% to 50%, needing minimal fresh water for salt removal.

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