Deficit Irrigation Management as Strategy Under Conditions of Water Scarcity; Potential Application in North Sinai, Egypt

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Abstract Water plays an essential role in yield productivity; however, in the near future it seems that many Arabian and African countries will suffer from water scarcity periods. Egypt, as one of the Arabian and African countries, reflects this

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phenomenon as a result of increases in population, economic activities, living standards, and cultivated land, as implemented by the plans of successive Egyptian governments. Total water withdrawal between 2010 and 2015 was 68.3 km^3/year, which was distributed among agricultural, municipal, and industrial sectors. The agricultural sector is considered the main consumer as it is the core of the Egyptian economy; the agricultural sector consumed approximately 59 km^3/year for irrigation purposes and other agricultural activities. With double cropping or two crops per year, intensive agriculture has doubled the water demand. In addition, loss of water by evapotranspiration from the cultivated lands is estimated to be 3 km^3/year. In order to identify both the effects of reduced water supply on yield characteristics and water use efficiency (WUE) in newly reclaimed lands, we applied our experiments in North Sinai, which is one of the strategic lands planned for reclamation by the Egyptian government.

Three irrigation treatments were performed: 3,600m^3/ha (W1), 6,000 m^3/ha (W2), and 7,200 m^3/ha (W3; normal and recommended irrigation dose) with water from the El-Salam canal, using faba bean (Vicia faba L.) as the dominant crop in this region. The obtained results revealed that a relative decrease in soil salinity, compared with the initial soil salinity, occurred in parallel with increasing water supply regimes, by an average of 33.0%, 37.4%, and 47.6% for W1, W2, and W3 respectively. The WUE showed another phenomenon. Using the W1 water regime with faba beans under saline soil situations saved approximately 50% of the added water and showed a higher WUE of 2.36 kg/m^3 compared with W2 and W3, which resulted in WUE values of 1.75 kg/m^3 and 1.39 kg/m^3, respectively. Also, we produced a simulated yield model of the obtained yield with the field characteristics (R^2 of 0.98), and the model performance indicated a small root mean square error, of 0.12.

Keywords Soil nutrients, Soil salinity, Water stress, Water use efficiency, Yield model

1 Introduction

Increasing competition for water resources among the agriculture sector and the domestic consumption sectors, such as the municipal and industrial sectors, will require new irrigation strategies to allow water saving, and these strategies could maintain efficient levels of production in semi-arid regions [1]. The National Sinai Development Plan that was implemented for the Sinai Peninsula (1997–2017) envisaged a national mega project for the development of 100,000 hectares (ha) of agricultural lands with the initiation of the El-Salam Canal [2]. This mega project planned to transfer part of the River Nile water eastwards (Damietta branch), aiming to divert it to Sinai for irrigating a strip of reclaimed land between the Suez Canal and North Sinai to create a new agriculture zone ending at Egypt's Eastern national border. With water scarcity being recognized, a national policy was implemented in the 1970s for a strategy of reusing agricultural drainage water for irrigation purposes.

For example, in the El-Salam canal in the eastern part of the Nile Delta, the Nile water is mixed with the agricultural drainage water at a ratio of 1:1 [3]. Total water withdrawal between 2010 and 2015 was 68.3 km^3/year, which was distributed among agricultural, municipal, and industrial sectors. The agricultural sector is considered the main consumer, as it is the core of the Egyptian economy; the agricultural sector consumed approximately 59 km^3/year for irrigation purposes and other agricultural activities. With double cropping or two crops per year, intensive agriculture has doubled the water demand. Also, the loss of water by evapotranspiration from the cultivated lands is estimated to be 3 km^3/year [4].

1.1 Food Security Under Conditions of Water Deficiency

Several definitions of food security have been used during the past two decades. The World Food Summit [5] defined it as “food security appears when all people have similar physical, economic, and social access to sufficient, safe food that meets their dietary needs and food preferences for healthy life”. However, owing to income disparities that could affect access to food, it is essential to distinguish between food security approaches at the national level and/or community level.

The Arabian countries are still suffering from a shortage of food commodities, especially cereals, in spite of efforts applied by their governments to overcome this critical issue. Another approach to food security refers to the availability of different commodities, such as cereals, carbohydrates, proteins, legumes, etc. Increasing cereal imports in Egypt and other Arabian countries has been attributed to many factors, such as the decline and loss of cereal yield as a result of land use changes, soil degradation, and increasing urbanization, with increased internal migration of people in rural areas to urban centers.

Egypt is suffering from shortages of many kinds of food, especially the most expensive commodities due water shortage. However, cereal production has increased from 5 billion Kg in 1961 to 23 billion Kg in 2008 [6]. Nevertheless, the production has never been sufficient to face the food demand for the increasing population. Thus, successive Egyptian governments have had to import cereals; the amounts ranged from 1.4 billion Kg in 1961 to 12.3 billion Kg in 2008 [7]. Egypt, as the largest wheat importer in the world, imported 10 billion Kg in 2010 [8]. In Egypt, food security is a result of different causes that can be attributed to international and/or domestic factors. Food prices for agricultural commodities have risen dramatically; these commodities are scarce in the global market as a result of the production of biofuels to replace oil, which consumes large areas worldwide that would have been used for cereal production [9]. Also, climate change has affected rainfall distribution in Egypt in many different areas, affecting the agrarian landscape. Increases in the cost of transportation have also had an important effect on food prices in Egypt. The increases in food prices overall can be attributed to the increase in total population, urbanization, and encroachment on arable land.

1.2 Arable Land Area

Egypt is an agrarian nation, and arable land areas have been a dominant issue since the beginning of the twentieth century. The total cultivated land area in 2008 was 3.5 Mha, and 90% of it was irrigated. The old land located in the Nile Delta covered 2.3 Mha, while reclaimed land located in the eastern and western portion of the Delta covered 1.0 Mha [5]. Irrigation systems used in Egypt comprise a mixture of conventional and modern techniques. The total area irrigated by flooding irrigation is 2.84 Mha, which comprises 89% of the total irrigated area. In the Nile delta, flooding irrigation (surface, and furrow) is used in 89% of the cultivated area along the Nile River. Sprinkler and drip irrigation, as modern irrigation systems, are also being used and practiced in greenhouse agriculture or reclaimed lands in large areas that have low water-holding capacity.

1.3 Water Resources

As Egypt, except for the northern region, is a semi-arid region, the rainfall amount is rather low. While intermittent torrents can occur in the north of the Sinai Peninsula and in Upper Egypt, this water flows into either streams or groundwater. Water resources can be distinguished as either conventional or non-conventional. Conventional resources confined to the Egyptian allocation are the withdrawal of fresh water from the Nile River, and the groundwater along the Nile River and its delta. Groundwater allocated on the northern and eastern coasts is identified as shallow groundwater, while that in the western and eastern deserts is identified as deep and non-renewable groundwater [10]. Non-conventional water resources consist of the reused water coming from treated wastewater, agricultural drainage, industrial drainage, and desalinized water that can be produced either from seawater or brackish water [11]. According to the treaty between the countries in the Nile Basin and Egypt, the water allocation from the Nile River for the Egyptian part is 56 km^3/year, which accounts for 98% of the total source of renewable fresh water and is for domestic use [10].

The majority of the Egyptian lands suffer from desertification and are distinguished as the western and eastern deserts. In these desert regions the renewable and non-renewable groundwater is considered to be the main source for agriculture and municipal use [12]. However, the river water sources are not accessible in the dominant delta regions. Thus, the local farmers have to use several methods to get fresh water, such as digging wells that mainly originate from the water percolation of the irrigation canals. Also, as a result of most Egyptian villages not having a potable water network, the residents drill small pumps manually to get fresh water for domestic and potable uses, and the renewable groundwater provides Egypt with 1.3 km^3/year [10].

Successive Egyptian governments have used several methods to identify and initiate other water resources, especially non-conventional resources. Reuse of agricultural drainage water has been considered for a long time. For example, the drainage water of El-Serw station was used for irrigation purposes in 1928, and a supporting station for recycling use was constructed in 1930. Shortly afterward, the government understood that the quality of the resultant agricultural drainage water from this station was close to that of the Nile water, and this drainage water resulting from the supporting station was pumped into the Nile River (Damietta branch). This strategy has been adopted since the 1970s [13], and policymakers set their strategies to be carried out through pumping of the agricultural drainage water of the main and branch drains and then mixing this water with fresh water in the Nile main and branch canals. In recent decades in Egypt, local farmers have directly used the agricultural drainage water from the drains closer to their farms for irrigation purposes, instead of depending on the irrigation canals, as many villages in the Delta drain their wastewater into the agricultural drains from which large areas are irrigated. In addition, treated wastewater is also used for irrigation. Reused wastewater resources, such as agricultural drainage and treated wastewater, represent 4.79 km^3/year of the water requirements in Egypt [12]. In this context, several researchers have reported that in coming decades more irrigated land will be drained, and hence more wastewater treatment stations should be constructed in the Delta region, a region that reflects the increasing use of treated wastewater, with an increase of 11 km^3/year projected to occur by 2017 [12].

1.4 Soil Water Management

In the modern world, the economic approach to water is regarded as *Blue Gold*. The agricultural sector is considered to be the most significant water consumer, consuming approximately 70% of the world's total water, and this will increase in the future [14]. In recent decades, scientists have identified the water consumed in agricultural production as *virtual water* [15, 16]. *Virtual water* is characterized by three components: blue, green, and gray. Blue water refers to surface and groundwater, while green water refers to rainfall water and/or soil water. Water that percolates into soil contaminated by chemical compounds (e.g., fertilizers and pesticides) or water that is disposed of as municipal effluent, is called gray water [17]. The stakeholders are using recent technologies to manage the processes of converting blue water and/or gray water to green water for irrigation to increase water use efficiency (WUE). Thus, the use of modern irrigation systems and irrigation at night and/or even in the early morning could result in increasing the WUE and decreasing water losses by evaporation.

Soil hydrological and physical properties strongly affect the hydrological balance, and knowledge and management of these properties can result in the preservation and management of green water that is lost by leaching and evaporation in arid regions. This strategy is also applied to enhance the soil water-holding capacity

(SWHC) and reduce losses by evaporation. Soil texture is strongly correlated with the SWHC, so that the finer the soil texture, the higher is the SWHC [18].

1.5 Deficit Irrigation

Deficit irrigation (DI) is a recent irrigation technique that is applied during various growth stages of drought-sensitive plants if irrigation is limited and/or rainfall provides a minimum supply of the required water. Thus, DI is an important approach to increase WUE [19, 20]. In arid regions, as there is limited water, plants reflect drought tolerance during the phenological stages of growth, especially in the vegetative stages and particularly during the late ripening period. While this limited water supply inevitably has effects on plant drought stress and production loss, DI enhances irrigation water productivity and WUE, which is the primary limiting factor in plant growth [21]. Furthermore, one of the aims of DI is stabilizing yields and obtaining relevant crop water productivity, rather than obtaining maximum yields [22]. The approach of increasing food production and food safety with less water, in countries with limited water, associated with the available land resources, has become a leading challenge in recent decades, owing to severe water scarcity [20]. Thus, new approaches to enhance irrigation scheduling should be considered to achieve optimum water supply for yield productivity, while maintaining the soil water content close to the field capacity to increase WUE. Also, the decision on irrigation scheduling is made by the local stakeholders to maximize profit, to determine when and how water should be applied to a field. This irrigation scenario aims to increase irrigation efficiency by supplying the soil with the precise amount of water needed to bring the soil water to the relevant level, and at the same time, save energy and water.

Deficit irrigation comprises irrigating into the root zone with less water than that required for evapotranspiration [22]. The best combination of acceptable yield reduction and water use that results from water-saving strategies is vital for different crops [21]. For areas with long summer droughts (North Sinai, Egypt) and water scarcity, DI is highly recommended for the overcoming of severe yield reductions and securing low yield levels [23]. A preliminary study in North Sinai [20, 24] showed that the influence of DI on crop yield and physiology led to significant variations in crop productivity, physiology, and quality. In addition, the awareness of WUE concepts and the significant relationship between soil water deficiency and crop productivity supported policymakers and farmers in optimizing water management and irrigation water supply [25]. The results obtained using DI in arid and/or semi-arid regions succeeded in increasing the total water-holding capacity of soils by 75% and contributed to increases in faba bean plant height, number of pods/plant, 100-seed weight, seed yield/plant, numbers of plant branches, and seed yield/ha [26]. Another study [27] found that adding 50% of the water requirements also significantly increased the crop productivity of the faba bean. Otherwise, irrigation using half of the required water supply during vegetative growth showed greater increases in yield productivity than those noted with the full irrigation. In addition, Marschner [28] mentioned that decreasing the water availability in soils affected the soil nutrient diffusion rate and concentration of the soil solution, revealing an apparent decrease in plant nutrient uptake. Soil salinity, the other major phenomenon in the arid and semi-arid environment, is considered a major and severe environmental threat for crop production in many parts of the world, especially those which depend on irrigated agriculture and those associated with high water tables and poor drainage. Annually, 2% of the arable land all over the world becomes unsuitable for cultivation as a result of the salinity effect and waterlogging [5]. As a result, plant growth can be inhibited for several reasons; the effect of salt types and their quantity in the soil solution, and subsequently the plant's ability to take up nutrients and water, lead to reduced plant growth rates. This action can occur owing to the mechanism of osmotic pressure and/or the water deficit effect of salinity [20, 29]. Also, when salts enter the plant in excessive amounts during the transpiration stream process, the cells involved in transpiration in the leaves would be injured. This would lead to deterioration in the phenology and photosynthesis processes and a reduction in the plant growth rate [25, 29].

2 Egypt Case Study

2.1 Experimental Site

The objectives for this case study were to determine the effect of different water supply scenarios on soil nutrients and their distribution through two growth seasons and different months under high saline soil conditions in North Sinai, Egypt, in a semi-arid Mediterranean climate. This study also aimed to identify and determine the WUE under that climatic condition, and the yield productivity of the faba bean (*Vicia faba L.*) in this environment.

Field experiments were carried out during two successive winter seasons, 2012/2013 and 2013/2014, at Gellbana village in Sahl El-Tina (Fig. 1), North Sinai Governorate, at an experimental farm (31° 00′ N latitude and 32° 30′ E longitude). The region has a continental climatic condition with a wet winter and hot dry summer. The lowest temperatures occur in January and February (22 and 20°C), while the maximum amount of rainfall is 12.7 mm/month, in February. The highest humidity is 70%, in January [3], and the soil is characterized as a sandy loam with pH 8.18, average salinity (EC) 10.23 $\mathrm{dSm^{-1}}$, $CaCO_3$ 6.90 $\mathrm{g\ kg^{-1}}$, and organic matter 0.44 $\mathrm{g\ kg^{-1}}$ [20].

The soil is irrigated from the El-Salam canal, with an average salinity (EC) of 1.38–1.47 $\mathrm{dSm^{-1}}$. Representative water samples in the study area were collected during the winter season (October, December, January, and March) for two successive years. The irrigation water was analyzed (Table 1) for cations and anions according to the methods outlined by Cottenie et al. [30].

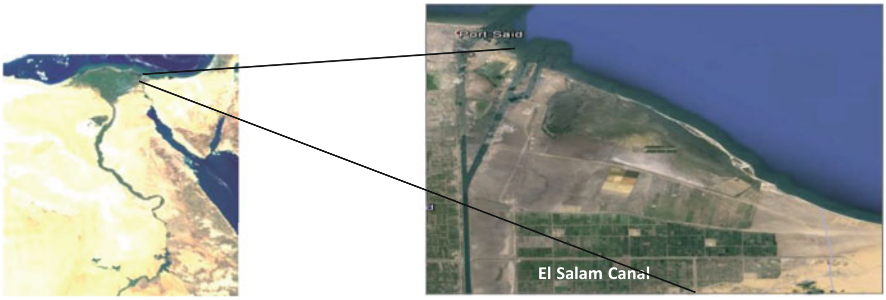

Fig. 1 Location of experimental area at Gellbana village in Sahl El-Tina, North Sinai. After Abu-hashim and Shaban [20]

2.2 Experimental Design

The experiment was prepared using a randomized complete block design with three replications. Faba bean (*Vicia faba L., cultivar* Sakha-3) was employed in this region as our test crop through the two seasons of the experiment. Three irrigation levels were implemented: W1 with 3,600 m^3/ha, W2 with 6,000 m^3/ha, and W3 with 7,200 m^3/ha (normal irrigation used by the local farmers). The irrigation supply was by surface flow through pipelines that had meter gauges to control the amount of added water. To overcome the soil salinity hazards that could affect the plant sowing processes, the experimental soils were irrigated for 4 h on the first day of plant sowing. On the second day of plant sowing, the soil was irrigated for 7 h, and then every 10 days. The sowing dates in the three regions were November 25th and 28th for the first and second seasons, respectively. The faba bean seeds were planted in hills on one side of a ridge, with 20 cm between the hills, at a rate of three seeds per hill. By thinning the seedlings at 35 days after sowing, one plant per hill was maintained. Each experimental plot consisted of six ridges; 5 m in width and 10 m in length, 60 cm apart.

The first part of the fertilization regime consisted of calcium superphosphate (15.5% P_2O_5) at 360 kg/ha applied before planting. Then potassium sulfate (48% K_2SO_4) was applied at 120 kg/ha in two equal doses at 21 and 45 days after sowing. The basic application of nitrogen, added as urea (46% N), was done at a rate of 48 kg/ha, on the same dates. Harvesting of the plants was performed at maturing (mid-May) in both seasons. To estimate plant height (cm), 100-seed weight (g), seed yield (t/ha), seed weight (g seed/plant), aboveground biomass (t/ha), and harvest index (%), samples of ten guarded plants from each experimental plot were taken randomly. The harvest index was calculated by dividing the seed yield by the aboveground biomass, and the WUE was determined according to Bos [31], depending on the aboveground biomass, using the following equation:

Table 1 Water characteristics of the El-Salam Canal, which was used for irrigation in two seasons (2012/2013 and 2013/2014)

	EC (dSm^{-1})		pH		SAR		Adj SAR		RSC		ESP	
Parameters	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
October	1.20	1.30	8.00	7.90	3.82	3.01	6.11	5.71	−4.11	−5.20	4.41	3.21
December	1.34	1.37	7.98	8.00	3.62	2.85	5.97	5.41	−4.21	−5.37	4.12	2.97
January	1.40	1.44	7.95	7.98	3.58	2.74	6.08	5.21	−4.24	−5.49	4.06	2.81
March	1.37	1.41	7.95	7.97	3.48	2.80	5.52	5.31	−4.39	−5.42	3.87	2.89

From Abu-hashim and Shaban [20]

1st first season (2012/2013), *2nd* second season (2013/2014), *SAR* sodium adsorption ratio, *Adj SAR* adjusted sodium adsorption ratio, *RSC* residual sodium carbonates, *ESP* exchangeable sodium percentage, *EC* salinity

WUE = seasonal biomass as dry matter/kg divided by seasonal water in ET.
ET = equivalent dry land or rain-fed plot.

2.3 Statistical Analysis

Data for yield and quality traits were statistically analyzed by one-way analysis of variance (ANOVA), using CoStat version 6.003 (CoHort Software), and the differences between means were evaluated for significance using the least significant differences (LSD) test, according to Sendecor and Cochran [32].

To compare the obtained results for yield productivity with the estimated results for yield from the measured field characteristics (simulated yield model), the root mean square error (RMSE) was applied as a criterion to reveal the goodness of the simulation.

This is expressed as:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\mathrm{Observed}_i - \mathrm{Simulated})^2}{n}}$$

where n is the total number of observations.

3 Results

3.1 Irrigation Water Characteristics

As the irrigation water of the El-Salam canal is a mixture of Nile water and agricultural drainage, the concentrations of cations and anions (except for Na^+) showed an increasing order from the first season of the experiment to the second one and from October to January (Fig. 2). Also, the results showed that excessive solutes in irrigation water are a widespread problem in semi-arid regions [33].

For the solute distributions according to months, the concentrations followed an ascending order for the cations; Ca^{2+}, Mg^{2+}, and K^+. However, the Na^+ concentrations displayed a descending order, where Na^+ decreased from 6.20 to 5.79 meq/l and decreased from 5.57 to 5.26 meq/l in the first and the second seasons, respectively.

For semi-arid regions, the Food and Agriculture Organization (FAO) [5] used the sodium adsorption ratio (SAR) as an efficient parameter to estimate the suitability of irrigation water, and they documented a range of 0–15 meq/l. The obtained results revealed that, for our case study in North Sinai, El-Salam canal water was already within such permissible SAR limits (Table 1).

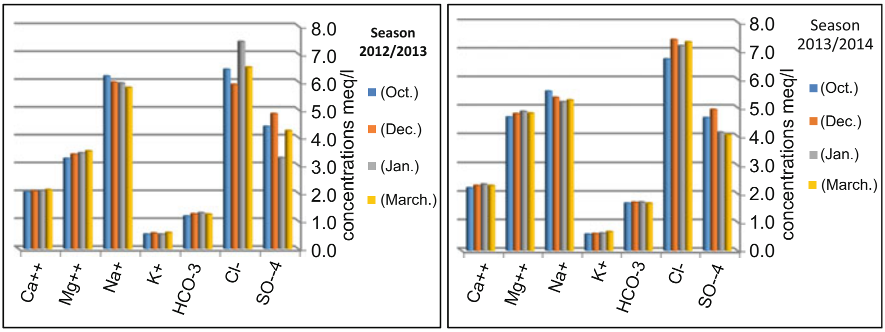

Fig. 2 Chemical parameters (meq/l) of the irrigation water of the El-Salam canal during representative months for the two successive winter seasons 2012/2013 and 2013/2014. After Abu-hashim and Shaban [20]

As the SAR is related to the sodium concentration in the irrigated water (in this case, the El-Salam Canal), the SAR ratio was affected by the seasonal changes during the investigated months. This phenomenon was also noted for other parameters investigated, such as the adjusted SAR, Soluble Sodium Percentage (SSP), and the exchangeable sodium percentage.

The obtained results for water salinity and its distribution during the two seasons and its changes during the investigated months revealed that the EC (dSm^{-1}) of the El-Salam canal was higher in the months of the second season than in the first season (Table 2). In addition, the salinity concentration revealed higher values in January, compared with the other months, in both seasons. This phenomenon could be a result of the Egyptian water irrigation strategy called deadline winter blockage, which occurs in January, in which the streams are closed and the water supply that can reach the El-Salam canal would be reduced. This strategy is usually carried out in winter every year, especially in the month of January, and it occurs in parallell with the impact of temperature in this semi-arid region, resulting in increased concentrations of the different solutes and so increasing the salinity concentration.

3.2 Canal Nutrient Characteristics

The nutrient concentrations varied with the investigated months and from one season to the other, and the concentrations followed an ascending order among the months (Fig. 3). For the first and second seasons, respectively, the NO_3-N concentration increased from 9.23 and 12.17 mg/l in October to 18.22 and 17.84 mg/l in March. Otherwise, for the first and second seasons, respectively, NH_4-N increased from 5.40 and 7.40 mg/l in October to 9.02 and 8.77 mg/l in March. The same phenomenon

Table 2 Effect of different irrigation supply regimes combined with the seasons' and the months' impacts on soil salinity (dSm^{-1}) and nutrient composition (mg kg^{-1})

Treatment	EC	N	P	K	Fe	Mn	Zn
S1 + M1 + W1	8.93	62.0	4.69	180.0	2.03	3.58	0.83
S1 + M1 + W2	7.95	64.1	4.75	193.0	1.98	3.66	0.90
S1 + M1 + W3	6.52	69.8	4.89	198.0	1.96	3.70	0.92
S1 + M2 + W1	7.30	65.0	4.77	184.0	2.12	3.63	0.85
S1 + M2 + W2	6.73	67.3	4.82	197.0	2.03	3.69	0.93
S1 + M2 + W3	5.23	69.5	4.93	202.0	2.05	3.73	0.95
S1 + M3 + W1	6.95	69.7	4.80	193.0	2.06	3.75	0.88
S1 + M3 + W2	6.32	72.2	4.86	206.0	2.06	3.71	0.95
S1 + M3 + W3	5.12	74.6	4.97	208.0	2.09	3.76	0.99
S1 + M4 + W1	6.46	74.0	4.83	198.0	2.10	3.73	0.93
S1 + M4 + W2	6.20	75.6	4.88	208.0	2.08	3.74	0.98
S1 + M4 + W3	5.03	76.3	4.96	212.0	2.10	3.78	0.98
S2 + M1 + W1	7.20	60.0	4.85	195.0	2.00	3.60	0.88
S2 + M1 + W2	6.85	65.9	4.88	201.0	2.04	3.68	0.93
S2 + M1 + W3	6.10	68.3	4.92	208.0	2.06	3.73	0.95
S2 + M2 + W1	6.88	64.0	4.90	198.0	2.04	3.64	0.93
S2 + M2 + W2	5.96	68.6	4.93	206.0	2.08	3.71	0.96
S2 + M2 + W3	5.09	71.6	4.95	213.0	2.09	3.75	0.98
S2 + M3 + W1	6.20	75.0	5.00	204.0	2.08	3.67	0.96
S2 + M3 + W2	5.83	69.3	4.98	208.7	2.10	3.75	0.98
S2 + M3 + W3	4.92	75.1	4.99	216.0	2.13	3.77	1.02
S2 + M4 + W1	5.79	70.0	5.02	207.0	2.11	3.74	0.98
S2 + M4 + W2	5.40	73.1	4.91	212.0	2.13	3.78	0.99
S2 + M4 + W3	4.88	77.9	5.01	218.0	2.16	3.81	1.04
LSD$_{0.05}$	0.02	0.17	ns	1.48	0.03	0.04	ns

From Abu-hashim and Shaban [20]

LSD least significant difference, *ns* not significant, *S1* and *S2* first and second seasons, *M1* October, *M2* December, *M3* January, *M4* March, *W1* irrigation with 3,600 m^3/ha, *W2* irrigation with 6,000 m^3/ha, *W3* normal irrigation with 7,200 m^3/ha

was noted for the phosphorus and potassium concentrations for the two successive seasons and within the months [34]. However, for the investigated heavy metals (Fig. 3), the highest heavy metal concentrations were noted for Mn (1.59–1.80 mg/l) and then Zn (1.05–1.15 mg/l), while the lowest was Fe (0.93–1.05 mg/l). A reduced concentration of ammonium nitrate in surface water was not apparent in the investigated samples. Leaching and surface runoff from agricultural practices, and water contamination with animal and human waste in the streams can lead to high ammonium nitrate values [35, 36]. Nevertheless, the concentrations of ammonium (5.40–9.02 mg/l) and nitrate (9.23–18.22 mg/l) found in this study could be within permissible limits [35]. Industrial residues are one of the most significant sources of heavy metals that can pollute the aquatic environment, as heavy metals are not

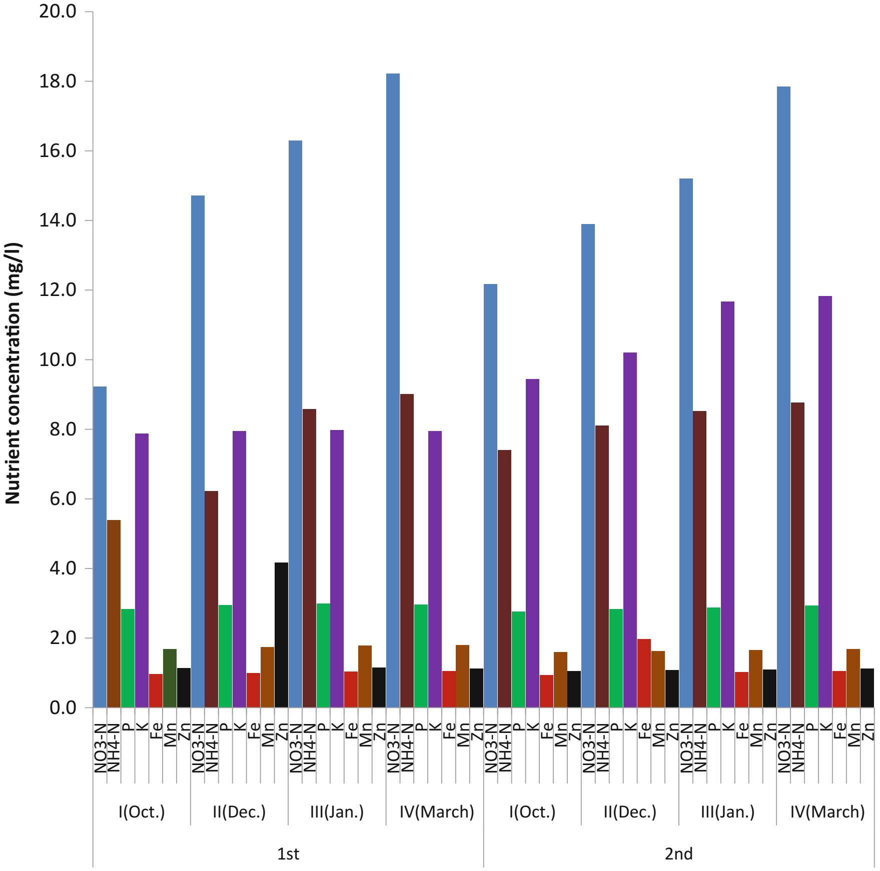

Fig. 3 Nutrient concentrations (mg l^{-1}) in the El-Salam Canal, which was used for irrigation in two seasons (2012/2013 and 2013/2014)

environmentally degradable. Their discharge into rivers and streams can cause deleterious health effects [37, 38]. Our chemical analysis of the El-Salam canal sediment revealed that the concentrations of Fe, Zn, and Mn met the allowable levels for irrigation [5]. The literature has revealed that for the Damietta branch, whence the El-Salam canal receives its main water resources [39], sediment analysis showed a high concentration of heavy metals, of the order of Fe > Mn > Cu > Zn > Pb > Cd. With the obtained field survey and the results of chemical analysis of these pollutants, it appears that the El-Salam canal carries wastewater with high potential levels of agrochemical residues and other terrestrial materials from the cultivated Nile Delta region to the eastern part of Sinai.

3.3 Water Stress Impact on Soil Salinity

In our study, to identify and estimate the impact of the irrigation supply regimes on soil salinity and soil nutrients for the two seasons, samples were collected from the soil surface layer (0–30 cm) 4 days after irrigation. The soil salinity in the investigated seasons and months indicated significant differences in the water stress (see Table 2). The initial soil salinity for Sahl El-Tina was 10.23 dSm^{-1}, and we noted that there was a relative decrease in soil salinity along with the increase in water supply. Compared with the initial soil salinity, the data for all field treatments in the different months and seasons revealed that, for the standard irrigation supply (W3), soil salinity was reduced in the first and second seasons by 46.5% and 48.7%, respectively.

3.4 Soil Nutrient Availability

Compared with the initial soil nutrient values in the study area, the soil nutrients were increased with increasing water amounts (see Table 3). The mean phosphorus value was increased by 16.5% using the W3 water regime compared with water regimes W1 and W2, with increases of 14.3% and 14.7%, respectively, compared with the initial soil phosphorus value (4.25 mg kg^{-1}). The heavy metals, i.e., Zn, Fe, and Mn, revealed a descending order with increasing water stress (see Table 4). The reduction of nitrogen and phosphorus availability with water stress (from W3 to W1 treatments) was attributed to the decrease in nutrient diffusive flux during the water stress [40].

Nutrient availability was enhanced by increasing the soil water; this approach agreed with the potassium availability, which decreased with increasing water stress (Table 3). Of note, Zeng and Brown [41] reported increased potassium flux and

Table 3 Soil nutrient availability, compared with the initial soil concentration, and its relative impact under the influence of different levels of deficit irrigation

Relative impact	Nutrient	Initial soil	Season					
			First season			Second season		
			W1	W2	W3	W1	W2	W3
Relative increase	N (mg kg^{-1})	45.00	0.50	0.55	0.61	0.50	0.54	0.63
	P (mg kg^{-1})	4.25	0.12	0.14	0.16	0.16	0.16	0.17
	K (mg kg^{-1})	178.0	0.06	0.13	0.15	0.13	0.16	0.20
	Zn (mg kg^{-1})	0.81	0.08	0.16	0.21	0.16	0.19	0.27
	Fe (mg kg^{-1})	1.39	0.49	0.47	0.48	0.48	0.50	0.52
	Mn (mg kg^{-1})	3.43	0.07	0.08	0.09	0.07	0.09	0.10

From Abu-hashim and Shaban [20]

W1 irrigation with 3,600 m^3/ha, *W2* irrigation with 6,000 m^3/ha, *W3* Normal irrigation with 7,200 m^3/ha, *1st* first season (2012/2013), *2nd* second season (2013/2014)

Table 4 Correlation analysis of the measured field parameters and the obtained yield in two seasons, 2012/2013 and 2013/2014

	Yield	Irrigation treatment	EC	N	P	K	Fe	Mn	Zn
Yield	1	0.885[a]	−0.579	0.714	0.348	0.703	0.416	0.768	0.703
Irrigation treatment		1	−0.825[a]	0.930[b]	0.529	0.787	0.507	0.939[b]	0.745
EC			1	−0.830[a]	−0.891[a]	−0.919[b]	−0.754	−0.926[b]	−0.877[a]
N				1	0.517	0.758	0.550	0.930[b]	0.702
P					1	0.877[a]	0.777	0.696	0.867[a]
K						1	0.866[a]	0.902[a]	0.995[b]
Fe							1	0.757	0.872[a]
Mn								1	0.863[a]
Zn									1

From Abu-hashim and Shaban [20]

[a] Correlation is significant at the 0.05 level (two-tailed)

[b] Correlation is significant at the 0.01 level (two-tailed)

increased soil efficiency with increases in soil moisture. Hagen and Tuker [42], in 1982, demonstrated that decreases in Mn, Fe, and Zn availability with soil water stress (Table 3) could be attributed to the high soil pH in soils that contain high concentrations of calcium carbonate; hence these nutrients would not be available to the root system.

3.5 Yield Characteristics

The correlation analysis results for the measured field experimental parameters and the obtained crop yield in both seasons (2012/2013 and 2013/2014), showed that the relationship of the crop yield and the water regime had a positive trend as a result of increasing the water supply (Table 4). On the other hand, a negative trend in response to the water supply regime and the soil salinity was noted. The same significant negative trend was also noted between the soil salinity and soil nutrients (N, P, K, Mn, and Zn).

The water regimes used in this experiment (W1, W2, and W3) showed differences in the biomass yield (Mg/ha) with drought stress (see Table 5). These results agree with those of DeCosta et al. [43], who reported that yield component analysis of faba bean had a positive yield response for the water supply regime, as well as for increases in total biomass.

Our field results showed that with the W2 water regime the biomass yield was more efficient than that with the W3 water regime (normal irrigation) and that with the W1 regime (Table 5). These results are consistent with the results of Hirich et al. [27], who reported that the DI strategy, using half of the required water, during vegetative growth revealed higher yield productivity than that seen with the full irrigation amount. We found that the WUE showed another phenomenon. Namely, using the W1 water regime under saline soil conditions in an arid region saved 50% of the required water amount and showed a higher WUE, at 2.36 kg/m^3, than using the W2 and W3 regimes, which led to WUE values of 1.75 kg/m^3 and 1.39 kg/m^3, respectively for the first and second seasons (see Table 5). These results are in agreement with the findings of Al-Suhaibani [44], Link et al. [45], and Alireze and Farshad [46].

3.6 Evaluation of Yield Simulation Model

The obtained field measurements were calculated by using the solver program of *Microsoft Office Excel 2010* to model the field data and find the optimal estimated value for the yield under the measured field parameters. The results revealed:

Table 5 Impact of water stress on yield and yield compound and water use efficiency for the two seasons 2012/2013 and 2013/2014

	Weight straw (g)/plant		Weight 100-seed (g)		Weight seed (Mg/ha)		Biomass yield (Mg/ha)		Harvest index (%)		WUE (kg/m^3)	
Parameter	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
W1	12.84	14.19	50.67	56.33	2.84	2.87	8.39	8.56	33.82	33.52	2.33	2.38
W2	20.67	18.14	67.00	76.33	3.01	3.06	10.37	10.60	29.06	28.87	1.73	1.77
W3	16.35	23.07	62.00	67.33	2.86	2.93	9.87	10.04	29.00	20.14	1.37	1.40

From Abu-hashim and Shaban [20]

WUE water use efficiency, *W1* irrigation with 3,600 m^3/ha, *W2* irrigation with 6,000 m^3/ha, *W3* normal irrigation with 7,200 m^3/ha, *1st* first season (2012/2013), *2nd* second season (2013/2014)

$$\text{Simulated yield} = 0.001\ \text{WSA} + 0.856\ \text{EC} - 0.296\ \text{N} + 0.808\ \text{P} + 0.042\ \text{K} + 0.944\ \text{Fe} + 0.865\ \text{Mn} + 1.007\ \text{Zn} + 0.961$$

where *WSA* is the water supply amount, *EC* is soil salinity (dSm^{-1}), and *N, P, K, Fe, Mn,* and *Zn* are the measured nutrients expressed as mg kg^{-1}. To compare the obtained yield productivity with the estimated yield of the measured data (simulated yield model), the RMSE was applied as a criterion to reveal the goodness of the simulation. The simulated yield model correlated well with the obtained yield results of the field measurements, with an R^2 of 0.98, and the good performance of this comparison can also be indicated by its small RMSE, of 0.115.

4 Conclusion and Recommendations

Most of the countries in the Middle East and North Africa are located in arid regions with high temperatures and low rainfall. In Egypt, the finite conventional water resources in the arable lands are decreasing with the continuous increase in population, and this is considered to be the principal cause of water scarcity in the country. The use of non-conventional water resources (i.e., treated industrial and wastewater drainage, reused agricultural drainage water, and desalinated water) is now one of the main approaches being explored to increase water resources. In addition, green water can be obtained by enhancing soil water conservation, such as by following conservation tillage methods, increasing soil organic matter, and covering soil surfaces with plant residues. Also, surface irrigation, which is employed extensively in the Egyptian arable lands, can be compensated by modern irrigation systems (sprinkler and drip, etc.).

Our case study of Egyptian saline soils with a shortage of water that does not lead to reasonable yields showed that efficient irrigation is required in the growing season. In the El-Salam canal water, the main source of irrigation in our study area, the results of our chemical analysis agreed with FAO permissible levels. In addition, the level of soil nutrients revealed a descending order with increasing water stress. We conclude that, although the soil salinity decreased by 47.6% with the normal water irrigation supply (W3), compared with the W1 and W2 regimes, the use of the W1 regime saved 50% of the supplied water and resulted in a higher WUE, at 2.36 kg/m^3, than using the W2 and W3 regimes, with WUE values of 1.75 kg/m^3 and 1.39 kg/m^3, respectively. Thus, we conclude that, with the water scarcity problem that has faced Egyptian stakeholders in recent decades and with the salinity problem that has appeared in several places, such as North Sinai, DI can save water and lead to acceptable crop productivity. For different crops in areas of long summer droughts, such as North Sinai, the best combination of an acceptable yield reduction and water use strategy resulting from water saving is important under conditions of water scarcity. Thus, DI is highly recommended for the overcoming of severe yield reductions and for securing the low yield level (Fig. 4).

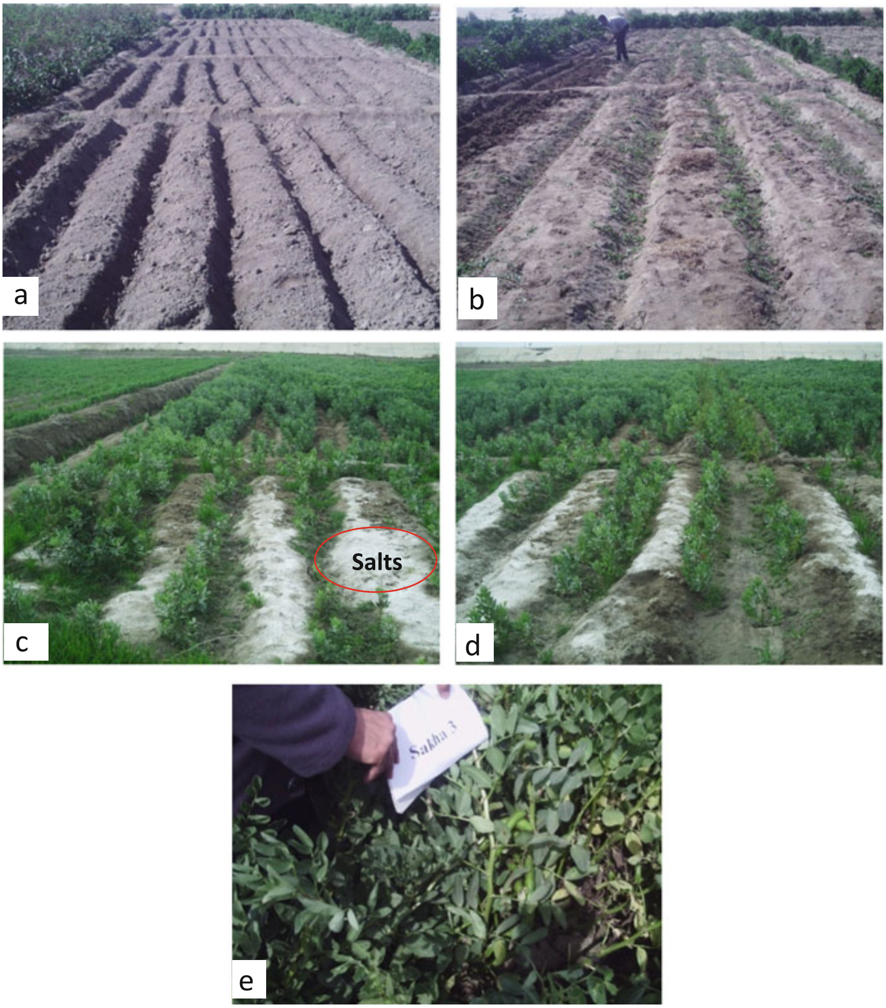

Fig. 4 (**a**–**e**) Growth of faba bean plants under high-salinity conditions. (**a**) Seedbed preparation before planting. (**b**) Sowing and treatment process. (**c**) Irrigation water at rate of 3,600m^3/ha, (**d**) irrigation water at rate of 6,000 m^3/ha, (**e**) irrigation water at rate of 7,200 m^3/ha per plot unit and planting of faba bean cultivar Sakha-3

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