SALINITY MANAGEMENT IN CENTRAL AND SOUTHERN IRAQ: PROSPECTS UNDER EXISTING DRAINAGE CONDITIONS

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The Iraq Salinity Project is an initiative of Government of Iraq, Ministries of Agriculture, Water Resources, Higher Education, Environment, and Science and Technology, and an international research team led by ICARDA – the International Center for Agricultural Research in the Dry Areas, in partnership with the University of Western Australia, the Commonwealth Scientific and Industrial Research organization (CSIRO) of Australia, the International Water Management Institute (IWMI), Sri Lanka, and the International Center for Biosaline Agriculture (ICBA), Dubai, United Arab Emirates.

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Key words: southern Iraq, central Iraq, spatial distribution, remote sensing, irrigation, salinity mapping.

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Executive Summary

Excessive irrigation and poor drainage conditions have contributed to rising groundwater tables leading to salinity-induced land degradation in the irrigated areas of central and southern Iraq. Soil salinity problems have robbed the production potential of 70 percent of the total irrigated area of Iraq with almost 30 percent gone completely out of production. Most of the reclamation efforts in the past have concentrated on the installation of surface and subsurface drainage systems. These systems were installed about 40-50 years ago. However, due to neglect and poor maintenance, most of these systems have become either abandoned or non-functional. As a result, problems of soil salinity and groundwater table rise have emerged on large tracts of irrigated lands. This situation has threatened the sustainability of irrigated agriculture and future food security in Iraq.

In (semi-) arid areas like Iraq, soil salinity caused by shallow groundwater table is often the limiting factor in crop production. Therefore, for these areas, selection of optimal irrigation amounts and groundwater table depths are of paramount importance to maximize crop yields and keep soil salinity within acceptable limits. In this study, the soil-water-atmosphere-plant (SWAP) relationship model was used to determine optimal irrigation amounts and groundwater table depth for maximizing wheat and maize crops in Al-Mussaib and Al-Dujaila project areas located in the central and southern parts of Iraq. Before application, SWAP model was calibrated for the soil, crop and climatic conditions prevailing in the area. SWAP was calibrated using field data from the study area during wheat and maize season of 2011-12.

The modeling results reveal that current irrigation practices (600 mm to wheat and 1000 mm to maize) waste more than 30% of applied irrigation water as deep percolation. This causes rise in groundwater table, increase in profile salinity and reduction in crop yields. The model results suggest that under prevailing soil salinity and groundwater table conditions in the Al-Mussaib project area, a wheat yield of 3.85 t ha^{-1} can be attained by applying 500 mm of irrigation water. For maize, 2.16 t ha^{-1} of maize yield will be possible with 600 mm of irrigation application. These optimized irrigation schedules will maintain soil salinity at 4.5 dS m^{-1}. In the Al-Dujaila project area where soil and groundwater salinity is high, maximum attainable yields will be relatively lower. The optimized irrigation applications will maintain soil salinity at 7.0 dS m^{-1} therefore yield reductions will be inevitable. The optimum wheat yield would be 2.52 t ha^{-1} whereas maize yields will not go beyond 1.80 t ha^{-1}.

For both project areas, a groundwater table depth of approximately 200 cm was found to be appropriate to attain near maximum crop yields under optimal irrigation regimes. Deeper drains may further lower the soil salinity however the resultant yield increases will be insignificant. Therefore drains deeper than 200 cm will not be economically viable as costs will increase and crop responses will be marginal. To achieve potential yields, removal of salts from the root zone through an effective drainage system would be indispensable. Under the current geo-political situation, large scale investments to enhance operational capacity of existing drainage systems seems difficult in near future. Therefore, irrigation management could be advantageous to control rising groundwater tables and soil salinity and attain optimal crop yields. However, for long-term sustainability of irrigated agriculture in these areas, restoration of existing drainage systems and installation of new drainage systems on priority basis will be inevitable.

1 Introduction

Iraq covers a geographic area of 45 million hectare (Mha) out of which 34 Mha (78%) is not suitable for agriculture. Presently, 6 Mha are under cultivation; nearly half of this area has very low productivity and can only be used for seasonal livestock grazing. Iraq can be sub divided into northern rain-fed and central and south irrigated zones. The central and south irrigated areas, located between the Tigris and Euphrates Rivers, produces more than 70 percent of the total cereal production in Iraq (Schnepf, 2003). Surface irrigation has been practiced for hundreds of years in Iraq (Wayne, 2003). However, development of drainage infrastructure could not keep pace with the irrigation development. This led to rising groundwater levels in most of the irrigated areas, which in turn have resulted in the accumulation of salts in the soil.

According to the FAO estimates, salinity has robbed the production potential of the 70 percent of the total irrigated area of Iraq with up to 30 percent gone completely out of production (FAO, 2011). It is estimated that 4 percent of irrigated areas is severely saline, 50 percent moderately saline and 20 percent slightly saline (Al- Taie, 1970). Other estimates indicate that the area of salt affected soils in Iraq is about 6.7 Mha (Abrol et al., 1988), however only 1.0 Mha are partially or totally reclaimed (Committee of Agriculture and water Resources Sector, 2009).

Excessive use of irrigation water and poor drainage conditions are the major factors contributing to rising groundwater tables in central Iraq. Existing drainage systems were installed 40-50 years ago. Since then not much rehabilitation work has been done to maintain operational capacity of these drainage systems. As a result, most of the existing drainage systems are either abandoned or malfunctioning. Many irrigated areas are in urgent need of drainage systems to keep the groundwater table below the root zone for salinity control (USAID, 2004).

In (semi-) arid areas, soil salinity caused by shallow groundwater table is often the limiting factor in crop production (Sarwar and Feddes, 2000b). In these areas, drainage needs are heavily dependent on irrigation component therefore groundwater table should be optimized to allow maximum groundwater contribution to the crops through capillary rise without permanently accumulating salts in the root zone (Hendrickx et al., 1990; Prathapar and Qureshi, 1999). Therefore it necessitates determination of optimal groundwater depths to maximize crop yields while keeping the soil salinization within acceptable limits (Qureshi et al., 2010). Sustainability of irrigated agriculture under these conditions further requires development of appropriate irrigation schedules especially when drainage systems are not functioning properly.

The strong and complex interaction between irrigation, crop production, groundwater table depth and soil salinity can be better studied by transient simulation models. The models are the best tools to describe soil-water-crop-climate interactions and to simulate water and salt balance terms under variety of climatic and physical conditions. This information can be used to evaluate long-term effects of different water management interventions on groundwater table, soil, environment and crop growth for which field data is not available or field trials could not be conducted. In this study, the soil-water-atmosphere-plant (SWAP) relationship model was used to determine optimal irrigation amounts and groundwater table depth for maximizing wheat and maize crops in Al-Mussaib and Al-Dujaila project areas located in the central and southern Iraq, respectively. Before application, SWAP model was calibrated for the soil, crop and climatic conditions prevailing in the area.

2 The SWAP model

Soil Water Atmosphere and Plant (SWAP) is a field scale agro-hydrological model. The model was developed by Feddes et al. (1978), which was further refined by Belmans et al. (1983), Wesseling et al. (1991), Van den Broek et al. (1994) and Van Dam et al. (1997). SWAP is designed to simulate unsaturated flow, solute transport, heat flow and crop growth in the soil–plant–atmosphere environment at the field scale. The model has successfully been applied to address practical questions in the field of agriculture and water management under variety of climatic and environmental conditions (Bastiaanssen et al., 1996; Sarwar, 2000; Singh, 2005; Qureshi et al., 2010). The model applies Richard's equation for soil water flow in the soil matrix described as below:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S(h)$$

Where h is the soil water pressure head (cm), K is the hydraulic conductivity (cm/day), C is the soil water capacity ($d\theta / dh$) (cm^{-1}), S is the soil water extraction rate by plant roots, z is the vertical coordinate positive in the upward direction and t is the time (d). SWAP solves the above partial differential equation using an implicit finite difference mechanism.

The potential root water extraction rate is equal to the potential transpiration rate, which is governed by atmospheric conditions. Stresses due to dry or wet conditions and/or high salinity concentrations may reduce water extraction. Water stress in SWAP is described by the function proposed by Feddes *et al*. (1978). For salinity stress the response function of Maas and Hoffman (1977) is used. They found that the reduction in crop yield due to salinity can be linearly related to the soil solution electrical conductivity. Crops can tolerate increases in soil salinity up to a threshold value, after which yield reduces linearly with increasing salt concentration.

$$\frac{Y_{act}}{Y_{pot}} = 1 \qquad \text{for} \qquad 0 \le EC_e \ge EC_e^*$$

$$\frac{Y_{act}}{Y_{pot}} = 1 - a(EC_e - EC_e^*) \qquad \text{for} \qquad EC_e > EC_e^*$$

where EC_e is the electrical conductivity of the soil saturation extract (dS m^{-1}), EC_e^* is the electrical conductivity of the soil saturation extract at which yield begins to decrease (dS m^{-1}) and a is the slope which equals the fraction yield decrease per unit of electrical conductivity increase. Salt tolerance data have been listed for a number of crops by Maas (1990).

The wide range of upper and lower boundary conditions being offered in SWAP is one of the key advantages of the model. The upper boundary conditions of the system are described by potential evapotranspiration rate, ET_{pot} (cm d^{-1}), irrigation and precipitation. At the bottom of the system, the boundary conditions can be described with various options. These include groundwater level as a function of time, flux to/from semi-confined aquifers, flux to/from open surface drains, an exponential relationship between bottom flux and groundwater table or zero flux, free drainage and free outflow (Van Dam *et al*., 1997). Irrigations in SWAP may be prescribed at fixed times or scheduled according to a number of criteria. The scheduling options allow the evaluation of alternative application strategies.

ET_{pot} is divided into potential transpiration rate, T_{pot} (cm d^{-1}) and potential soil evaporation rate, E_{pot} (cm d^{-1}) based either on the leaf area index, *LAI* (m^2 m^{-2}) or the soil cover fraction, *SC* (-), both as a function of crop development. Reduction of the potential soil evaporation rate into actual soil evaporation rate, E_{act} (cm d^{-1}) depends on the maximum soil water flux in the top soil according to Darcy's law or is calculated by an empirical function following either Black *et al*. (1969) or Boesten and Stroosnijder (1986).

Under water limiting conditions, it is important to know the minimum amount of irrigation water needed to ensure the maximum production of a certain crop. For this study, a linear relationship between relative yield and relative transpiration was assumed. The validity of De Wit's linear relationship in field experiments was confirmed by several researchers in different climates (Hanks, 1974; Stewart *et al*., 1977; Feddes, 1985). Further details of SWAP are described by Van Dam *et al*. (1997) and the program use is documented by Kroes *et al*. (1999).

3 Material and methods

3.1 Characterization of the study area

This study was conducted in two extensively monitored project sites i.e. Al-Mussaib area and Al-Dujaila area. These project areas represent typical environment and climate of the central and southern regions of Iraq. Al-Mussaib project is located on the left bank of Euphrates River near to Al-Mussaib city within the Babylon governorate. Dujaila project is one of the oldest irrigation projects in Iraq and is located in Wasit governorate on the right bank of Tigris River and left bank of Al-Garraf River. Both project areas fall under the Mesopotamian plain which represents a hot sub-desert climate. It is characterized by short cool winters and long hot summer with almost no spring or autumn season. Rainfall is very seasonal and occurs in winter from December to February. Average annual rainfall is about 135 mm. Winters are cold with a day temperature of about 18°C dropping at night to 7°C. Summers are dry and hot to extremely hot and long season with shaded temperature of over 44°C during July and August and dropping at night to 26°C. Geographic locations of both study sites are shown in Figure 1.

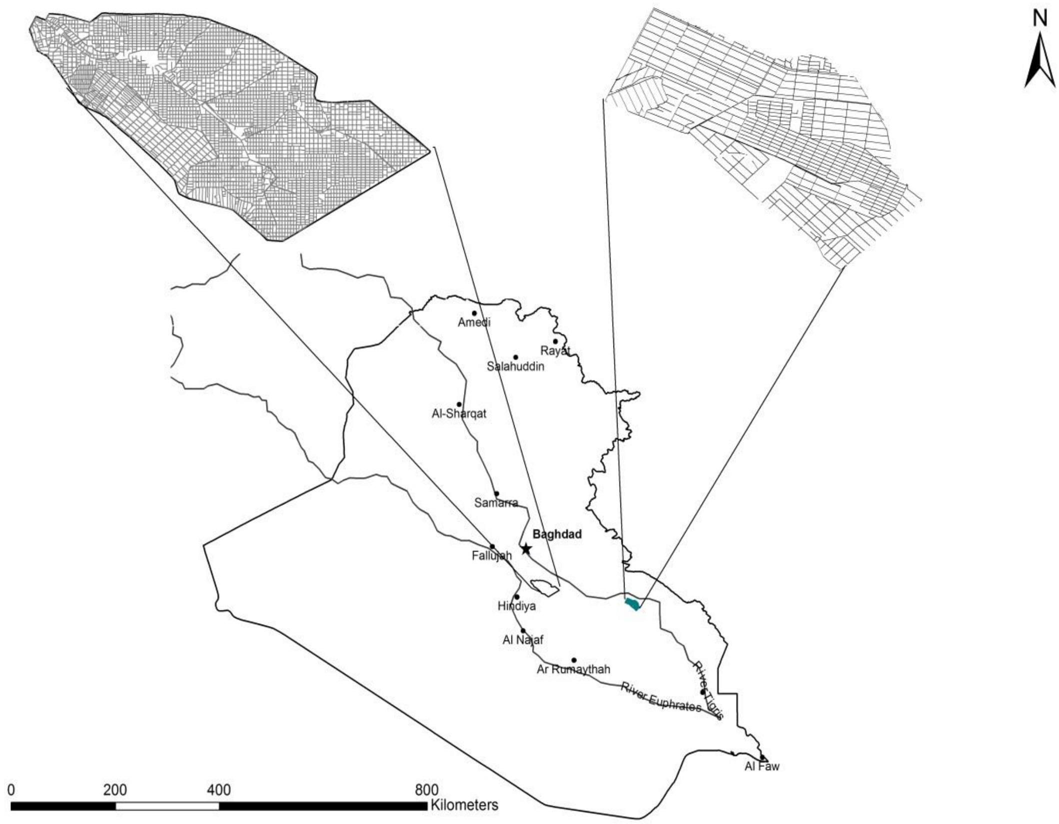

Figure 1: Geographic location of Al-Mussaib and Al-Dujaila project areas in Iraq.

The total area of the Al-Mussaib project is 51,168 ha with net irrigated area of 33,394 ha. Euphrates River with its tributaries is the major sources of surface irrigation in the area. Irrigation water to the fields is supplied through a network of unlined canals. In the 1950s, the project area was equipped with a drainage network which consists of open field drains, collector drains and branch and secondary drains connected to the main outlet drains of the project. The groundwater table depth in the project area varies from 100 to 150 cm with minor variations within months based on irrigation and evapotranspiration activity. Electrical conductivity (EC) of groundwater ranged from 3.5 to 10 dS m^{-1}.

The total area covered by Al-Dujaila project is 72,500 ha with net irrigated area of 22,418 ha. About 19,000 ha are reclaimed through a network of drainage system. The project includes a semi-reclaimed area of 14000 ha (equipped with main drainage system but without field drains). The rest of the project lands are non-reclaimed. The project lands are irrigated from the right side of Tigris River upstream of Al-Kut barrage directly by Al-Dujaila main canal. The groundwater table in Al-Dujaila area varies between 45 and 200 cm. Groundwater salinity is extremely high with seasonal variations 4 to 43 dS m^{-1} based on irrigation activity and drainage efficiency. Severe soil salinity and waterlogging are considered as the major problems of this area. These problems are the result of intensive surface irrigation and lack of drainage facilities.

The Iraqi irrigation system is mainly gravity flow and owned by the government. This enables the government to fix water duties at the beginning of a cropping season. The reported irrigation duty is 3 mm d^{-1} for gross cultivated area. Water distribution in the fields is entirely the responsibility of farmers. However, due to years of neglect and poor maintenance, the drainage network has been partially destroyed or become non-functional. This has led to rising groundwater table in the area with serious consequences of soil salinization and reduction in crop yields in most of the project area.

The soils of the Mesopotamian plain are rich in calcium carbonate, moderate in lime (25 to 30 percent lime is quite common and less than 20 percent is rare) and low in organic matter (Al-Jaboory, 1987; Buringh, 1960; Boumans et al., 1977). Large tracts of the irrigated lands of the project area are salinized. The degree of salinization varies along the latitude, depending on various factors which include quality of irrigation water, irrigation practices, soil types, natural drainage and the status of groundwater table. Irrigation applications without proper drainage facility have added huge amounts of salts in the soil profile. Boumans et al. (1977) has reported that in central Iraq, almost one Mega Ton (1×10^9) of salts is present in the top 5 m of soil.

Main crops cultivated in the project areas are wheat , barley and maize with small proportions of clover, sunflower, and winter/summer vegetables. The cropping intensity is 80 percent in winter and 20 percent in the summer (Al-Zubaidi, 1992). Poor on-farm irrigation management practices waste a considerable amount of water as deep percolation to the groundwater. This causes groundwater table to rise resulting in increased soil salinity and low crop yields. The average yields of wheat and maize are around 2.0 t ha^{-1} compared to the production potential of up to 4-5 t ha^{-1}. Crop calendar and average yields of major crops in both project areas are given in Table 1.

Table 1. Crop calendar and average yields of main crops.

Crops	Sowing and harvesting dates	Yields (t ha^{-1})
Wheat	15/Dec. – 30/Apr.	1.2 – 3.0
Barely	15/Dec. – 30/Apr.	1.0 – 2.8
Corn	15/Jul. – 01/Nov. 15/Mar. – 01/Jun.	1.0 – 2.8
Cotton	15/Mar. – 15Aug.	2.0 – 2.4
Sun flower	15/Feb. – 01/Jul. 01/Jul. – 15Nov.	1.2– 2.0

3.2 Data collection and model calibration

Iraq is a data scarce region. The on-going war and current unfavorable security conditions made it difficult to acquire the needed data for model calibration. However, as part of this project, a 0.5 ha farmer field was extensively monitored at each project site) during April 2011 to May 2012 to collect the most needed data for model calibration. The upper boundary condition of soil profile was described on daily basis by ET_{pot}, actual rainfall and irrigation. Daily climatic data were used to calculate reference evapotranspiration (ET_o) by the Penman-Monteith (PM) method (FAO, 1998). ET_{pot} was calculated by multiplying reference evapotranspiration (ET_o) by the crop factor (K_c). The K_c values were taken from Al-Falahi and Qureshi (2012). Soil samples collected at depths of 0-30, 30-60 and 60-90 cm were used to compare model simulated salinity values. Precipitation and reference evapotranspiration during the calibration period is shown in Figure 2.

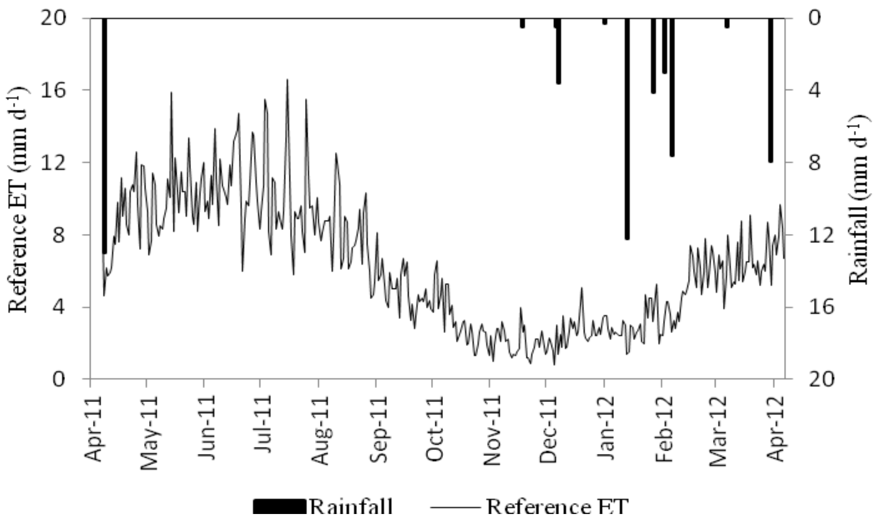

Figure 2: Rainfall and reference evapotranspiration during the calibration period.

The Boesten model (Boesten and Stroosnijder, 1986) was used for the reduction of E_{pot} into E_{act}. The calibrated value of Boesten factor was 0.63. Agronomic parameters including sowing and harvesting dates, crop development stages and crop height estimates were recorded during the field surveys. Data on rooting depth, leaf area index (LAI) and soil cover values as a function of crop development stage were taken from Sarwar et al. (2000) as no local data was available. LAI, crop height and rooting depth are used by SWAP to simulate crop growth.

The maximum rooting depths for wheat and maize were taken as 100 cm and 120 cm, respectively (Sarwar et al., 2000). Root length distribution was considered to decline linearly with depth. Root water uptake was described semi-empirically by a sink term, which is a function of the maximum root water uptake and the soil water pressure head (Feddes et al., 1978). The maximum root water uptake at a particular depth is proportional to the root length, which is described as a function of the relative rooting depth (Feddes et al., 1988; Prasad, 1988). Crops react differently to soil water limitations and their sensitivity to matric potential needs to be specified in the model as input. The *h1* to *h4* values refer to the sink term theory of Feddes et al. (1978). The sink term values were taken from Sarwar et al. (2000). Crop parameters used for this study are given in Table 2.

Table 2. Agronomic and crop parameters used for simulations with the SWAP model.

Parameters	Wheat	Maize
Sowing date	15-11-2011	15-07-2011
Harvesting date	30-04-2012	31-10-2011
Growing season (days)	167	108
Number of irrigations	6	9
Total irrigation depth (mm)	600	1000
Maximum rooting depth (cm)	100	120
Maximum crop factor	1.15	1.2
Limiting pressure heads (cm)	$h_1 = -0.1; h_2 = -20.0; h_3^h = -500; h_3^l = -900; h_4 = -16000$	$h_1 = -10; h_2 = -20.0; h_3^h = -325; h_3^l = -600; h_4 = -8000$

Detailed soil profile information for both project areas was taken from Boumans et al. (1977) and Al-Jeboory (1987). Based on this information, a soil profile of 300 cm was taken for both project areas. The analyses of soil samples showed that in the Al-Mussaib project area, the first layer (0-60 cm) belongs to clay loam, second layer (60-110 cm) to silt loam and the third layer (110-300 cm) to silt clay loam textural class. For Al-Dujaila project area, the first layer (0-60 cm) belongs to loam, second layer (60-150 cm) to silt loam and the third layer (150-300 cm) to silt loam textural class. The 300 cm soil profile was divided into 40 numerical compartments. As most of the soil evaporation under field conditions occurs in top few centimeters of the soil, the nodal distance for the first 25 cm of the soil profile was taken as 2 cm. The thickness of the soil compartments below this depth was gradually increased to 25 cm.

For each soil layer, soil hydraulic properties were described by the Van Genuchten-Mualem (VGM) parameters (Mualem, 1976; Van Genuchten, 1987). These parameters are saturated soil moisture content (θ_{sat}), residual soil moisture content (θ_{res}), saturated hydraulic conductivity (K_{sat}), empirical shape parameters (λ, α, n). As no measured data on VGM parameters was available for this area, soil hydraulic functions were taken from pedo-transfer functions (Wösten et al., 1998) and were slightly adjusted during the calibration process. The K_{sat} values for the surface layer in Al-Mussaib area were significantly higher than Al-Dujaila area. However, K_{sat} values for deeper layers were higher in Al-Dujaila area. Lower K_{sat} values in the deeper layers of the Al-Mussaib area could be due to the presence of more clay content in the soil. Final calibrated VGM parameters for both project sites are given in Table 3.

Table 3. Calibrated Van Genuchten-Mualem (VGM) parameters.

Parameter	Al-Mussaib			Al-Dujaila		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
Depth of layer (cm)	0 - 60	60 - 110	110 - 300	0 - 60	60 - 150	150 – 300
Soil Texture	Clay loam	Silt loam	Silt clay loam	Loam	Silt loam	Silt loam
Res. moisture content (θ_r) ($cm^3\ cm^{-3}$)	0.010	0.010	0.01	0.01	0.01	0.01
Sat. moisture content (θ_{sat}) ($cm^3\ cm^{-3}$)	0.48	0.44	0.50	0.48	0.47	0.47
Sat. hydraulic conductivity (K_{sat}) ($cm\ d^{-1}$)	38.65	18.76	13.88	21.25	21.12	24.38
Shape parameter α (cm^{-1})	0.058	0.049	0.052	0.099	0.075	0.068
Shape parameter λ (-)	0.97	1.01	0.79	1.98	1.60	1.74
Shape parameter n (-)	1.168	1.253	1.136	1.043	1.040	1.034

Despite shortage of irrigation water and non-availability of suitable drainage systems, irrigation practices of farmers are based on the traditional perceptions "*more irrigation-more yield*". Excessive irrigation applications are not only wasting precious irrigation water but also causing excessive percolation losses and rise in groundwater table depths which, in turn, accelerate salinity problems.

Irrigations were applied to bring soil moisture up to 70 percent of the field capacity. In this study, good quality canal water (EC = 0.80 dS m^{-1} ??) was used for all irrigations. During the study period, farmers applied 6 irrigations (600 mm) to wheat and 9 irrigations (1000 mm) to maize crop. Amount and date of all irrigations to wheat and maize during the calibration period is given in Table 4.

Table 4. Irrigation schedule followed for wheat and maize crops during the calibration period.

Wheat		Maize	
Date	Irrigation depth (mm)	Irrigation date	Irrigation depth (mm)
01-01-2012	80	23-07-2012	100
17-01-2012	85	01-08-2012	100
02-02-2012	85	12-08-2012	120
18-02-2012	95	23-08-2012	120
06-03-2012	90	03-09-2012	120
22-03-2012	85	14-09-2012	120
07-04-2012	80	25-09-2012	120
		06-10-2012	100
		17-10-2012	100

Groundwater table depth was monitored twice a month with the help of observation wells installed in both monitoring field. The bottom boundary condition of the soil profile was described as "*free drainage*" and model was set to simulate daily groundwater table depths. The simulated groundwater table depth was compared with the observed groundwater table depth data for model calibration as on moisture content data was available.

The salinity parameters in the classical convection-dispersion equation that describe salt transport are the dispersivity, D_{dis} (cm), and the diffusion, D_{dif} (cm^2 day^{-1}). The model is more sensitive to dispersion than to diffusion. The value of D_{dis} typically ranges from 0.5 cm, or less, for laboratory-scale experiments involving disturbed soils, to about 10 cm or more for field-scale experiments (Nielsen et al., 1986). The values for D_{dis} and D_{dif} that gave best results during the model calibration were 0.48 cm and 15 cm^2 day^{-1}, respectively. For salinity stress the response function of Mass and Hoffman (1977) was used. The threshold values for salinity stress for wheat and maize were taken as 6.0 dS m^{-1} and 1.7 dS/m, respectively.

4 Results and Discussions

4.1 Groundwater table depth

Figure 3 shows a comparison of observed and simulated groundwater table (GWT) depths for both project areas. The simulated values are on daily basis whereas observed values are on bi-weekly basis. It is pertinent to note that irrigation has a significant effect on the groundwater table depth as the amount of precipitation during the calibration period was only 35 mm. Heavy irrigation applications during maize season influences groundwater much more than the wheat season. The groundwater table depth in Al-Mussaib area rose to 156 cm from 175 cm which further rose to 117 cm during the wheat season.

In Al-Dujaila project area, GWT was shallow as compared to Al-Mussaib project area and registered a sharp rise during maize and wheat cropping season as a result of irrigation activity and finally rose to about 70 cm at the end of wheat season. This rise in GWT made the root zone saturated causing reduction in yields. This shows that in the absence of an effective drainage system, management of irrigation volumes could be a good strategy to control GWT rise and consequent soil salinity. A good match between observed and simulated GWT gives confidence on calibrated soil, crop and hydrological parameters used for this study.

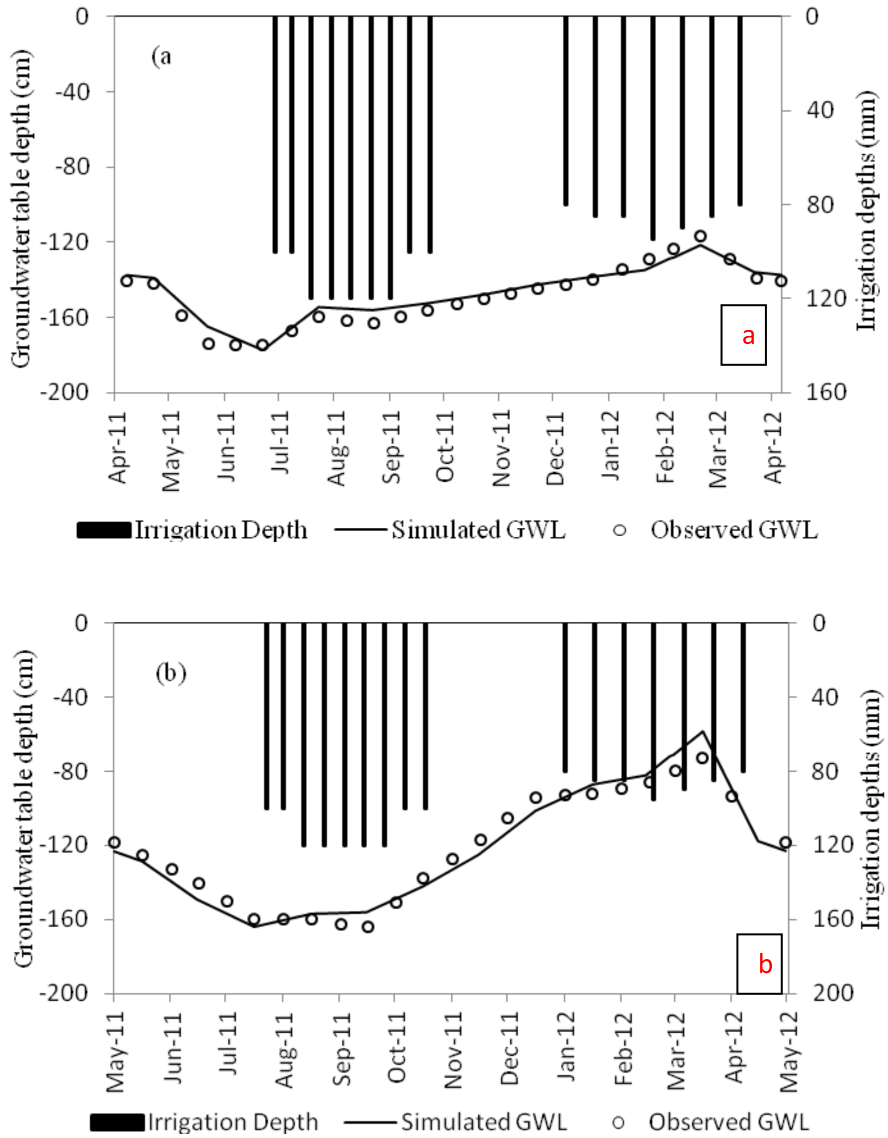

Figure 3: Comparison of observed and simulated groundwater table depth at (a) Al-Mussaib and (b) Al-Dujaila project areas during the calibration period.

4.2 Salinity of the soil profile

The measured EC_e values for both monitoring sites were available only for 2 days during the study period therefore a comparison could only be accomplished for those days (Figure 4). The simulated values are within the standard deviations of the observed salinity values. The close proximity between measured and simulated values reveals that the calibrated model is good enough to represent salinity at the field scale. It is pertinent to note that the profile salinity in Al-Dujaila project area is two to three times higher than Al-Mussaib project area. This can be ascribed to high groundwater salinity in Al-Dujaila project area. The high standard deviation values show that there are large variations in salinity within same field. These differences are attributed to inequitable canal water supplies and non-uniform application of irrigation water in the field due to poor land leveling. This uneven distribution of water produces patches of low and high water infiltration, which in turn produces patches of low and high salinity within the same field. Relatively high groundwater table conditions during the wheat season might have caused higher root zone salinity and more reduction in wheat yield as compared to maize.

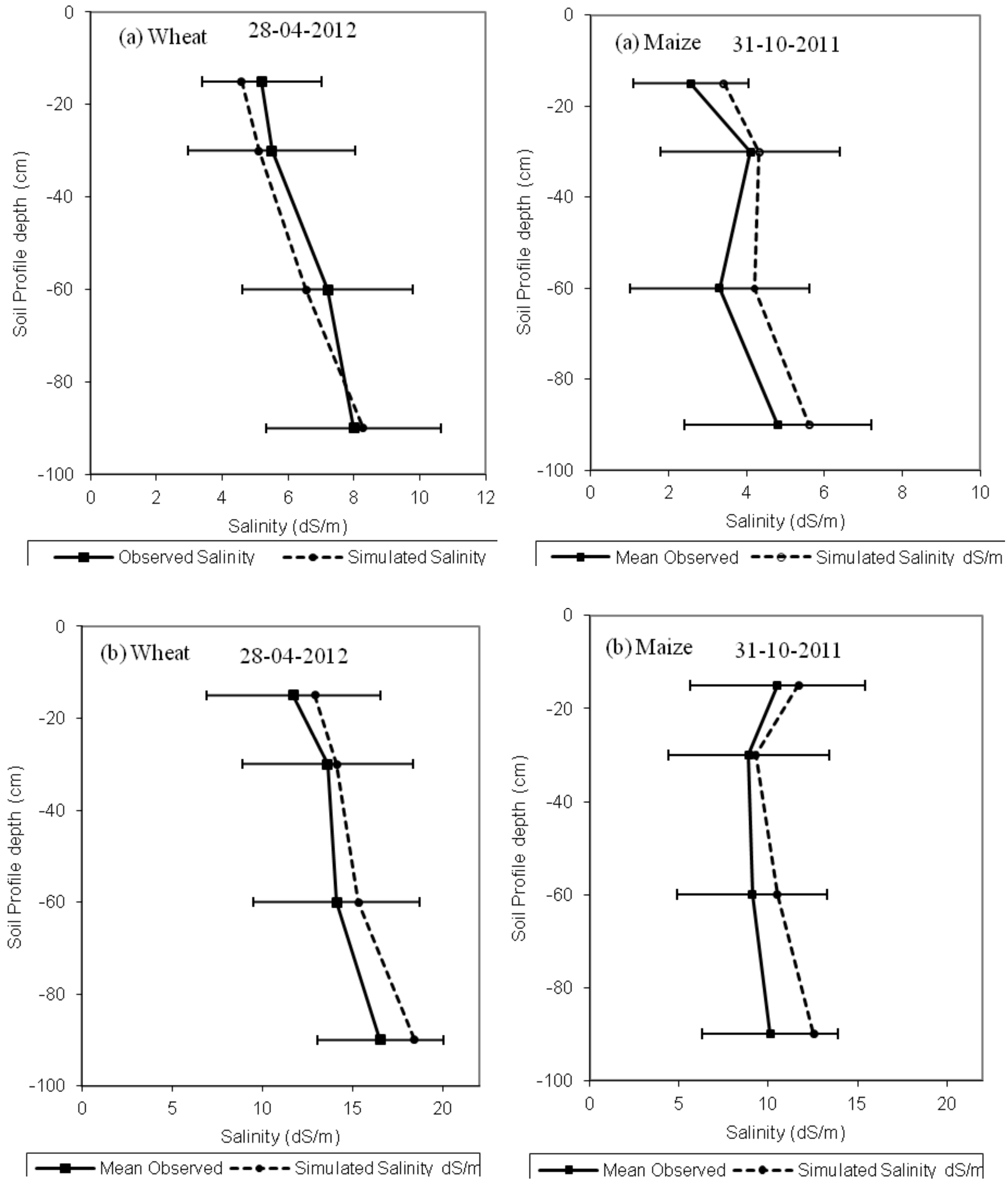

Figure 4: Observed and simulated profile EC_e in (a) Al-Mussaib and (b) Al-Dujaila project area.

4.3 Simulated soil water balance components

Table 5 summarizes simulated water and salt balance components for wheat and maize crops. The calibrated soil hydraulic parameters, measured irrigation depths and other input data were used in SWAP model to simulate the salt and water balance components. The simulated water balance components include ET_{act}, E_{act}, T_{act}, salt storage change (*SSC*) and bottom flux (q_{bot}). The positive value of q_{bot} represents addition of water to the soil profile from the groundwater.

Table 5 shows that under current irrigation practices, 25 to 30 percent of the applied irrigation water is wasted as deep percolation (q_{bot}) causing groundwater to rise and crop transpiration to decline. T_{act}/T_{pot} for wheat and maize remained little over 0.30 for the Al-Mussaib area. For Al-Dujaila project area where soil and groundwater salinity is high, T_{act}/T_{pot} ratio was even lower than 0.30. T_{act}/T_{pot} ratio is considered equivalent to relative crop yields because it takes into account the effect of both soil water and salinity and reflects overall conditions in the unsaturated zone and their effect on crop yields. The maximum attainable yields of wheat and maize for both project areas are taken as 4.0 t ha^{-1} and 3.0 t ha^{-1}, respectively (FAO, 2011)). In Al-Mussaib project area, the simulated yields for wheat and maize were found to be 1.24 t ha^{-1} and 1.27 t ha^{-1} while the corresponding figures for the Al-Dujaila project area were 1.09 t ha^{-1} and 0.85 t ha^{-1}, respectively. The simulated yields remained within 5 percent of the measured yields, which proves the authenticity of agronomic and crop parameters used for model calibration.

Table 5. Simulated water balance components for wheat and maize crops.

Water Balance components	Al-Mussaib		Al-Dujaila	
	Wheat	Maize	Wheat	Maize
Irrigation (mm)	600	1000	600	1000
Rainfall (mm)	35	0	35	0
Actual Evapotranspiration, ET_{act} (mm)	194	335	175	307
Potential Evapotranspiration, ET_{pot} (mm)	610	1080	610	1080
Actual Transpiration, T_{act} (mm)	154	264	135	235
Potential Transpiration, T_{pot} (mm)	495	830	495	830
Actual Evaporation, E_{act} (mm)	43	88	41	72
Potential Evaporation, E_{pot} (mm)	112	246	112	258
T_{act} / T_{pot}	0.31	0.32	0.27	0.28
$Y_{measured}$ (t ha^{-1})	1.20	1.35	1.10	0.90
$Y_{simulated}$ (t ha^{-1})	1.24	1.27	1.08	0.85
Bottom flux, q_{bot} (mm)	194	284	188	255
Salt Storage Change, *SSC*	0.034	0.116	0.910	0.775

SSC ($\Delta C/C_{initial}$) is the salt storage change in top one meter of the soil profile. ΔC is the salt concentration change over the crop growing period and $C_{initial}$ is the initial salt concentration.

Table 5 further shows that during the calibration period, addition of salts in the soil profile in Al-Dujaila project area is considerably higher than Al-Mussaib project area. This is probably due to high groundwater salinity in the Al-Dujaila project area. This increase in root zone salinity is the basic reason for low measured and simulated yields in the Al-Dujaila area. In addition to water and salt stress under field conditions, other factors such as nutrition deficiency. Pests and diseases may affect crop yields. However, SWAP does not consider these factors and assumes optimum nutrition conditions without any pest or disease stress.

5 SCENARIO ANALYSIS

5.1 Al-Mussaib project area

Determining optimal irrigation amounts

The calibrated SWAP model was used to determine optimal irrigation amounts and groundwater table depth (GWT) for maximizing crop yields and controlling soil salinization. The model simulations were performed to evaluate the effect of four GWT depths (i.e. 150, 175, 200 and 250 cm) and four irrigation regimes for wheat (600, 550, 500 and 450 mm) and six irrigation regimes for maize (i.e. 1000, 700, 600, 500, 400 and 300 mm) on root zone salinity and crop yields. The results of these simulations are presented in Figure 5.

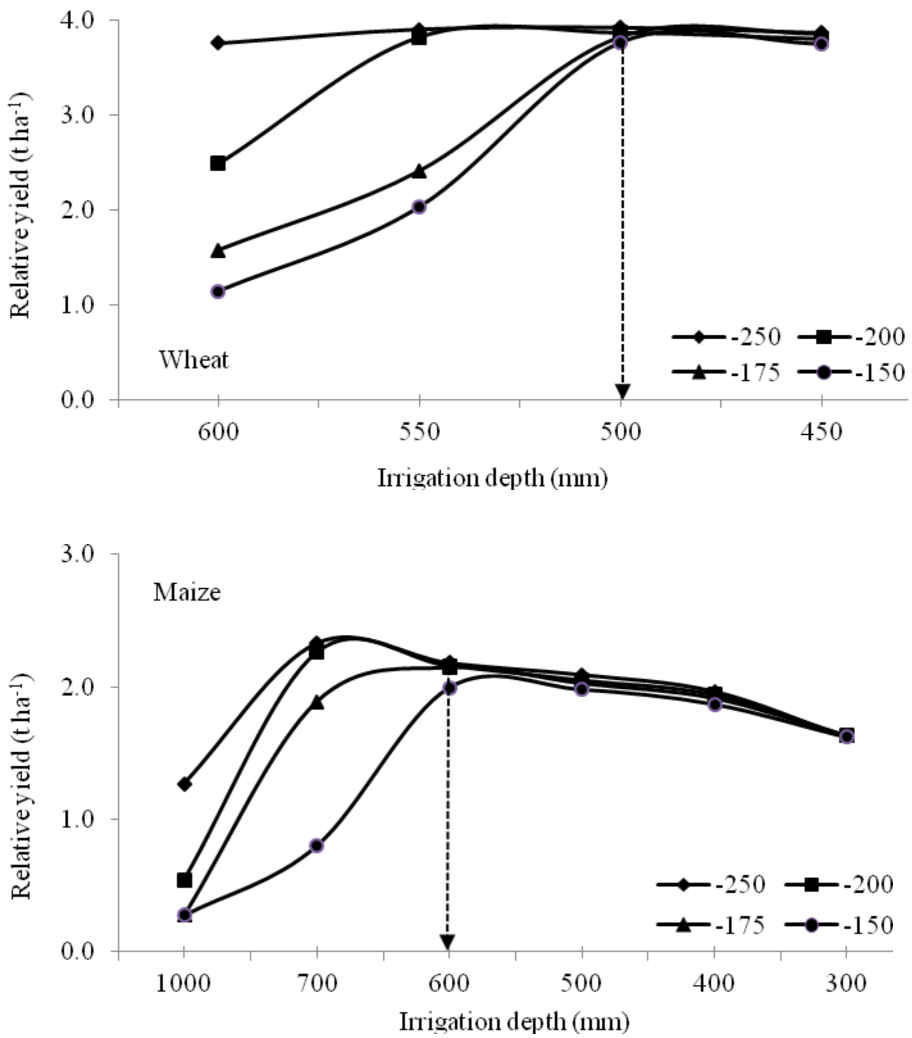

Figure 5. Wheat and maize yields as affected by different GWT depths and irrigation regimes.

Figures 5 show the relationship between GWT depth, irrigation application and crop yields. The wheat crop seems sensitive to GWT depths. Under existing GWT conditions (150-200 cm) and irrigation application of 600 mm, reduction in wheat yields is inevitable. Under current irrigation practice of 600 mm, wheat yield above 2.0 t ha^{-1} is only possible when GWT depth is maintained below 200 cm. Wheat yields will be reduced to 1.58 t ha^{-1} at GWT depth of 175 cm and 1.14 t ha^{-1} at GWT depth of 150 cm.

Modeling results reveal that for wheat crop, reduction in irrigation amounts to 500 mm would produce near optimal yields even at shallow GWT depths. The reduced irrigation application would allow crop roots to extract water from groundwater to meet their transpiration demand and keep GWT below root zone (Figure 6). This is possible in Al-Mussaib project area because groundwater salinity is relatively low (3.5-7.0 dS m^{-1}) and the danger of increase in root zone salinity will be minimum. Irrigation applications below 500 mm can cause water stress.

Maize is comparatively high delta crop and is more sensitive to salinity than wheat. In Iraq potential yield of maize is 3.0 t ha^{-1} (FAO, 2011), while the maximum simulated yield in the study area is 80 percent of the potential which represents a loss of 20 percent due to soil salinity. Figure 5 illustrates that in case of maize, reducing irrigation amounts to 600 mm would almost double the yield under the existing GWT depth conditions. Irrigation amounts lower than 600 mm seems insufficient and can cause reduction in maize yields. This clearly suggest that in Al-Mussaib area, controlling irrigation amounts will not only save significant amount of fresh water but also be a useful strategy to control rising groundwater tables and manage soil salinity and improve crop yields. It should be understood that this management intervention is a short-term solution of the existing salinity and waterlogging situation prevailing in the study area. However, for long term sustainability of irrigated agriculture and maximizing crop yields, restoration of existing drainage systems cannot be ruled out.

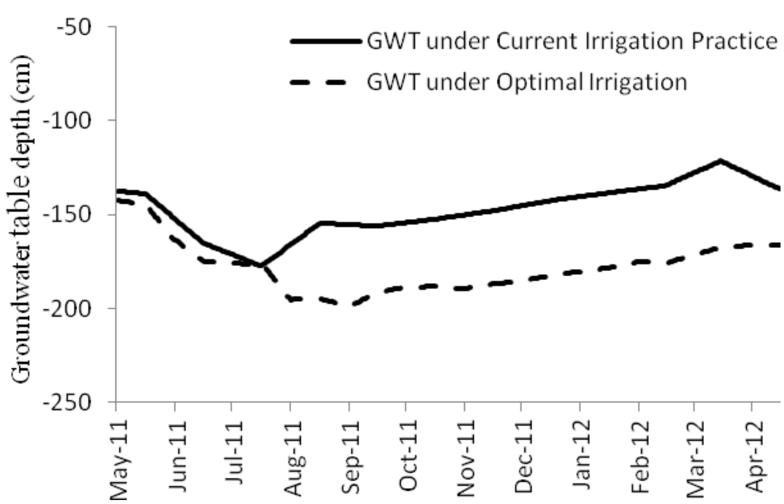

Figure 6: Comparison of simulated GWT depth under current and optimal irrigation regimes.

Determining optimal groundwater table depth

The optimal GWT depth is the one which can guarantee optimal crop yields while keeping profile salinity within acceptable limits. During this study, simulations were performed to (to) evaluate the impact of optimal irrigation amounts for wheat (500 mm) and maize (600 mm) under different GWT depths on crop yields and soil salinity. Figure 7 compares average salinity in the top one meter of the soil profile and relative yields for wheat and maize using optimal irrigation amounts under different GWT depths.

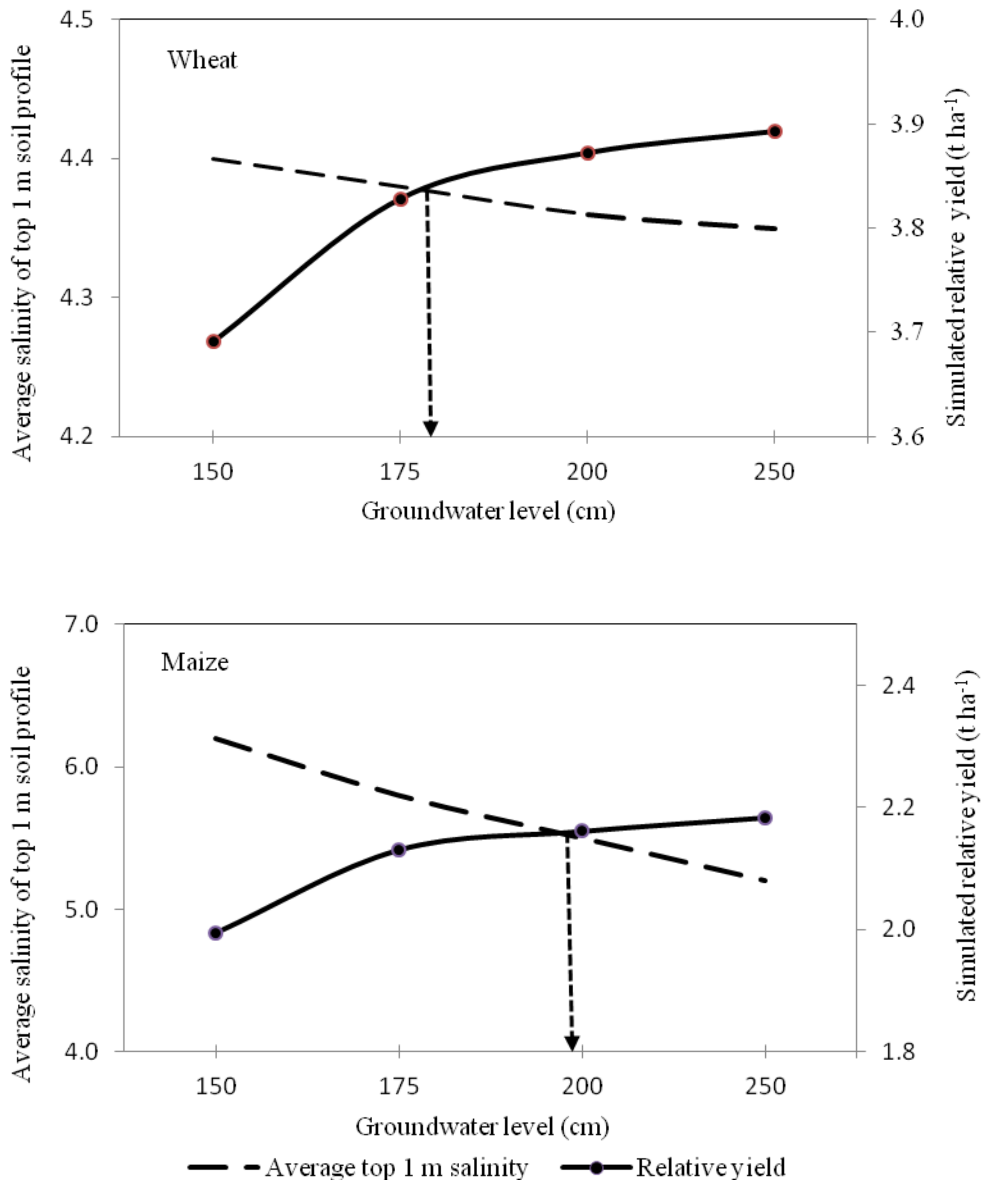

Figure 7. Relationship between root zone salinity and crop yields as affected by different groundwater table depths.

Figure 7 shows that wheat yields of 3.85 t ha^{-1} can be attained at GWT depth of around 180 cm while maintaining average root zone salinity around 4.35 dS m^{-1}. Since wheat is relatively tolerant to salinity, yield is not affected by this salinity. For maize, best compromise is found at a GWT depth of about 200 cm with a corresponding yield of 2.16 t ha^{-1} and average root zone salinity of 5.5 dS m^{-1}. As maize is sensitive to presence of excessive salts in the root zone, salinity levels above 5.0 dS m^{-1} will cause significant reduction in yields. For this reason, maize yield under optimal irrigation amount remained around 2.0 t ha^{-1}. The simulated maize yield is almost double than the yield obtained under current irrigation practices although they remain well below the potential yields in the area. The root zone salinity might decrease further below 200 cm GWT depth however resultant increases in wheat and maize yields will be marginal.

This clearly demonstrates that for Al-Mussaib area, optimal yields can be obtained by applying 500 mm (5000 m^3 ha^{-1}) to wheat and 600 mm (6000 m^3 ha^{-1}) to maize crop if the GWT depth is maintained at 200 cm. In order to get potential yields of 4.0 t ha^{-1}, leaching of excessive salts from the soil profile through freshwater application will be inevitable. This can be made possible by restoring existing drainage system and installing new drainage systems wherever necessary.

5.2 Al-Dujaila project area

Determining optimal irrigation amounts

Figures 8 show relationship between GWT depth, irrigation amounts and crop yields in Al-Dujaila project area. Under existing GWT depth and groundwater quality situation, reduction in wheat yields is inevitable with the irrigation application of 600 mm especially at shallow GWT depths. Like Al-Mussaib project area, wheat yield of 2.0 t ha^{-1} will only be possible when GWT depth is maintained at or below 200 cm. Wheat yields will be reduced to 1.10 t ha^{-1} at GWT depth of 175 cm and 0.77 t ha^{-1} at GWT depth of 150 cm. These reductions are much higher than the Al-Mussaib area because groundwater salinity in Al-Dujaila area is 3 to 4 times higher than the Al-Mussaib area. Therefore management of GWT depth in Al-Dujaila area is much more critical than in Al-Mussaib area.

For Al-Dujaila area, near optimal wheat yields can also be obtained by applying 500 mm of irrigation water regardless of groundwater table depth. However, optimal yields (3.39 t ha^{-1}) obtained in Al-Dujaila area will be 11 percent lower than the Al-Mussaib area (3.82 t ha^{-1}) under similar irrigation regime of 500 mm. These differences are due to increased root zone salinity in the Al-Dujaila area as a result of lower groundwater quality. Further reduction in irrigation amounts will be detrimental as the soil salinity will be further increased.

In Al-Dujaila project area, maize yields obtained under existing irrigation practices are less than 1.0 t ha^{-1} against a potential of 3 t ha^{-1} (FAO, 2011), Figure 8 illustrates that reduction in irrigation amounts to 600 mm would almost double the maize yield (regardless of GWT depth) although it will remain well behind the potential. Irrigation amounts lower than 600 mm seems insufficient to meet crop water requirements and maintain favorable salt balance in the root zone resulting in drastic reductions in maize yield. This suggests that in Al-Dujaila area, the situation is much more fragile as compared to Al-Mussaib area. Therefore revival of effective drainage system should be given a top priority in this area.

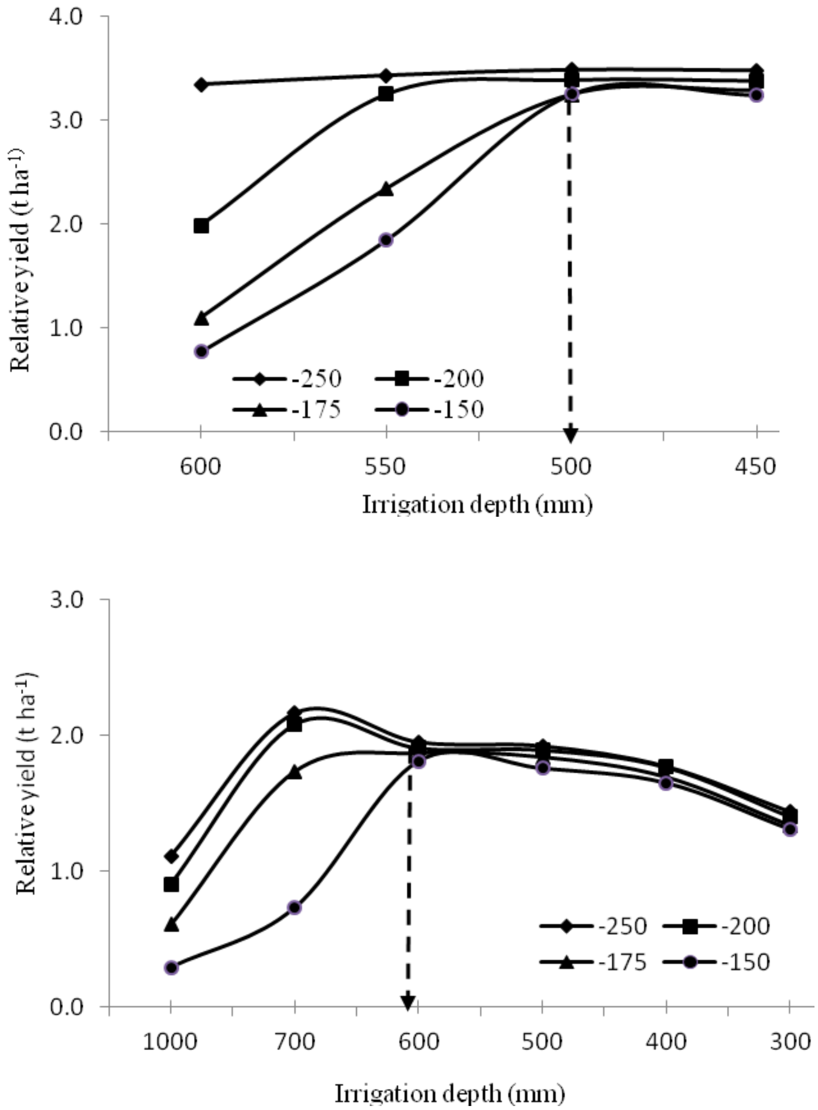

Figure 8. Wheat and maize yields as affected by different GWT depths and irrigation regimes.

Figure 9 clearly shows that reduced irrigation applications are beneficial in keeping groundwater table well below the root zone to avoid excessive salt accumulation in the soil profile, which in turn improves soil health and increase crop yields. In view of high salinity of groundwater in Al-Dujaila project area, keeping groundwater out of root zone is of extreme importance to control soil salinization especially because drainage systems in the area are also non-functional. However, one should keep in mind that these management measures are for short-term benefits and does not guarantee long-term improvements in the soil health. To ensure long-term sustainability of irrigated agriculture in these areas, rehabilitation of existing drainage systems should be done on priority basis.

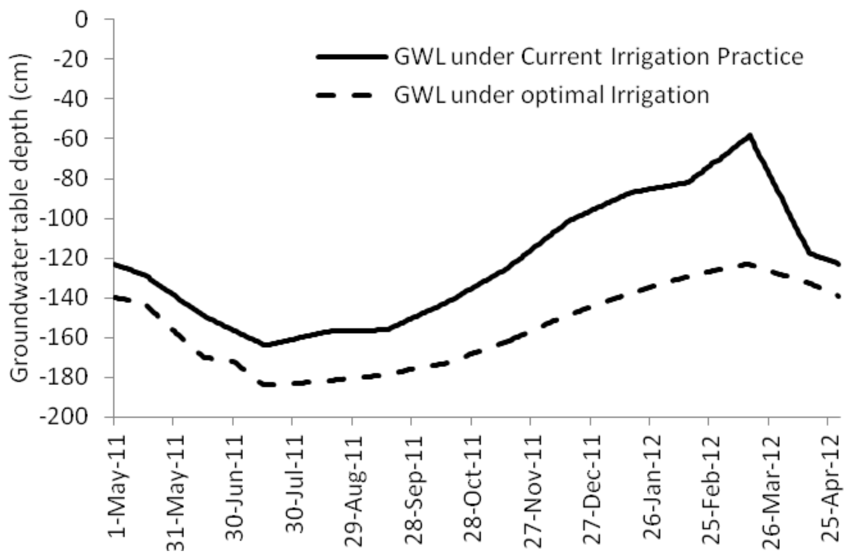

Figure 9: Comparison of simulated GWT depth under current and optimal irrigation regimes.

Determining optimal groundwater table depth

Figure 10 shows that under the saline soil and groundwater conditions prevailing in the Al-Dujaila project area, maximum wheat yield that can be obtained with 500 mm of irrigation water is 2.52 t ha^{-1} when GWT depth is maintained at 200 cm. This combination of groundwater table depth and irrigation application will keep the soil salinity around 4.3 dS m^{-1} which is safe as far as wheat crop is concerned. In case of maize, maximum attainable yield would not go beyond 1.80 t ha^{-1} with reduced irrigation application of 600 mm and groundwater table maintained around 200 cm. With these modifications, soil salinity will be maintained close to 7.0 dS m^{-1}. As maize is sensitive to root zone salinity, reduction in yields will be unavoidable. Therefore under the existing conditions in the Al-Dujaila project area, maize yields have to be compromised unless existing drainage systems becomes operational.

The above results suggest that under the existing shallow and saline groundwater conditions prevailing in the Al-Dujaila area, optimal yields of wheat (2.52 t ha^{-1}) and maize (1.80 t ha^{-1}) can be obtained by adopting optimal irrigation schedules (5000 m^3 ha^{-1} to wheat and 6000 m^3 ha^{-1} to maize) maintaining groundwater table depth at 200 cm. In order to get potential yields, leaching of excessive salts from the soil profile through freshwater application will be inevitable. This will require rehabilitation of existing drainage system on priority basis and installation of new drainage systems wherever necessary. The network of surface drains also need to be cleaned to improve their efficiency in transporting saline drainage effluent away from irrigated areas. This requires substantial financial resources and time. Under the existing geo-political situation of the country, this seems difficult in the immediate future. Till then, managing irrigation to optimize crop production and control rising groundwater table and soil salinity could be a useful strategy to keep producing sufficient food for the Iraqi people.

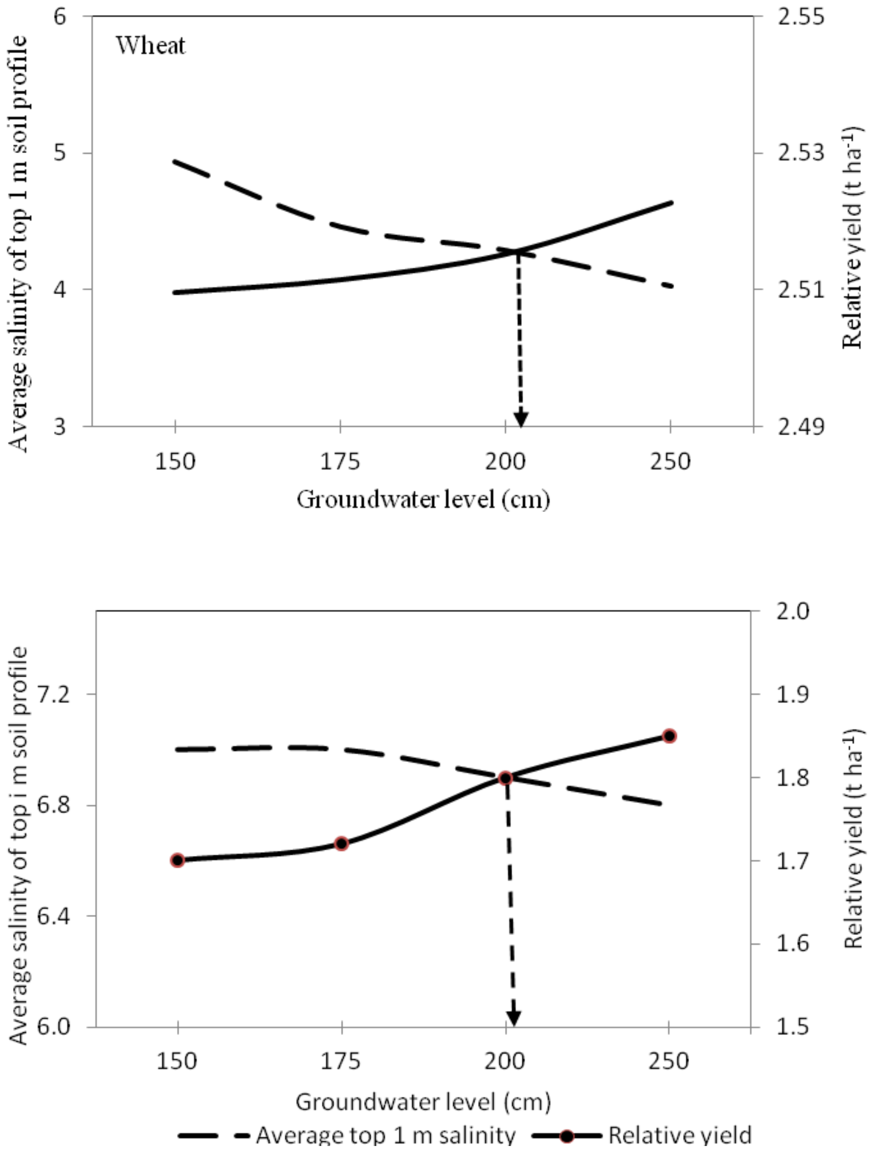

Figure 10. Relationship between root zone salinity and crop yields as affected by different groundwater table depths.

6 Conclusions

In arid regions like Iraq, irrigation is often essential to achieve economically viable crop productions. Benefits from irrigation may be partially offset by detrimental effects of rising groundwater tables and soil salinization. Excessive irrigation applications and poor on-farm irrigation practices could waste a fair amount of water as deep percolation. This not only reduces the water availability to other crops but also increases the drainage requirements, which can be an economic burden and an environmental problem for disposing effluent. Therefore it necessitates precise calculations of irrigation requirements to halt environmental degradation and foster crop production.

In this study, a physically based agro-hydrological model SWAP was calibrated using field data from two farmer fields located in the Al-Mussaib and Al-Dujaila project areas located in central and southern Iraq, respectively. In the absence of soil moisture data, observed and simulated groundwater table depths and soil salinity data were used for model calibration. Good agreement was found between observed and simulated groundwater table depths and soil salinity at different depths. Simulated yields of wheat and maize also remained within 5 percent of the measured yields. This gives confidence on soil, crop and agronomic parameters used for he model calibration.

Modeling results revealed that the current irrigation practice of applying 600 mm of irrigation water to wheat and 1000 mm to maize are unsuitable for both sites as more than 25-30% of the applied water is wasted as deep percolation. As drainage systems are non-functional at both sites, this deep percolation is the major reason for the rising groundwater tables, increased soil salinity and reduced crop yields. The simulation results suggest that in the absence of effective drainage systems, controlling irrigation amounts could be a beneficial strategy to control rising groundwater table and consequent soil salinity. For the prevailing groundwater and salinity conditions in both sites, optimum irrigation amounts were found to be 500 mm for wheat and 600 mm for maize. These irrigation amounts can produce optimal crop yields while keeping groundwater table depth and soil salinity within acceptable limits.

The calibrated SWAP model was also used to do additional simulations to determine optimal groundwater table depth that can guarantee optimal crop yields by controlling salt accumulation in the root zone. For the existing soil and water conditions in both study areas, a groundwater table depth of approximately 200 cm was found to be sufficient to attain near maximum crop yields by applying optimal irrigation amounts. In Al-Mussaib project area, wheat yield of 3.85 t ha^{-1} can be attained. As maize is more sensitive to salinity, yield of 2.16 t ha^{-1} would only be possible. With these practices, soil salinity will be maintained around 4.5 dS m^{-1}. In the Al-Dujaila area where soil and groundwater salinity is high, maximum attainable yields under the existing conditions will be relatively lower. The maximum attainable wheat yield would be 2.52 t ha^{-1} whereas maize yields will not go beyond 1.80 t ha^{-1}.

To achieve maximum yields, an effective drainage system would be essential to evacuate excessive salts from the root zone. At deeper groundwater table depths, although average root zone salinity will be further decreased but the resultant yield increases will be marginal. Therefore drains deeper than 200 cm will not be economically viable for these areas as costs will increase and crop responses will be negligible.

This study suggests an early rehabilitation of existing drainage systems and installation of new drainage system wherever needed. Introduction of a comprehensive on-farm water management program to educate farmers on precise irrigation requirements under the existing salinity and groundwater table depth conditions should also be given priority. It seems that due to political and financial constraints, rehabilitation of existing drainage system in the area will remain a challenge for some time to come. Therefore managing irrigation to control rising groundwater table and consequent soil salinity problems seems more viable solution for the near future.

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