Water Flow and Solute Transport Under Drip Irrigation in Sand Dune Field

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Abstract: The scarcity of fresh water in arid and semi-arid regions (ASAR) makes saline water a valuable alternative water source for irrigation of agriculture crops, if we can improve the management of saline water to avoid its deleterious effects. Variables affecting soil water content (θw) and soil solute salinity (ECw), including time after irrigation and crop growth stages; early (ES), mid (MS) and late (LS) stages, were investigated at different radius from the emitter (lateral pipe). The simultaneous distribution of water and solute under drip irrigation was measured using Time Domain Reflectometry (TDR) method. The results indicated that θw and ECw increased in the order ES < MS < LS. The maximum θw and minimum ECw coincided at 10 cm radius from emitter (r90) during ES, MS and LS. The same trend applied for 20 cm radius from emitter (r80) during ES and MS. The ECw increased significantly in the order r90 < r80 < r50 during all crop growth stages. Time elapsed since irrigation was terminated till θw increased to a maximum level at the r90 during ES, MS and LS was 4, 3 and 3 h, respectively. It is therefore suggested that irrigation should commence 3 h before noon to coincide the maximum θw (minimum ECw) with maximum crop evapotranspiration (ETc). Interaction between θw and ECw for a given radius and different crop growing stages showed that the influence of θw on ECw was restricted to a small radius of about 20 cm from the emitter, which decreased further to only 10 cm during LS. Beyond this range, increasing θw was not enough to significantly affect ECw. The information obtained from this research is essential for the design, operation and management of saline water use with drip irrigation system in sand dune fields.

Key words: Drip irrigation, saline water, soil water content, salt load

INTRODUCTION

Use of saline water for irrigation of agricultural crops is of high priority in arid and semi-arid regions (ASAR) with limited water resources. However, improper use of saline water for irrigation is hazardous to the soil and plants due to potential salt accumulation in the soil. Water flow and solute transport processes through the soil is very complex, even in relatively uniform soils, as they are affected by many factors e.g., physical, chemical and biological properties of the soil profile with temporal and spatial variability and management practices (Wallach et al., 1991). Irrigation is one of the main factors affecting the transport of solutes in soils especially those in ASAR (Yaron et al., 1985). Wetting patterns and solutes distributions from emitters are important for design and management of drip irrigation systems (Camp, 1998). Our understanding of the various effects of the irrigation methods on solute transport is still relatively poor.

Drip irrigation is becoming common in ASAR because of its improved utilization of water and nutrients (Buoks et al., 1982) and ability to use saline water. Numerical simulation is an efficient approach to investigating optimal drip management practices (Meshkat et al., 1999; Schmitz et al., 2002; Cote et al., 2003). Numerical models and laboratory experiments that describe water flow and solute transport in soil have been available for a long time. Models of infiltration from a point source (emitter) have been presented by Clothier et al. (1985), Omari and Ligon (1992) and Moncef et al. (2002). Moreover, the number of comprehensive solute transport studies at field scale is still rather limited. Some complications involved with such studies arise because of difficulties in controlling the spatial and temporal variability of the soil’s hydraulic and transport properties and the preferential flow phenomenon, which has been reported in both well-structured and unsaturated soils (Rice et al., 1991). It is common to use soil solution samplers that are introduced into soil trenches. However, this technique provides temporary discrete rather than continues data, hence critical periods are easily missed (Mantell et al., 1985; Ayars et al., 1985; Amente et al., 2000) and sometimes the

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results are not precise (Souza and Matsura, 2003). While recently measurement techniques have been improved considerably (Eching et al., 1994), they are generally still far too expensive for routine characterization of large fields at appropriate resolution.

Most field studies did not include point sources in the estimation of soil water content and solute distributions (Jury et al., 1986; Butters et al., 1989). In studies where point sources were included, usually they were conducted with controlled inputs of water and solutes for a short duration of time. Evaluated water flow and solute distribution from a point source through a coarse loamy soil using 15, 20 and 25 L of solution, each in three concentrations, with different water application rates. They found that soil solute concentration increased with increasing solution concentration, applied solution volume and solution application rate, up to a depth of about 25 cm and radial distance of about 30 cm, beyond which the difference in concentration of the solution was not significant (Khan et al., 1996). Evaluation of water flow and solute transport in the field under irrigation with saline water can be a useful factor in the design, operation and management of saline water use with drip irrigation system (Ayars et al., 1985; Khan et al., 1996; Amente et al., 2000). However, to the best of our knowledge, this vital information is still lacking.

The objective of this research was to study the effect of: Time after termination of irrigation, plant growth stages and radius from emitter (lateral pipe), on soil water content (6w) and soil solute salinity (ECw) in saline water drip irrigated sand dune field.

**MATERIALS AND METHODS**

Field experiments were conducted at the Arid Land Research Center (ALCRC), Tottori University, Japan (34°32' N, 134°13' E), using saline water in corn (Zea mays) field. The soil was a siliceous sand classified as Haplic Arenosol (FAO-UNESCO, 1997) or Typic Udipsamn (Anonymous, 1998). The soil was air dried to a depth of 60 cm and repacked uniformly while setting up the experimental system. Soil texture was determined using the hydrometry method and wet soil particle size distribution analysis (Table 1). The maximum water holding capacity (FC) and initial wilting point (Wp) of field soil were 0.074 and 0.025 cm\(^3\) cm\(^{-3}\), respectively.

The experimental drip irrigation system was set in a corn field covered by a transparent plastic sheet, 2 m above the ground, to prevent the interference of rainfall. A water-tank was used to prepare the saline irrigation water that was pumped into the drip irrigation system. The saline water was prepared by mixing sodium chloride and calcium chloride to achieve a water salinity of ECw = 3.5 dS m\(^{-1}\) and SAR = 5.0. The main pipeline was branched to three lateral pipes, 1 m apart, to avoid interference from emitters of adjacent lateral pipe. Each lateral pipe was operated by a separate manual valve and had 11 emitters, 40 cm apart. The emitters spacing on a lateral pipe was selected based on previous research (Yamamoto and Cho, 1978) to avoid interference from adjacent emitters. The corn seeds were planted along each lateral pipe, 2.0-3.0 cm away from the emitters at a spacing of 40 cm between seeds (emitter distance). The irrigation system was operated in 0.1 MPa to achieve emitter discharge of 2 L h\(^{-1}\). Emitter’s discharge was checked weekly to avoid emitter discharge variation due to emitter clogging.

A site calibrated Time Domain Reflectometry (TDR) was used to measure 6w and Ecw. Nine soil-TDR probes with three-rod wave-guide were used (Dehghanianj et al., 2004b). They were connected to one data-logger (Campbell Co. TDR100) and two multiplexes (SDMX30) by Fujikura RG-58A cable tester. The soil-TDR probes were installed in a vertical grid to the middle lateral pipe, on one side of the middle emitter and in 3 radius (10 cm = r\(_{10}\), 20 cm = r\(_{20}\), 30 cm = r\(_{30}\)). In each radius, 3 soil-TDR probes were installed at depths of 10, 25 and 45 cm (Fig. 1).

The experiments were carried out from June 2006 (corn seeding season) until the middle of September (corn harvesting season). The irrigation system was operated based on daily estimation of optimum crop water requirement. Optimum crop water requirement level was determined using a method based on the class A pan evaporation suggested by Goldberg et al. (1976) and revised for Tottori area by Yano et al. (1977) and Dehghanianj et al. (2004a). According to this method, the daily crop requirements of irrigation water, ETc (mm), can be calculated by the equation;

\[
ETc = Ep\times Kc
\]

Where:
\[
Ep = \text{Class A pan evaporation (mm)}
\]
\[
Kc = \text{Crop coefficient}
\]

In present study, the Kc values were calculated following the procedure recommended by FAO for dual crop coefficient under drip irrigation system (Allen et al., 1998).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Textural fractions (%)</th>
<th>Texture class</th>
<th>Soil bulk density (g cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>96.1±1.69, 0.4±0.22, 3.5±1.06</td>
<td>Sandy</td>
<td>1.5±0.07</td>
</tr>
<tr>
<td>20-40</td>
<td>95.7±1.53, 0.6±0.28, 3.7±1.49</td>
<td>Sandy</td>
<td>1.5±0.12</td>
</tr>
<tr>
<td>40-60</td>
<td>93.5±1.97, 0.7±0.17, 5.8±1.08</td>
<td>Sandy</td>
<td>1.4±0.09</td>
</tr>
</tbody>
</table>
Fig. 1: The experimental layout and pattern of the soil-TDR probes in the soil cross section

The $\theta_w$ (cm$^3$ cm$^{-3}$) and ECw (dS m$^{-1}$) were measured simultaneously every hour between each irrigation interval (24 h) and during the 3 crop growth stages, early stage (ES), mid-stage (MS) and late crop growth stage (LS). Soil solute concentration at the end of the irrigation season was measured by soil samples taken at 0, 10, 20, 30 and 40 cm radius from both side of the middle emitter located on the middle lateral pipe and the 2 adjacent emitters as replications. The corresponding depths of the soil samples were 0-5, 5-10, 10-25 and 25-45 cm.

Replications were not applied by installing other sets of soil-TDR probes beneath the emitter, because of the experimental intensity used in this research and consequently the excessive demands in term of time and labor.

The data were analyzed using the analysis of variance (Snedecor and Cochran, 1967). The changes in mean $\theta_w$ and ECw values with time after irrigation, radius from emitter and during crop growth stages were compared using Duncan's multiple range tests (Steel and Torrie, 1960), for which purpose the Statistical Package for the Social Sciences (SPSS) was used. To study the effect of time after termination of irrigation on $\theta_w$ and ECw at any given radius, the number of the readings was 3 (hourly reading by 3 soil-TDR probes at each radius) × 1 (one reading for each hour) × 30 (irrigations) for ES and 3 × 1 × 45 and 3 × 1 × 30 for MS and LS, respectively. The number of the reading to study the effect of plant growth stages on $\theta_w$ and ECw at any given radius was 3 (hourly reading by 3 soil-TDR probes at each radius) × 24 (hourly reading in each day) × 30 (irrigations) for ES and 3 × 24 × 45 and 3 × 24 × 30 for MS and LS, respectively.

RESULTS AND DISCUSSION

The amount of daily irrigation water (ETc) varied between 1.3 and 9.1 mm a day according to the crop growth stages and the climatic condition. Due to lower
temperatures during the rainy season (June and July) and consequently low pan evaporation, the amount of irrigation water was reduced in some days of MS.

**Moisture distribution in the soil cross section:** The $\theta w$ at the end of each crop growing stage as a function of distance (radius) from the emitter are presented in Fig. 2, for the time before the next irrigation. Obviously, $\theta w$ decreased with increasing distance from emitter during all crop growth stages, confirming the results obtained by Assouline (2002) and Michelakis et al. (1993). The highest $\theta w$ was at the 25 cm soil depth. We can conclude that the 0-25 cm soil layers supplied the major amount of water for crop evapotranspiration (ETc). This depth is varying during the crop growth stages (Wang et al. 2006). However, the number of soil- TDR probes and their location in current study cannot support the results by Wang et al. (2006). They reported that under a drip irrigated potato, soil water in the upper soil layer changed more dramatically than in the lower layer. During the early growth period (20-50 days from planting), the $\theta w$ showed some change, but only at depths of 10 and 20 cm with no significant change occurring below 30 cm. However, with increases in air temperature, evapotranspiration increased and $\theta w$ varied greatly within the soil profile at depths from 10 to 30 cm during the middle planting period (50-80 days from planting). At those depths below 30 cm, however, $\theta w$ variations increased as irrigation frequency decreased. During the late period (80-99 days from planting), variations in $\theta w$ for the three treatments were similar at depths from 10 to 50 cm.

The $\theta w$ distribution at any given radius was affected by crop growth stages. The maximum $\theta w$ for ES occurred generally at 4, 8 and 6 h after irrigation commenced for $r_{10}$, $r_{25}$ and $r_{50}$, respectively, while it occurred 3, 6, 5 h and 3, 5, 4 h after irrigation commenced, for the above radiiuses, during MS and LS, respectively. The results indicated that with the advance of crop growth stages, the time that soil water reached a maximum level, at any given radius, decreased probably due to increasing of ETc. The time elapsed after irrigation until $\theta w$ reached a maximum level was longer for $r_{50}$ than $r_{25}$ and $r_{10}$, which can be attributed to longer time of water redistribution from $r_{10}$ to $r_{50}$ than that from $r_{10}$ toward $r_{50}$.

In ES, $\theta w$ increased significantly ($<0.05$) at $r_{50}$ and $r_{25}$ 2 h after irrigation commenced, while it took 5 h for $r_{10}$. In MS, $\theta w$ increased significantly ($<0.05$) in $r_{10}$ and $r_{25}$, 2 and 3 h after irrigation commenced respectively, while it took 1 and 3 h for the LS. However, the changes in $\theta w$ at $r_{50}$ were not significant during both MS and LS. These results showed that increasing the $\theta w$ after irrigation was significant before maximum $\theta w$.

The average $\theta w$ increased in the order ES < MS < LS. The variability in $\theta w$ during the crop growth stages for the various radiiuses is summarized in Table 2. The $\theta w$ increased significantly in the order $r_{10} > r_{25} > r_{50}$ during all crop growing stages. The crop growing stages affected significantly on $\theta w$ at any given radius (Table 2). The $\theta w$ varied in the order ES > MS < LS at $r_{50}$, but varied in the order ES > MS > LS at $r_{25}$. The $\theta w$ increased significantly at $r_{50}$ in the order ES < MS < LS. The decrease in the average $\theta w$ from ES to MS and the observed increase in
Fig. 3. Soil solution salinity (ECw) distribution in the soil cross section at the end of the different crop growth stages (ES: Early Stage, MS: Mid-Stage, LS: Late Stage) and the various radiiuses (● r = 10 cm, ▲ r = 20 cm, ■ r = 30 cm), before the next irrigation

| Table 2: Effect of radius distance from emitter (r₁₀ = 10 cm, r₂₀ = 20 cm, r₃₀ = 30 cm) and crop growth stages |
|-----------------|-----------------|-----------------|-----------------|
| Crop growth     | Stage           | r₁₀             | r₂₀             | r₃₀             |
| ES              | 0.0737<sup>a</sup> | 0.0650<sup>c</sup> | 0.0273<sup>c</sup> |
| MS              | 0.0673<sup>a</sup> | 0.0629<sup>c</sup> | 0.0340<sup>c</sup> |
| LS              | 0.0688<sup>a</sup> | 0.0624<sup>c</sup> | 0.0397<sup>c</sup> |

*: Between columns (of the same row) and **: Between rows (of the same column). (ES: Early Stage, MS: Mid-Stage, LS: Late Stage) on soil water content (θw, cm²/g). Means followed by the same letter do not differ significantly at the 0.05 probability level.

LS at r₃₀ can be attributed to changes in ETc during crop growth stages and the crop's root activity. It is obvious that the crop's root activity at r₁₀ increased from ES to MS but it did not change much from MS to LS. However, the crop's root activity at r₃₀ was in the order ES > MS > LS.

Salinity distribution in the soil cross section: The ECw at the end of each crop growing stage as a function of the distance (radius) from the emitter is shown in Fig. 3 for the time before the next irrigation. The ECw was generally higher in r₁₀ than in r₁₁ and r₅₀, especially at the topsoil (≤ 10 cm) layer. Same results is reported by Wallender et al. (2007) on saline water use by grape drip irrigated. In the 10 cm soil depth the ECw varied in the order r₁₁ < r₅₀ < r₁₀ at the end of ES; then it changed to r₁₀ < r₅₀ < r₃₀ at the end of LS. This can be attributed to transportation of solute from r₅₀ to r₃₀ as ETc increased from ES to LS.

| Table 3: Effect of radius distance from emitter (r₁₀ = 10 cm, r₂₀ = 20 cm, r₃₀ = 30 cm) and crop growth stages (ES early stage, MS mid-stage, LS late stage) on soil solution salinity (ECw, dS m⁻¹). Means followed by the same letter do not differ significantly at the 0.05 probability level |
|-----------------|-----------------|-----------------|
| Crop growth     | Stage           | r₁₀             | r₂₀             | r₃₀             |
| ES              | 7.68<sup>a</sup> | 13.48<sup>b</sup> | 14.48<sup>c</sup> |
| MS              | 7.51<sup>c</sup> | 11.40<sup>c</sup> | 17.87<sup>b</sup> |
| LS              | 7.67<sup>c</sup> | 13.16<sup>c</sup> | 25.07<sup>b</sup> |

*: Between columns (of the same row) and **: Between rows (of the same column).

Across the crop growth stages, the ECw was maximum in r₁₀ when θw was minimum and vice versa. Similar θw-ECw relations were found for r₁₀ during the ES and MS. However, in the LS, the minimum ECw occurred 1 h before the maximum θw and the maximum ECw occurred 3 h before the minimum θw. In r₁₀ the maximum ECw occurred when θw was minimum, during the ES and MS, but in the LS it occurred 2 h before the minimum θw. The minimum ECw in r₁₀ was delayed compared with maximum θw for all crop growth stages, which occurred 1, 2 and 2 h after the time of maximum θw for ES, MS and LS respectively. The results clearly indicated that the equality of elapsed time after irrigation commenced for maximum θw and maximum ECw level or minimum θw and maximum ECw level at r₁₀ affected by increasing the distance from emitter. This trend can be ascribed to a lack of effect of θw on ECw due to decreasing θw with increasing distance from emitter.
The average ECw increased in the order ES < MS < LS. The differences in ECw during the crop growth stages for the various radius are shown in Table 3. The ECw varied significantly with the distance from the emitter in the order \( r_{10} < r_{20} < r_{30} \) for all crop growing stages (Table 3). The ECw increased significantly from ES to MS at both \( r_{10} \) and \( r_{30} \), and decreased from MS to LS. This is probably because of the increase in ETo with the advance of crop growth stage, especially from MS to LS and transport of accumulated salt towards the boundary of the wetted soil volume. The ECw increased significantly at \( r_{10} \) in the order ES < MS < LS. We suggest that the most bulk of the salt that was transported from \( r_{10} \) and \( r_{20} \) probably concentrated at \( r_{30} \).

The values of ECw were less than 8 dS m\(^{-1}\) in the radius < 10 cm during all crop growing stages and increased toward the fringes of the wetted soil volume. Considering the results of salt distribution in sandy soil when ETo = 0 (Bresler, 1975), the main reasons for the higher salt concentration near the soil surface (0-10 cm) is soil evaporation.

The results of salt distribution, measured manually beneath the 3 emitters (middle emitter and 2 adjacent emitters of the middle lateral pipe), at the end of the irrigation season did not differ significantly (< 0.05). The averages of the manually measured salt distribution and salt loads, as a function of soil depth and radius from emitter are shown in Table 4. These results clearly demonstrate that the major salt concentration was in \( r_{20} \) and \( r_{30} \) (\( r_{30} < r_{30} \)) and in the 0-10 cm deep layer. The accumulation of salt near the soil surface or at the boundary of wetted volume could be attributed to combined effects of solute transport by water flow and selective water uptake by crop roots (leaving salt behind) or evaporation from soil surface. Similar results were also reported by Mantell et al. (1985) and Ayars et al. (1985). They studied salt distribution under cotton trickle irrigation with saline water and reported that the combined effects of solute convection by water flow and selective water uptake by crop roots result in relatively low salt concentration near the emitter and increased concentrations toward the fringes of the wetted soil volume.

The amount of salt load at the end of the irrigation season was about 4.64 mg ha\(^{-1}\) in the 0-45 cm soil layer. For a new cultivation season, probably an intense leaching will be required prior to planting, to wash the salts below the root zone.

**Interaction between water and salt:** To assess the affect of salt accumulation under the drip irrigation system, the interactions between \( \theta_w \) and ECw were calculated at a given radius and for each different crop growing stage (Fig. 4-6). The interaction between \( \theta_w \) and ECw is presented under two conditions after irrigation was terminated: (a) when \( \theta_w \) was beginning to increase and
Fig. 5: The interaction between soil water content (θw) and soil solution salinity (ECw) during the mid-stage (MS) at r₁₀ (10 cm radius from emitter) and r₂₀ (20 cm radius from emitter); (a) θw was beginning to increase after irrigation and (b) θw was beginning to decrease. Each point represent simultaneously measured ECw and θw.

Fig. 6: The interaction between soil water content (θw) and soil solution salinity (ECw) during the late stage (LS) at r₁₀ (10 cm radius from emitter) and r₂₀ (20 cm radius from emitter); (a) θw was beginning to increase after irrigation and (b) θw was beginning to decrease. Each point represent simultaneously measured ECw and θw.

(b) when θw was beginning to decrease (Fig. 4-6). A power regression equation was used that gave the best-fit coefficient of determination (R²) between θw and ECw. A high correlation was found between θw and ECw at r₁₀ and r₂₀, during the ES and MS (Fig. 4-5), while a low correlation was found for LS due to increasing of ECw (Fig. 3). There was no correlation between θw and ECw at r₅₀ for the three growing stages (not presented in the figures), which can be attributed to low θw during ES and MS and increasing of ECw during MS and LS (Fig. 2-3). In Fig. 4-6 the slope of the curves is steeper for r₅₀ compare with r₁₀ because ECw was always higher and θw was generally lower. The slope of the curves in condition (b) are slightly higher compare with condition (a) at r₁₀, probably because of longer elapsed time for (b) condition compare to (a) condition. In r₂₀ there were similar results.
for ES, the slope of the curve in condition (b) was slightly higher compare with condition (a). However, in MS the slope of the curve in condition (a) was slightly higher compare with condition (b). In r30, the slope of the curves in MS is considerably higher compare to ES for both conditions (a and b), which can be attributed to increasing of ETc.

Non-uniformity of salt accumulation appeared during LS (Fig. 6) especially at r30. In the combination of r30 and LS (Fig. 6a, b) two sets of data are presented, one for soil-TDR probe located at 10 cm depth (high level of ECw) and another for soil-TDR probes located at 25 and 45 cm depth (low level of ECw). The reason for this phenomenon was the significantly higher ECw (salt accumulation) in 10 cm depth compare to 25-45 cm depth (Fig. 3, LS).

These results showed that the interaction between θw and ECw was considerably affected by distance from emitter and crop growing stages. The assessing of the interaction between θw and ECw in different radius from emitter can assist in predicting ECw in the area between 2 consecutive emitters and then determining the optimal distance between 2 consecutive emitters on lateral pipe when saline water is used for irrigation. This results can improve our knowledge to approach practically use of saline water under drip irrigation system.

CONCLUSIONS

The ECw and θw increased in the order LS > MS > ES. The θw decreased and ECw increased significantly with distance from the emitter at any given radius, across the crop growing stages. The increase in ETc, during the crop growth stages caused an increase in ECw especially at r30 and in LS. The maximum θw coincided with minimum ECw at r30 during ES, MS and LS; the same trend applied for r30 during ES and MS, but no similar relations occurred at r30. Based on the time elapsed for maximum θw at r30 and the relationship between θw and ECw, we suggest that the irrigation should commence 3 h before noon to synchronize the maximum θw (minimum ECw) with solar noon, when maximum ETc is expected. There was a high correlation between θw and ECw at r10 and r30 during ES and MS. The correlation decreased slightly at r50 and there was very low correlation at r30 during the LS. The correlation between θw and ECw was very low at r30 during all the crop growth stages due to salt accumulation. At the end of the irrigation season, most of the salt accumulated at r30 and in the 0-10 cm soil layer. Based on the interaction between θw and ECw for a given radius, a distance of less than 40 cm is recommended for 2 consecutive emitters on a lateral pipe to minimizing ECw in a sand dune field.

REFERENCES


