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Effects of drain depth on crop yields and salinity in subsurface drainage in Nile Delta of Egypt

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ABSTRACT

The subsurface drainage system is the vast majority of Egypt's Nile Delta agricultural land to drain excess water from the soil, improve crop productivity, and guarantee the irrigated agriculture sustainability. This research aims to propose and assess drain depths that unequivocally connect the drainage system's structure to crop yields, water preservation, and soil salinity. For achieving this study's objective; three experiment sites in the Nile Delta in Zanklon, Tokh, and Hosh Essa were setup and a numerical model (DRAINMOD) was applied to simulate the hydrology, crop yield, and salinity. The tested drain depths were 140, 120, and 100 cm. The results were introduced for different crops and lateral spacing. The study concludes that a 28.5% decrease in drainage depth leads to conservation in the irrigation water by 15%, with a reduction in crop yield varying between 1.2% and 5.8% according to the cultivated crop and the sustaining soil salinity.

1. Introduction

Agricultural drainage is essential for sustainable agricultural land and so food productivity worldwide. In humid areas, drainage gives site traffic the ability to conveniently planting, harvest, and removes excess water from the root zone. In dry and semiarid areas, drainage is essential for waterlogging and salinity control. Despite the dramatic changes in cultivating rehearses and water resource deficiency, the structure models for the agriculture drainage system in Egypt have not been reviewed during the most recent three decades. The Egyptian Public Authority for Drainage Projects (EPADP) mandate is to implement conduct the subsurface drainage system in Egypt. The current design criteria are mainly centered around controlling water-logging and soil salinity with minor contemplations for the subsurface drainage effect on water amount. The EPADP set the principle design criteria of the subsurface drainage system in Egypt to sustain land productivity and effective farming operations.

Numerous researches were associated with controlling drainage; Abdel-Gawad [4] reasoned that around 8–14% of irrigation water was saved on account of controlling drainage in the winter months without a critical reduction in crop yield. Implementing control drainage can lead to a decrease in drainage water. John et al. [5] and Sojka et al. [6]. Gamall et al. [7] and Wahba et al. [8] announced that it was conceivable to save around 15–20% of the necessary irrigation amounts by the presence of a well-planned drainage system. The saved water can be used in cultivating larger areas or even in any human utilities. Helmers et al. [10] assumed that the amounts of drainage water were decreased by around 30–40% through the drainage water management by actualizing a shallow drainage system. Ayars and Evan [11] structured an agricultural water management system to improve the crop yield and water quality by utilizing a procedure to control and lessening the drainage water and the related nitrate. Christen and Ayars [2] expressed that to decrease water irrigation quantities. A combination of the irrigation and drainage system should be worked out. Idris [12] investigated free flow drainage in the southeast of Turkey; the investigation showed that the drainage irrigation ratio was 12.5% while the ratio reduced to 8% when controlling drainage applied.

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Nomenclature

DRAINMOD	Drainage Water Management Suite of Models
EPADP	The Egyptian Public Authority for Drainage Projects
N	North Direction
E	East Direction
Fed.	Feddan = 4200 m^2
MAE	The Mean Absolute Error
EF	Nash-Sutcliffe modeling efficiency
PPM	Part Per Million
FAO	Food and Agriculture Organization of the United Nations

Hamidreza et al. [13] noticed that a large amount of drainage water with low effectiveness brought about by the regular free subsurface water in North West of Iran. The environment was passively affected, as well. Henceforth, the study was engaged with applying a controlled drainage system for a similar region. The results exhibited that the controlled drainage drove the remarkable decrease in drainage water, which was 33%, 45%, and 44% for wheat, barley, and maize, respectively.

Concentrating on controlling drainage in Egypt, particularly in the delta, uncounted inquiries were introduced. Wahba et al. [1] derived that a large amount of drainage water was decreased to 68% in the summer season and 28% in the winter season as an immediate consequence of drainage control. Vlotman and Jansen [3] suggested that Egypt's agricultural drainage system should be changed to a controlled drainage system, which can significantly decrease the amount of irrigation water required for a given agricultural region. Henk [9] demonstrated that the ideal strategy to control Egypt's drainage was the coordination between the gatherings concerned, including the official authorities and the farmers. Additionally, the examination guaranteed that for the example of applied shallow drainage, a noteworthy decrease in the necessary irrigation water amount was commented. Thus, a monetary decrease for actualizing a farming drainage system is going to be an additive gain.

As indicated by the (Drainage Research Project I&II, [15]), it was inferred that the current design criteria utilized by EPADP that dependent on Hooghoudt's condition prompted misfortune 32–44% of irrigation water. Additionally, the recent design criteria did not consider the impacts of drainage on water amount and conservation of irrigation water. Along these lines, the main objective of several previous types of research associated with control drainage was to reduce the drain depth and save a quantity of irrigation water and study its impact on productivity. However, the implementation of controlled drainage can lead to increases in soil salinity over time. The current research objectives are suggesting a convenient drain depth in Egypt while considering the incorporation between irrigation and drainage schemes by achieving the optimum design criteria that affords high crop yields, water conservation and soil salinity preservation.

2. Materials and methods

2.1. General site information

Three sites were chosen in the current Study. All sites were located in the Nile Delta in Egypt; they were Zankalon, Tokh, and Hosh Essa as shown in Fig. 1.

2.1.1. The first site

The first site is the Zanklon Research station located in the Eastern Nile Delta, Sharqia Governorate. Precisely lies between latitudes 30° 34′ 56″ N, 30° 34′ 43″ N and 31° 25′ 55″ E, 31° 26′ 06″ E longitudes. It was comprised of 3 main plots; 3 Feddans for each. Each main plot has 3 subplots; 1 Feddan for each. The individual primary plot was drained by a sole sub-collector that conveys its discharge to a collector then to an open drain; Fig. 2.

The predominant cultivated crops in winter and summer seasons were wheat, and corn, separately. While the trefoil was planted in mid-seasons. The irrigation was performed through pumping from the El-Afandy canal. The irrigation water was passed on to the cultivated area through fixed mesqas related to an explicit opening on subplots. The single primary plot was drained by 5 laterals situated at a 1.4 m depth of 20 m dividing each. The laterals convey their discharge to 5 manholes at a similar spacing located by each lateral's end.

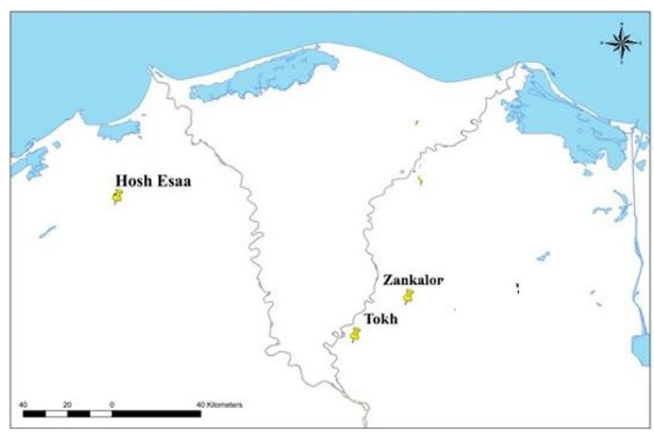

Fig. 1. The studied areas.

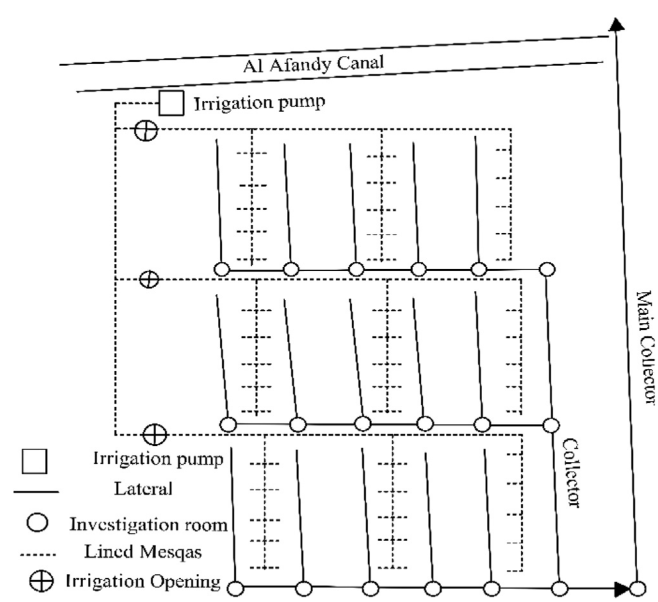

Fig. 2. General layout for Zankalon research station.

2.1.2. The second site

The second site is 29 Feddan near Tokh City, located in the middle of the Nile Delta in Qalubea Governorate. It's actually lied between latitudes 30° 24′ 50.57″ N, 30° 24′ 28.71″ N and 31° 10′ 55.07″ E, 31° 10′ 52.93″ E longitudes. Tokh site was known by collector No. 4, AymanTahla Drain. The most cultivated crop in the winter season was potatoes, while the corn was the prevailing yield for the summer season. Additionally, the trefoil was planted unpredictably in the mid-seasons. The cultivated area was irrigated from El-Kobaar canal, yet in case the water in the canal was deficient; the region was irrigated by pumping the underground water. The irrigation water was conveyed to the cultivated subareas in lined mesqas. The considered site was drained by a set of laterals at 1.4 m depth with 30 m apart; Fig. 3.

2.1.3. The third site

The third site is situated in the Western of Nile Delta in Beheira Governorate in Hosh Essa city between latitudes of 30° 56′ 39.82″ N, 30° 56′ 15.98″ N and 30° 12′ 10.30″ E and 30° 12′ 12.42″ E longitudes. Hosh Essa site was known by collector No. 15, Aysar Al-Gayar drain. The site area 59 Feddan, cultivated wheat in winter and tomatoes in summer seasons. Hosh Essa canal is the source for irrigation for the entire region. The irrigation water was passed on in lined Mesqas. The site was drained by laterals at 1.4 m depth and 40 m dividing. Eight manholes at various dispersing were situated on the collector; Fig. 4.

2.2. Methodology

The EPADP depended on Hooghoudt's equation, Eq. (1) for designing the drainage system.

$$L^2 = \frac{8k_b d_e h + 4k_a h^2}{q} \quad (1)$$

where L is the lateral spacing in (m), k_a is the saturated hydraulic conductivity in the layer above the drain level in (m/day), k_b the saturated hydraulic conductivity in the layer below the drain level in (m/day), h is the height of the water table above the water level in the drain in (m), q is the drainage coefficient in (m/day), d_e is the equivalent depth. Regarding Eq. (1), it should be mentioned that both k_a and k_b are equal because of the homogeneous nature of the soil according to the Egyptian conditions. However, the equivalent

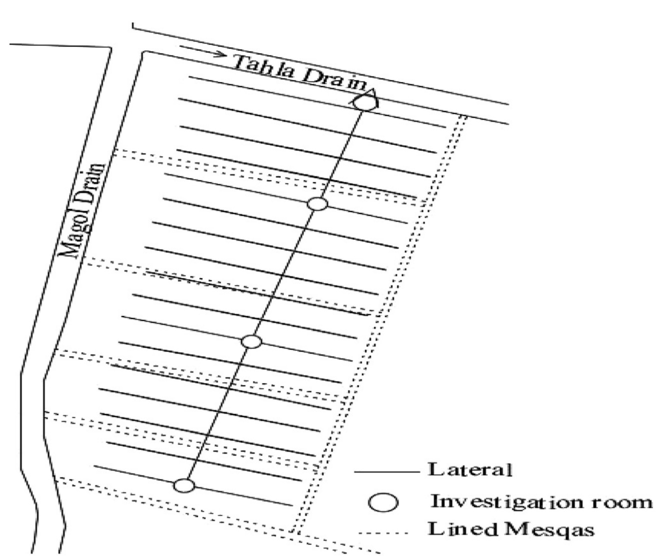

Fig. 3. Layout for Tokh site.

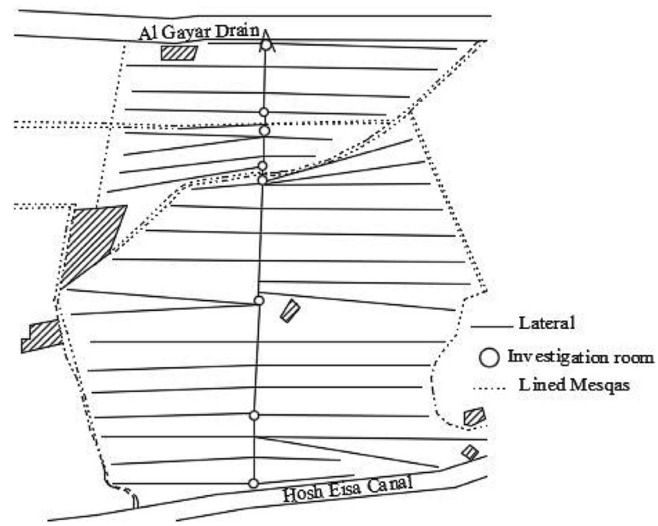

Fig. 4. Layout for Hosh Essa site.

depth is calculated from design tables by knowing L, r, and D or the closed-form expression.

$$d_e = \begin{cases} \frac{D}{1+\frac{8D}{\pi L}\ln\left(\frac{D}{\pi r}\right)} D < 0.25L(2) \\ \frac{\pi L}{8\ln\left(\frac{L}{\pi r}\right)} D \geq 0.25L(3) \end{cases}$$

where r is the radius of the laterals usually ranged between 0.04 and 0.05 m, and D is the elevation of the water level in the drain from the impervious layer.

Proposed drain depths were simulated and assessed where a numerical field-scale model called DRAINMOD was applied. The model has engaged with simulation and prediction of the hydrology of inadequately or falsely drained agricultural regions. Furthermore, the related drainage water the board systems dependent on water adjusts on hourly and day by day time scales. The model was also applied to simulate the crop yield for crop rotation conditions, cultivating practices, soil type, irrigation water management, and drainage intensity of three observed sites over the delta. The hydrologic factors (the infiltration, water table depth, surface runoff, evapotranspiration, vertical and lateral seepage, subsurface drainage, and drained or water-free pore space in the soil profile) were anticipated. The model results were accessible day by day, month to month, yearly, and positioned bases were discretionary. Various situations were directed to characterize the ideal lateral depths that forestalls water-logging with the least drainage flows, considering the effect on the crop yield.

The model results were contrasted with estimated drained flows expecting to assess the hypotheses of how far the current drainage systems cause critical misfortunes in the amount of the irrigation water. As the DRAINMOD is a numerical model, along these lines, it should be calibrated and verified utilizing sets of field measurements to ensure the model results with the least percentages of errors. The procedure of field information assortment and the measuring procedures were completely discussed in the accompanying subsection.

2.3. Monitoring activities

Sets of field measurements and laboratory analysis were conducted at the selected three sites. The measurements incorporate the water table's depth, the drained water out of the laterals, and the amounts of irrigation water.

2.3.1. Soil sampling

Soil samples were collected after harvesting or just before harvesting (before any other farming activities). The sampling location was at 5 m from the lateral in the free side of any irrigation source. Three samples were collected along 3 depths (0–15 cm, 15–30 cm, and 30–45 cm). Soil samples were analyzed, and the essential soil physical properties and hydraulic parameters as presented in Table 1.

2.3.2. Water table depth

Groundwater table was Monitored using a pressure transducer called 3001 level logger edge; Fig. 5. Charles et al. [14] announced that this sort of transducer has 0.05% precision. Two perception wells were monitored with a solitary pressure transducer introduced inside each groundwater observing well. The monitoring wells were introduced precisely in the midpoint between laterals to increase the accuracy of the monitoring. A solitary pressure transducer was hanged in the air to compensate the atmospheric pressure.

2.3.3. Lateral drainage measurement

Lateral outflows were measured and monitored using an adjusted 30° V- notch weir of 0.50 m length, 0.30 m width, and 0.25 m height, regardless of pressure transducer arrangement. The V- notch weir was constructed for a single lateral in each site for the various cultivated crops, as the amount of drained water was relied upon to be unaltered. Because all laterals have similar characteristics with respect to diameter and material of construction; henceforth, the unpredicted little contrasts in the drained water out of every lateral might be disregarded in the current study as it was insignificant.

2.3.4. Irrigation quantities:

The irrigation quantities for each site were estimated by measuring water depth in upstream weir (y_1) by floating level-logger called 3001 and by using the chart shown in Fig. 6 of calibrated 30 cm weir; Fig. 5.

The irrigation amounts for every yield in various seasons are presented in Table 2. The base and most extreme irrigation amounts were for wheat and tomatoes cultivated in Hosh Essa. Regardless of the cultivation site, the tomatoes consumed more irrigation water quantities than wheat and corn, as the tomatoes had a longer time of growth in the field. Stressing Table 2, little contrasts in the amount of irrigation water for a similar crop cultivated in various regions were noticed; (for example, the corn in Tokh consumed water 2.76% higher than Zankalon). Initially, the temperature contrasts in every area with respect to the site's temperature and the evaporation increments, so additive irrigation water was required. Likewise, the dates of cultivation may contrast a few days between various sites. Finally, the soil permeability and the characteristics of the drainage network regarding the spacing of laterals.

Table 1
Physical properties and hydraulic parameters.

Soil physical properties and hydraulic parameters	Zankalon	Tokh	Hosh Essa
Sand (%)	7	7	55
Silt (%)	41	33	13
Clay (%)	52	60	32
Saturated water content (cm3/cm3)(Θs)	0.51	0.51	0.39
Residual water content (cm3/cm3)(Θr)	0.10	0.10	0.07
Curve parameter (1/cm)(α)	0.01	0.02	0.03
Curve shape parameter (N)	1.31	1.25	1.27
Tortuosity (L)	1.10	1.70	2.06
Saturated hydraulic conductivity (cm/day) (K)	19.81	27.28	48.24

3. DRAINMOD model evaluation

To ensure the accuracy of the applied numerical model in the present study and how far the output was valid, the DRAINMOD was calibrated then validated. These procedures were done by comparing the model predicted results (subsurface drainage rate and water table depths) with field measurements.

The model input parameters were adjusted to improve the calibration and validation processes. Underscoring the hydraulic conductivity by layer Ksat (cm/day) and the impermeable layer's depth were acclimated to limit the change between the observed and simulated water tables and drained volumes; Table 3.

The comparison between predicted and observed values were statically analyzed in terms of the mean absolute error (MAE), Nash-Sutcliffe modeling efficiency (EF) based on Skaggs et al. [16]. Limit esteems for acceptable, good, and excellent agreements, as showed by MAE and EF values for water table depth and drainage volume were presented in Table 4. These values depend on results revealed in the literature for a broad scope of soils, drainage conditions, and drainage models.

The DRAINMOD model was calibrated by utilizing the experimentation technique by justifying the hydraulic conductivity by layer and the impermeable layer's thickness within practical ranges. The model parameters were identified for three sites to run calibration and validation processes before beginning the simulation. Likewise, to ensure the accuracy of model results, regardless of the fast track calibration and validation processes, the field measurements for the groundwater table and the amount of drained water were recent, as they were accounted for the most recent few years. For Zanklon, the gathered field estimations in 2018 were utilized in model alignment. Nonetheless, the data gathered in 2019 were utilized for validation. Concentrating on different sites (for example, Tokh and Hosh Essa), the calibration and validation processes were conducted using measurements gathered in 2017 and 2018, individually. The results of model assessments were introduced in Figs. 7–9 and Table 5.

The model results and the field measurements for the three areas had great acceptance. The presented following figures demonstrate the multi-peak values for the water table and the drainage depths for a given area. The crop should be irrigated each counted number of days to be shielded from apparent wilting.

Along these lines, on the first day of irrigation, the water table depth has the peak value at that point begins to diminish by time, up to the following irrigation it will result in general increment once more. On the opposite, the drainage depth as the minimum values were monitored at the primary day of irrigation, and afterward, by the time it increased by the guide of gravitational water as it reached the peak before the following irrigation. Subsequently, each peak water table has a comparing least drainage depth. With respect to model evaluation, by consolidating the discoveries of Figs. 7–9 and Table 5 considering the givens in Table 3, it was reasoned that the model results had a good match with field measurements in terms of the water table depth for the three sites. Accentuating the drainage depth, the model introduced " Excellent execution" in simulation for Zankalon and Tokh regions, while for Hosh Essa, it was "Acceptable". Along these lines, the model was trusted for application.

4. Results and discussion

The present drain depth in the three areas was at 140 cm; however, the spacing and crop were varied as presented in Table 6. The

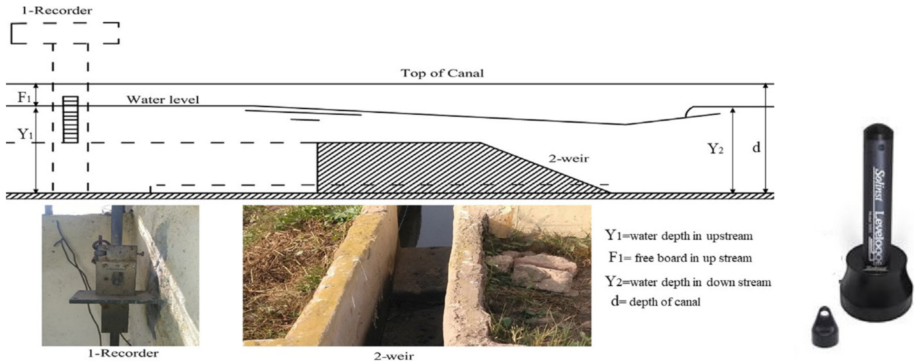

Fig. 5. Irrigation quantities measuring system.

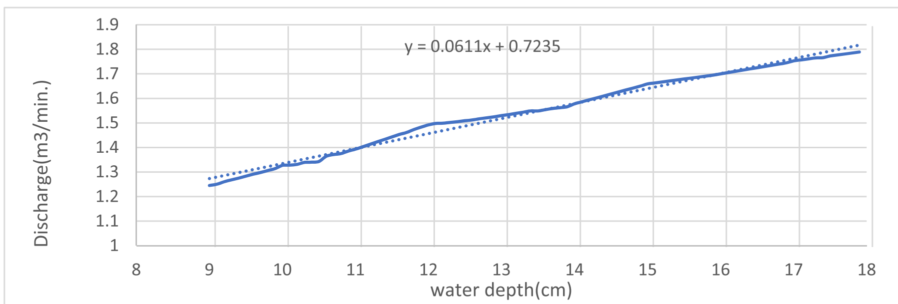

Fig. 6. Chart of calibrated 30 cm weir.

Table 2
The irrigation water quantities.

Region	Crop	Season	Irrigation quantity (m^3/fed.)
Zanklon	Wheat	Winter	2250
	Corn	Summer	3250
Tokh	Potatoes	Winter	2200
	Corn	Summer	3340
Hosh Essa	Wheat	Winter	2000
	Tomatoes	Summer	3640

model reduces the drain depth by 14.29% and 28.57% (drain depth, i.e., 120 cm and 100 cm, individually). There was a comparison between three different drain depths in the three areas at 140 cm, 120 cm, and 100 cm. At that point, check the impact on the water table depth, drained volume, soil salinity, crop yield, and the quantity of saved water.

4.1. Water table depth

Regardless of the tested sites, the cultivated crop, and the spacing between laterals, it was found that the water table depths range was found between 140 and 100 cm. Likewise, the investigation showed how far the drain depth influenced the water table depth; as the normal water table depth was found few centimeters underneath the drain depth, subsequently as the water table raises, as the drain depth decrease.

Combining the findings of Figs. 10–12 and Table 7, it was noticed that the water table depth was intensively impacted by the decrease of drain depth at the Zankalon site. Decreasing the drain depth from 140 to 100 cm prompted ascending the water table depth by 23.85%. Nonetheless, the water table's depth at Hosh Essa was least touchy to the drain depth variations, where decreasing the drain depth to 120 and 100 cm raised the water table depth by 3.84 and 6.73%, respectively. Consequently, the utilization of the present study aiming to decrease the drain depth demonstrated more advantage at the Hosh Essa site than the other sites regardless of the crop yield and the adjustments in soil salinity.

4.2. The drained water depth

The simulation results of the drained water depth showed that the drained water depth was distinctly influenced by the drain depth. The relations between the drain depth and the drained water depth introduced in terms of daily and cumulative drainage are presented in Figs. 13–15, which are more Tables 8 and 9. Regardless of the region and the cultivated yield, it was seen that the percentage of decrease in the drained water came about by ascending the drain depth was exceptional.

Table 3
Initial and calibrated parameters.

Site	Saturated hydraulic conductivity (cm/day) (K)		Depth of impermeable layer (cm)	
	Initial	Calibrated	Initial	Calibrated
Zankalon	19.81	17.5	500	350
Toukh	27.28	25	500	300
Hosh Essa	48.24	43.2	500	400

Table 4
Criteria for statistical measures of agreement between predicted and measured water table depth and drained volume, [16].

Parameter	Statistic	Criteria		
		Acceptable	Good	Excellent
Water table depth (cm/day)	MAE (cm)	<20	<15	<10
	EF (%)	>0.4	>0.6	>0.75
Drained volume (cm^3/cm^2/day)	EF (%)	>0.4	>0.6	>0.75

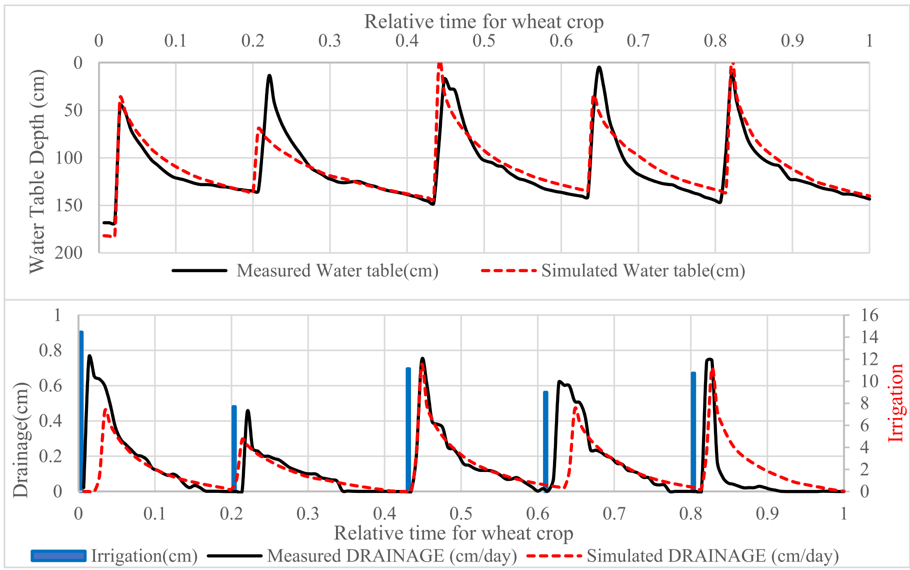

Fig. 7. Model evaluation for Zanklon Research Station.

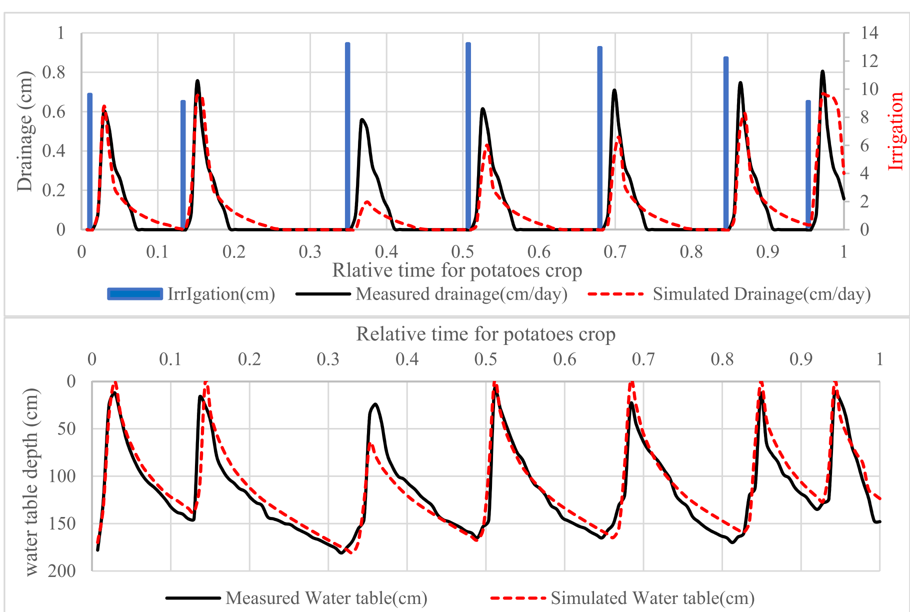

Fig. 8. Model evaluation for Tokh site.

Where the results showed that as drain depth decreases, the drained water amount also decreases. The average daily and the cumulative drainage gave their tops for the currently installed 140 cm drain depth, while they were limited for 100 cm drain depth. Thus, it was reasoned that large amounts of irrigation water were lost with no considerable advantage by utilizing the currently installed drain depth of 140 cm, which was broadly utilized in many agricultural areas in the Nile Delta of Egypt.

It was noticed that for the equivalent cultivated area and drain depth, the amount of drained water has differed with respect to the peak during the yield lifetime. That was contemplated by the differences of the irrigation water amounts regardless of the weathering actions.

Regarding the cultivated regions in the present investigation, Fig. 13 revealed that at Zanklon the most extreme drain depth occurred twice along the yield lifetime on the 65th day and the

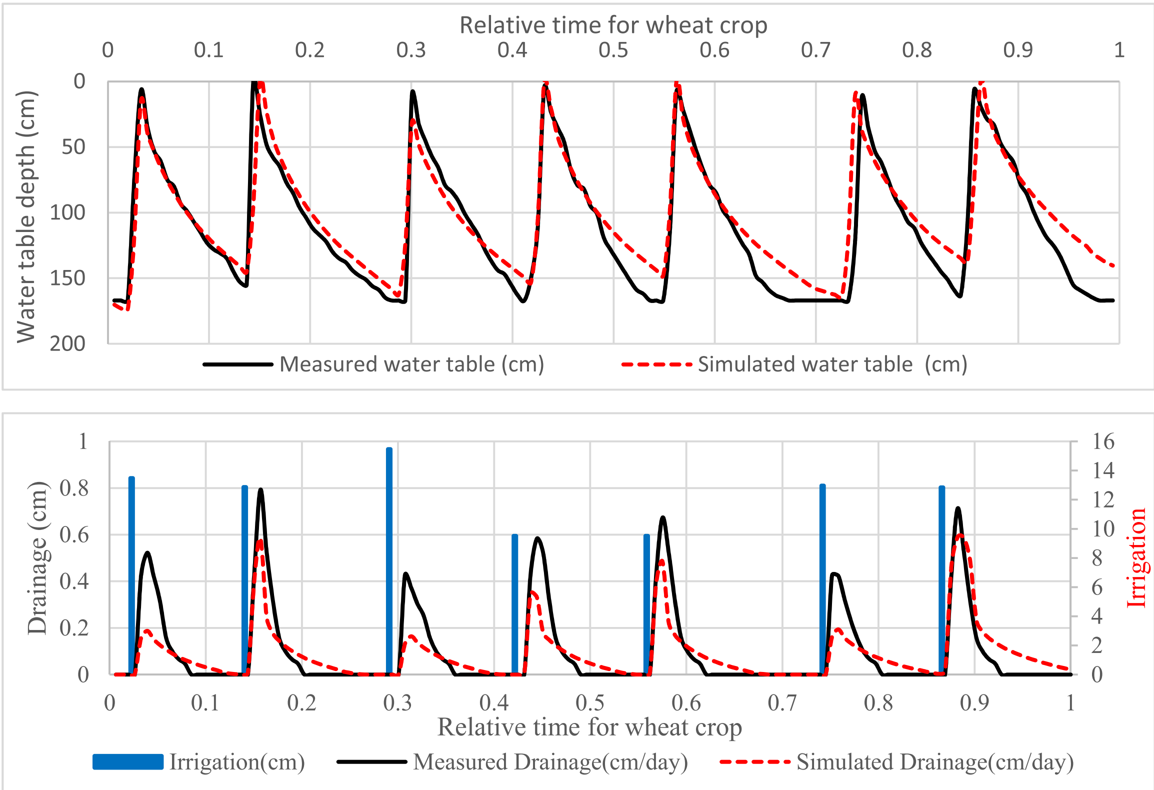

Fig. 9. Model evaluation for Hosh Essa site.

Table 5
Statistical model evaluation.

Region	Water table depth (daily)			Drainage (daily)	
	MAE (cm)	EF%	Average percentage of errors %	EF%	Average percentage of errors %
Zanklon	10.15	0.77	3.21	0.98	6.94
Toukh	12.00	0.85	3.88	0.69	9.09
Hosh Essa	13.10	0.83	6.58	0.58	12.41

Table 6
Drains spacing and crops for regions.

Region	Drain spacing (m)	Crops	
		Winter	Summer
Zanklon Research Station	20	Wheat	Corn
Toukh Region	30	Potatoes	Corn
Hosh Essa Region	40	Wheat	Tomatoes

120th day from the starting day. That can be outlined in Fig. 10. On the 65th and the 120th day, the water table depth indicated the least values, in like manner the vast majority of the water was drained.

For Tokh site, Fig. 14 introduced that the most extreme drainage was 0.69, 0.62, and 0.54 cm/day, for drain depths of 140, 120, and 100 cm, respectively. Considering Hosh Essa site, Fig. 15 showed that the most significant drainage was 0.59, 0.52, and 0.46 cm/day, for drain depths of 140, 120, and 100 cm, respectively. That guarantees the effectiveness of decreasing the drain depth on limiting

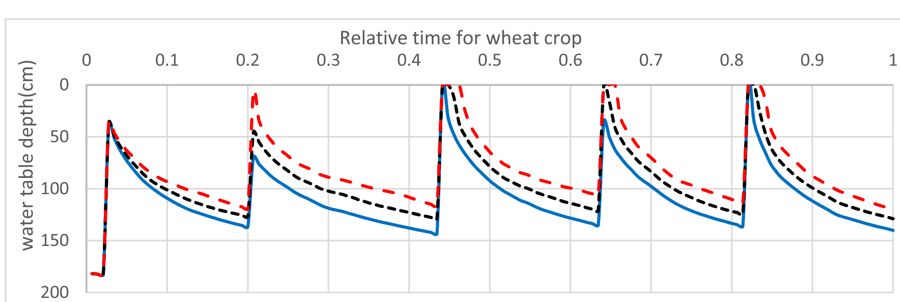

Fig. 10. Water table depth, Zanklon Research Station.

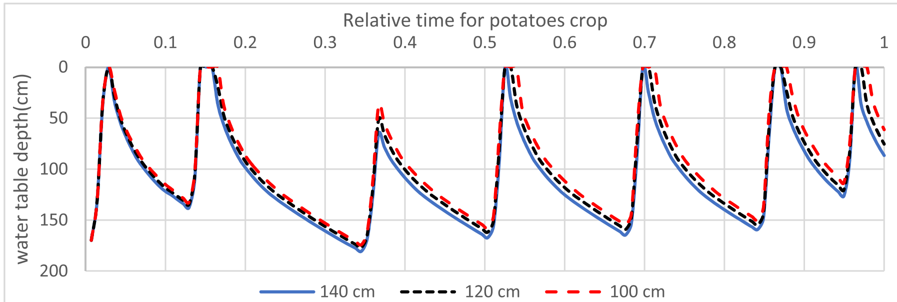

Fig. 11. Water table depth, Toukh site.

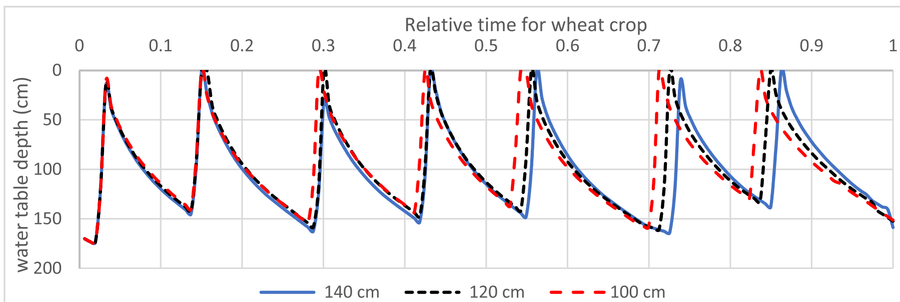

Fig. 12. Water table depth, Hosh Essa site.

Table 7
Effect of drain depth on water table depth.

Region	Crop	Water table depth (cm)			Percentage of rising up the water table depth (%)	
		at 140 cm drain depth	at 120 cm drain depth	at 100 cm drain depth	at 120 cm drain depth	at 100 cm drain depth
Zanklon	Wheat	109	95	83	12.84	23.85
Toukh	Potatoes	109	102	95	6.42	12.84
Hosh Essa	Wheat	104	100	97	3.84	6.73

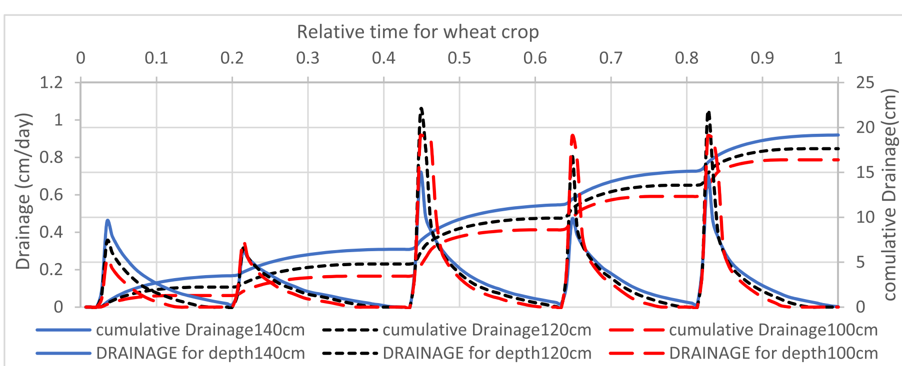

Fig. 13. Drainage volume and cumulative drainage, Zanklon Research Station.

the amount of drained water, and accordingly, a financial saving because of the lessening in drain diameter was appreciable.

Regarding Tables 8 and 9, it was seen that for fixed drain depth, the rates of decrease in drained water and cumulative drainage were unaltered and found conversely relative to the drain depth. Besides, the maximum and minimum decreases in the drained water were at Hosh Essa and Zanklon, respectively regardless of a similar crop was cultivated and the drain spacing at Hosh Essa twice times of Zanklon. That assures the outlined conclusion in Section 4.1, which suggested the decrease of drain depth was profited at Hosh Essa given that the crop profitability and the organic soil ingredients, including salinity, while the crop yield reduction was minor, which was explained in the following subsections.

4.3. The soil salinity

Salinity was of most significant concern in soils that were irrigated with water high in salts; inadequately drained, and that was because of an excess of evaporation from the soil surface.

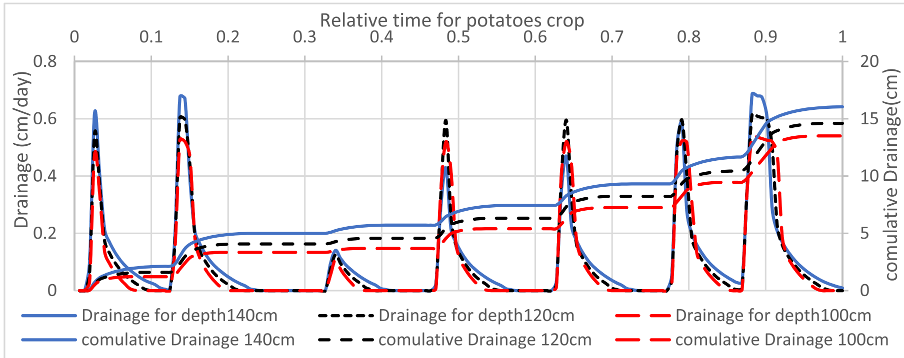

Fig. 14. Drainage volume and cumulative drainage, Tokh site.

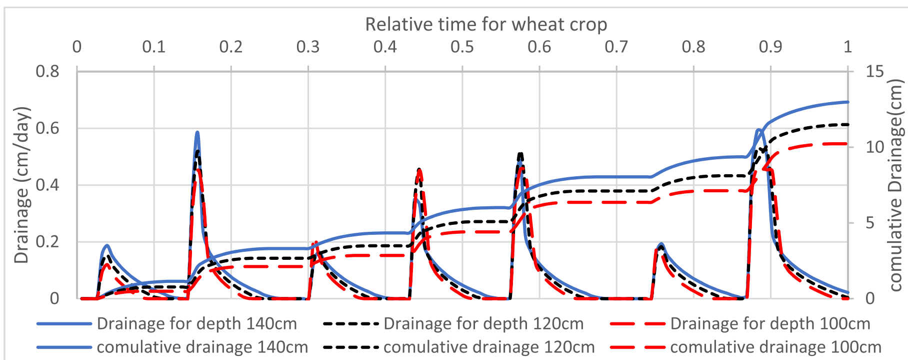

Fig. 15. Drainage volume and cumulative drainage, Hosh Essa site.

Table 8
Effect of drain depth on the drainage volume.

Region	Crop	Average daily drainage (cm^3/cm^2)			Percentage of reduction in the drained water (%)	
		at 140 cm drain depth	at 120 cm drain depth	at 100 cm drain depth	at 120 cm drain depth	at 100 cm drain depth
Zanklon	Wheat	0.132	0.122	0.113	7.58	14.39
Toukh	Potatoes	0.105	0.095	0.088	9.52	16.19
Hosh Essa	Wheat	0.085	0.075	0.067	11.76	21.18

Table 9
Effect of drain depth on the cumulative drainage.

Region	Crop	Cumulative drainage (cm)			Percentage of reduction in the cumulative drainage (%)	
		at 140 cm drain depth	at 120 cm drain depth	at 100 cm drain depth	at 120 cm drain depth	at 100 cm drain depth
Zanklon	Wheat	19.16	17.63	16.39	7.94	14.41
Toukh	Potatoes	16.05	14.60	13.50	9.03	15.89
Hosh Essa	Wheat	12.99	11.50	10.23	11.47	21.25

Consequently, the drain depth has an extensive role in controlling the soil salinity. Decreasing the drain depth caused raise the groundwater table in the soil profile, thusly decline the irrigation water amount, which directly affects soil salinity accordingly the crop yield as well.

Salt issues occurred when water stays close to the surface and evaporates, additionally when salts were not dissolved and conveyed beneath the root zone. In this manner, it was essential to guarantee that the amounts of irrigation water utilized after its decrease contemplated by raising the drain depth still adequate for long-term soil leaching. A detailed study was directed to predict the relationship between the drain depth and the soil over the long run simulation (15 years) for the three areas included in the current study.

The results were summarized in Table 10. Despite that, the average soil salinity was expected to be increased as the irrigation water was decreased and the drain depth was nearer to the plant root zone, which implies a lack of water utilized for soil leaching. However, the investigation demonstrated the different; the average soil salinity decreased as the drain depth declined, regardless of the considered area. That can be explained; that the deeper drains the irrigation water consumes a longer time to be drained. Subsequently, the wetted soil profile was increased, giving adequate time for the liquefied salts conveyed by the irrigation water to be dissolved in soil, prompting increasing its salinity.

Since one of the objectives of the study was to save irrigation water and sustain soil salinity by decreasing the drain depth, Soil salinity was investigated with respect to the experimented drain

Table 10
Effect of drain depth on the soil salinity.

Region	Crop	Average salinity (ppm)			Percentage of reduction in salinity (%)	
		at 140 cm drain depth	at 120 cm drain depth	at 100 cm drain depth	at 120 cm drain depth	at 100 cm drain depth
Zanklon	Wheat	1607.70	1539.87	1494.62	4.22	7.03
Toukh	Potatoes	1500.21	1436.54	1384.53	4.24	7.71
Hosh Essa	Wheat	1738.24	1630.40	1554.77	6.20	10.55

depths for the three study areas. Figs. 16–18 were plotted for the three areas when 100 cm drain depth was performed to characterize the impact on soil salinity over the long run.

Combining the results of Figs. 16–18 and Table 10, it was noticed that for all tested cases, regardless of the drain depth, spacing, and crop, the soil salinity did not exceed the permissible limits indicated by the Food and Agriculture Organization of the United Nations (FAO) [17] as they detailed that the farming soil salinity shouldn't exceed 4000 ppm.

Therefore, it was concluded that the irrigation water amounts for the drain depths under 140 cm were adequate enough for long-term soil leaching. For the studied regions, a regression analysis was accomplished for the long-term soil salinity; the figures exhibited that the soil salinity was directly decreased along time.

The coefficients of determination for Zanklon, Tokh, and Hosh Essa were 0.66, 0.76, and 0.75, respectively, which was considered reasonable. Fig. 16 presented a long-term simulation of 15 years (from 2018 to 2033) for Zanklon research station. It was seen that the trend of soil salinity was linearly decreased along time by 28.94%. With respect to drain depth, Table 6 revealed that the average soil salinity was diminished by 4.22 and 7.03% for 120 and 100 cm drain depths, respectively compared with 140 cm.

For Tokh and Hosh Essa sites, the long-run simulation was accomplished for the period from 2017 to 2032; the results were introduced in Figs. 17 and 18, respectively. The trend line of soil salinity was decreased by 23.78% for Tokh and 27.98% for Hosh Essa sites. Concentrating on the impact of drain depth, the same noticed comments at Zanklon site were rehashed, where the average soil salinity was diminished as the drain depth decline.

Therefore, the 100 cm drain depth indicated 7.71% and 10.55% decrease in the average soil salinity contrasted with the at present introduced 140 cm drain depth for Tokh and Hosh Essa sites, respectively. It should be referenced that the varieties in soil salinity relied upon innumerous parameters regardless of those considered in this examination (e.g., irrigation water quality, amount of precipitation, type and amount of fertilizers, field's attributes, and farming history).

4.4. The crop yield and quantity of saved water

Several parameters were influenced by the drain depth, however, the primary objective was to accomplish the balance between saving irrigation water and keeping the crop yield passively unaffected. Table 11 was created to demonstrate the percentages of saved irrigation water and reduction percentage of the crop yield as a result of decreasing the drain depth.

The available results were for drain depths of 120 cm and 100 cm compared with 140 cm for the various cultivated crops in the regions. The table demonstrated that the cultivated crop and cultivation area, introducing a drain depth of 100 cm, gave the most extreme saving in the irrigation water and the most significant decrease in the yield. Where the most extreme saved water was 15%, except the corn cultivated at Zanklon was 14%. The related decrease in the crop yield by utilizing 100 cm drain depth differed between 5.8% for tomatoes cultivated at Hosh Essa and 4.8% for potatoes cultivated at tokh.

Unique underline on every area independently, it was prescribed to introduce 120 cm drain depth at Zanklon. Where 10% of irrigation water were saved (i.e., 225 m3/fed) and 8% (i.e., 260 m3/fed) in winter and summer, respectively. However, the decrease in crop yield was inconsiderable. For Tokh site, the 120 cm drain depth was additionally suggested, as the amount of irrigation water was saved by 10% (i.e., 220 m3/fed) in winter and 9% (i.e., 300.6 m3/fed) in summer.

These amounts were noteworthy as the base decrease in crop yield was found. At last, for Hosh Essa site, the study prescribed to utilize 100 cm drain depth; as the saved irrigation water was maximized.

Concentrating on the decrease in crop yield, it was seen that the differences between the decrease in crop yield by utilizing 100 cm and 120 cm drain depths were minor compared to the saved

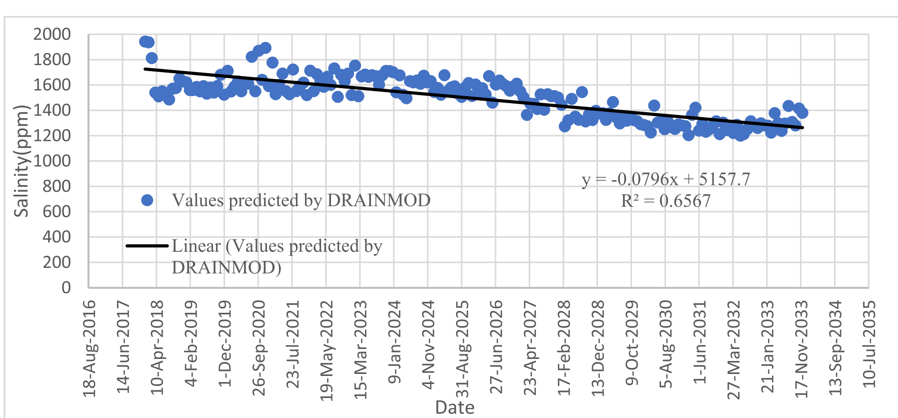

Fig. 16. Soil salinity, Zanklon Research Station.

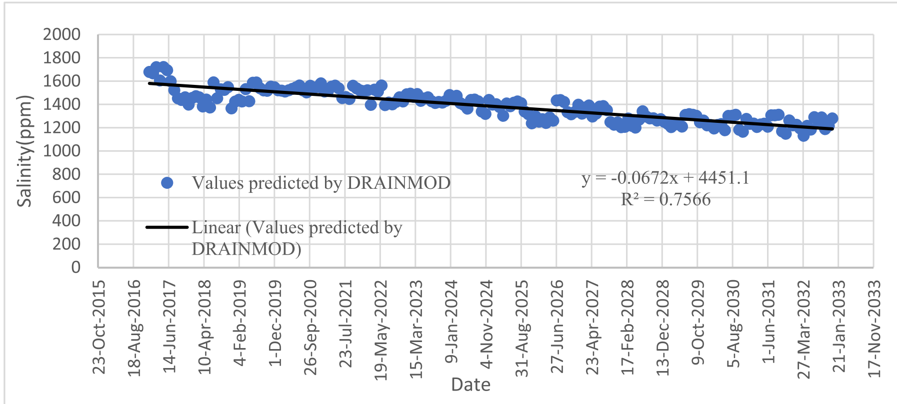

Fig. 17. Soil salinity, Tokh Site.

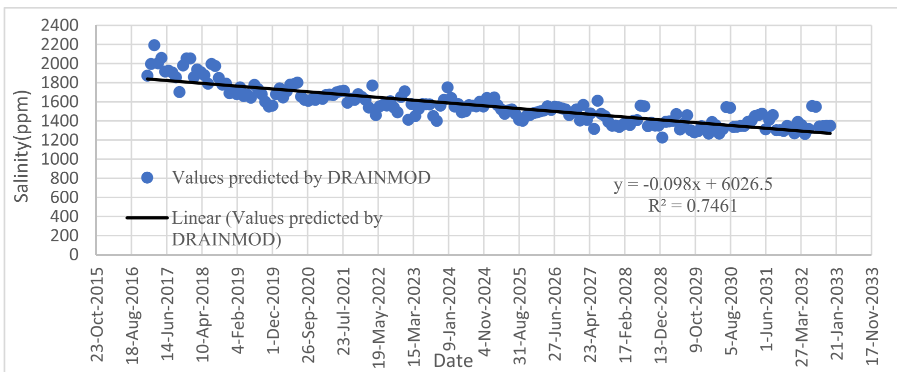

Fig. 18. Soil salinity values, Hosh Essa Site.

Table 11
The saved water and the effect on crop yield.

Region	Crop type	Season	Drain depth (cm)	Drain spacing (m)	Yield reduction (%)	Percentage of saved irrigation water (%)
Zanklon	Wheat	Winter	140	20	—	—
	Wheat		120		1.5	10
	Wheat		100		5.5	15
	Corn	Summer	140		—	—
	Corn		120		1.9	8
	Corn		100		4.6	14
Tokh	Potatoes	Winter	140	30	—	—
	Potatoes		120		1.2	10
	Potatoes		100		4.8	15
	Corn	Summer	140		—	—
	Corn		120		2	9
	Corn		100		4.9	15
Hosh Essa	Wheat	Winter	140	40	—	—
	Wheat		120		3.1	10
	Wheat		100		5.5	15
	Tomatoes	Summer	140		—	—
	Tomatoes		120		2.3	9
	Tomatoes		100		5.8	15

irrigation water. Utilizing 100 cm of drain depth saved 15% of the necessary irrigation water for both winter and summer crops, which were significant, particularly in the summer season where tomatoes were cultivated as 546 m3/fed amount of water was saved.

By talking about water-saving perspective regardless of the decrease in crop yield; where the crop yield might be compensated by the guide of agricultural researchers. For wheat, similar rates were accounted for the saved water at Zanklon and Hosh Essa in case of utilizing 100 cm drain depth. That suggests cultivating the wheat at Hosh Essa, as the irrigation amount was 250 m3/fed less than the required at Zanklon. Similarly, concerning corn, it was recommended to be cultivated at Zanklon than Tokh utilizing 100 cm drain depth to save 90 m3/fed irrigation water.

5. Conclusion and recommendations

As indicated by the previous analysis and results by simulating the scenarios of decreasing the drain depth at three different sites situated in three governorates, which were cultivated by various seasonal crops representing different regions of the Nile Delta in Egypt, several conclusions were reached:

- The current design for subsurface drainage system criteria applied by EPADP should be updated to reduce drainage water losses, save a significant amount of irrigation water, and sustain crop production and soil salinity.
- As the drain depth decrease, the amount of drained water is reduced.
- Reducing the drain depth from 140 to 120 cm by (i.e., 14.29%) saved about 10% of the irrigation water with a decrease in crop yield fluctuated somewhere in the range of 1.2% and 3.1% as indicated by the cultivated crop.
- Reducing the drain depth from 140 to 100 cm by (i.e., 28.57%) saved about 15% of the irrigation water with a decrease in crop yield varied between 4.6% and 5.8% according to the cultivated crop.
- Decreasing the drain depth indicated an insignificant influence on the soil salinity over the long run.
- It was recommended to decrease the drain depth to 120 cm at Zanklon and Tokh areas, while for Hosh Essa, decreasing the drain depth to 100 cm was significant, keeping the drain spacing unaltered for the three regions.
- From a water sparing perspective, it was prescribed to cultivate wheat at Hosh Essa and corn at Zanklon under fixed 100 cm drain depth while the current drain spacing stays unchanged.
- The scarcity of the water resource as of now confronting Egypt makes the research focused on saving the irrigation water convenient and critically required.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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