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A Model Study on Irrigation Efficiency and Salinity Control Under Shallow Water Table Conditions

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ABSTRACT

In the presence of a shallow water table, the contribution of groundwater to the evapotranspiration (ET) effects irrigation efficiency as well as soil and groundwater salinity. A mass balance model was developed for level basin irrigation to study performance along a field as well as the spatial and temporal changes in soil and shallow groundwater salinity with and without a shallow water table contribution to the ET demand. Cases with one, two and three-week irrigation intervals and ET rate of 7 mm day^{-1} were studied. For each case, application efficiency without water table contribution and application efficiency with water table contribution increase and leaching fraction without water table contribution and leaching fraction with water table contribution decrease non-linearly along the field. Irrigation efficiency improves significantly with a water table contribution to the ET demand. The comparison of with and without groundwater contribution to the ET demand show the spatial and temporal changes in soil and groundwater salinity are affected significantly by groundwater contribution. Groundwater contribution causes higher soil salinity along the field and throughout the irrigation season. Groundwater salinity, increases throughout the irrigation season for both cases and is higher for the case of groundwater contribution.

Key Words: Shallow water table; Surface irrigation; Irrigation performance; Salinity

INTRODUCTION

Irrigation performance measures are important for design, evaluation and management of surface irrigation (Wallender & Rayej, 1987). A commonly used criterion for performance in design and evaluation of surface irrigation systems is application efficiency (E), which is the ratio of water stored in the soil root zone to water applied to the field. Where a shallow water table is present, as much as 59 to 70% of the total-season evapotranspiration (ET) can be contributed by groundwater (Wallender *et al.*, 1979). Therefore, where the water table is shallow and groundwater contributes to the plant water requirement, the effect of a shallow water table on irrigation performance should be considered. They also noted that the successful use of a shallow water table depends on several factors, including water table depth, the water retaining and transmitting properties of the soil, evapotranspiration demand and the distribution of the plant root zone system.

Many irrigated lands especially in arid regions are affected by shallow groundwater and soil salinity (Hanson & May, 2001). Capillary soil Stalinization from a shallow water table is a major concern for agricultural production, especially in irrigated arid regions. The dual problems of soil salinity and a shallow water table exist in irrigated agricultural fields. Researchers have studied crop water use from saline as well as non-saline shallow water tables. Shih (1986) studied sweet sorghum under shallow water table and found that ET and water use efficiency are inversely related to water table depth. Bali *et al.* (2001) studied alfalfa water use in saline, shallow water tables of the Imperial Valley of Southern California and they estimated that the shallow water table contributed approximately 12% of the total applied water during two year study, of which just over 8% occurred during the first year. It was also found that the average soil salinity changed across the soil profile during the study period and the salinity levels near the base of the profile doubled from the beginning to the end of the study, because of water table contributions. The contribution of groundwater to alfalfa water use for the second year of study was less, because higher soil salinity reduced plant water uptake. Benz *et al.* (1985) conducted a sub-irrigation experiment to study the effects of four shallow constant water table depths and three surface irrigation levels on corn and sugar beet yields and actual evapotranspiration. The results show that a shallow water table can and will contribute to ET in sizable quantities if rainfall and surface irrigation are inadequate. They also noted that sub-irrigation can provide a usually inexpensive alternative to the more expensive surface irrigation. Ali *et al.* (2000) noted that a saline shallow water table can contribute significantly to salinity increases in the crop root zone and root zone salinity is one of the major factors adversely affecting crop production. Pitts *et al.* (1993) studied the influence of water table management on sugarcane on sandy soils and noted that the optimum water table depth to allow sufficient upward flux to meet ET requirements is affected by both soil texture and rooting characteristics of the plant. Kruse *et al.* (1993) showed the portion of total seasonal evapotranspiration supplied from shallow groundwater was strongly affected by water table depth and for corn and wheat, slightly affected by salinity of the water in the saturated zone. Torres and Hanks (1989) studied water table contributions to plant water requirements for spring wheat under three water table depths of 50, 100 and 150 cm and concluded that for these water table depths the contributions of water table to crop water requirements are 90, 41 and 7%, respectively. Gilfedder *et al.* (2000) conducted an experiment to measure the salt transport processes within a border-irrigated field with shallow saline groundwater and cracking soils. They found that the shallow groundwater reduces deep drainage of water, preventing significant deep leaching of soil salts and acted as a supply for upward capillary salt movement.

As shown above shallow water table can be considered as an important resource to satisfy part or all of the crop water requirements. Also, use of this shallow water table for irrigation is a useful strategy for managing water. Therefore, irrigation performance measures should reflect crop water uptake from the shallow water table. Also, surface irrigation methods including basin, border and furrow are most widely used throughout the world (Osman *et al.,* 2003). The main objective of this research is to model and study the spatial distribution of application efficiency and leaching fraction and the spatial and temporal changes in soil and shallow groundwater salinity for level basin irrigation with and without a shallow water table contribution to plant water requirements.

MATERIALS AND METHODS

Mass balance models were developed for level basin irrigation to simulate the changes in application efficiency and leaching fraction as well as soil and groundwater salinity along a field with and without a water table contribution using excel program. In level basin irrigation there is no run-off and this simplifies the calculation of performance and salinity, because applied water either remains in the soil root zone and is used by plants or exits the soil root zone through deep percolation following water application.

Initial conditions. The model was run for ideal fields having complete irrigation at the downstream end for different irrigation intervals of one, two and three weeks and the same ET rate of 7 mm day^{-1}. The simulated irrigation season was twelve weeks. For the one week irrigation interval the model was run for twelve consecutive irrigations, for the two week irrigation interval it was run for six consecutive irrigations and for the three week irrigation interval for four consecutive irrigations. The input data such as soil depth (1 m), soil water before irrigation (SWb), (0.15 m), soil water at field capacity (FC), (0.25 m), lowest allowable soil water (0.15 m), irrigation water EC (1 dS/m) and soil water EC at the beginning of the season (ECswb), (0.5 dS/m) were assumed. The unit used for EC was dS/m and for salt mass was g/ 5 m section throughout this study. Furthermore infiltrated water was assumed to decrease linearly from the up-stream end to the down-stream end of the field with a slope of 0.09%. Desired soil water after irrigation at the down-stream end of the 100 m field was 0.25 m. For example, the applied water (AW) at the up-stream end was 0.19 m and decreased linearly to 0.10 m at the down-stream end, which resulted in soil water equal to field capacity at the down-stream end (0.10 m + 0.15 m).

Calculations. A diked (no run-off) level field having a unit (1 m) width and a length of 100 m was divided into 20 sections of equal length. Computations were based on the center point of each soil section along the field. Prior to the first irrigation there was no groundwater in storage. Based on the above input data, AW, deep percolation (DP), net deep percolation (DPnet), soil water after irrigation (SWa), water stored in the soil (SWa - SWb), ET uptake from soil water (ETsw), groundwater (GW), ET uptake from groundwater (ETgw), ET deficit (ET deficit), groundwater deficit (GW deficit), soil water before the next irrigation (SWbni), groundwater before the next irrigation (GWbni), soil water salt before irrigation (Sswb), salt applied with irrigation water (Saw), soil water salt after irrigation (Sswa), salt added to the soil from irrigation water, soil water EC after irrigation (ECswa), deep percolation EC (ECdp), salt leaving the soil as deep percolation (Sdp), soil water salt after deep percolation (Sswadp), soil water EC after deep percolation, groundwater EC after irrigation (ECgwa), groundwater salt after irrigation (Sgwa), salt contribution from groundwater to the soil (Setgw), net salt leaving the soil as deep percolation (Sdpnet), soil water salt before the next irrigation (Sswbni), soil water EC before the next irrigation (ECswbni), groundwater salt before the next irrigation (Sgwbni) and groundwater EC before the next irrigation (ECgwbni) were computed for each section along the field. For each consecutive irrigation, input data and information from the previous irrigation were used.

Efficiency and leaching parameters. For each section along the field and for all irrigations, the above parameters including application efficiency and leaching fraction were calculated with and without a water table contribution to ET demand. E (application efficiency without water table contribution) was calculated based on water stored in the soil and the applied water (infiltrated).

$$E = \frac{SWa - SWb}{AW} 100 \tag{1}$$

E' (application efficiency with water table contribution) was calculated by adding ET uptake from groundwater (up to the amount available) to water stored in the soil.

$$E' = \frac{(SWa - SWb) + ETgw}{AW} 100 \qquad (2)$$

Leaching fraction without water table contribution (LF) was a function of the ratio of deep percolation to the applied water.

$$LF = \frac{DP}{AW} 100 \qquad (3)$$

Leaching fraction with water table contribution (LF') was related to the ratio of net deep percolation (DP - ETgw) to the applied water.

$$LF' = \frac{DP - ETgw}{AW} 100 \qquad (4)$$

Salt balance. The salt balance for a soil section along the simulated field with unit width (w) and depth and length (l) of 5 m is shown in Fig. 1. Perfect mixing, piston flow, no lateral groundwater flow, no vertical groundwater flow at depth and conservative salts were assumed. According to the law of mass conservation for a given time period, salt-in (Sin) minus salt-out ($Sout$) equals to the change in salt storage (ΔS).

$$\Delta S = Sin - Sout \qquad (5)$$

For the soil section shown in Fig. 1 and for the time period equal to the irrigation interval, the continuity equation gives:

$$\Delta S = (Saw + Setgw) - Sdp \qquad (6)$$

As, the soil water salt at the end of each irrigation interval equals to soil water salt at the beginning of the next irrigation, it follows that:

$$Sswbni = Sswb + \Delta S \qquad (7)$$

From soil water salt at the beginning of the next irrigation, the soil water EC at the beginning of the next irrigation may be calculated as:

$$ECswbni = Sswbni/(SWbni * w * l * C) \qquad (8)$$

Where,

C was a factor equal to 640 (Jurinak, 1981).

The same salt budget procedure as shown above was used for each soil section along the length of the field and for all irrigations throughout the irrigation season to calculate salt and EC for different stages of irrigation such as before irrigation, after irrigation, after deep percolation and after groundwater contribution. To consider the temporal changes in salt and EC for the soil and groundwater, the salt budget computations for each soil section and for all irrigations were conducted using a daily time step from the beginning of the first irrigation to the end of the irrigation season of 84 days.

RESULTS AND DISCUSSION

Water Balance/Regime

One week interval. Water budget components and performance measures for the case of one week irrigation intervals are given in Figs. 2 and 3. For the first irrigation interval, soil water before irrigation (SWb) is assumed uniform along the field at 0.15 m (Fig. 2). Irrigation occurs and the applied water (AW), which all infiltrates, decreases linearly from 0.19 m at the up-stream end to 0.1 m at the down-stream end. The sum of AW and SWb raises the soil water to field capacity at the down-stream, a complete irrigation, while at the up-stream end soil water exceeds field capacity. Excess water drains leaving soil water after irrigation (SWa) uniformly equal to field capacity (0.25) along the field. Deep percolation (DP), which is applied water plus soil water before irrigation minus soil water at field capacity, decreases linearly from 0.09 m at the up-stream end to zero at the down-stream end. The DP is initially added to groundwater storage (GW). Water to meet the ET demand is first extracted from the soil water storage and then, if needed and available, from groundwater GW. In this example of a one week irrigation interval with ET demand of 49 mm, there is sufficient soil water to meet the demand (ET = ETsw) and prior to the next irrigation, soil water is uniform and equal to 0.2 m (SWa - ETsw). Net deep percolation (DPnet = DP - ETgw) equals deep percolation, because there is no groundwater discharge to meet the ET demand (ETgw = 0, not shown in Fig. 2). The first irrigation interval is complete.

The variation in irrigation efficiency and leaching fraction along the field are given in Fig. 3. E (Equation 1) increases non-linearly from 52.6% at the up-stream end to 100% at the down-stream end, because applied water decreases, while the water stored in the soil is constant (SWa - SWb, Fig. 2). As a corollary, E increases as DP decreases. LF (Equation 3) decreases non-linearly from 47.4% at the up-stream end to zero at the down-stream end even though AW and DP decrease linearly at the same rate, because AW is greater than DP (Fig. 2). Finally, because DP = DPnet, E = E' (Equations 1 & 2, respectively) and LF = LF' (Equations 3 & 4, respectively).

Individual values at each location along the field are combined to calculate field irrigation system performance assuming lateral homogeneity. Spatial average application efficiency is equal to 71.6% and spatial average leaching fraction is 28.4%. Because efficiency and leaching fraction vary non-linearly, if average DP, AW and SWb-SWa are used to calculate E and LF, they are different at 68.9% and 31.0%, respectively (Wallender & Grismer, 2002).

Two week interval. For the case of two week irrigation intervals with ET of 98 mm and a complete irrigation at the down-stream end results (not shown) are similar to the case of one week irrigation interval. In this example, there is sufficient soil water to meet the ET demand (ET = ETsw = 0.098 m) and groundwater has no contribution to the ET

Fig. 1. Salt budget schematic for a soil section

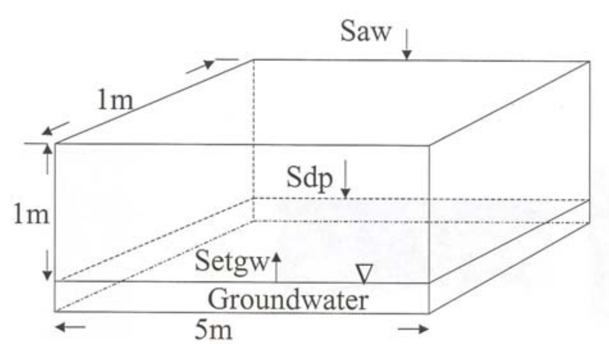


Fig. 2. Water budget components for first irrigation with 7-day irrigation interval and complete irrigation at the downstream end

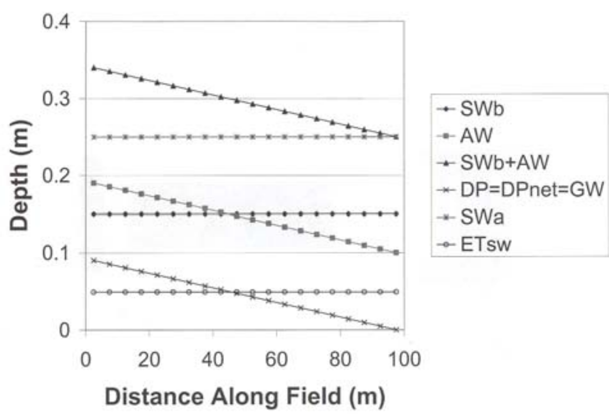
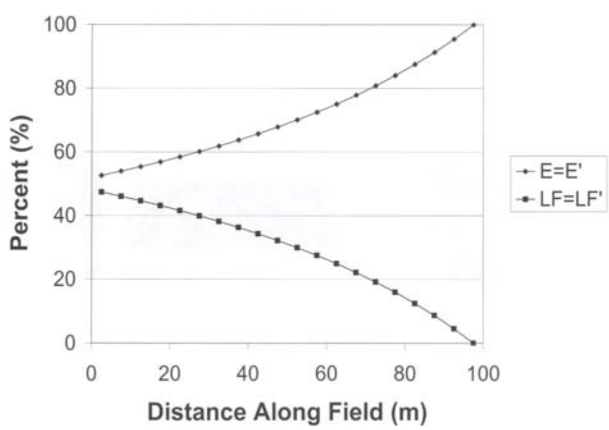


Fig. 3. Irrigation performance with and without a water table contribution along the field for first irrigation with 7-day irrigation interval and complete irrigation at the downstream end



demand (ETgw = 0).

Three week interval. Water budget components and performance measures for the case of three-week irrigation intervals with ET of 147 mm are given in Figs. 4 and 5. For the first irrigation SWb, AW, SWa and DP are the same as for one week irrigation interval case (Fig. 2). In contrast to the case of a one week irrigation interval in which water for ET is extracted exclusively from soil water storage, all the available soil water is extracted (ETsw = 0.1 m) and then, if available, water is removed from groundwater. It is shown in Fig. 4 that from the up-stream end to the middle of the field there is sufficient groundwater to satisfy the remaining ET demand (0.147 m – 0.1 m = 0.047 m = ETgw). Beyond the field midpoint, ET is constrained by the available groundwater and the ET deficit increases linearly to 0.047 m at the down-stream end. Thus, ETgw and ETgw + ETsw equal 0.047 m and 0.147 m, respectively to the middle of the field and thereafter decrease linearly to zero and 0.1 m at the down-stream end, respectively. Therefore, as ET deficit increases, ETgw and ETgw + ETsw decrease at the same rate. The groundwater contribution to the ET demand is 32% (ETgw/ET = 0.047 m/0.147 m) from the up-stream end to the middle of the field, 14.5% (0.021 m/0.147 m) from the middle of the field to the down-stream end and 23% (0.034 m/0.147 m) for the field average.

Irrigation efficiency and leaching fraction along the field is affected by the groundwater contribution (Fig. 5). E (Equation 1) increases non-linearly from 52.6% at the up-stream end to 100% at the down-stream end, just as in Fig. 3 for one week irrigation intervals, because applied water and water stored in the soil (SWa - SWb) are the same for both cases. In contrast E' (Equation 2) is higher and increases non-linearly from 77.3% at the up-stream end to 100% at the middle of the field, because applied water decreases along the field (Fig. 2), while SWa - SWb + ETgw is constant from the up-stream end to the middle of the field (Fig. 4). From the middle of the field to the down-stream end E' is 100%, because SWa - SWb + ETgw is equal to applied water. LF (Equation 3) decreases non-linearly from 47.4% at the up-stream end to zero at the down-stream end, just as in Fig. 3 for one week irrigation interval, because applied water and DP are the same for both cases. However LF' (Equation 4) is smaller and decreases non-linearly from 22.7% at the up-stream end to zero at the middle of the field, because from the up-stream end to the middle of the field net deep percolation DPnet = DP – ETgw and applied water decrease (Figs. 4 & 2, respectively). From the middle of the field to the down-stream end LF' is equal to zero, because ETgw equals DP (Figs. 2 & 4, & Equation 4). Spatial average E, E', LF and LF' are equal to 71.6, 93.8, 28.4 and 6.2%, respectively showing higher performance and lower leaching for the case of groundwater up flow.

Salt balance/regime. Salinity condition for the case of one and two week irrigation intervals for the first irrigation (not shown) is similar. As mentioned above in both cases there is sufficient soil water to meet the ET demand and groundwater has no contribution to the ET demand. The discussion therefore focuses on the case of the three week irrigation interval.

Fig. 4. Water budget components for first irrigation with 21-day irrigation interval and complete irrigation at the downstream end

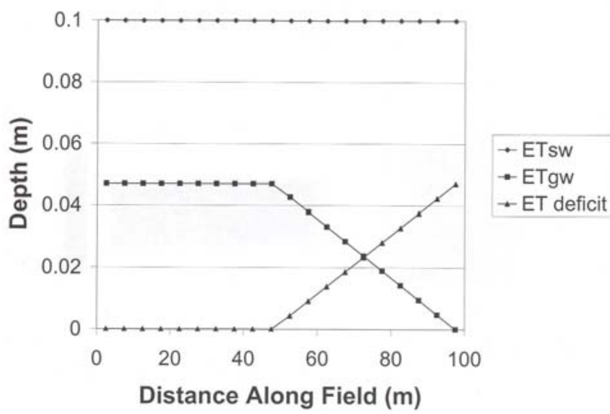
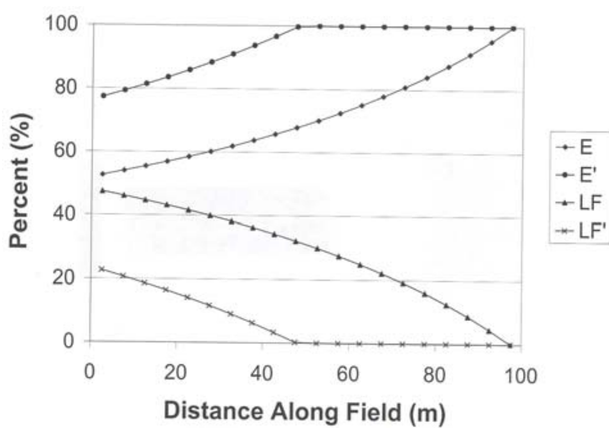


Fig. 5. Irrigation performance with and without a water table contribution along the field for first irrigation with 21-day irrigation interval and complete irrigation at the downstream end



Salinity condition along the field for the first irrigation is given in Fig. 6. Before the seasonal irrigations begin Sswb is assumed uniform along the field at 240 g/section, which is equivalent to soil water EC of 0.5 dS/m. Irrigation occurs and the applied salt (Saw) decreases linearly from 608 g at the up-stream end to 320 g/section at the down-stream end. The sum of Sswb and Saw raises the soil water salt after irrigation (Sswa = Sswb + Saw) to 848 g/section at the up-stream end, which decreases linearly to 560 g at the down-stream end. Applied water mixes with soil water and excess water drains, leaving soil water salt after deep percolation (Sswadp) equal to 624 g/section at the up-stream end, which decreases linearly to 560 g/section at the down-stream end. The salt leaving the 1 m soil depth as deep percolation (Sdp) is 224.6 g/section at the up-stream end and it decreases linearly to zero at the down-stream end. From the up-stream end to the middle of the field there is sufficient groundwater to satisfy the remaining ET demand and upward salt movement is constant (Setgw = constant). Beyond the field midpoint, ET is constrained by the available groundwater. Thus, the salt contribution from groundwater to the soil (Setgw) is constant and equals to 117.2 g/section at the up-stream end with no change to the middle of the field and thereafter decreases linearly to zero at the down-stream end. Net deep percolated salt (Sdpnet = Sdp – Setgw), which is equal to Sgwbni, is 107.4 g/section (224.6 - 117.2) at the up-stream end and decreases linearly to zero at the middle of the field and thereafter remains constant. This is the situation at the end of the first irrigation and beginning of the second irrigation.

Salt along the field for the case of the three-week irrigation interval for the fourth irrigation is given in Fig. 7. Soil water salt before irrigation (Sswb) prior to the fourth irrigation is 1551 g/section at the up-stream end and increases non-linearly to 1648 g/section at the middle of the field and thereafter decreases linearly to 1200 g at the down-stream end. It shows that salt has accumulated in the 1 m soil depth. Saw is the same as for the first irrigation. Soil water salt after irrigation (Sswa = Sswb + Saw) is nearly uniform from the up-stream end to the middle of the field with an average value of 2102 g/section and thereafter decreases linearly to 1520 g/section at the down-stream end. After mixing, salt leaving the soil as deep percolation (Sdp) is 559 g/section at the up-stream end and decreases linearly to 333 g/section at the middle of the field and thereafter it decreases linearly to zero at the down-stream end. The soil water salt after deep percolation (Sswadp) decreases from pre-deep percolation levels to 1551 g/section at the up-stream end and increases non-linearly to 1782 g/section at the middle of the field and thereafter decreases linearly to 1520 g/section at the down-stream end. The groundwater salt after irrigation (Sgwa) is the volume weighted average of initial groundwater and deep percolation salinity. It is 1122 g/section at the up-stream end, decreases non-linearly to 333 g/section at the middle of the field and thereafter decreases linearly to zero at the down-stream end. The salt contribution from groundwater to the soil (Setgw) is 240 g/section at the up-stream end; it increases non-linearly to 333 g/section at the middle of the field and thereafter decreases linearly to zero at the down-stream end. The cumulative net deep percolated salt (Sdpnet = Sdp – Setgw) is equal Sgwbni (881 g/section) at the up-stream end, it decreases non-linearly to zero at the middle of the field and thereafter remains constant. Comparing Fig. 7 and Fig. 6 shows the increase in soil and groundwater salinity, because irrigation water and groundwater both contribute to soil salinity for each irrigation. Groundwater salinity (Sgwbni) increases, because salt is transported via net deep percolated irrigation water.

Soil water EC before the next irrigation following the first and fourth irrigation with and without groundwater contribution for three-week irrigation intervals is shown in Fig. 8. For the first irrigation without groundwater contribution, ECsw is 1.3 dS/m at the up-stream end and decreases linearly to 1.2 dS/m at the down-stream end. With

Fig. 6. Salt budget for first irrigation for 21-day irrigation interval

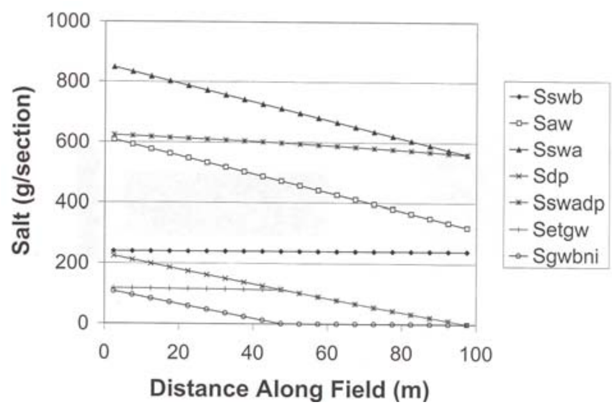


Fig. 7. Salt budget for fourth irrigation for 21-day irrigation interval

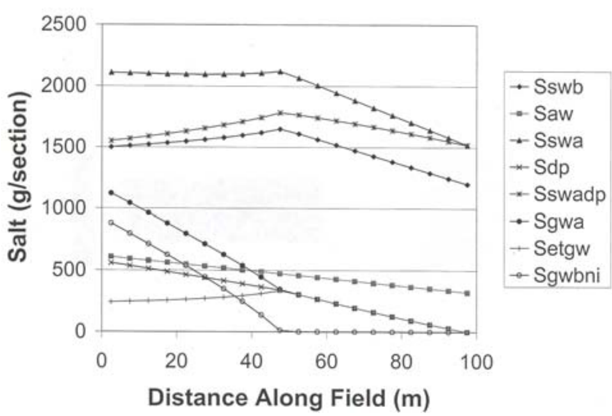
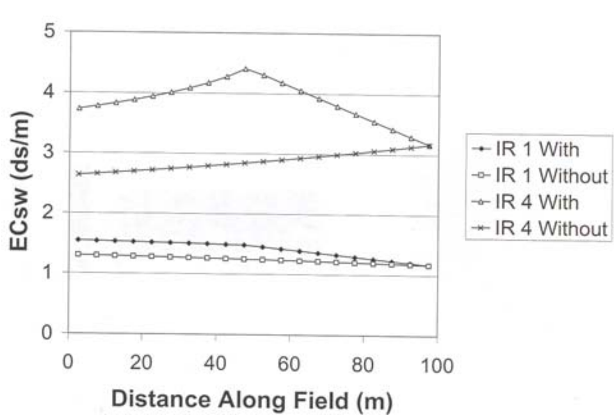


Fig. 8. Soil water EC for first and fourth irrigation with and without groundwater contribution for 21-day irrigation interval



groundwater contribution, ECsw is nearly 1.5 dS/m from the up-stream end to the middle of the field and thereafter decreases linearly to 1.2 dS/m at the down-stream end. With groundwater contribution, ECsw is higher, because Setgw is added to the soil water salt. For the fourth irrigation without groundwater contribution, ECsw increases nearly linearly from 2.6 dS/m at the up-stream end to 3.2 dS/m at the down-stream end, because salt removal by drainage water decreases linearly along the field (Fig. 6) and there is no salt return from groundwater to the soil. With groundwater contribution, ECsw is 3.7 dS/m at the up-stream end and increases non-linearly to 4.4 dS/m at the middle of the field and thereafter decreases linearly to 3.2 dS/m at the down-stream end. The distribution of ECsw follows that of Sswadp shown in Fig. 7 via Equation 8. At the down-stream end the curves meet (Fig. 8), because there is no groundwater contribution. With groundwater contribution ECsw is higher, because water taken from groundwater to satisfy the ET demand is used by plants leaving the salt in the soil, which accumulates from irrigation to irrigation.

Groundwater EC before the next irrigation following the first and fourth irrigation with and without groundwater contribution for three-week irrigation intervals is shown in Fig. 9. For the first irrigation with or without groundwater contribution, the average ECgw is the same at 0.76 dS/m from the up-stream end to the middle of the field, because the quality of deep percolation water is the same. From mid-field and beyond ECgw for the case of with groundwater contribution decreases to zero, because as shown in Fig. 6, Sgwbni is zero. At the fourth irrigation without groundwater contribution, the ECgw along the field has increased to a nearly constant average value of 1.25 dS/m. For the fourth irrigation with groundwater contribution, ECgw is 1.6 dS/m at the up-stream end and increases non-linearly to 2.2 dS/m at the middle of the field. The ECgw increases non-linearly, because Sgwbni and GWbnir, that are used to compute ECgw, decreases non-linearly and linearly, respectively from the up-stream end to the middle of the field resulting in higher mass of salt with less volume of water with distance. At mid-field, ECgw decreases to zero, because as shown in Fig. 7, Sgwbni is zero from the middle of the field to the downstream end.

Seasonal regime/variations. Soil water EC with time at up-stream, middle and down-stream sections is given in Fig. 10 for the case of groundwater contribution to ET. ECsw increases with time between water applications via evapotranspiration and then falls immediately after a water application due to leaching. Fourteen days after each irrigation at the down-stream end the ECsw becomes constant, because there is no groundwater available for ET. For the up-stream and middle sections there is groundwater to be used for the ET demand along the field and this causes a continuous increase in soil water EC during each irrigation interval. At the beginning of irrigation season ECsw is nearly the same for each section and about 0.7 dS/m, while at the end of the irrigation season ECsw for the middle, up-stream and down-stream sections are 4.3, 3.6 and 3.1 dS/m, respectively. Compared to the middle section ECsw is lower at the up-stream end, because the groundwater is more diluted (Fig. 9) and lower at the down-stream end, because less salt is applied (Fig. 7). In contrast to results shown in

Fig. 9. Groundwater EC for first and fourth irrigation with and without groundwater contribution for 21-day irrigation interval

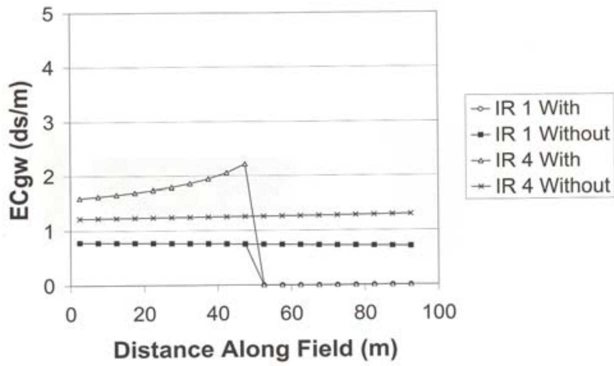


Fig. 10. Soil water EC with groundwater contribution with time at upstream, middle, and downstream section for 21-day irrigation interval

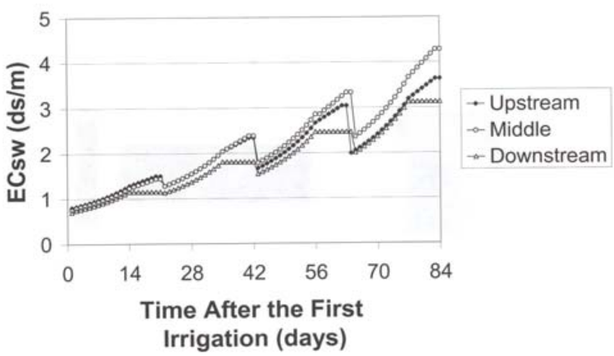


Fig. 10, where groundwater contributes to ET and hence soil salinity, in the case of no groundwater contribution, soil salinity is lower (Fig. 11). Furthermore, ECsw does not increase late in the interval, because there is no groundwater discharge carrying salt into the root zone. For the down-stream section groundwater has no contribution to the ET demand in either case and there are no differences between Figs. 10 and 11.

Groundwater EC with groundwater contribution over time at up-stream and middle sections is shown in Fig. 12 (no groundwater at down-stream end). For the first irrigation interval ECgw for the up-stream and middle sections are the same, because ECdp is the same as ECgw in both cases. The ECgw after the first irrigation interval is higher for the middle section compared to the up-stream section and increases from irrigation to irrigation, because ECsw is greatest at mid field (Fig. 10). Without groundwater contribution, ECgw is less and the difference between up-stream and middle of the field is also less (Fig. 13) than when groundwater contributes to ET, because no salt is discharged from the groundwater into the root zone.

Field-average soil water EC at the end of each irrigation interval and at the end of irrigation season is higher with groundwater contribution (Fig. 14). The

Fig. 11. Soil water EC without groundwater contribution with time at upstream, middle, and downstream section for 21-day irrigation interval

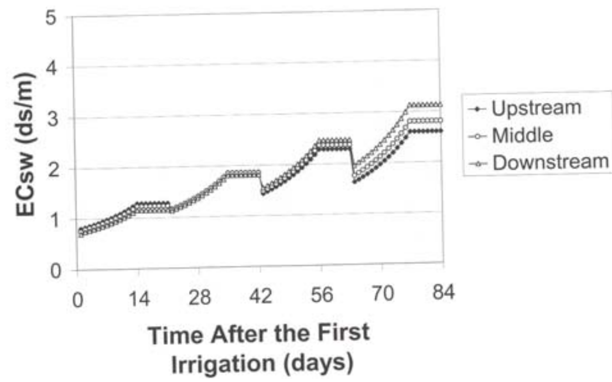
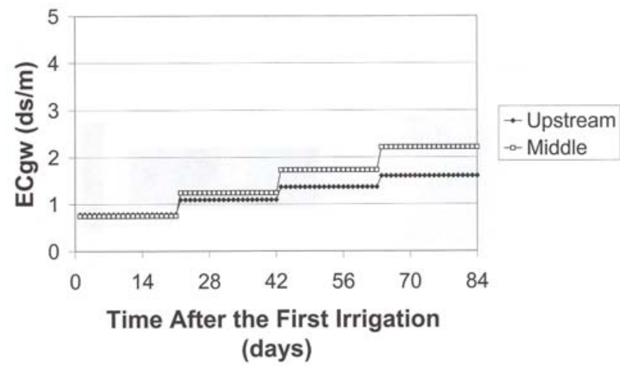


Fig. 12. Groundwater EC with groundwater contribution with time at upstream and middle section for 21-day irrigation interval



differences increase from irrigation to irrigation throughout the irrigation season. During the first 14 days the difference is constant, because up to that time there is enough soil water to satisfy the ET demand and it evapoconcentrates at the same rate in both cases. Thereafter, salty groundwater contributes to the ET demand and therefore soil water concentration increases in the groundwater contribution case.

Likewise field-average groundwater EC after deep percolation with and without groundwater contribution also increases after each irrigation event (Fig. 15). For the first irrigation interval ECgw is the same for both cases and thereafter the difference increases, because with groundwater contribution, more salt is retained in the soil and the deep percolated water from the saline soil causes higher groundwater salinity.

Field-average soil water EC (Fig. 16) and groundwater EC (Fig. 17) for 7, 14 and 21 days irrigation intervals trend up-ward in time. Field-average ECdp for 7, 14 and 21 days irrigation intervals for first irrigation, is the same as ECsw (Fig. 16) and is the same as ECgw (Fig. 17) and is equal to 0.75 dS/m. For 7 and 14 days irrigation intervals as mentioned earlier there is sufficient soil water to meet the

Fig. 13. Groundwater EC without groundwater contribution with time at upstream and middle section for 21-day irrigation interval

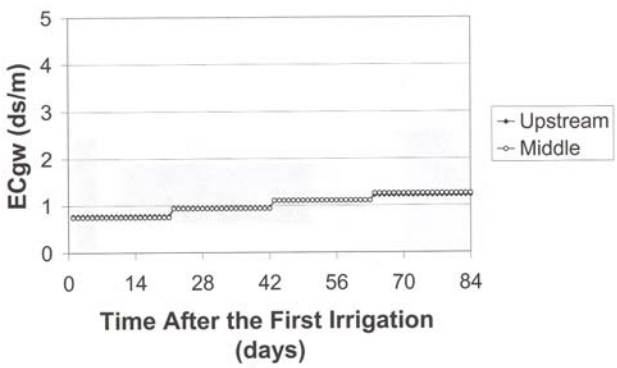


Fig. 14. Field average soil water EC with and without groundwater contribution with time for 21-day irrigation interval

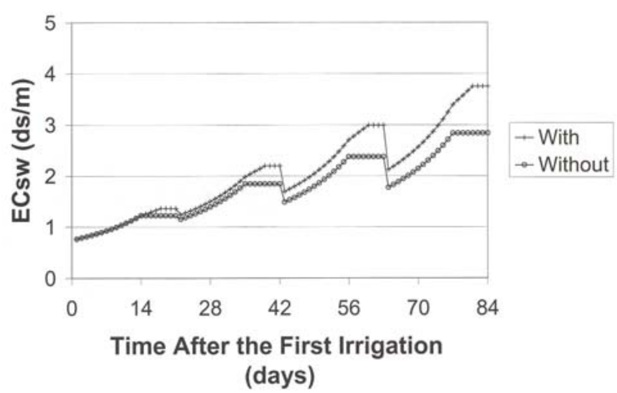
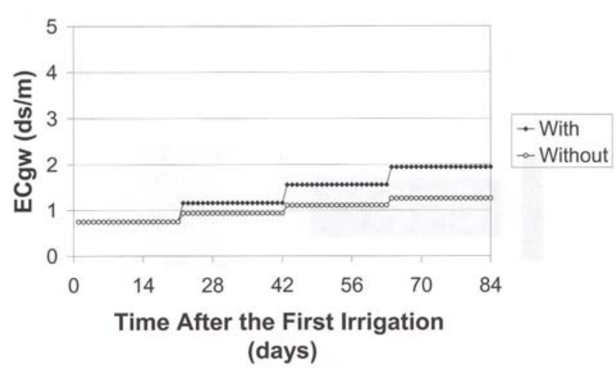


Fig. 15. Field average groundwater EC with and without groundwater contribution with time for 21-day irrigation interval



ET demand and groundwater has no contribution to the ET demand. After water application, as shown in Fig. 16, ECsw increases with time, because soil moisture declines with time due to root water extraction for all three irrigation intervals, while soil salt remains constant (for 7 & 14 days irrigation intervals) or even increases (for 21 days irrigation interval). The reduction of soil moisture for the 14 days irrigation interval is higher than 7 days irrigation interval, which results in higher ECsw with time for the 14 days irrigation interval. For the 21 days irrigation interval, reduction of soil moisture with time and increase of soil salt due to GW contribution causes higher ECsw compared to the other irrigation intervals. The ECdp immediately after water application, near the beginning of each irrigation interval, is the same as Ecsw, because the irrigation water is assumed to mix perfectly with the pre application soil water. For example, the field-average ECdp or ECsw immediately after water application for the 7, 14 and 21 days irrigation intervals for the last irrigation is 2, 2.2 and 2.1 dS/m, respectively. These values are nearly the same, because the large volume of high quality irrigation water mixes with a smaller volume of lower quality soil water. Total water application and deep percolation increases as the interval decreases. Total applied water for 7, 14 and 21 days irrigation intervals is 1.18, 0.86 and 0.58 m, respectively while total deep percolation for 7, 14 and 21 days irrigation intervals are 0.54, 0.27 and 0.18 m, respectively. Higher total applied water and deep percolation and no groundwater contribution to the ET demand as well as less water uptake from soil for ET demand cause lower soil salinity for shorter intervals (Fig. 16). Soil water salinity is least for the 7 days interval, while the ranking of the 14 and 21 days intervals changes in time. In contrast to the 7 and 14 days cases for the 21 days interval, salinity plateaus at the end of each interval, because the applied water is insufficient to meet ET demand from soil water and groundwater. This causes the soil water salinity ranking to change with time.

For the first irrigation, field-average ECgw is the same as field-average ECdp and equals 0.75 dS/m for all three irrigation intervals (Fig. 17), because the high volume of high quality irrigation water perfectly mixes with the low volume of relatively high quality soil water. For 7 and 14 days irrigation intervals, as mentioned above, there is sufficient soil water to meet the ET demand and there is no groundwater contribution. Furthermore, ECgw during the first irrigation interval remains constant, because the GW solution concentration is un-affected even if water moves up into the root zone as in the case of the 21 days interval.

For subsequent irrigations, the ECgw for 7 and 14 days irrigation intervals are nearly the same, while the ECgw for the 21 day irrigation interval is higher, particularly during the second half of the season (Fig. 17). For the second and later cycles of the 7 and 14 days irrigation intervals ECgw is lower than ECdp (ECsw Fig. 16), while for 21 days irrigation interval ECgw is nearly the same as ECdp. For 21 days irrigation interval, the ECdp for each irrigation is nearly the same as Ecgw, because groundwater contributes to ET demand and nearly all the deep percolated salt returns to the soil, leaving near zero groundwater in storage available for dilution. In the case of 7 and 14 intervals the early season high quality groundwater dilutes the incoming leachate. For the 21 days irrigation

Fig. 16. Field average soil water EC with time for 7(without GW contribution)-, 14 (without GW contribution)-, and 21 (with GW contribution) -day irrigation intervals

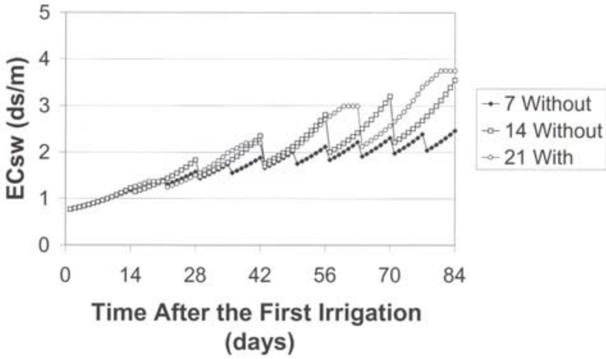
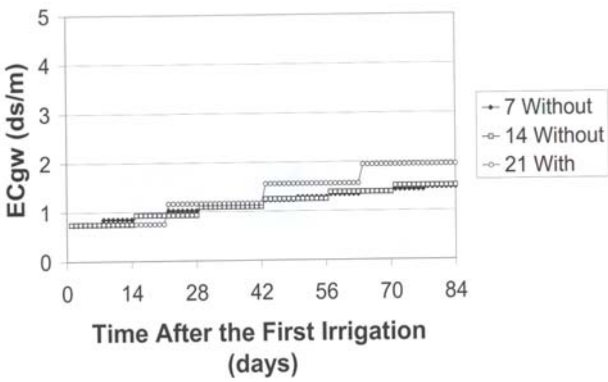


Fig. 17. Field average groundwater EC with time for 7(without GW contribution)-, 14 (without GW contribution)-, and 21 (with GW contribution) -day irrigation intervals



intervals, without groundwater contribution, field-average ECgw is the same as 7 and 14 days irrigation intervals (not shown). Without groundwater contribution, the field-average ECgw is nearly the same for all three irrigation intervals.

CONCLUSION

Soil and groundwater salinity regimes along level basin irrigated field were simulated with and without a water table contribution to the ET demand. Cases studies one, two and three weeks irrigation intervals and an ET rate of 7 mm day $^{-1}$. Irrigation efficiency, which changes non-linearly along the field, improves significantly with a water table contribution to the ET demand. The spatial and temporal changes in soil and groundwater salinity are affected significantly by groundwater contribution. With groundwater contribution soil and groundwater salinity is higher throughout the irrigation season and the peak in soil and groundwater salinity is at mid-field, because the highest salt contribution from groundwater to the soil occurs at the mid-field and less water of higher EC percolates below the root zone at mid-field. Weekly irrigations have the lowest soil salinity throughout the irrigation season and without groundwater contribution the ECgw is nearly the same for all irrigation intervals.

Contribution of shallow groundwater of acceptable quality to the crop water requirements improves irrigation performance and reduces the cost of irrigation and drainage systems, because less water is required for irrigation, less deep percolation occurs and less drainage and pumping are required. However, reduction in wetlands, salination of the root zone as well as local and regional groundwater may outweigh the benefits. Hence, salt in the root zone and in the local and regional groundwater system is influenced significantly by this groundwater contribution to ET. Shallow water tables require careful management to use groundwater as a resource for irrigation water and to control soil and groundwater salinity at acceptable levels for optimum plant growth.

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