Journal of Applied Sciences

ISSN 1812-5654

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Journal of Applied Sciences 7 (20): 2997-3005, 2007
ISSN 1812-5654

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 (r_{10}) during ES, MS and LS. The same trend applied for 20 cm radius from emitter (r_{20}) during ES and MS. The ECw increased significantly in the order $r_{10} < r_{20} < r_{30}$ during all crop growth stages. Time elapsed since irrigation was terminated till θw increased to a maximum level at the r_{10}, 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 (Bucks *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; Schemitz *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), Omary 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 (θw) 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 (ALRC), Tottori University, Japan (35°32′N, 134°13′E), using saline water in corn (*Zea mays*) field. The soil was a siliceous sand classified as Haplic Arensol (FAO-UNESCO, 1997) or Typic U dipsamment (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.

Table 1: Soil texture and soil bulk density measured at different depths of the experimental field

Depth (cm)	Textural fractions (%) Sand	Silt	Clay	Texture class	Soil bulk density (g cm^{-3})
0-20	96.1±1.69	0.4±0.22	3.5±1.06	Sandy	1.56±0.07
20-40	95.7±1.53	0.6±0.28	3.7±1.49	Sandy	1.51±0.12
40-60	93.5±1.97	0.7±0.17	5.8±1.08	Sandy	1.49±0.09

A site calibrated Time Domain Reflectometry (TDR) was used to measure θw and Ecw. Nine soil-TDR probes with three-rod wave-guide were used (Dehghanisanij *et al*., 2004b). They were connected to one data-logger (Campbell Co. TDR100) and two multiplexes (SDMX50) 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 Dehghanisanij *et al*. (2004a). According to this method, the daily crop requirements of irrigation water, ETc (mm), can be calculated by the equation;

$$ETc = Ep \times Kc \tag{1}$$

Where:

Ep = Class A pan evaporation (mm)

Kc = 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).

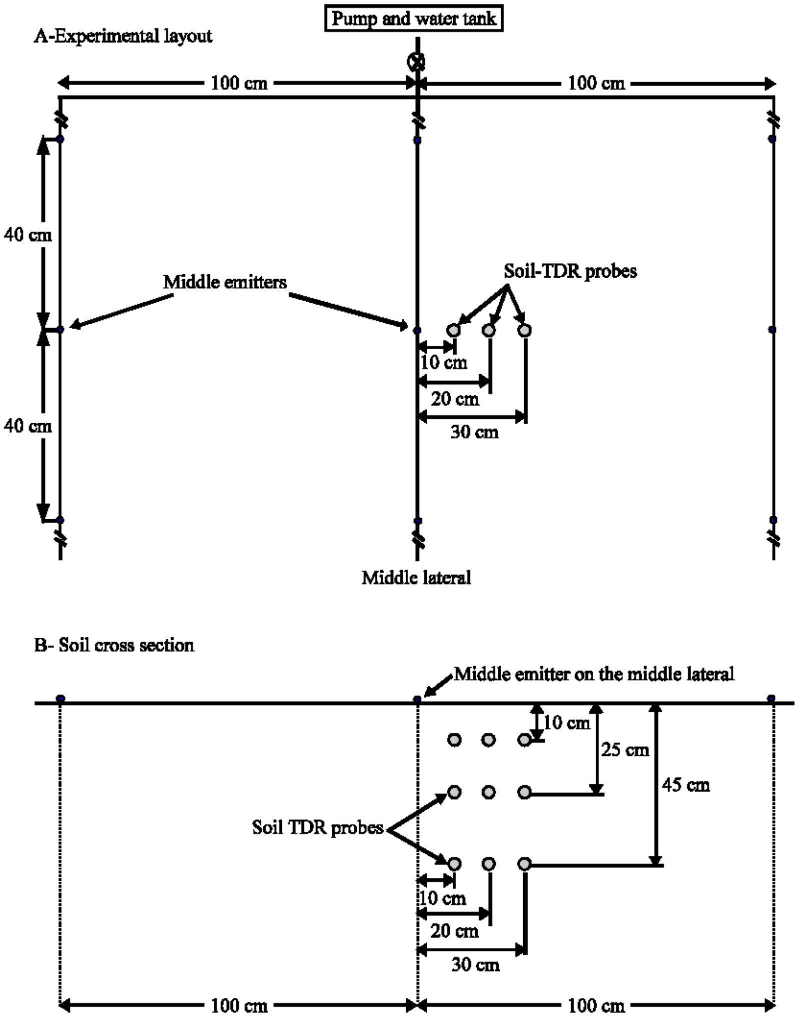

Fig. 1: The experimental layout and pattern of the soil-TDR probes in the soil cross section

The θw (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 θw 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 θw 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 θw 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

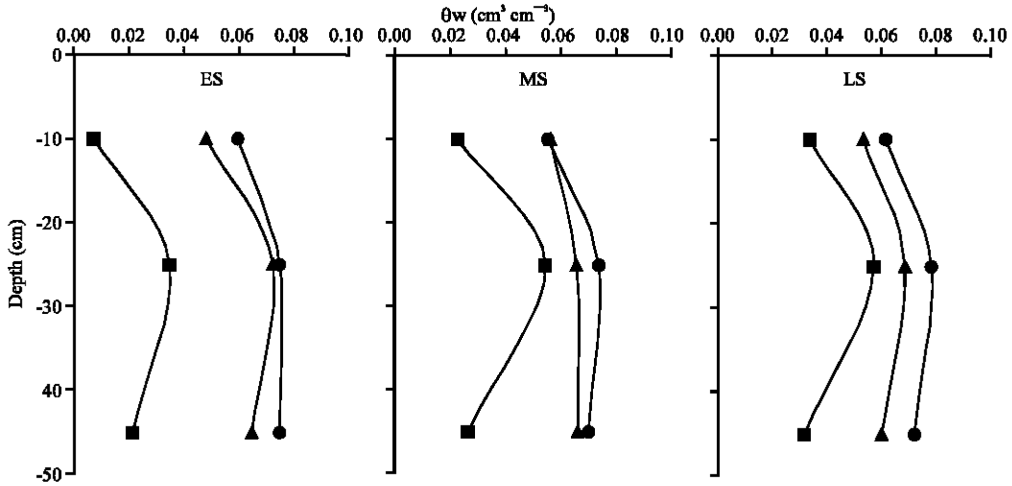

Fig. 2: Soil water content (θw) distribution in the soil cross section at the end of the different crop growth stages (ES: Early Stage, MS: Mid-Stage, LS: Late Stage) and the various radiuses (● r = 10 cm, ▲ r = 20 cm, ■ r = 30 cm), before the next irrigation

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 θw 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, θw 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 θw 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 θw 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 θw 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, θw variations increased as irrigation frequency decreased. During the late period (80-99 days from planting), variations in θw for the three treatments were similar at depths from 10 to 50 cm.

The θw distribution at any given radius was affected by crop growth stages. The maximum θw for ES occurred generally at 4, 8 and 6 h after irrigation commenced for r_{10}, r_{20} and r_{30}, respectively, while it occurred 3, 6, 5 h and 3, 5, 4 h after irrigation commenced, for the above radiuses, 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 θw reached a maximum level was longer for r_{20} than r_{10} and r_{30}, which can be attributed to longer time of water redistribution from r_{10} to r_{20} than that from r_{20} toward r_{30}.

In ES, θw increased significantly (≤ 0.05) at r_{10} and r_{20}, 2 h after irrigation commenced, while it took 5 h for r_{30}. In MS, θw increased significantly (≤ 0.05) in r_{10} and r_{20}, 2 and 3 h after irrigation commenced respectively, while it took 1 and 3 h for the LS. However, the changes in θw at r_{30} were not significant during both MS and LS. These results showed that increasing the θw after irrigation was significant before maximum θw.

The average θw increased in the order ES < MS < LS. The variability in θw during the crop growth stages for the various radiuses is summarized in Table 2. The θw increased significantly in the order $r_{10} > r_{20} > r_{30}$ during all crop growing stages. The crop growing stages affected significantly on θw at any given radius (Table 2). The θw varied in the order ES > MS < LS at r_{10}, but varied in the order ES > MS > LS at r_{20}. The θw increased significantly at r_{30} in the order ES < MS < LS. The decrease in the average θw from ES to MS and the observed increase in

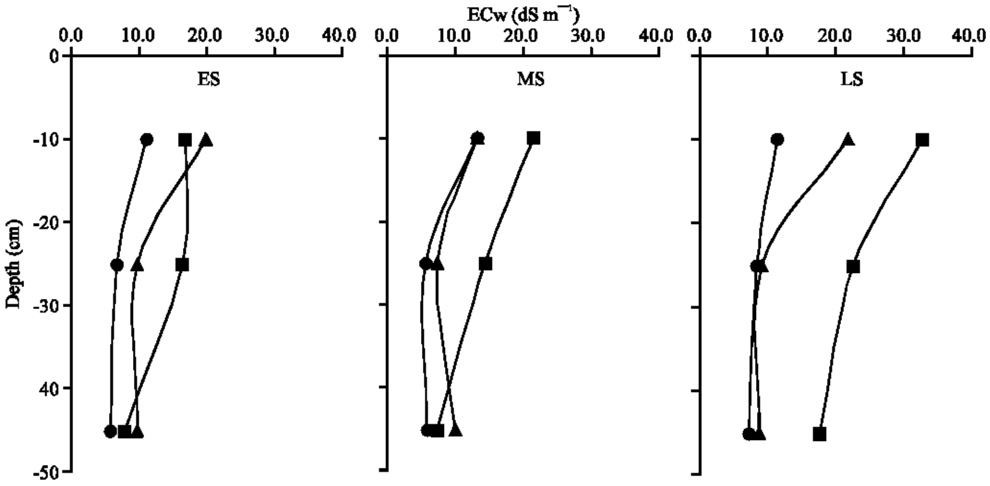

Fig. 3: Soil solution salinity (ECw) distribution in the soil cross section at the end of the different crop growth stages (ES: Early Stage, MS: Mid-Stage, LS: Late Stage) and the various radiuses (● r = 10 cm, ▲ r = 20 cm, ■ r = 30 cm), before the next irrigation

Table 2: Effect of radius distance from emitter (r_{10} = 10 cm, r_{20} = 20 cm, r_{30} = 30 cm) and crop growth stages

Crop growth stage	Radius from emitter (cm) r_{10}	r_{20}	r_{30}
Effect of radius distance*			
ES	0.0737^{c}	0.0650^{b}	0.0273^{a}
MS	0.0673^{c}	0.0629^{b}	0.0340^{a}
LS	0.0688^{c}	0.0624^{b}	0.0397^{a}
Effect of crop growth stages**			
ES	0.0737^{c}	0.0650^{c}	0.0273^{a}
MS	0.0673^{a}	0.0629^{b}	0.0340^{b}
LS	0.0688^{b}	0.0624^{a}	0.0397^{c}

*: Between columns (of the same row) and **: Between rows (of the same column). (ES: Early Stage, MS: Kid-Stage, LS: Late Stage) on soil water content (θw, cm^3 cm^{-3}). Means followed by the same letter do not differ significantly at the 0.05 probability level

LS at r_{10} 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 r_{10} increased from ES to MS but it did not change much from MS to LS. However, the crop's root activity at the r_{20} 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 r_{30} than in r_{10} and r_{20}, 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 $r_{10} < r_{30} < r_{20}$ at the end of ES; then it changed to $r_{10} < r_{20} < r_{30}$ at the end of LS. This can be attributed to transportation of solute from r_{20} to r_{30} as ETc increased from ES to LS.

Table 3: Effect of radius distance from emitter (r_{10} = 10 cm, r_{20} = 20 cm, r_{30} = 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	Radius from emitter (cm) r_{10}	r_{20}	r_{30}
Effect of radius distance*			
ES	7.68^{a}	13.48^{b}	14.48^{c}
MS	7.51^{a}	11.40^{b}	17.87^{c}
LS	7.67^{a}	13.16^{b}	25.07^{c}
Effect of crop growth stages**			
ES	7.68^{b}	13.48^{b}	14.48^{a}
MS	7.51^{a}	11.40^{a}	17.87^{b}
LS	7.67^{b}	13.16^{b}	25.07^{c}

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

Across the crop growth stages, the ECw was maximum in r_{10} when θw was minimum and vice versa. Similar θw-ECw relations were found for r_{20} 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 r_{30} 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 r_{30} 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 minimum ECw level or minimum θw and maximum ECw level at r_{10} affected by increasing the distance from emitter. This trend can be ascribed to feckless 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_{20} and decreased from MS to LS. This is probably because of the increase in ETc 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_{30} 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 ETc = 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} ($r_{20} < r_{30}$) 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 fridges 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 θw and ECw were calculated at a given radius and for each different crop growing stage (Fig. 4-6). The interaction between θw and ECw is presented under two conditions after irrigation was terminated: (a) when θw was beginning to increase and

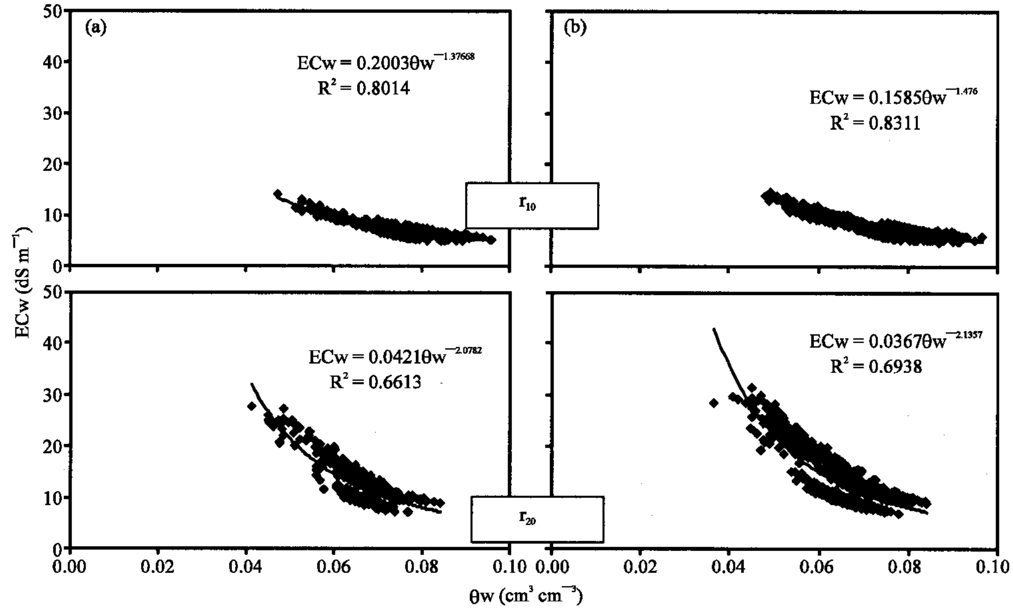

Fig. 4: The interaction between soil water content (θw) and soil solution salinity (ECw) during the early stage (ES) at r_{10} (10 cm radius from emitter) and r_{20} (20 cm radius from emitter); (a) θw was beginning to increase after irrigation and (b) θw was beginning to decrease. Each point represent simultaneously measured ECw and θw

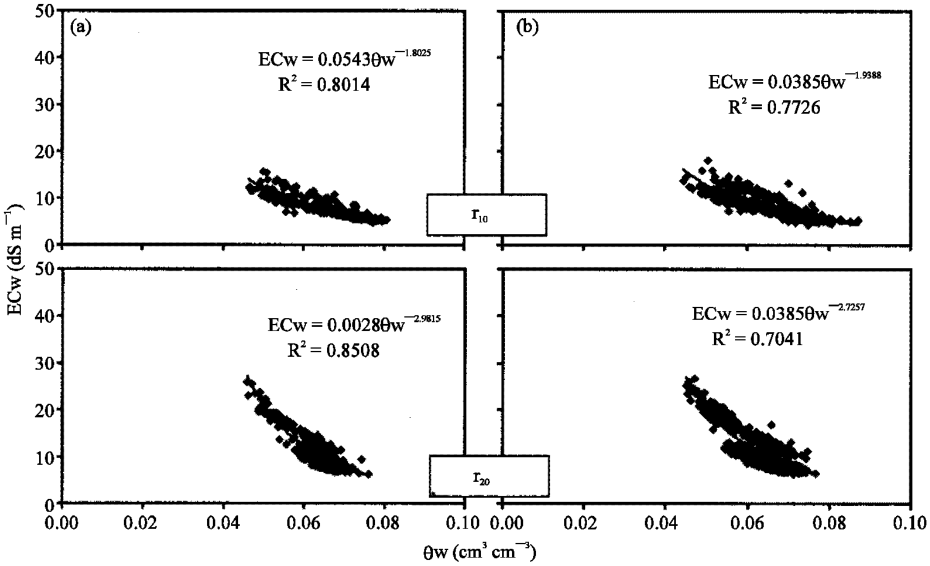

Fig. 5: The interaction between soil water content (θw) and soil solution salinity (ECw) during the mid-stage (MS) at r_{10} (10 cm radius from emitter) and r_{20} (20 cm radius from emitter); (a) θw was beginning to increase after irrigation and (b) θw was beginning to decrease. Each point represent simultaneously measured ECw and θw

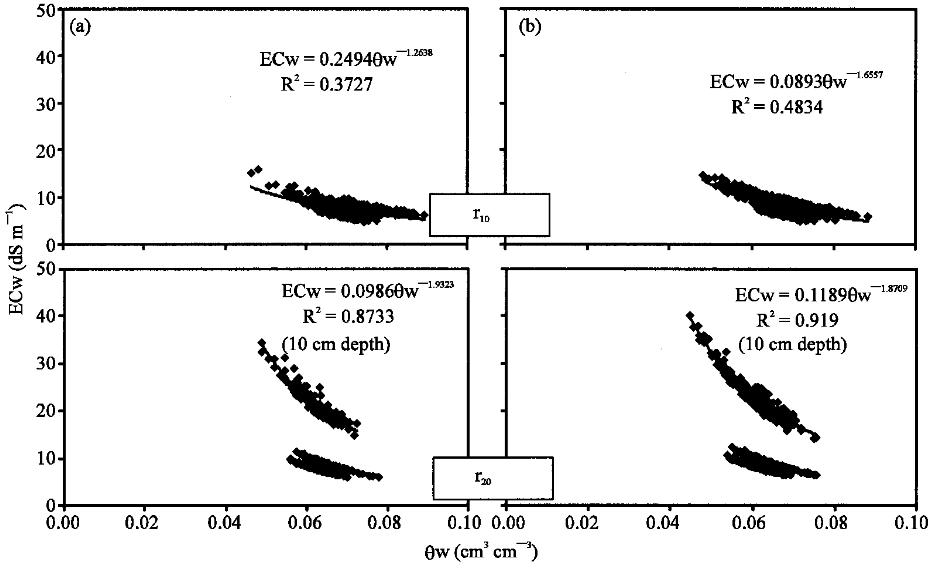

Fig. 6: The interaction between soil water content (θw) and soil solution salinity (ECw) during the late stage (LS) at r_{10} (10 cm radius from emitter) and r_{20} (20 cm radius from emitter); (a) θw was beginning to increase after irrigation and (b) θw was beginning to decrease. Each point represent 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 (R^2) between θw and ECw. A high correlation was found between θw and ECw at r_{10} and r_{20}, 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 r_{30} 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 r_{20} compare with r_{10} 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 r_{10}, probably because of longer elapsed time for (b) condition compare to (a) condition. In r_{20} there were similar results

Table 4: Average salt distribution and salt load at the end of the irrigation season

Depth (cm)	Salt distribution ------------------- ($g\ kg^{-1}$ soil) ----------------------- Radius distance from emitter (cm)				Salt load ($Mg\ ha^{-1}$)
	0	10	20	30	
0-5	0.56±0.04	1.58±0.11	6.03±0.21	0.67±0.05	1.20
5-10	0.16±0.01	0.62±0.03	2.16±0.17	8.11±0.31	2.15
10-25	0.13±0.01	0.11±0.00	0.19±0.02	0.77±0.04	0.88
25-45	0.10±0.01	0.14±0.00	0.14±0.01	0.14±0.01	0.41
Salt load ($mg\ ha^{-1}$)	0.01	0.21	1.27	2.37	4.64

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 r_{20} 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 r_{20}. In the combination of r_{20} 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 r_{30} and in LS. The maximum θw coincided with minimum ECw at r_{10} during ES, MS and LS; the same trend applied for r_{20} during ES and MS, but no similar relations occurred at r_{30}. Based on the time elapsed for maximum θw at r_{10} 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 r_{10} and r_{20} during ES and MS. The correlation decreased slightly at r_{10} and there was very low correlation at r_{20} during the LS. The correlation between θw and ECw was very low at r_{30} during all the crop growth stages due to salt accumulation. At the end of the irrigation season, most of the salt accumulated at r_{30} 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.

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