Open Journal of Soil Science, 2025, 15(6), 388-407
https://www.scirp.org/journal/ojss
ISSN Online: 2162-5379
ISSN Print: 2162-5360

Evaluating the Effect of Subsurface Drainage on Soil Properties and Maize Crop Production in Tina Plain Egypt

Arabi Ahmed Mohmmadien Eissa[1], Mohamed Bakr Abdel Ghany[1], Bassem Mohsen Elsayed Hassan Ebead[2], Ahmed Ibrahim Mohamed Ahmed[2]

[1]Drainage Research Institute, National Water Research Center (NWRC), Ministry of Water Resources and Irrigation (MWRI), Cairo, Egypt
[2]Department of Soil and Water Science, Faculty of Agriculture, Suez Canal University, Ismailia, Egypt
Email: ahmed_shabak@yahoo.com

How to cite this paper: Eissa, A.A.M., Abdel Ghany, M.B., Ebead, B.M.E.H. and Ahmed, A.I.M. (2025) Evaluating the Effect of Subsurface Drainage on Soil Properties and Maize Crop Production in Tina Plain Egypt. *Open Journal of Soil Science*, **15**, 388-407.
https://doi.org/10.4236/ojss.2025.156017

Received: April 20, 2025
Accepted: June 21, 2025
Published: June 24, 2025

Abstract

An experimental field was carried out at Tina plain region represented a pilot area (27 Fadden) located at the south-west part of Sinai Peninsula (Latitude of 30˚59'9.56"N and of longitude 32˚26'59.60"E). Irrigation and drainage networks served the studied pilot area. The current study investigated the impact of subsurface drainage on soil properties and crop growth under low-quality irrigation water conditions in the Tina Plain region of North Sinai. Soil samples were analyzed before and 12 years after installing a tile drainage system with 40-meter spacing and a depth of 140 cm. The results showed that subsurface drainage led to a lower water table, improved soil aeration, and better water and heat conditions, fostering a more favorable environment for biological activity and nutrient balance. These improvements protected the soil from the adverse effects of alkalinity and salinity, ultimately enhancing crop growth and production. Additionally, subsurface drainage expanded the cultivated area by eliminating the need for surface drainage canals. The findings highlight the significant role of subsurface drainage in sustaining soil health and boosting agricultural productivity.

Keywords

Subsurface Drainage, Available Water Depletion, Soil Properties, Maize Production, Tina-Plain, Low Water Quality

1. Introduction

Agricultural drainage is critical for improving soil productivity and ensuring sustainable farming, particularly in irrigated regions. Effective drainage regulates excess water, maintains optimal moisture, enhances root development, and supports yield stability. In arid and semi-arid areas such as Egypt, inadequate drainage leads to waterlogging, salinity, and alkalinity buildup, which significantly reduce soil fertility and crop productivity. The implementation of surface and subsurface drainage systems mitigates these issues by improving aeration, reducing salt accumulation, and preserving long-term soil health. Assessing the long-term impacts of subsurface drainage is essential, as it affects key soil properties including structure, porosity, and salinity. These effects are particularly pronounced when low-quality irrigation sources (e.g., saline or treated wastewater) are used. Without proper drainage management, salt accumulation, compaction, and nutrient imbalance can occur, degrading land productivity. Continuous monitoring and adaptive management are therefore necessary for optimizing drainage performance and sustaining agricultural output.

In Egypt, the Egyptian Public Authority for Drainage Projects (EPADP) oversees the planning, design, and maintenance of subsurface drainage networks. EPADP's design principles aim to sustain soil productivity and enhance irrigation efficiency. A simulation study using DRAINMOD evaluated the hydrological and agronomic impacts of drain depths (100, 120, and 140 cm) at three Nile Delta sites (Zanklon, Tokh, Hosh Essa). Results indicated that reducing drain depth by 28.5% decreased irrigation water use by 15%, but also led to yield reductions (1.2% - 5.8%) depending on crop type and salinity levels [1].

[2] assessed subsurface drainage impacts in four Pakistani projects (MSP, FDP, CCADP, MTDP). Post-drainage, crop yields improved by 13% - 94%, except at MTDP where rice yield declined by 23% due to inadequate irrigation. The most notable increases were observed in CCADP (cotton +80%, sugarcane +94%, wheat +67%). In MSP, rice yield rose by 46%, and in MTDP, chili yield increased by 147%. [3] investigated the impact of drainage spacings (5, 10, 20 m) on crop yields in southeastern Indiana versus an undrained control over a 37-year period starting in 1984. Results showed drainage increased corn (*Zea mays*) yields by 12% - 17%, while soybean (Glycine max) yields remained stable. Corn yields stagnated in undrained plots but improved steadily under drainage. Excessive rainfall within 14 days post-planting reduced yields; however, drainage mitigated these negative effects.

[4] evaluated yield benefits of a data-driven surface drainage approach on a commercial row-crop farm by analyzing corn and soybean yields (2008-2021) in two Indiana fields. Integrating field topography, drainage data, and historical yield maps, the study improved surface drainage strategies versus traditional ad hoc methods. Results showed corn yield increases of 18.3% and 13.9% in Fields 1 and 2, respectively. Targeted areas exhibited greater gains, ranging 15.9% - 26.5% (Field 1) and 21.4% - 40.2% (Field 2). Soybean yields similarly improved in modified drainage zones. These findings demonstrate that data-driven surface drainage planning effectively enhances corn and soybean production. The objectives of the Study are to: Evaluate changes in soil properties due to subsurface drainage.

Assess improvements in crop growth and productivity.

2. Materials and Methods

2.1. Study Area and Methodology

2.1.1. Study Area

The experimental site is located in the Tina Plain, northern Sinai Peninsula, Egypt (30˚59'9.56"N, 32˚26'59.60"E). The plain has a V-shaped configuration, bounded by the Mediterranean Sea (north and east), the Sinai Sand Sea (south), and the Suez Canal (west) (Figure 1). The field area spans ~27.36 acres, measuring 638.3 m (N-S) by 193.2 m (E-W), bordered by Drain No. 6 (east), Village No. 7 (west), and Area No. 2 in Galbana (south) (Figure 1). An irrigation canal, supplied by Al-Salam Canal, runs north-south across the field.

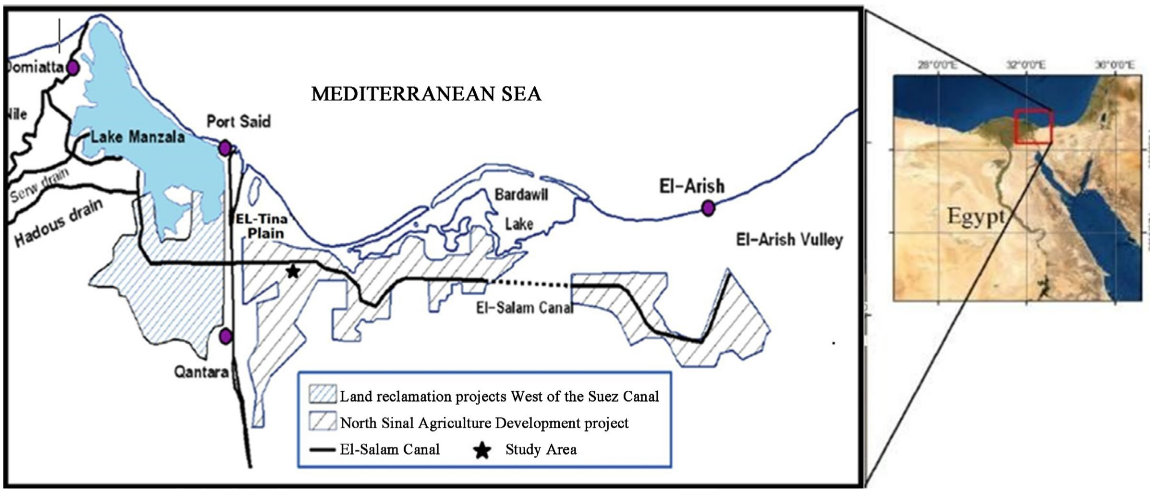

Figure 1. Experimental field site.

To assess the long-term effects of subsurface drainage on soil and crop parameters, soil samples were collected before drainage installation in 2010 and again 12 years later in 2022.

2.1.2. Climate and Hydrology

4uThe southern part of the Tina Plain experiences a Mediterranean arid climate, characterized by hot, dry summers and cold winters with minimal rainfall.

- Temperature: In July, the maximum temperature reaches 31.3˚C, while in January, it drops to a minimum of 4.9˚C.
- Rainfall: The region receives an annual precipitation of only 33.3 mm, occurring exclusively in winter, with minimal runoff due to the low rainfall.
- Sunshine & Solar Radiation: The area enjoys an average of 8.3 sunshine hours per day, with solar radiation averaging 16.8 MJ/m^2 per day, creating favorable conditions for crop growth [5].

2.1.3. Topography and Hydrogeology

The study area lies at an elevation of 0.4 to 0.5 meters above sea level and features a flat terrain. Irrigation water for the Tina Plain is supplied by the El-Salam Canal Project, which crosses the Suez Canal via a siphon and extends eastward into northern Sinai's desert. This project was designed to irrigate a total of 460,000 feddans, including:

- 220,000 feddans west of the Suez Canal.
- 400,000 feddans east of the canal in Sinai.

The canal transports a total annual discharge of 4.45 billion m^3, composed of:

- 2.2 billion m^3/year from Nile freshwater.
- 2.25 billion m^3/year from the Bahr Hadous and Lower Serw drains.

The water in the El-Salam Canal is a 50:50 mixture of freshwater and drainage water, maintaining an electrical conductivity (EC) below 1250 ppm, ensuring its suitability for irrigation [6].

The dominant soil texture of the experimental field is sandy loam, consisting of 75% sand, 20% silt, and approximately 5.2% clay. The soil pH ranges from 8.5 to 8.3. During the period of growth, and the total dissolved solids in the water used for irrigation ranged between 1.25 and 1.75 dS/m (800 to 1100 ppm). Drainage System, the main collector, is made of Polyvinyl Chloride (PVC), and was installed at a depth of 1.75 meters below the soil surface. The laterals were 75 meters long and spaced 40 meters apart, and installed at a depth of 150 cm. Each manhole connected with two laterals Both the laterals and the collector had a slope of 0.1%. The diameter of the lateral pipes was 80 mm, while the main collector had a diameter of 200 mm. To support soil profile modeling, saturated hydraulic conductivity (Ks) was measured using undisturbed core samples from each plot. Samples were extracted at depths of 0 - 50 cm, 50 - 100 cm, and 100 - 150 cm. Following borehole drilling, aluminum rings of known dimensions were driven vertically and horizontally into the soil at each depth using a ring holder and hammer. The cores were secured in vibration-resistant containers and transported to the lab, where they were saturated and subjected to hydraulic overpressure for Ks determination.

Physical and chemical analyses within the soil were conducted in the laboratory of the Drainage Research Institute in Egypt. At the start of the field experiment, (prior to the installation of the drainage system), the findings showed that the soil was sandy loam and the calcium carbonate content ranged from 3.3% to 3.8%.

2.1.4. Water Table Depths

Table 1 shows that 10 observation wells were installed in the study area. The results indicated an increase in water table depths across the area: Initial Soil water table depth (cm) prior to the installation of the drainage system.

2.1.5. Cultivated Crop

Maize (*Zea mays*) was cultivated over two cropping cycles in a 12-year field study: one prior to tile drainage installation in 2010 and another in 2022. Standard agronomic practices, including conventional tillage, pest control, and region-specific fertilization regimes, were applied. Nitrogen fertilizers (nitrate form) were applied in limited quantities post-emergence. Crop management included

Table 1. Locations of groundwater observation wells with Initial Soil water table depth (cm) prior to the installation of the drainage system.

Well Name	Location (Coordinates)		Water table (cm) Mean
	Latitude—Northing (N)	Longitude—Easting (E)	
Well No. 1	30.985368˚	32.448133˚	65.7
Well No. 2	30.985361˚	32.448521˚	66.0
Well No. 3	30.985353˚	32.448929˚	66.9
Well No. 4	30.985391˚	32.449379˚	66.9
Well No. 5	30.985393˚	32.449704˚	66.9
Well No. 6	30.984935˚	32.448198˚	66.0
Well No. 7	30.984946˚	32.448533˚	66.2
Well No. 8	30.984948˚	32.448973˚	66.0
Well No. 9	30.984940˚	32.449382˚	66.5
Well No. 10	30.984978˚	32.449779˚	66.6

scheduled planting, harvesting, fertilization, and pre-harvest irrigation, followed by soil preparation for the next cycle. Drain outflow was monitored weekly to assess bypass activity, and effluent samples were collected once per growing season during active drainage for analysis. The profundity of water table were measured midway between the drains using observation wells (**Table 1**) and **Figure 2**. General water table information is provided, and the base map showing the research area outlines and the outer boundaries. The wells were made of PVC pipes with a diameter of 5 cm and a length of 2 meters, and were perforated at the bottom and wars aped with a casing to aid in measuring water table depth.

Figure 2. Locations of observation wells in the study area.

2.2. Methodology

2.2.1. Subsurface Drainage System Design

Wrapped tile drainpipes (with synthetic material) were installed in the field (mechanically) at spacing 40 -meter. Between late drains and 140 cm depth below soil surface.

2.2.2. Soil and Crop Analysis

- Soil samples were collected before drainage installation and after 12 years after that.
- Monitoring water table depth, and salinity changes.
- Measuring crop growth, root development, and yield improvements.

2.3. Field Measurement

Ground water table depth: was measured daily between two consecutive irrigation intervals using a tape measure connected to a sounder [7].

Hydraulic Conductivity: Hydraulic conductivity (K) was measured on-site using the auger whole method, as described by [8]. The hole had a depth of 160 cm from the soil surface and a diameter of 10 cm.

2.4. Lab Measurements

Soil samples

Soil samples were collected both before the installation of the tile drainage system in 2010 and after its installation in 2022. Fifteen soil profiles were dug up to a level of 150 cm, where samples were taken from three depths: 0 - 50 cm, 50 - 100 cm, and 100 - 150 cm. The samples were air-dried, carefully crushed, and then prepared for routine chemical analysis.

- Total soluble salts were measured using an Electrical Conductivity (EC) apparatus in the soil paste extract [9].

- Soluble Cations: (Ca^{2+}, Mg^{2+}, Na^+, K^+) and soluble anions (CO_3^{2-}, HCO_3^-, Cl^-) were measured in meq/liter. Calcium and magnesium, as well as calcium alone, were determined by titration using versenate solution. Eriocromblau. K was used as the indicator for Ca^{2+} and Mg^{2+}, while ammonium purpurate was used to determine Ca^{2+} [10].

- Carbonates and Bicarbonates: were measured in meq/L by the application of a titration standard potassium hydrogen sulfate solution. Phenolphthalein was used as the indicator for carbonates, and methyl orange was used for bicarbonates [11].

- Sodium Adsorption Ratio, SAR: was calculated utilizing the subsequent formula.

$$\mathrm{SAR} = \mathrm{Na} \Big/ \sqrt{\frac{\mathrm{Ca} + \mathrm{Mg}}{2}}$$

Na^+, Ca^{2+} and Mg^{2+} were determined in the of saturated soil paste extract according to [9].

- Chlorides were titration determined according to Mohr's method [12].

- Sulphate was calculated by difference between total cations and total anions.

- Soil texture was determined using the worldwide pipette technique, as described by [13].

- Soil reaction, pH, was estimated in a soil-water suspension (1:2.5) according to [10].

- Organic matter content was ascertained utilizing the Walkley-Black method [10].

- Calcium Carbonate was determined using a calcimeter, as outlined by [14].

- Gypsum content in the soil was determined through precipitation, as described by [15].

2.5. Crop Production

Maize (a summer crop) are predominant in the region and selected for drainage evaluation. Specific areas within the experimental field (1 m^2) were chosen both before and after the drainage installation. The weights of maize, the parameters of vegetative growth (plant height and leaves dry weight), ear (length and diameter) and harvest (grain and Stover yields) were measured, with results expressed as tons per feddan.

3. Results and Discussion

3.1. Main Soil Characteristics

3.1.1. Soil Texture

The data indicated illustrates the particle size distribution in the studied soil profiles, with a summary of these values (by soil depth) before and after drainage installation of drainage system. The data reveal that the soil predominantly falls into the sandy or sandy loam categories. For the tile drainage system, the percentages of sandy, silt, and clay particles at different depths are as follows: 0 - 50 cm (65.9%, 18.4%, and 15.7%), 50 - 100 cm (68.9%, 15.4%, and 15.7%), and 100 - 150 cm (72.5%, 13.3%, and 14.2%). In contrast, for the non-wrapped pipe drains with synthetic envelope, the particle distribution is: 0-50 cm (74.5% sand, 21.6% silt, and 4.0% clay), 50 - 100 cm (73.9% sand, 20.7% silt, and 5.4% clay), and 100 - 150 cm (75.7% sand, 18.2% silt, and 6.1% clay). the data indicate that sandy loam or sandy textural classes are predominant, as compiled within **Table 2** After tile drainage system installation its observed that, sand, silt, and clay percentages ranged from 64.4% to 83.7% (average 69.1%), 11.2% to 22.3% (average 15.7%), and 5.1% to 18.7% (average 15.2%), respectively. For the non-wrapped drains, the ranges are 67.9% to 89.1% (average 74.7% sand), 7.3% to 24.4% (average 20.1% silt), and 3.7% to 7.7% (average 5.1% clay). Additionally, it was observed that clay content slightly increased with depth after drainage installation. This clay particle migration due to the installation process where drainage machine mixes the upper soil texture with the lower soil profile and also the moving of fine particles due to leaching through the continuous irrigation of agricultural lands during the study. The relatively coarse texture within the soil is linked to a low ability to retain moisture, making it crucial to manage water use efficiently for plant growth. The predominance of drainable pores, *i.e.* macro- and meso- soil porosity, and the siliceous characteristics within the soil, dominated by sand, assist in the limited capacity for retaining sufficient moisture for plants. Further details are available in **Table 2**. The soil textural classes in the studied profiles remained unchanged before and after the installation of the tile drainage system. The coarse texture observed is entirely influenced by the parent material and geological formation.

Table 2. Weight mean of particle size distribution values before and after drainage Installation.

Location	Before tile drainage			After tile drainage		
	Sand	Silt	Clay	Sand	Silt	Clay
1	74.7	20.7	4.5	66.4	15.8	17.8
2	73.5	21.7	4.8	67.4	14.8	17.8
3	71.4	24.1	4.5	67.6	13.7	18.7
4	71.7	23.6	4.7	67.8	14.8	17.4
5	72.0	23.2	4.8	68.0	15.9	16.1
6	71.8	23.4	4.8	68.0	13.7	18.3
7	72.2	22.7	5.1	68.4	13.7	17.8
8	73.7	21.5	4.8	64.4	17.9	17.6
9	72.3	22.9	4.8	67.7	15.5	16.8
10	71.5	23.4	5.1	70.7	13.8	15.5
Mean	**72.5**	**22.7**	**4.8**	**67.6**	**15.0**	**17.4**
max	**74.7**	**24.1**	**5.1**	**70.7**	**17.9**	**18.7**
min	**71.4**	**20.7**	**4.5**	**64.4**	**13.7**	**15.5**
STDEV.S	**1.1**	**1.1**	**0.2**	**1.6**	**1.4**	**1.0**

3.1.2. Soil Reaction (pH)

The data, presented in **Figure 3** and **Table 3**, showed that the average pH value for soil before drainage was 8.53, whereas the average pH for the soil after drainage implementation was 7.41. The implementation of the tile drainage system notably reduced soil pH, especially on the upper layer of the soil profile.

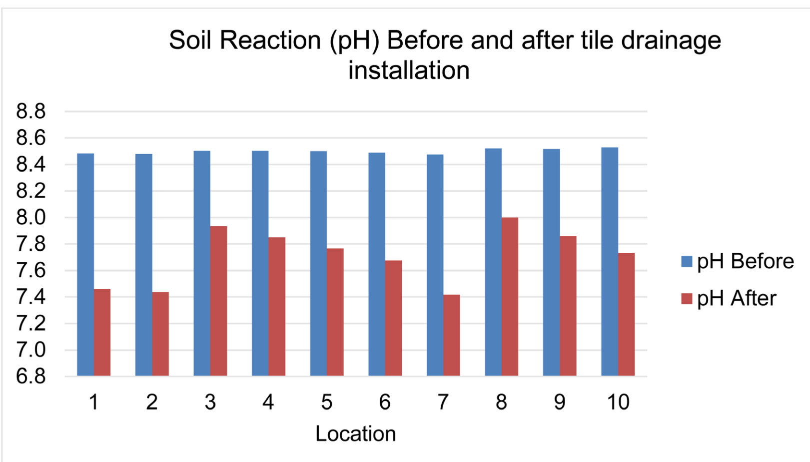

Figure 3. Soil Reaction (pH) before and after tile drainage installation.

This reduction in pH is attributed to leaching of soil salts due to drainage system and the organic matter content on the upper soil layers compared to the lower layers. These results are consistent with findings reported by [16].

Table 3. Weight mean of soil pH, organic matter (O.M.), EC, SAR and ESP values as affected by tile drainage and non-drainage.

Location	pH		O.M		EC ($dS\cdot m^{-1}$)		SAR		ESP	
	Before drain	After drain	Before dr.	After dr.	Before dr.	After dr.	Before dr.	After dr.	Before dr.	After dr.
1	8.5	7.5	0.3	0.8	40.7	4.4	28.9	6.5	34.6	8.1
2	8.5	7.4	0.5	0.9	52.5	4.2	38.0	6.6	45.4	8.3
3	8.5	7.9	0.4	0.9	34.9	6.0	24.5	7.5	29.4	9.3
4	8.5	7.9	0.6	1.0	60.4	4.5	40.8	7.4	48.8	9.2
5	8.5	7.8	0.8	1.0	85.7	3.0	57.2	7.3	68.3	9.1
6	8.5	7.7	0.5	0.9	52.5	4.2	38.0	6.6	45.4	8.3
7	8.5	7.4	0.4	0.9	64.3	4.1	47.1	6.7	56.1	8.5
8	8.5	8.0	0.4	0.9	69.7	3.9	49.0	7.4	58.4	9.3
9	8.5	7.9	0.7	1.0	66.4	4.7	47.2	7.8	56.2	9.7
10	8.5	7.7	0.7	1.1	69.3	5.8	51.7	8.6	61.5	10.6
Mean	8.5	7.7	0.5	0.9	59.6	4.6	42.2	7.2	50.4	9.0
max	8.5	8.0	0.8	1.1	85.7	7.6	57.2	8.6	68.3	10.6
min	8.5	7.4	0.3	0.8	34.9	3.0	24.5	6.5	29.4	8.1

3.1.3. Soil Salinity

Salinity levels, expressed as electrical conductivity (EC) of saturated soil paste extracts (dS/m), are presented in **Table 3**. Prior to drainage installation, surface layer EC values ranged from 14.7 to 90 dS/m, while subsurface values ranged from 17.8 to 81.7 dS/m. Across profiles 1 and 10, average salinity ranged from 34.9 to 85.7 dS/m, with a mean of 59.6 dS/m. The data clearly confirm that the soil under study exhibited extremely high salinity, likely due to the high groundwater salinity in the eastern north region [17]. However, following the installation of the drainage system, soil salinity profiles significantly decreased to acceptable levels below 3.0 ds/m within 12 years. This improvement can be attributed to the installation of tile drainage, which facilitated the removal of soluble salts that are leached from the root zone. Additionally, the enhancement in soil salinity conditions due to continuous cultivation, improved soil aggregation. These findings agreed with the results reported by [18].

3.1.4. Sodium Adsorption Ratio and Exchangeable Sodium Percentage in Soil

Data in **Table 3**, indicated that the average sodium adsorption ratio (SAR) in non-drained soil ranged from 16.2 to 60.1, using a mean of 41.6 (Standard Deviation =

16.291). After the installation of tile drainage, SAR values decreased, ranging between 6.5 and 14.9, with a mean of 8.5 (Standard Deviation = 2.582). This reduction was most pronounced on the surface layers of the soil profiles. The decrease is likely due to the high leaching of sodium (Na^+) relative to calcium (Ca^{++}) and magnesium (Mg^{++}). These findings are consistent with the results reported by [19].

Additionally, SAR values increased with soil depth, the trend is attributed to the downward movement and accumulation of soluble sodium that was drained from the surface layers. [20] noted a strong positive correlation (0.76) between soil electrical. conductivity (EC) and SAR before the installation of the tile drainage system, while the correlation coefficient between EC and SAR after installation was nearly zero (0.04).

The percentages of exchangeable sodium (ESP) for all data are presented in Table (3)., in non-drained soil, ESP values ranged from 19.4 to 89.5, using a mean of 49.8 (Standard Deviation = 19.046). After installing the drainage system, ESP values decreased significantly, ranging from 5.7 to 25.4, using a mean of 10.6 (Standard Deviation = 3.059). A positive correlation with r = 0.85 was observed between electrical conductivity of soil (EC) and ESP before the installation of the tile drainage system. However, after installation, there was no significant correlation between EC and ESP.

The reduction in ESP following the construction of tile drainage is attributed to increased leaching of Na^+ ions, which in turn leads to a decrease in SAR. These results are consistent with those reported by [21]. Additionally, ESP values increased with soil depth under all studied conditions. This rise is because of the higher solubility of sodium salts, which move downward more readily with leaching process and irrigation water in contrast to calcium and magnesium salts [16].

3.1.5. Organic Matter

Organic matter (OM) content data, summarized in **Table 3**, showed a consistent decline with increasing soil depth. The highest OM concentrations were detected in surface layers, attributed to crop residue accumulation from continuous cultivation. In undrained soils, mean OM content was 0.36%, increasing to 1.08% following tile drainage installation. The most substantial increase was recorded in the topsoil. Pre-drainage OM values were 0 - 50 cm (0.61%), 50 - 100 cm (0.47%), and 100 - 150 cm (0.38%). Post-drainage values increased to 1.19%, 0.95%, and 0.77%, respectively. These improvements reflect the role of colloidal materials in enhancing aggregate stability and water retention, thereby improving moisture availability within the root zone.

Organic colloidal particles not only enhance soil structure but also modify the solid-liquid interface by altering the contact angle between soil particles and water [22]. According to [23], application of 10 t ha^{-1} farmyard manure combined with chemical amendments significantly improved soil bulk density, total porosity, and hydraulic conductivity. As reported by [24], increased water retention in coarse soils treated with colloids is attributed to: (a) reduced bulk density and increased porosity, (b) improved soil structure and pore size distribution, (c) superior water-holding capacity of colloids compared to sand particles, and (d) decreased hydraulic conductivity due to structural modification. Organic amendments in sandy soils enhanced moisture retention, reduced bulk density, and increased porosity. Additionally, organic matter and compost served as nutrient sources, improving soil fertility. Recent findings [25] indicate that compost combined with chemical fertilizers further increased biomass and grain yields in rice and wheat.

3.1.6. Water Table Fluctuation

Water table fluctuation data before and after tile drainage installation are presented in **Table 3**. Prior to drainage, water table recession occurred gradually. Two days post-irrigation, depths ranged from 18.4 to 26.8 cm (mean = 22.6 cm). In contrast, after tile drainage installation, depths increased to 41.3 - 49.2 cm (mean = 45.25 cm). By day five, pre-drainage depths ranged from 41.6 to 49.1 cm (mean = 43.7 cm), while post-drainage depths reached 90.4 - 98.2 cm (mean = 92.5 cm). Ten days post-irrigation, depths increased to 85.4 - 99.3 cm (mean = 88.9 cm) before drainage, and 120.3 - 129.4 cm (mean = 122 cm) after drainage. **Figure 3** illustrates the drawdown ratio, which was consistently higher after drainage installation. The rate of drawdown accelerated, particularly within 4 - 8 days post-irrigation, indicating improved drainage performance and water table control following the system's implementation. Water table levels in tile-drained fields decreased more rapidly than pre-drainage, with mean levels dropping by ~35%, consistent with findings by [26], who examined drainage effects on groundwater and drain flow, comparing open and pipe drainage systems with varying spacing and depths. Their results showed that without pipe drainage, groundwater remains near the soil surface during heavy rainfall. Additionally, [27] reported that soil salinity reduction is positively correlated with groundwater table control, highlighting the role of effective drainage in regulating both water level and soil salinity.

3.1.7. Soil Hydraulic Conductivity

Hydraulic conductivity (Ks) values for the studied soil profiles are presented in **Table 4** and **Figure 4**. Ks consistently increased after tile drainage installation across all profiles, attributed to trench excavation causing soil restructuring, enhancing aggregate formation, pore space, and water pathways. Pre-installation, Ks ranged up to 0.46 m/day with a mean of 0.38 m/day (standard deviation = 0.052), while post-installation values ranged from 0.65 to 1.29 m/day, with a mean of 0.83 m/day (standard deviation = 0.19).

Hydraulic conductivity depends on pore geometry, particle surface characteristics, and factors such as soil texture, structure, density, degree of cementation, organic matter content, and the presence of Ca^{2+} or Na^{+} ions, as well as the type of clay minerals [28]. The design and performance of tile drainage systems are heavily dependent on soil's saturated hydraulic conductivity (K) [29], where this parameter is employed in all drain-spacing equations. Consequently, accurately determining of the K-value is critical when designing or assessing a drainage project. It can be concluded that the tile drainage system implemented in the experimental field effectively lowers the water table depth and enhances soil hydrological properties. This improvement is reflected in increased water table draw-down rates, greater drainage intensity, and higher soil hydraulic conductivity. Maintaining nutrient balance for long-term agricultural use.

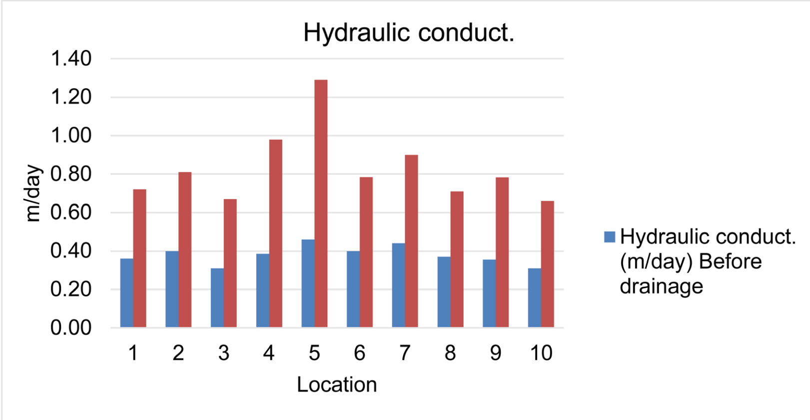

Figure 4. Average Soil hydraulic conductivity before and after tile drainage installation.

Table 4. Average Soil hydraulic conductivity before and after tile drainage installation.

Profile	Hydraulic conduct. (m/day)	
	Before drainage	After drainage
1	0.36	0.72
2	0.40	0.81
3	0.31	0.67
4	0.39	0.98
5	0.46	1.29
6	0.40	0.79
7	0.44	0.90
8	0.37	0.71
9	0.36	0.78
10	0.31	0.66
Mean	**0.38**	**0.83**
max	**0.46**	**1.29**
min	**0.31**	**0.66**
STDEV.S	**0.05**	**0.19**

3.2. Crop Yield

Maize Growth and Yield as Affected by the Drainage System

Seed germination percentage, growth parameters (plant height, leaf dry weight), maize ear traits (length, diameter), and biological yield (grain and stover) of representative maize plants are summarized in Table 5 and Figures 5-8. Results indicate that all measured parameters from 2010 to 2022 in fields irrigated with El-Salam canal water under drainage showed significantly higher values post-tile drainage installation compared to pre-installation. Statistical analysis (L.S.D., $p < 0.05$) confirmed significant improvements in maize growth and yield parameters following drainage implementation across all studied seasons.

Table 5. Average Germination percentage, vegetative and harvest parameters of maize as affected before and after drainage system.

Drainage system (DS)	Germination %	Vegetative growth parameters		Maize ear parameters		Harvest parameters	
		Plant height (cm)	Leaves dry weight / plant (g)	Length (cm)	Diameter (cm)	Grain yield (ton/fed)	Dry weight of maize stalk (kg/fed)
Before drainage	16.05	32.4	16.61	5.18	1.28	0.54	1067
After drainage	82.08	179.44	67.27	17.64	4.44	2.18	2957

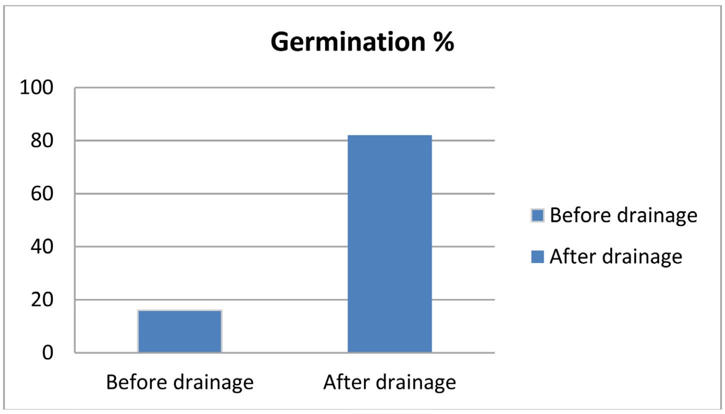

Figure 5. Average Germination percentage of maize as affected by before and after drainage system.

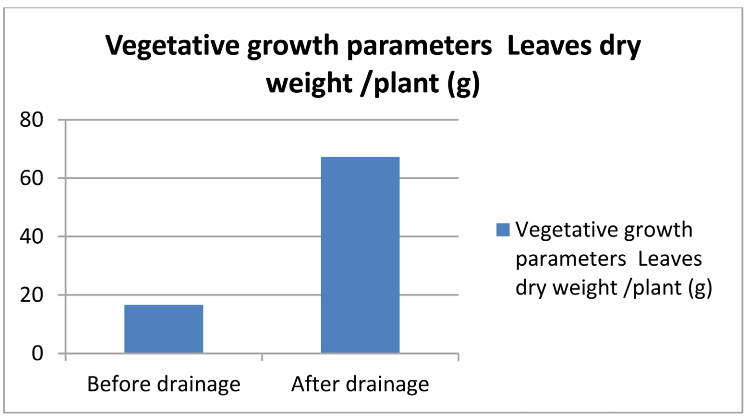

Figure 6. Average Leaves dry weight of maize as affected by before and after drainage system.

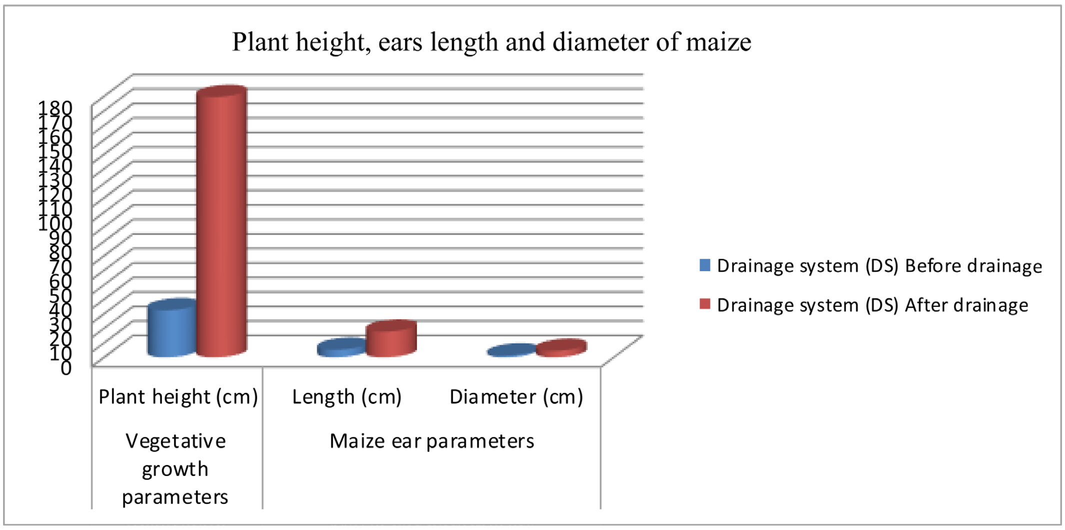

Figure 7. Average Plant height, ears length and diameter of maize as affected by before and after drainage system.

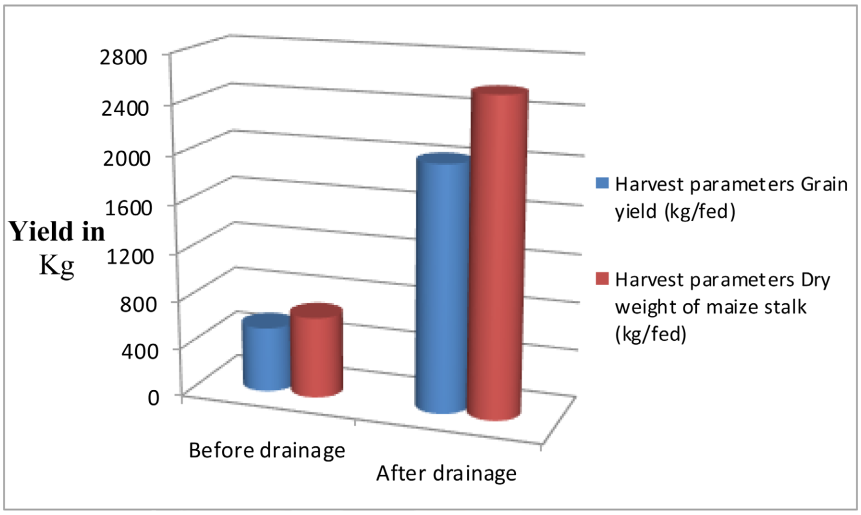

Figure 8. Average Grain and Straw yield of maize as affected by before and after drainage system.

A gradual, significant increase in all studied plant parameters was observed from 2010 to 2022, coinciding with a progressive decrease in soil salinity and sodicity over the cultivation period. The benefits of the drainage system include reducing nutrient dilution and minimizing losses of available water and nutrients beyond the effective root zone. Conversely, prior to drainage installation, plant performance was constrained by soil moisture stress and imbalanced soil water-air relations, which suppressed photosynthesis and disrupted hormonal and physiological processes, negatively affecting vegetative growth, dry matter accumulation, and causing flower defoliation [30]. Post-drainage improvements are attributed to enhanced soil water-air balance, promoting nutrient uptake and sustaining soil fertility, thereby providing optimal conditions for seed germination and root development [31].

Table 5 shows that post-drainage maize harvest parameters were grain yield of 2.18 ton/fed and stalk dry weight of 2957 kg/fed, compared to 0.54 ton/fed and 1067 kg/fed, respectively, before drainage. These results align with studies [32] [33] indicating that moderate soil moisture stress allows deeper root water extraction and more efficient water use, whereas excessive soil moisture depletion reduces water use efficiency.

In summary, the increase in maize harvest parameters closely paralleled corresponding vegetative growth values (Table 5). Post-drainage vegetative and ear parameters were: germination 82.08%, plant height 179.44 cm, leaf dry weight 67.27 g/plant, ear length 17.64 cm, and diameter 4.44 cm. Before drainage, these values were significantly lower: germination 16.05%, plant height 32.4 cm, leaf dry weight 16.61 g/plant, ear length 5.18 cm, and diameter 1.28 cm. This response magnitude likely depends on the drainage system type and associated soil moisture stress, as plots with drainage consistently showed higher values compared to those without. These results align with [34], who attributed maize yield declines mainly to reduced soil moisture availability limiting water and nutrient uptake. Additionally, [35] [36] reported that tile drainage effectively lowers root-zone salinity, enhances crop yield, and reduces waterlogging.

Similar findings were reported by [37], who observed a 6.9% increase in crop yield due to drainage, attributed to improved soil water content in the root zone by maintaining an optimal water table depth. [38] documented enhanced maize and soybean yields with drainage in a two-year field study in eastern Ontario, while [39] reported a 64% maize yield increase under drained conditions. Likewise, [40] found that a water table at 0.70 m improved moisture availability in the root zone, enhancing water and mineral uptake and increasing alfalfa dry matter yield. Conversely, [41] noted yield declines at 1.2 m water table depth, likely due to reduced available water and nutrient leaching-induced low soil fertility. Maize, being highly responsive to irrigation volume, showed increased dry weight with higher water levels, reflecting improved rhizosphere moisture that enhances photosynthesis, cell division, stem elongation, and biomass accumulation. [42] reported significant annual maize yield variability influenced by climate, with drained and controlled drainage systems achieving the highest yields (up to 14.5 t ha^{-1} grain), representing average increases of 27.3% in grain maize and 4.0% in silage maize.

3.3. Drainage and Crop Production

Data showed that maize yields under tile drainage systems are higher than in non-drained soils, showing a 76% increase in corn yield. This improvement is attributed to tile drainage's enhancement of soil properties, including maintaining optimal air-water balance and thermal conditions, which promote biological activity and nutrient availability. The system also mitigates soil salinity and alkalinity effects. Moreover, tile drainage conserves land otherwise used for open canals, enabling increased cultivation area and improved soil productivity.

These findings align with [43], demonstrating that tile drainage enhances yields in crops such as corn and forages [44] [45]. For example, [46] reported a 46.77% yield increase in corn. Additionally, tile drainage improves machinery efficiency on drier soils, reducing labor hours [47] and lowering fossil fuel use and associated costs [48].

4. Conclusions and Recommendations

4.1. Conclusions

Subsurface drainage significantly improves soil conditions and crop productivity.

Essential for sustainable agriculture in saline-prone regions like Sinai. The Subsurface Drainage System is notably effective in creating a lower water table, reducing salinization and alkalinization, and improving soil water, air, and heat conditions. These improvements lead to better soil conditions that boost biological activity and maintain nutritional balance by protecting the soil from the detrimental consequences of salinity and alkalinity. Additionally, it conserves land that would otherwise be used for constructing surface canals. Compared to non-drained soils, this system significantly lowers salt concentrations. It also helps retain water in the subsurface layer, promoting better plant growth. Implementing a System of Subsurface Drainage on a farm scale in the southwest part of the Tina plain region can be beneficial, especially in conserving low-quality irrigation water. The effectiveness of a drainage system depends on local site characteristics, including soil characteristics, land slope, climate, cropping practices, nutrient management, and the keep of the system of drainage itself. Over the next 20 years, water conservation will become increasingly crucial due to constraints from the fixed Nile water share, rising population, industrial growth, and horizontal expansion plans. Enhancing the efficiency of arable land is essential for sustainable development. Effective drainage techniques are used to improve soil quality and support sustainable farming practices while preserving agricultural yields, managing soil and water resources, and controlling farmer costs.

Subsurface drainage can effectively address issues of high groundwater levels and soil salinity, while boosting crop yields in semi-arid regions. In the context of maize, it was observed that crops grown and irrigated with a subsurface drainage system were benefitted from optimal management practices, resulting in the highest productivity per unit area. Additionally, this approach contributed to improved grain quality for both maize.

4.2. Recommendations

- Wider adoption of subsurface drainage in similar environments.
- Further research on optimizing drainage system design.
- Integration with other sustainable agricultural practices for long-term soil health.
- Expansion into new areas is a crucial task that must be prioritized to address population growth.

- Leaching is a vital process for reclaiming saline and alkaline soils, such as the Tina Plain.
- Low-quality water (non-conventional water) is recommended for use in leaching, saline soils. During the leaching process, soil amendments must be applied to prevent soil from deteriorating to alkalinity.
- Monitoring soil EC and pH are essential during the leaching process.
- Installing subsurface drainage after soil reclamation is important to remove excess water from the soil profile. Design criteria for newly reclaimed areas must be carefully studied, especially in regions using modern irrigation systems.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Muhammad, E.S., Ibrahim, M.M. and El-Sayed, A. (2021) Effects of Drain Depth on Crop Yields and Salinity in Subsurface Drainage in Nile Delta of Egypt. *Ain Shams Engineering Journal*, **12**, 1595-1606. https://doi.org/10.1016/j.asej.2021.01.008

[2] Azhar, H. and Masood, M. (2011) Subsurface Drainage Impact Assessment on Crop Yield. *The Journal of Animal & Plant Sciences*, **21**, 857-861.

[3] Rui, Y., Goller, B. and Kladivko, E.J. (2024) Long-Term Crop Yield Benefits of Subsurface Drainage on Poorly Drained Soils. *Agronomy Journal*, **116**, 2151-2162. https://doi.org/10.1002/agj2.21621

[4] Regmi, S., Davidson, P. and Allen, C. (2024) Yield Impact of Data-Informed Surface Drainage: An On-Farm Case Study. *Agriculture*, **14**, Article 2210. https://doi.org/10.3390/agriculture14122210

[5] Gabr, M.E. and Fattouh, E.M. (2021) Assessment of Irrigation Management Practices Using FAO-CROPWAT 8, Case Studies: Tina Plain and East South El-Kantara, Sinai, Egypt. *Ain Shams Engineering Journal*, **12**, 1623-1636. https://doi.org/10.1016/j.asej.2020.09.017

[6] Donia, N.S. (2012) Development of El-Salam Canal Automation System. *Journal of Water Resource and Protection*, **4**, 597-604. https://doi.org/10.4236/jwarp.2012.48069

[7] Ritzema, H.P. (1994) Subsurface Flow to Drains. In: Ritzema, H.P., Ed., *Drainage Principles and Applications*, ILRI Publication, 263-304.

[8] Van Beers, W.F.J. (1965) Some Monographs for the Calculation of Drain Spacing's. ILRI Publication.

[9] Richards, L.A. (1954) Diagnosis and Improvement of Saline and Alkali Soils. *Soil Science*, **78**, 154. https://doi.org/10.1097/00010694-195408000-00012

[10] Jackson, M.L. (1962) Soil Chemical Analysis. Constable and Company Ltd.

[11] Nelson, R. (1982) Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42 Version 1.0.

[12] Rhoades, J.D. (1982) Soluble Salts. In: *Methods of Soil Analysis*. *Part* 2. *Agronomy Homograph*, American Society of Agronomy Inc.

[13] Piper, C.S. (1950) Soil and Plant Analysis Inter. Science Publication Inc.

[14] Klute, A. (2018) Water Retention: Laboratory Methods. In: *SSSA Book Series*, *Soil Science Society of America*, American Society of Agronomy, 635-662. https://doi.org/10.2136/sssabookser5.1.2ed.c26

[15] Bower, C.A., Reitemeier, R.F. and Fireman, M. (1952) Exchangeable Cation Analysis of Saline and Alkali Soils. *Soil Science*, **73**, 251-262. https://doi.org/10.1097/00010694-195204000-00001

[16] Abou Hussien, E.A. and Abou EL-Khir, A.M. (1999) Evaluation of Effect of Tile Drainage and Gypsum Application on Soil Chemical Properties and Some Nutrients and Trace Elements Status. *Journal of Agricultural Sciences*, **24**, 3725-3736.

[17] Moukhtar, M.M., El-Hadidy, E. and EL-Shewikh, M.B. (2003) Improving Water Table Condition in Deteriorated Salty Clay Soil in Egypt. 9*th Drainage Workshop*, Utrecht, 10-13 September 2003.

[18] El Osta MM, E.S.M. (2013) Study of the Phenomenon of Groundwater Levels Rise in South El Qantara Shark Area, Ismailia, Egypt. *Journal of Hydrogeology & Hydrologic Engineering*, **2**, Article 2. https://doi.org/10.4172/2325-9647.1000109

[19] Abou-Sinna, M.A., Somya, A.H., Selem, M.I. and Kandil, N.F. (1994) Effect of Irrigation with Bahr El Bagar Drain Water on III: Some Soil Physical Properties. *Computer Science-Research and Development*, **46**, 131-149.

[20] Habib, I.M., Sadek, S.H.A., Moukhtar, M.M. and Abdel-Mawgoud, A.S. (1994) Chemical Amendments Efficiency for Salt-Affected Soil Reclamation. *Minufiya Journal of Agricultural Research*, **19**, 2335-2353.

[21] Madramootoo, D.M. and Buckland, G.D. (1990) The Use of Shallow Sub-Surface Drains to Reclaim Saline and Water-Logged Lands Due to Canal Seepage in Southern Alberta, Canda. 4th International Commission on Irrigation and Drainage.

[22] Sadek, M.I., Amal, A.M., *et al.* (1992) Effect of Some Physical Properties of Sandy Soil. *Annals of Agricultural Science*, *Moshtohor*, **30**, 2081-2091.

[23] Hussain, N., Hassan, G., Arshadullah, M. and Mujeeb F. (2001) Evaluation of Amendments for the Improvement of Physical Properties of Sodic Soil. *International Journal of Agriculture and Biology*, **3**, 319-322.

[24] Tayel, M., Ghazy, A., Abdel Aal, R. and Wanas, S.H. (2001) Improving Sand Soils Using Cellulose Derivatives. 2: Pore Size Distribution, Soil Water Retention, Soil Hydraulic Conductivity and Soil Hydraulic Resistivity. *Egyptian Journal of Soil Science*, **41**, Article 231.

[25] Sarwar, G., Hussain, N., Schmeisky, H., Sarwar, S., Hussain, G.N. and Muhammad, S. (2007) Use of Compost an Environment Friendly Technology for Enhancing Rice-Wheat Production in Pakistan. *Pakistan Journal of Botany*, **39**, 1553-1558.

[26] Ibrahim, S.M. (1992) Drainage Effects in Marsh Soils, I. Effects on Water Table and Drain Flow. *Proceedings of* 6*th International Drainage Symposium*, Nashville, 30 August-3 September 1992, 169-176.

[27] Zhou, F.X., Feng, W.W., Wei, S.H., Gui, W.X. and Ling, H.C. (2010) Effects of Controlled Drainage on Soil Salinity in Green House. Irrigation and Drainage.

[28] Montagne, D., Cornu, S., Le Forestier, L. and Cousin, I. (2009) Soil Drainage as an Active Agent of Recent Soil Evolution: A Review. *Pedosphere*, **19**, 1-13. https://doi.org/10.1016/s1002-0160(08)60078-8

[29] Oosterbaan, R.J. and NIjland, H.J. (1994) Determining the Saturated Hydraulic Conductivity. In: RItzema, H.P., Ed., *Drainage Principles and Applications*, International Institute for Land Reclamation and Improvement.

[30] Kerlous-Amany, N.K. (1997) Effect of Sowing Dates and Water Stress on Productivity

of Bean (*Phaseolus vulgaris* L.) Plants. Master's Thesis, Ain Shams University.

[31] Davies, B., Eagle, D. and Finney, B. (1982) Soil Management. 4th Edition, Farming Press Book.

[32] Tisdal, S.L., Nelson, W.L. and Beaton, J.D. (2001) Soil Fertility and Fertilizers. 5th Edition, Collier Macmilan.

[33] Taha, I.H.B. (2001) Studies on Water Requirements for Some Crops under Different Cropping Systems. Master's Thesis, Cairo University.

[34] Saied, M.M. (1997) Impact of Water and Nitrogen Fertilizer Levels on Maize Yield and Its Water Relations at North Delta. *Journal of Agricultural Science—Mansoura University*, **22**, 3393-3402.

[35] Asim, S.M. (1999) Impact of Tile Drainage on Soil and Water Quality in Swabi SCARP Area. Master's Thesis, NWFP Agricultural University Peshawar.

[36] Bhutta, M.N., Wolters, W. and Siddiqui, W.Z. (1996) Performance of Pipe Drainage in Pakistan. *Proceedings of 6th Drainage Workshop on Drainage and Environment*, Ljubliena, 21-23 April 1996, 79-88.

[37] Abdel-Gawad, S.T., Wahba, M.S., Abbott, C.L. and Counsell, C.J. (2000) Controlled Drainage Strategies to Save Water in Semi-Arid Agricultural Areas such as the Nile Delta, Egypt. *International Conference on the Challenges Facing Irrigation and Drainage in the New Millennium*, Fort Collins, 20-24 June 2000.

[38] Mejia, M.N., Madramootoo, C.A. and Broughton, R.S. (2000) Influence of Water Table Management on Corn and Soybean Yields. *Agricultural Water Management*, **46**, 73-89. https://doi.org/10.1016/s0378-3774(99)00109-2

[39] Ng, H.Y.F., Tan, C.S., Drury, C.F. and Gaynor, J.D. (2002) Controlled Drainage and Subirrigation Influences Tile Nitrate Loss and Corn Yields in a Sandy Loam Soil in Southwestern Ontario. *Agriculture, Ecosystems & Environment*, **90**, 81-88. https://doi.org/10.1016/s0167-8809(01)00172-4

[40] Noory, H., Liaghat, A.M., Chaichi, M.R. and Parsinejad, M. (2009) Effects of Water Table Management on Soil Salinity and Alfalfa Yield in a Semi-Arid Climate. *Irrigation Science*, **27**, 401-407.

[41] Antar, S.A., Khafagi, H.A., Nasr El-Din, I.E. and El-Saiad, I.A. (2012) Effect of Tile Drainage and Laser Land Leveling on Some Soil Properties and Production of Sugar Beet and Wheat Crops. *Journal of Soil Sciences and Agricultural Engineering*, **3**, 1-15.

[42] Tolomio, M. and Borin, M. (2019) Controlled Drainage and Crop Production in a Long-Term Experiment in North-Eastern Italy. *Agricultural Water Management*, **222**, 21-29.

[43] Abdel Dayem, M.S. and El-Safty, M. (1992) Review of Egyptian Experience in Implementing subsurface Drainage Projects. *Proceedings 5th International Drainage Workshop*, Lahore, 8-15 February 1992, 4-76.

[44] Warin, F., Zimmer, D., Kao, C., Hendrickx, F., Dulhoste, C. and Cooper, T. (1998) Surface and Subsurface Drainage Functioning in Florida Flatwoods. *Proceedings of the 7th Annual Drainage Symposium*, Orlando, 8-10 March 1998, 488-495.

[45] Buscaglia, H.J., van Es, H.M., Geohring, L.D., Vermeulen, H.C.A.M., Fick, G.W. and Lucey, R.F. (1994) Alfalfa Yield and Quality Are Affected by Soil Hydrologic Conditions. *Agronomy Journal*, **86**, 535-542. https://doi.org/10.2134/agronj1994.00021962008600030015x

[46] Colwell, H.T.M. (1978) The Economics of Increasing Crop Productivity in Ontario and Quebec by Tile Drainage Installation. *Canadian Farm Economics*, **13**, 1-7.

[47] Plamenac, N. (1988) Effects of Subsurface Drainage on Heavy Hydromorphic Soil in the Nelindvor Area, Yugoslavia. *Agricultural Water Management*, **14**, 19-27.

[48] Madramootoo, C.A. (1997) Management of Agricultural Drainage Water Quality: Introduction. In: Madramootoo, C.A., Johnston, W.R. and Willardson, L.S., Eds., *Management of Agricultural Drainage Water Quality*, International Commission on Irrigation and Drainage, Food and Agriculture Organization of the United Nations Rome.