Controlled drainage in the Nile River delta of Egypt: a promising approach for decreasing drainage off-site effects and enhancing yield and water use efficiency of wheat postprint

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Abstract

North Africa is one of the regions most impacted by water shortage. The implementation of controlled drainage (CD) in the northern Nile River delta of Egypt represents one strategy to decrease irrigation requirements, thereby alleviating the negative impacts of water scarcity. This study investigated the effects of CD at different levels on drainage outflow, water table level, nitrate loss, grain yield, and water use efficiency (WUE) of various wheat cultivars. Two CD levels—0.4 m below the soil surface (CD-0.4) and 0.8 m below the soil surface (CD-0.8)—were compared with subsurface free drainage (SFD) at 1.2 m below the soil surface (SFD-1.2). Under each drainage treatment, four wheat cultivars were grown for two growing seasons (November 2018–April 2019 and November 2019–April 2020). Compared with SFD-1.2, CD-0.4 and CD-0.8 decreased irrigation water by 42.0% and 19.9%, drainage outflow by 40.3% and 27.3%, and nitrate loss by 35.3% and 20.8%, respectively. Under CD treatments, plants absorbed a significant portion of their evapotranspiration from shallow groundwater (22.0% and 8.0% for CD-0.4 and CD-0.8, respectively). All wheat cultivars responded positively to CD treatments, with the highest grain and straw yields obtained under CD-0.4. Using the initial soil salinity as a reference, soil salinity under CD-0.4 treatment increased two-fold by the end of the second growing season without negative impacts on wheat yield. Modifying the drainage system by raising the outlet elevation and considering shallow groundwater contribution to crop evapotranspiration promoted water-saving and enhanced WUE. Different responses may be obtained based on plant tolerance to salinity and water stress, crop characteristics, and growth stage. Site-specific soil salinity management practices will be required to avoid soil salinization due to the long-term

adoption of shallow groundwater management in Egypt and other similar agroecosystems.

Full Text

Preamble

Controlled drainage in the Nile River delta of Egypt: a promising approach for decreasing drainage off-site effects and enhancing yield and water use efficiency of wheat

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Abstract: North Africa is one of the regions most impacted by water shortage. The implementation of controlled drainage (CD) in the northern Nile River delta of Egypt represents one strategy to decrease irrigation requirements, thereby alleviating the negative impacts of water scarcity. This study investigated the effects of CD at different levels on drainage outflow, water table level, nitrate loss, grain yield, and water use efficiency (WUE) of various wheat cultivars. Two CD levels—0.4 m below the soil surface (CD-0.4) and 0.8 m below the soil surface (CD-0.8)—were compared with subsurface free drainage (SFD) at 1.2 m below the soil surface (SFD-1.2). Under each drainage treatment, four wheat cultivars were grown for two growing seasons (November 2018–April 2019 and November 2019–April 2020). Compared with SFD-1.2, CD-0.4 and CD-0.8 decreased irrigation water by 42.0% and 19.9%, drainage outflow by 40.3% and 27.3%, and nitrate loss by 35.3% and 20.8%, respectively. Under CD treatments, plants absorbed a significant portion of their evapotranspiration from shallow groundwater (22.0% and 8.0% for CD-0.4 and CD-0.8, respectively). All wheat cultivars responded positively to CD treatments, with the highest grain and straw yields obtained under CD-0.4. Using the initial soil salinity as a reference, soil salinity under CD-0.4 treatment increased two-fold by the end of the second growing season without negative impacts on wheat yield. Modifying the drainage system by raising the outlet elevation and considering shallow groundwater contribution to crop evapotranspiration promoted water-saving and enhanced WUE. Different responses may be obtained based on plant tolerance to salinity and water stress, crop characteristics, and growth stage. Site-specific soil salinity management practices will be required to avoid soil salinization due to the long-term adoption of shallow groundwater management in Egypt and other similar agroecosystems.

Keywords: drainage ratio; nitrate loss; water use efficiency; yield; soil salinity; Nile River delta

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1 Introduction

Countries in the Middle East and North Africa (MENA) are characterized by hot-dry climates with average annual rainfall below 300 mm (Radhouane, 2013). The resulting acute water shortage limits crop growth and production as a function of water availability (Abdallah et al., 2018). This problem is expected to intensify due to climate change and rapid population growth (Hamed et al., 2018). Predicted increases in rainfall variability and air temperature are expected to increase crop evapotranspiration and result in more frequent drought events (Zekry et al., 2020, 2022; Abdallah et al., 2021). Under such conditions, attaining food security is a daunting task. Despite these challenges, over-irrigation and free drainage dominate agricultural production in many regions of MENA countries, such as the Nile River delta of Egypt, leading to over-drainage (El-Ghannam et al., 2021). Excessive drainage results in inefficient use of water and fertilizers as well as adverse socio-economic and environmental effects (Campus, 2019; Sojka et al., 2019).

Controlled drainage (CD) has proven to be a promising tool that can decrease drainage water volumes, maintain crop yield, and reduce drainage off-site effects—namely nitrate and phosphorus (P) outflow to surface water and groundwater (Ayars et al., 2006a; Ritzema 2016; Javani et al., 2018; Sojka et al., 2019; Li et al., 2021). CD is a water table management tool that maintains water at a desired depth, ensuring sufficient aeration and moisture in the root zone (Lavaire et al., 2017). In CD systems, the water table is elevated to a particular depth either through shallower drain placement or by blocking drains at the required depth. Therefore, CD has the potential to decrease drainage outflow and increase upward water flow by capillary action, thus replenishing depleted soil moisture to meet evapotranspiration demands (Lu et al., 2016). In this way, CD increases water availability during dry periods, thereby lessening the negative impact of water shortage stress on rainfed agriculture and limiting water use in irrigated agriculture (Skaggs et al., 2012). The adoption of CD has been shown to decrease drained water volumes by 16%–85% (Skaggs et al., 2010, 2012) and reduce nitrogen (N) and P transport by 18%–75% and 35%–45%, respectively (Helmers et al., 2012; Lavaire et al., 2017; Craft et al., 2018; Liu et al., 2019). Such reductions in drainage outflow and nutrient transport have been shown not only to decrease off-site impacts but also to enhance crop yields and improve water and nutrient use efficiencies in many parts of the world, including Canada (Drury et al., 2009), Sweden (Wesström and Messing, 2007), Egypt (El-Ghannam et al., 2021), the USA (Youssef et al., 2018; Zhang et al., 2019), Iran (Javani et al., 2018), and the Netherlands (Rozemeijer et al., 2016). However, the potential benefits of CD on wheat yield, nitrate loss, and water use efficiency (WUE) in the northern Nile River delta of Egypt have not been investigated.

Egypt imports large quantities of wheat because local production provides only about 50% of the country's wheat consumption. As the most populous country in the MENA region, Egypt is below the water poverty limit, and this problem is aggravated by rapid population growth (World Water Assessment Programme, 2020). Rainfall is rare in most regions of Egypt, with the highest amounts received on the north coast averaging 150–200 mm annually, mainly during the winter season (November–February). Despite this situation, flood irrigation dominates in the Nile River delta because farmers have small land holdings and adopt conventional crop management practices (El-Ghannam et al., 2021). In the northern Nile River delta, the region is served by subsurface free drainage (SFD) in which drains are installed at 1.2 m below the soil surface. The combination of flood irrigation and SFD leads to excessive drainage and inefficient use of water and fertilizers. Optimizing WUE could be achieved through several options, including agronomic water management and planting drought-tolerant crop cultivars. However, any increase in WUE must not be attained at the cost of yield to ensure farmer acceptance of proposed practices. The adoption of CD and cultivation of water-efficient cultivars could maximize WUE while maintaining crop yield. It is widely accepted that different wheat cultivars respond differently to agronomic practices (Elbasyoni et al., 2019; Morsy et al., 2021). Information about the potential benefits of CD on WUE of wheat in the northern Nile River delta is lacking, and the response of different wheat cultivars to CD has not yet been investigated. Therefore, this study examined the effects of different CD treatments on drainage outflow, nitrate loss, grain yield, and WUE of various wheat cultivars. We hypothesized that wheat cultivars may respond differently to CD adoption in the northern Nile River delta, leading to decreased irrigation water application while maintaining crop productivity. The results of this study could identify water-saving techniques that can be utilized in Egypt and other countries or regions to enhance future food security through higher WUE while maintaining crop productivity and farmer profitability.

2.1 Experimental Site and Climatic Conditions

A two-year field experiment (2018–2019 and 2019–2020) on CD was conducted at three isolated fields at the Sakha research farm, Motobus District (31°15$‘51’‘*N*, 30°47’06”$E) in the northern Nile River delta of Egypt. The climate of the study area is typically arid Mediterranean (El-Ghannam et al., 2021). Meteorological data were collected from a weather station located at the field site. The five-year average (2015–2020) showed that the lowest monthly average temperature occurred in January, while the highest values were recorded in July (Fig. S1). The average annual rainfall is 134 mm (five-year average), with the highest rainfall in December and no rainfall during the summer season (May–September) (Fig. 1 [Figure 1: see original paper]). During the study period (2018–2019 and 2019–2020), the highest rainfall was recorded in December (91.5 and 71.5 mm for 2019 and 2020, respectively; Fig. 1). The region is served by SFD at 1.2 m below the soil surface (SFD-1.2) and is irrigated with Nile River water. The soil is silt clay in texture and classified as typic Torrifluvents (Soil Survey Staff, 2014). Before establishing the experiment, representative soil samples were collected from each field at depths of 0–30, 30–60, and 60–90 cm. Summaries of the soil's physical and chemical characteristics are shown in Table 1 . Soil texture was determined using the pipette method (Baruah and Barthakur, 1999) and classified according to the United States Department of Agriculture (USDA) system (Soil Survey Division Staff, 1993). Soil bulk density was measured using the core method (Blake and Hartge, 1986). Soil pH was measured in a soil-water suspension with a ratio of air-dried soil to distilled water of 1.0:2.5, while electrical conductivity (EC), cations, and anions were determined in soil paste extract following the standard methods of Jackson (1973).

In the northern Nile River delta, the dominant irrigation system is flood irrigation using high-quality Nile River water (EC = 0.5 dS/m) with subsurface drainage at 1.2 m depth. The region is dominated by the rice-wheat cropping system, which is water- and energy-intensive; therefore, less-water-demanding alternative systems (e.g., maize-wheat and sunflower-wheat) are emerging (El-Ghannam et al., 2021). The groundwater level ranges from 0.9 m (in summer) to 1.1 m (in winter), and groundwater salinity ranges from 0.90 dS/m (in winter) to 1.23 dS/m (in summer) (El-Ghannam et al., 2021). The quaternary Nile River aquifer is a renewable shallow aquifer underlying the Nile River delta, considered semi-confined due to the upper clay layer (Negm et al., 2018). Groundwater resources in the Nile River delta provide approximately 85% of total groundwater abstractions (6.1×10^9 m^3/a) in Egypt (Negm et al., 2018). The aquifer is characterized by high productivity with relatively shallow wells at low pumping costs (Abd El Moniem, 2009; El-Rawy et al., 2021) and is replenished by seepage from the Nile River, canals, and drain networks (Abd El Moniem, 2009; Negm et al., 2018; El-Rawy et al., 2021).

2.2 Experimental Design and Description of Treatments

The experimental site consisted of three separate and isolated fields within the same farm, each with an area of 0.6 hm^2. One field was drained with SFD-1.2, while two fields were under CD with drains at 1.2 m below the soil surface and connected to a weir (outlet elevation) at either 0.4 m below the soil surface (CD-0.4) or 0.8 m below the soil surface (CD-0.8). Each field was drained separately with a control unit fixed at the existing drainage system, allowing the water table to rise to depths of 0.4 and 0.8 m (Fig. 2 [Figure 2: see original paper]). The outlet elevation remained unchanged throughout the growing season. Within each field, parallel laterals (inner diameter of 75 mm and drain spacing of 20 m) were connected to a manhole in which the control unit was installed. Each field (drainage treatment) was divided into 12 plots of 300 m^2 each (12 m width × 25 m length), with four wheat cultivars (Sakha95, Misr3, Giza171, and Sids14) randomly arranged in three replicates. The selected cultivars represent the most widely grown commercial cultivars characterized as highly productive in terms of grain and straw yield (straw yield is also vital for farmers in the region as animal feed).

2.3 Crop Management

All wheat cultivars were sown in rows (25 cm apart) at a seeding rate of 110 kg/hm^2. In the first growing season (2018–2019), all wheat cultivars were sown on 15 November 2018 and harvested on 25 April 2019. In the second growing season (2019–2020), all wheat cultivars were sown on 20 November 2019 and harvested on 27 April 2020. Recommended doses of N, P, and potassium (K) fertilizers were applied in a single application: P fertilizer (15.0% P_2O_5; 350 kg/hm^2) and K fertilizer (48.0% K_2O; 120 kg/hm^2) were applied during land preparation before planting. N fertilizer (46.5% N; 360 kg/hm^2) was applied in two equal doses—before irrigation and planting, and before the second irrigation. Weeds were controlled using recommended rates and types of herbicides.

2.4 Irrigation Water Input and Drain Discharge

At the first irrigation, equal water depth was applied by flooding to all treatments to ensure uniform crop germination and establishment. A water flow meter was installed for each field (drainage treatment) to quantify the applied water volume. Subsequent irrigation for all drainage treatments was applied based on crop requirements. After 50.00% depletion of available water capacity (soil moisture of 30.84%) for the SFD-1.2 treatment, all treatments were re-watered to field capacity. Soil moisture content between irrigation intervals was measured for all main-plot treatments using time-domain reflectometry (HH2 Moisture Meter, Delta-T Devices, Cambridge, England). The irrigation depth for each field was calculated based on root depth (measured directly before irrigation) and soil water content before irrigation. The required irrigation depth for each drainage treatment varied according to the moisture content prior to irrigation. Available water capacity was computed by subtracting soil water content at the permanent wilting point (21.70%) from the corresponding values at field capacity (39.98%).

Throughout the growing season, drains were monitored after each irrigation or rainfall event. Drain discharge (mm/d) was determined twice daily until drains showed negligible drainage. The quantity of water running from the drain for a specific period was determined using a calibrated tank and stopwatch (Javani et al., 2018; El-Ghannam et al., 2021). Cumulative drainage water (mm/(hm^2 · season)) was computed. Drainage water samples were collected at different times of day, and composite daily samples were analyzed for nitrate concentration. Daily nitrate loss (kg/(hm^2 · d)) from each field was estimated by multiplying the daily nitrate concentration by the daily drainage water volume, and cumulative nitrate loss (kg/(hm^2 · season)) was then computed.

2.5 Water Table Observation

To monitor water table level throughout the season, three observation wells were installed within each drainage treatment (main plot). The wells were constructed using polyethylene tubes (5 cm diameter and 200 cm length; with 30 cm perforated at the lower end). The tubes were inserted in well-prepared auger holes to 140 cm below the soil surface, with 60 cm extending above the soil surface. The perforated lower 30 cm was covered with a permeable screen to avoid clogging. Water table levels in observation wells were regularly recorded using a sounder device and averaged monthly.

2.6 Crop Water Uptake from Shallow Groundwater

To estimate evapotranspiration (ETc; mm), we calculated crop water uptake according to Allen et al. (1998) using the following formula:

$$ETc = ET_0 \times Kc$$

where ET_0 is reference evapotranspiration (mm/d) and Kc is the crop coefficient (0.4, 0.8, 1.2, and 0.7 for the first, second, third, and fourth growth stages, respectively). ET_0 was calculated using the ET-calculator software (Raes, 2012), which applies the Penman-Monteith formula recommended by the Food and Agriculture Organization of the United Nations (FAO).

Crop water uptake from shallow groundwater was estimated according to El-Ghannam et al. (2021) using the following calculation:

$$G_i = I_i + P - D_i - \Delta S$$

where G_i (mm) is crop water uptake from shallow groundwater for a certain treatment that received irrigation water I_i (mm) and had drainage water D_i

(mm); P is precipitation (mm); and ΔS is the change in soil moisture (%), measured as the increase or decrease in soil water content (prior to an irrigation event) with respect to soil water content after depleting 50.00% of available water capacity (30.84%).

2.7 Crop Growth and Yield Parameters

Plant height (cm), measured as the distance from base to top of the main stem spike, was recorded for ten plants and averaged. The whole plot was harvested, air-dried, and threshed, and grain yield (kg/hm^2) was measured. Straw yield (kg/hm^2) for each plot was also measured. Finally, 1000 grains were counted and the corresponding mass (g) was determined.

2.8 Drainage Ratio and Water Use Efficiency (WUE)

The drainage ratio (DR) is the ratio between the amount of drainage (D; mm/season) and the amount of water involved in crop production (VW; mm/season)—the sum of irrigation and rainfall—calculated as follows (Bahçecİ, 2016):

$$DR = \frac{D}{VW}$$

WUE (kg/m^3) was computed as the ratio of grain yield (GY; kg/hm^2) to the total amount of water involved in crop production (VT; m^3/hm^2) (Abdallah et al., 2018; Javani et al., 2018). Irrigation WUE (IWUE; kg/m^3) was computed as the ratio of grain yield to the volume of applied irrigation water alone (VI; m^3/hm^2). The calculation formulas are as follows:

$$WUE = \frac{GY}{VT}$$

$$IWUE = \frac{GY}{VI}$$

2.9 Soil Salinity Analysis

For each field, soil salinity was determined before sowing wheat cultivars (first growing season) and after final harvest (second growing season). Soil samples were collected at depths of 0–20, 20–40, 40–60, and 60–80 cm. Soil salinity was measured in saturated soil paste extract following the standard method of Jackson (1973).

2.10 Statistical Analysis

Data on crop growth parameters and WUE for each wheat cultivar were subjected to analysis of variance (ANOVA) using a one-way completely randomized design (CRD) in the Glmmix procedure in SAS 9.4. Differences between means were separated using Tukey's test at $P \leq 0.05$. Mean values were calculated to compare non-randomized parameters (drainage outflow, water table level, drainage ratio, WUE, and nitrate loss), as these data were non-randomized.

3.1 Drainage Outflow, Irrigation Input, Nitrate Loss, and Drainage Ratio

Across the two growing seasons, CD deployment decreased drainage time and average drain discharge, resulting in reduced drainage outflow. The reduction in drainage outflow was proportional to drainage depth (Fig. 3 [Figure 3: see original paper]). Compared with SFD-1.2, CD reduced drainage outflow by 36.0% and 17.0% for CD-0.4 and CD-0.8, respectively, in the first growing season, and by 44.6% and 37.6% for CD-0.4 and CD-0.8, respectively, in the second growing season (Fig. 3). Moreover, CD application decreased irrigation water input during both growing seasons (Fig. 3). CD reduced irrigation water by 39.1% and 18.7% for CD-0.4 and CD-0.8, respectively, in the first growing season. In the second growing season, irrigation water decreased by 45.0% and 22.0% for CD-0.4 and CD-0.8, respectively. A reduction in drainage ratio was observed due to CD implementation, with the drainage ratio decreasing by 19.0% and 17.1% for CD-0.4 and CD-0.8, respectively, compared with SFD-1.2 (Fig. 3). CD also decreased nitrate loss in drainage water, with lower losses observed for CD-0.4 (19.1% and 51.5% for the first and second growing seasons, respectively) and CD-0.8 (9.0% and 32.6% for the first and second growing seasons, respectively) compared with SFD-1.2 (Fig. 3).

3.2 Water Table Level

The monthly average water table level for drainage treatments across the two growing seasons is presented in Figure 4 [Figure 4: see original paper]. As expected, CD application raised the water table level, particularly in the CD-0.4 treatment. The seasonal average water table level decreased from 110 to 64 cm for CD-0.4 and from 110 to 90 cm for CD-0.8 in the first growing season. Similar trends were observed in the second growing season. Additionally, water table level fluctuated in response to rainfall and irrigation under CD-0.4 treatment. During the rainfall period (December–February), CD-0.4 maintained a water table level ranging from 45 to 50 cm, after which it decreased to approximately 65–70 cm. However, CD-0.8 and SFD-1.2 showed relatively constant water table levels from December to May (85–95 cm and 115–120 cm, respectively).

3.3 Water Uptake from Shallow Groundwater

In this study, actual evapotranspiration was calculated as the difference between total water input (sum of irrigation and rainfall) and drainage water from the control treatment (SFD-1.2). The SFD-1.2 treatment, with water management practices designed to prevent water stress, served as a reference. Using this approach, all treatments were assumed to have the same actual evapotranspiration (396.7 and 385.3 mm for the first and second growing seasons, respectively). Water uptake from shallow groundwater was higher for CD treatments, particularly CD-0.4 (Table 2). During the first growing season, water uptake from shallow groundwater was 95.0 and 52.7 mm/season for CD-0.4 and CD-0.8, respectively, amounting to 23.1% and 12.8% of actual evapotranspiration. In the second growing season, groundwater contribution was 105.7 and 40.5 mm/season for CD-0.4 and CD-0.8, respectively, amounting to 26.4% and 10.1% of actual evapotranspiration (Table 2).

3.4 Grain and Straw Yields of Wheat Cultivars

Irrespective of wheat cultivar, CD had minimal effect on 1000-grain weight (Table 3). However, CD increased plant height, grain yield, and straw yield (Table 3). Compared with SFD-1.2, CD increased plant height by 9.6% and 11.7% for CD-0.4 and CD-0.8, respectively, in the first growing season, and by 5.0% and 6.0% for CD-0.4 and CD-0.8, respectively, in the second growing season. More importantly, average grain yield under CD treatment was higher than under SFD-1.2 by 10.3% and 8.3% for CD-0.4 and CD-0.8, respectively, in the first growing season. In the second growing season, grain yield under CD treatment was higher by 4.8% and 3.3% for CD-0.4 and CD-0.8, respectively. Straw yield under CD-0.4 and CD-0.8 treatments was 15.0% higher than under the control for both growing seasons.

Among the tested wheat cultivars, Sakha95 showed the highest grain and straw yields across all drainage treatments (Table 3), whereas Sids14 showed the lowest yields. Irrespective of drainage treatment, the highest average grain yield (6150.00 kg/hm^2; two-season average) and straw yield (6210.00 kg/hm^2) were recorded for Sakha95, while Sids14 recorded the lowest average grain yield (5000.00 kg/hm^2) and straw yield (5500.00 kg/hm^2). The highest grain yield (6430.00 kg/hm^2) and straw yield (6500.00 kg/hm^2) were recorded for Sakha95 under CD-0.4 treatment. In contrast, Sids14 recorded the lowest grain yield (4800.00 kg/hm^2) and straw yield (4850.00 kg/hm^2). Adoption of CD increased grain yield of Sakha95 by 500.00 and 600.00 kg/hm^2 for CD-0.4 in the first and second growing seasons, respectively, while CD-0.8 enhanced grain yield by 350.00 and 240.00 kg/hm^2 for the first and second growing seasons, respectively. Similar trends were observed for straw yield.

3.5 WUE

Irrespective of wheat cultivar, CD had a significant positive effect on WUE and IWUE (Table 4). WUE under CD-0.4 and CD-0.8 treatments was 55.60% and 18.86% higher, respectively, than under SFD-1.2 treatment in the first growing season. Similar trends were observed in the second growing season. Interestingly, CD-0.4 and CD-0.8 increased IWUE by 1.85 and 1.28 times, respectively, relative to SFD-1.2 (two-season average). Irrespective of drainage treatment, Sakha95 showed the highest WUE (1.45 kg/m^3), while Sids14 recorded the lowest value (1.25 kg/m^3). The highest WUE (1.71–1.85 kg/m^3) was recorded for Sakha95 under CD-0.4 treatment. In contrast, the lowest WUE (0.98–1.13 kg/m^3) was observed for Sids14 under SFD-1.2 treatment, as was the case for Giza171 (1.04–1.06 kg/m^3). Regarding IWUE, Sakha95 showed the highest value (2.65 kg/m^3), while Sids14 recorded the lowest (2.23 kg/m^3), irrespective of CD treatments. The highest IWUE (3.80 kg/m^3) was recorded for Sakha95 under CD-0.4 treatment, whereas the lowest IWUE (1.62 kg/m^3) was observed for Sids14 under SFD-1.2 treatment.

3.6 Soil Salinity

Soil salinity was affected by CD under the wheat cropping system during the two growing seasons (Fig. 5 [Figure 5: see original paper]). Before establishing the study (2018–2019), soil salinity values were 2.50, 2.95, 3.00, and 3.45 dS/m at depths of 0–20, 20–40, 40–60, and 60–80 cm, respectively, with an average of 2.97 dS/m. After the second wheat harvest, soil salinity values increased under CD-0.4 treatment, particularly in upper soil layers, while soil salinity under SFD-1.2 treatment was unaffected (Fig. 5a). In the upper surface layer (0–20 cm), soil salinity was significantly higher under CD-0.4 and CD-0.8 treatments compared to both initial soil salinity and SFD-1.2. At 20–40 cm depth, soil salinity under CD-0.4 treatment was greater than under other treatments (Fig. 5a). Below 40 cm depth (40–60 and 60–80 cm), no significant difference in soil salinity was observed between SFD-1.2 and CD treatments, but soil salinity at 40–60 cm depth was significantly greater than initial soil salinity and soil salinity under CD treatment (Fig. 5a).

At the end of the study, average soil salinity across the soil profile (Fig. 5b [Figure 6: see original paper]) was significantly higher under CD-0.4 treatment relative to SFD-1.2 treatment and initial soil salinity, while CD-0.8 showed an intermediate response (Fig. 5b). By the end of the second growing season, CD-0.4, CD-0.8, and SFD-1.2 increased soil salinity by 33.2%, 17.5%, and 13.0%, respectively, compared to initial soil salinity. At 0–40 cm depth, CD-0.4, CD-0.8, and SFD-1.2 increased soil salinity by 32.4%, 22.0%, and 1.8%, respectively, relative to initial soil salinity. In summary, soil salinity after the second growing season increased significantly for CD-0.4, while CD-0.8 and SFD-1.2 showed non-significant trends toward increased average soil salinity.

4 Discussion

Globally, water is a critical resource for food security, generating vital interest in reducing water losses and enhancing WUE, particularly in the MENA countries representing the driest region. Optimizing WUE can be achieved through adopting water-saving practices and cultivating drought-tolerant crops or cultivars. However, any increase in WUE must not be attained at the cost of yield to ensure farmer acceptance of proposed practices (Abdallah, 2017). The potential for water savings while maintaining productivity through CD adoption is substantial. CD decreases drainage outflow, thus preserving soil water in the rhizosphere to support plant growth. In the northern Nile River delta of Egypt, we evaluated the effects of CD-0.4, CD-0.8, and SFD-1.2 on drainage outflow, nitrate loss, water table level, grain yield, straw yield, and WUE of different wheat cultivars.

4.1 Water Table Level, Drainage Outflow, and Applied Irrigation Water

It is well established that blocking water outflow from a drainage network retains water availability for plant use when evaporative demand is highest (Wesström and Messing, 2007; Ritzema, 2015; Liu et al., 2019). In this study, decreased drainage time and discharge under CD treatments led to reduced overall drainage outflow. This reduction (27.3%–40.3%) was confirmed by higher water tables in CD treatments, particularly after irrigation events. The observed decline in drainage outflow from CD treatments has been widely documented globally (Wesström and Messing, 2007; Drury et al., 2009; Helmers et al., 2012; Jaynes, 2012; Ritzema, 2015; Rozemeijer et al., 2016; Sunohara et al., 2016; Negm et al., 2017; Poole et al., 2018; Youssef et al., 2018; Liu et al., 2019; El-Ghannam et al., 2021). Compared to SFD, individual case studies have reported decreased drainage outflows of 33%–45% (Javani et al., 2018), 30% (Youssef et al., 2018), 17%–80% (Skaggs et al., 2010, 2012), 25% (Negm et al., 2017), and 40%–100% (Gunn et al., 2015). Such variability may be due to differences in soil properties, drainage network technical parameters, irrigation systems, and rainfall amount, distribution, and intensity (Negm et al., 2017; Youssef et al., 2018). The lowest drainage outflow was recorded under CD-0.4 treatment, supporting findings from other researchers in different regions (Sojka et al., 2019; El-Ghannam et al., 2021).

The water saved through reduced drainage outflow remains in the soil for utilization by plant roots (Rozemeijer et al., 2016), leading to significant declines in applied irrigation water as observed for CD treatments. Under SFD-1.2 treatment, irrigation water requirements were 1.72 and 1.38 times higher than under CD-0.4 and CD-0.8, respectively. Interestingly, adopting CD, particularly CD-0.4 treatment, raised the water table level and increased groundwater storage in the root zone. This observation supports Rozemeijer et al. (2016), who revealed that CD decreased drainage outflow and augmented shallow groundwater storage in the effective root zone. Sustaining a shallow water table in silt clay soil enhances groundwater availability in the root zone through capillary rise (Ayars et al., 2006a, b; El-Ghannam et al., 2016, 2021). The significant increase in soil salinity under CD-0.4 and CD-0.8 treatments reinforces this conclusion (Ayars et al., 2006b). In this study, water uptake from shallow groundwater amounted to 22.0% and 8.0% of total evapotranspiration for CD-0.4 and CD-0.8, respectively (two-season average). Similarly, groundwater contribution to plant water uptake has been reported as 37.0%, 29.0%, 53.0%, 63.0%, and 31.0% of crop evapotranspiration for cotton, corn, wheat, sugar beet, and sunflower, respectively (Ayars et al., 2006b; El-Ghannam et al., 2021).

4.2 Wheat Growth, Yield, and Yield Attributes

The observed increase in crop productivity resulting from CD has been previously documented (Drury et al., 2009; Nash et al., 2015; Sunohara et al., 2016). Such yield improvements have been mainly attributed to mitigating drought stress and decreasing nitrate loss. In this study, yield improvements amounted to 9.3%. Based on the fact that all treatments were designed to avoid water stress across both seasons, the observed increases in grain and straw yields could be explained by reduced drainage outflow and limited nitrate outflow, subsequently increasing N availability for plant growth. The observed reduction in nitrate loss (35.3% and 20.8% for CD-0.4 and CD-0.8, respectively) supports this interpretation. Under different environmental conditions, CD adoption has reduced nitrate loss by 18.0%–75.0% (Ale et al., 2012; Craft et al., 2018; Liu et al., 2019; Sojka et al., 2019). Researchers attribute low nitrate loss under CD treatments to reduced drainage outflow (Negm et al., 2017; Poole et al., 2018; Liu et al., 2019; Sojka et al., 2019). In addition to measuring nitrate outflow, future studies should consider measurements of soil nitrate and plant N status.

The results showed that Sakha95 achieved the highest grain and straw yields and yield attributes compared to other tested wheat cultivars (Misr3, Giza171, and Sids14). The superiority of Sakha95 could be explained by its better grain filling, which translated to higher test weight (1000-grain weight).

4.3 WUE of Different Wheat Cultivars

CD enhances WUE through direct effects on two main factors: enhancing grain yield and decreasing applied irrigation water. The marked increase in WUE under CD treatments aligns with findings from arid regions such as Iran (Javani et al., 2018) and Egypt (El-Ghannam et al., 2021). Increasing the outlet elevation minimizes drainage outflow and increases soil moisture between irrigation events. Several studies have reported higher irrigation system efficiency under CD treatments (Bonaiti and Borin, 2010; Javani et al., 2018; Youssef et al., 2018; El-Ghannam et al., 2021).

4.4 Soil Salinity Affected by Controlled Drainage Treatments

The data clearly demonstrate that a shallow water table leads to salt accumulation, particularly in topsoil layers. For example, soil salinity values in the top layer under CD-0.4 treatment were almost two-fold greater than in deeper layers. Upward water movement, particularly within fine-textured soils, leads to evaporation at the soil surface or uptake by plants, leaving soluble salts in topsoil layers. In this study, increased soil salinity associated with CD had no detrimental effect on grain and straw yields because maximum soil salinity (4.00 dS/m) remained below the threshold (6.00 dS/m) known to negatively affect wheat growth. However, soil salinity under SFD-1.2 treatment was unaffected across both seasons, suggesting over-drainage as indicated by drainage ratio and outflow (El-Ghannam et al., 2021; Li et al., 2021). Similarly, Christen et al. (2001) observed the association between over-drainage and lower soil salinity in most SFD systems in Australia. Due to expected soil salinization associated with CD, careful soil salinity management must be implemented to avoid long-term salt accumulation that could lead to yield losses.

This study demonstrated that CD and selection of suitable cultivars could enhance WUE of wheat in the northern Nile River delta. Additionally, CD adoption could decrease surface and groundwater pollution by reducing nitrate outflow (Ritzema, 2015). Similarly, in arid and semi-arid regions, the main adjustment required in subsurface drainage systems is raising the outlet elevation and considering plant water uptake from shallow groundwater (Ayars et al., 2006a; Darzi-Naftchali et al., 2013; Javani et al., 2018; El-Ghannam et al., 2021). Although the observed soil salinity increase during the two seasons had no significant influence on crop yield, long-term shallow groundwater management could lead to soil salinity accumulation resulting in significant yield losses and adversely affecting farmer profitability. Therefore, monitoring and managing soil salinity when adopting CD is vital for long-term sustainability. Careful water management and appropriate cropping systems (salt-tolerant crops and cultivars), crop establishment techniques (e.g., raised beds), and agronomic practices (e.g., balanced fertilization and mulching crop residues to decrease soil surface evaporation) could reduce salinity accumulation risks and mitigate detrimental impacts of soil salinity (Ayars et al., 2006a). CD adoption can contribute to considerable water savings, with saved water used to expand wheat cultivation in other regions to minimize the gap between production and consumption. Long-term studies are required to investigate the effects of prolonged CD adoption on soil salinity and to determine the most suitable production systems that maximize CD benefits while minimizing soil salinity.

5 Conclusions

This study aimed to improve agricultural WUE in the northern Nile River delta of Egypt using a CD approach. CD substantially reduced drainage outflow, irrigation water, and nitrate loads compared to SFD-1.2, thus limiting drainage off-site effects. Under CD treatment, plants acquired part of their required evapotranspiration from shallow groundwater, which provided 22.0% and 8.0% of wheat evapotranspiration for CD-0.4 and CD-0.8, respectively. In addition to irrigation water savings, modifying SFD by increasing outlet elevation decreased nitrate loss while increasing WUE. In the northern Nile River delta, CD adoption could be a viable approach for enhancing WUE. Careful salinity management—including use of salt-tolerant crops and cultivars, raised bed cultivation methods, and maintaining crop residue on the soil surface—should be considered to decrease salinity accumulation and avoid future yield losses.

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Appendix

Fig. S1 [FIGURE:S1] Monthly average temperature (a) and average monthly rainfall (b) from 2016 to 2020 in Motobus District, Kafr El-Sheikh Governorate, Egypt

Note: Figure translations are in progress. See original paper for figures.

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