Long-term effects of using controlled drainage on: Crop yields and soil salinity in Egypt

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ABSTRACT

Egypt suffers from a lack of rainwater and hot weather most of the year, which represents a challenge to the current trend to achieve optimum utilization of newly reclaimed land. Egypt’s agriculture depends on irrigation that consumes about 85% of the available water resources. How this problem is managed is the aim of the study, where the controlled drainage (CD) application was evaluated as a water-saving tool and the long-term impacts of using such practice on crop productivity and soil salinity were predicted using DRAINMOD-S for El-Tina plain in the northwestern corner in Sinai. Soil texture of the plain varies between sandy loam to clay. Collected data of wheat and corn as winter and summer crops, respectively, were used to check the model reliability. The water table fluctuations were monitored on a daily basis. At the same time, drains discharges and salinities were also monitored during the whole growing season. The salinities of the topsoil till 1.0 m depth were measured. The obtained results from the model were assessed compared with the observed values of the daily water table fluctuations; lateral discharges, salt concentrations in the soil profile, and relative crop yield during each season. Simulation results satisfactorily matched the data collected from the field. Simulation values obtained for 10 years indicated that the average quantity of drain discharge increased by increasing the managed drainage depth which makes (CD) a promising tool for regulating the draining intensity, a remarkable increase in the soil salinity of the root zone will take place if the irrigation water salinity reaches values above 800 ppm, and consequently the high irrigation water salinity values will badly affect most of the crops that grow normally in the field under study except the high salt tolerance ones as wheat. A noticeable decrease in crop yields will be the inevitable result if both the managed drainage depth and water salinity are increased. The outputs of the study can be considered as guidelines for how to utilize the controlled drainage application under Egyptian conditions.

Introduction

Soil salinity is defined as an undesirable amount of dissolved inorganic soluble salts in the soil profile (Rhoades, 1990). Water tables rising and geologic erosion could form salts. These salts precipitate by evapo-concentration process. Typically, salts accumulate in the topsoil layers and leach progressively into lower layers of the soil profile. In arid regions, lack of rainfall and dry climatic conditions increase both evaporation and upward capillary flow causing minimal leaching which increases the salinity of the top soil layers. In agricultural and land management applications proper irrigation practices are important to control salinization. Under-irrigation minimizes the net downward movement of water that helps leach salts from the surface of the soil and the plants’ root zone area. Also, over-irrigation causes a rise in the groundwater table, where salts in the shallow groundwater precipitate and accumulate (Rhoades, 1992).

Recently, CD is defined as a management method followed in humid areas aiming to reduce the nitrate concentrations in surface water. CD system uses a control device to keep the water table shallower during certain periods of the growing season according to the development of the root depth. The main benefit comes from the upward flux which increases and contributes to providing moisture to the plant. Studies indicated a remarkable decrease of nitrate in drain effluent discharged from CD systems (Lalonde, Madramootoo, Trenholm, & Broughton, 1996). In situations where water is out of reach for sub-irrigation, CD allows approximately no drainage (small amounts) and saves crops from wilting (Skaggs, Fausey, & Nolte, 1981).

Hornbuckle, Christen, Ayars, and Faulkner (2005) and Hornbuckle (2003) used a vineyard farm to demonstrate controlled drainage effects on drainage effluent and total flow salinity. The experiment resulted in much larger drainage effluent and salt load from the uncontrolled drainage plots compared to the controlled ones. Doering, Benz, and Reichman (1982) also, recommended designing drainage systems using shallow water table concept to reduce drainage effluent.

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The environmental concerns were the motivating reasons behind adopting controlled drainage concept as; controlling water tables is an easy way that facilitates managing salt accumulation and water use of the shallow water table (Ayars, Christen, & Hornbuckle, 2006).

Due to system complexity, simulation models are essential to assess the system's efficiency that includes subsurface drainage, surface drainage, and irrigation. Recently, computer simulation models constitute a great tool for planning of Water Management Systems (WMS). In the present study, DRAINMOD-S was used to assess the use of CD system as a water management tool under Egyptian condition. The model applications have been used in many countries on a large scale under different conditions (Skaggs, 1999).

**Methodology**

Most previous studies in humid regions focused on the off-site environmental impacts of using controlled drainage aiming basically to reduce nitrate content in drainage water. In arid or semi-arid regions the priorities are different lack of rain and irrigation water makes the on-site impacts of using such practice much important as they may directly affect the soil and the plant itself. From this perspective, this research was submitted specifically to predict the long-term impacts of using controlled drainage on the salinity of root zone, and crop yields using (DRAINMOD-S) simulation model.

**Study area**

Experimental field situated in El-Tina plain. The plain lies in the north of Sinai, Latitude (30° 59') and longitude (32° 26’55”). It has a V shape; its borders are the Suez Canal to the west, the Mediterranean Sea to the north and the northern Sinai Sand Sea to the south (Figure 1).

The land level of the study area ranged between 0.4 m and 0.5 m above sea level and characterized by a flat terrain. El-Tina plain has two different aquifers. The first aquifer is confined aquifer and lies below within heavy clay layer which limits any vertical water movement into, or out of the aquifer. The top clay layer is deep in the west direction and its depth gradually decreases toward the East till it disappears. It is sensitively affected by rain and irrigation water movement which infiltrates directly through the ground surface.

Climate in El-Tina plain is known as the Mediterranean arid climate (hot dry summer, and cold-limited rain winter). The (max-min) air temperatures are 31.3°C during July and 4.9°C in January, respectively. The annual rainfall is 33.3 mm obtained in winter only.

The plain receives its needs of irrigation water from El-Salam canal. The mixed water of El-Salam canal consists of half freshwater and half drainage water. This ratio gives an EC value not to exceed 1500 ppm just to ensure irrigation water suitability for cultivated crops.

The Experimental field dominant soil texture is composed of sandy loam, with 75% sand, 7.8% silt, and about 16.4% clay content. The (pH) of soil ranges from 7.1 to 8.0. During the growing period, irrigation water total dissolved solids were in the range between 1.25 and 1.72 dS/m (800–1100 ppm).

The plain is a newly reclaimed land provided with a pipe drainage system to permit the necessary leaching and to hold the water table to be at sufficient depth, preventing the upward movement of salt capillary water from reaching the crop root zone.

![Figure 1. Experimental study area site.](image-url)
**Experimental layout**

The experimental field was divided into six cultivated plots each of 0.3 hectare. In these cultivated plots, the traditional land drainage system used in Egypt was combined with one water table control scheme to perform a CD treatment. The plot size was 75 m$^2$ x 40 m. A lateral drain was used for each plot to be drained separately. The main collector made of Poly Venial Chloride (PVC) was installed at a depth of 1.40 m below the soil surface. Lateral length and spacing were 75 m and 40 m, respectively. Each manhole jointed two laterals (Figure 2). The slopes for laterals and collector were 0.1%. At the same time, the lateral pipe diameter was 80 mm while it was 200 mm for the main collector. PVC rising device was inserted at the outlet of the pipe of each lateral of plots, to allow drainage in case the effluent reaches the device top part (Figure 3). The surface irrigation system used in the field consisted of two main canals and the irrigation water is distributed among the plots throughout opening the entrance of the desired plot while closing the entrances of other plots.

**Crop rotation, water table management tool, and monitoring process**

The crops planted during the study were winter wheat (*Triticum aestivum*) followed by corn (*Zea mays*). The field study lasted for 3 years representing two crop rotations for years (2014–2015) and (2015–2016). Winter wheat and corn were planted on the 1st of October and 1st of May, respectively, for each crop rotation. During the study period, traditional tillage, pest control practices, and fertilizer, commonly used in the region were followed. Small rates of nitrogen fertilizers were added as nitrate for winter wheat approximately 50 days after planting.

In controlled drainage, the valves were set at a depth of 60 cm below the soil surface throughout the whole season which was increased to 140 cm just before harvesting and before soil plowing to carry out farm field operations like tillage, seeding, fertilization, or harvesting. The drain outflow was measured once every 2 h a day only if laterals discharged. During flow periods, samples of drain effluent were collected to be analyzed twice a month. The depth of the groundwater was measured halfway between drains using observation wells, fitted with automatic recorders for recording the water table fluctuation depths.

**Model description**

The DRAINMOD simulation model (Skaggs, 1978, 1991) is capable of analyzing the movement of soil water for drained agricultural lands in humid areas. The model predicts subsurface drainage, surface runoff, infiltration, deep seepage, water table depth, and evapotranspiration as affected by changes in weather conditions, crop cover, soil type, and drainage system design. The version of the model, DRAINMOD-S (Kandil, 1992), was
developed to be able to predict solute transport and to estimate the design criteria effects on crop yield in arid conditions.

**Input data**

The data needed for applying or calibrating the model are weather data, soil hydraulic properties of the field, parameters describing the used drainage system, inputs for crops, and inputs for the irrigation process. (Skaggs, 1980; Workman, Parsons, Chescheir, Skaggs, & Rice, 1994).

**Climatic data**

Rainfall and max-min temperatures were obtained daily from Port Said-meteorological station which located 2 km from the experimental field. Thornthwaite default method was used to estimate Potential Evapo-Transpiration (PET).

**Soil properties**

The DRAINMOD soil file preparation program needs soil moisture content data and soil-saturated hydraulic conductivity (Ks) for each layer. In DRAINMOD it is available to enter up to five soil layers. These properties were measured for the site using six (50 mm diameter) soil cores collected from the experimental field.

Undisturbed soil samples were used for determining soil Pf curve using the pressure cocker apparatus. The average volumetric water content at the different pressures for the media is presented in Table 1.

A constant head method was used to measure the saturated hydraulic conductivity of the site, as described by Klute (1986) and the average measured value was about 16 cm/h.

**Crop parameters**

Crop parameters contain working day parameters (WDP), yield reduction parameters (YRP), and rooting depth parameters (RDP). WDP describe field conditions suitability for soil plowing, seed preparation, and harvesting operation. YRP describe potential losses in crop yield as a result of (excess-deficit) water conditions and planting setbacks. YRP, per crop, include a scheduled function describing the rooting depth throughout each stage of plant growth.

| Soil water tension head (cm of water) | -0.01 | -60 | -80 | -100 | -330 | -500 | -2000 | -5000 | -10000 | -15000 |
|--------------------------------------|-------|-----|-----|------|------|------|-------|-------|--------|--------|
| Volumetric Water content (cm³ cm⁻³)   | 0.429 | 0.386 | 0.376 | 0.366 | 0.311 | 0.293 | 0.264 | 0.239 | 0.211 | 0.194 | 0.185 |

Figure 3. Schematic of PVC control device used on individual laterals for controlling subsurface drainage flow.
Table 2. Summary of input drainage design parameters.

| Parameter               | Drained depth (cm) | Drained spacing (cm) | Effective radius of drains (cm) | Actual distance from surface to impermeable layer (cm) | Drained coefficient (cm/d) | Initial water table depth (cm) | Maximum surface storage (cm) |
|-------------------------|--------------------|----------------------|-------------------------------|-------------------------------------------------------|---------------------------|-------------------------------|-------------------------------|
| value                   | 140                | 4000                 | 1.0                          | 400                                                   | 1.0                       | 110                           | 9.0                           |

**Drainage system parameters**

Table 2 shows drainage system parameters for the surface and subsurface components of the onsite drainage system. Through the calibration process, the depth of the surface depressional storage was obtained, and based on former data, the drainage coefficient was also determined.

**Salinity parameters**

To measure the soil salinity, samples were collected along with the soil profile at 25 cm increments up to 100 cm beneath the upper soil surface prior to winter wheat cultivation (as primary soil salinity) and after both crops (wheat and corn) harvesting.

**Model calibration and validation**

DRAINMOD calibration and validation process was performed by comparing model estimations of drainage discharges and water table fluctuations with the collected data from the field according to Youssef, Skaggs, Chescheir, and Gilliam (2006). Common performance criteria were used to assess the appropriateness among the model outputs and the observed data: the mean error, ME, the mean absolute error, MAE, the Nash-Sutcliffe coefficient of efficiency, EF, and the percent-normalized error NE.

According to:

\[ ME = \frac{\sum_{i=1}^{n} (P_i - O_i)}{n} \]  

\[ MAE = \frac{\sum_{i=1}^{n} |P_i - O_i|}{n} \]  

\[ NE = 100 \times \frac{\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} O_i}{\sum_{i=1}^{n} O_i} \]  

\[ EF = \frac{\sum_{i=1}^{n} (O_i - \bar{O})^2 - \sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \]

where \( o_i \) is the observed data at time \( i \), \( P_i \) is the simulated data at time \( i \), \( \bar{O} \) is the mean observed data, and \( n \) is the total number of both observed-modeled events.

The simulation process was performed for 3 years (2014–2015–2016). Data for years 2014–2015 were used for calibration, and data for 2015 and 2016 were used for validation.

**Results and discussion**

**Short term simulation results**

**Water table depth**

For the calibration process, the regression analysis results for simulated and observed values of WTD for years 2014–2015 showed good agreement between the two values (Figure 4 and Table 3) during the study period, the MAE regarding to the WTD was 13.3 cm for wheat and 15.0 cm for corn (Table 3). Also, the EF values ranged between (0.71–0.81) which were classified as a good prediction for water table according to Youssef et al. (2006).

In the same way, the validation process was conducted for years 2015–2016. (Table 3) provides a summary of statistics indicating the model performance. The agreement of simulated and observed WTD values was considered very good, the EF values were ranging between 0.65 and 0.75, while the MAE values were 13 and 15 cm.

**Subsurface drainage**

In the same manner, drainage discharges were also in agreement (Figure 5 and Table 3). Over the calibrated period, the EF value for simulated and observed monthly outflow was 0.93. The NE absolute value for simulated and observed cumulative outflow was −7.7%. The low value of NE indicates that the model underestimates drainage discharges a bit.

For the validation period, the (MAE) of monthly predicted drainage was only 0.82 cm. The coincidence of simulated and observed monthly outflow was excellent, as shown in Table 5 and according to MAE and EF values; the model successfully predicts monthly and annual drainage on that site.

**Soil salinity**

Initial, observed, and simulated soil salinities at different soil profiles depths (before and after growing seasons of wheat and corn) are shown in (Figure 6). The Statistical performance measures used to assess matching between observed and simulated soil salinities were correlation coefficient, (R²), and (EF). Results showed very good soil salinity estimation, with EF values of (0.84 and 0.93) for all layers during the calibration period and validation period as shown in Table 4.

Four different sampling points are given in (Figure 7) to reveal salt accumulating behavior within the soil profile. The results indicated that salinity remarkably increased all over the soil profile with enormous increases in the top layer particularly (0–0.5) depth layer (calibration period).
The observed and simulated relative yields for the calibration period were 95–96.2% for wheat and 72–69% for corn, respectively (Figure 8). Table 5 shows the results of the simulated relative yields (calibration and validation periods). Predicted corn yields during the study period revealed that the productivity was adversely affected by the high salinity of the soil.

**Crop yield predictions**

Long-term simulation results

To evaluate the long-term effects of controlled drainage as a water management policy, a two-dimensional model (DRAINMOD-S) was used to predict salt concentrations in the soil profile and the effects of stresses due to soil salinity on crop yields. To achieve these goals three scenarios were considered for two crops, winter wheat, and summer corn.

For root zone salinity equalled 1400 mg/l (the measured root zone soil salinity of the study area), the assumed scenarios were as follows: 1 – The first scenario (A), salinity of the irrigation water was assumed to equal 400 mg/l (normal irrigation water salinity), 2 – The second scenario (B) salinity of the irrigation water was assumed to equal 800 mg/l (normal salinity of El-salam mixed water canal), 3 – The third scenario (C), salinity of the irrigation water was assumed to equal 1000 mg/l (highest salinity of El-salam mixed water

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**Table 3. Summary of statistics indicating the accuracy of predicted water table fluctuations.**

| Crop | MAE (cm) | EF | MAE (cm) | EF |
|------|----------|----|----------|----|
| wheat | 13.3 | 0.71 | 13 | 0.65 |
| corn  | 15 | 0.81 | 15 | 0.75 |

**Figure 4. Simulated and observed water table fluctuations (calibration period).**
The effects of different managed drainage depths on drain discharge rate were also simulated for a period of 10 years. The average quantity of drainage water throughout the simulation period increased as a result of increasing the managed drainage depth. The simulation process was performed for managed drainage depths equaled (0.6, 0.8, and 1.0 m) and the amount of drainage effluent corresponding to those depths equaled (0.052, 0.058, and 0.065 m), respectively.

Influence of irrigation water salinity on salinity build up in root zone

The output data from the model showed that significant increases in root zone salinity were observed due to the increase in the water salinity. For example after 10 years, with the same managed drainage depth equaled 0.6 m and water salinity of 400, 800, and 1000 ppm, the salinity of the topsoil cap increased from about 7200 to 12500 ppm in the 10th year (Figure 9). Therefore, when irrigating with high water salinity it should be important to consider more precautions under applying the controlled drainage systems.

The influence of varying irrigation water salinity on crop yield

The results of the long-term simulation (10 years) are shown in (Figure 10). For wheat, the simulation results indicated that – under the same managed drainage depth and irrigation water salinity (400, 800, and 1000 ppm) – soil water conditions in the root zone were favorable. Stresses due to neither excessive soil water nor deficit soil water limited yield at any managed drain depth (MDD). On the other hand, stresses due to soil salinity lightly reduced yields for all managed depths despite its high tolerance to salinity and the highest wheat overall yield obtained for any scenario was at (MDD) equaled 60 cm.

But for corn using the same conditions as illustrated in the previous section, the simulation results demonstrated that the yield reductions were primarily due to high salinity in the root zone. Both of excessive soil water stresses and deficit soil water stresses did not limit yields at any MDD. The highest corn overall yield obtained for any scenario was at managed drain depth equaled 60 cm but the drainage intensity considered did not provide sufficient salinity control for acceptable yields.

Figure 11 illustrates that in case of increasing both the water salinity and managed drainage depth, the overall yield decreased significantly for highly sensitive crops that are not highly tolerated to salinity like corn.

Conclusions

Data obtained from a field experiment in El-Tina plain on the northern Sinai coast, Egypt, was used to check the reliability of DRAINMOD-S as one of the models used in assessing water management systems and the suitability of its use under the distinctive climatic conditions of Egypt. The experiment lasted for four seasons; winter wheat was cultivated in 2014–2016 and maize in 2015–2016.
Figure 6. Initial, observed and simulated soil salinity values for wheat (a) and corn (b) (calibration period).

Table 4. Regression analysis between observed and simulated soil salinities.

| Depth cm | Calibration period 2014–2015 | Validation period 2015–2016 |
|----------|-----------------------------|-----------------------------|
|          | $R^2$ | WHEAT | CORN | $R^2$ | WHEAT | CORN | $R^2$ | WHEAT | CORN |
| 0–25     | 0.85  | 0.71  | 0.83  | 0.84  | 0.70  | 0.77  | 0.85  | 0.76  | 0.73  |
| 25–50    | 0.8   | 0.75  | 0.83  | 0.77  | 0.76  | 0.73  | 0.82  | 0.76  | 0.73  |
| 50–75    | 0.87  | 0.72  | 0.84  | 0.76  | 0.73  | 0.72  | 0.80  | 0.72  | 0.73  |
| 75–100   | 0.87  | 0.72  | 0.84  | 0.76  | 0.73  | 0.72  | 0.80  | 0.72  | 0.73  |

Table 5. The simulated relative yields for both calibration and validation periods.

| Crop         | Excess (RYw) | Deficit (RYw) | Delay (RY) | Salinity (RYs) | Overall (RY) | Excess (RYw) | Deficit (RYw) | Delay (RY) | Salinity (RYs) | Overall (RY) |
|--------------|--------------|---------------|------------|----------------|---------------|--------------|---------------|------------|----------------|---------------|
| Winter wheat | 96.2         | 100           | 100        | 100            | 96.2          | 100          | 100           | 100        | 86.8           | 86.8          |
| Corn         | 100          | 100           | 69         | 69             | 100           | 100          | 100           | 100        | 40.2           | 40.2          |
The model evaluation process relied on comparing different observed and simulated parameters. Simulation results indicated good agreement with the observed values. The study outcomes revealed that DRAINMOD-S could be used for long-term simulation and preparation of WTM schedules and policies in Egypt in areas with similar characterization as EL-Tina plain at Sinai.

The simulation results of adopting this management tool, (CD), in the study area (for 10 years), showed that: (a) The average quantity of drainage outflows throughout the simulation period increased as a result of increasing the managed drainage depth; (b) A remarkable increase in root-zone overall salinity will occur if the irrigation water salinity rises over 800 ppm; (c) Consequently, high salinity will damage the vast majority of crops normally grown in the study area, with the exception of high salt-tolerant ones such as wheat; (d) A more noticeable decrease in crop yields should be foreseeable in case of increasing both the managed drainage depth and salinity used for irrigation. The results demonstrate that controlled drainage
Figure 9. Influence of different irrigation water salinities on the root zone salinity.

Figure 10. Influence of varying irrigation water salinity on crop yield.
is a long-term investment and could be used as a strategy to optimize water use and reduce drainage but it may not provide yield benefit every year if being used for continuous and long time.

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