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SOIL RECLAMATION

Modeling the Impact of Field Irrigation Management on Soil Water-Nitrate Dynamics: Experimental Measurements and Model Simulations

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Abstract—Irrigation systems and watering rates in Iraq often exceed crop water requirements, which yield high soil nitrate (NO_3) leaching out of the effective depth of crop roots. This work was conducted to discover the impact of different irrigation management conditions on the soil water-nitrate dynamics to develop management practices for minimizing soil NO_3 leaching out of the effective crop roots. The Root Zone Water Quality Model (RZWQM2), which integrates water-nitrate dynamics and related processes, can assist in improving the acknowledgment of soil water-nitrate dynamics. A field experiment was conducted at Al-Raeeid Research Station, Baghdad, Iraq; with a wheat crop irrigated by sprinkler and surface irrigation systems at different watering rates of 30, 50, and 70% of the available soil water. RZWQM2 was used to explore the interactions between irrigation practices and soil nitrate dynamics. The model satisfactorily worked for the study field conditions after the calibration process and simulated the impact of irrigation management on the soil water-nitrate dynamics. The results indicate that the high watering rate of irrigation led to a higher amount of soil water content and soil nitrate in the surface soil depths for both irrigation systems. Sprinkler irrigation yielded 0 mg/cm^2/day nitrate flux toward the groundwater for all watering rates, whereas surface irrigation produced 314, 94, and 183 mg/cm^2/day for the watering rate of 30, 50, and 70%, respectively. Hence, the best irrigation management strategy for the local area of high temperatures is increasing the number of irrigation events with low application rates to achieve an appropriate balance of high crop yield and low nitrate leaching toward the groundwater.

Keywords: irrigation systems, soil water dynamics, soil nitrate dynamics, RZWQM2, wheat, Typic Torrifluvents

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INTRODUCTION

Nitrogen (N) fertilization is one of the essential nutrients for improving crop growth and production [14, 36]. However, the global consumption of nitrogen fertilizer, which becomes more than 100 million tons per year, is mainly caused by applied poor agricultural field management, especially the fertigation practice [9]. Applying oversupplied N for the cropping system with overuse of irrigation requirements produces a high accumulation of nitrate out of the root zone and in the groundwater [22]. Nitrate in soils may accumulate in the soil profile or move to groundwater due to heavy rainfall or overuse of irrigation water [36]. Accumulating a high amount of nitrate in some soil layers and groundwater leads to degrading the quality of soil and groundwater, which threatens agroecosystem sustainability.

Developing an appropriate modeling system for agricultural field management, especially, the irrigation practice and related processes becomes critical for achieving the best crop water productivity for all world regions [48]. Modern irrigation systems such as drip and sprinkler irrigation have become the critical need for irrigating crops in Iraq due to increased water scarcity. Irrigating crops with low watering rates and high frequency at specific soil depths is to apply required irrigation water to closely meet crop demand with low water amounts [6, 31]. However, the potential movement of water and nitrate into the deeper layers of the root zone and the groundwater is still high due to the excessive applications of water and nitrogen which leads to severe nitrate contamination. Therefore, it is well known that the interactions between the applied irrigation water (rate, amount, and system) and nitrate dynamics in the soil profile still need more study to achieve a better water-nitrate management practice. Irrigation practice management is the main controlling factor of water and nitrate transport in soils due to the intrinsic association between water and nitrate dynamics in soil [7, 14, 28]. It is well understood that irrigation system and watering rate significantly affect N status in soil, and the water and nitrate have a huge interaction [11]. However, this interaction is also dependent on the soil type and especially on the soil hydraulic properties [5]. Soil hydraulic properties are very critical for understanding the water-nitrate dynamics in the field soil [41], which is mentioned in many papers under various soil, environmental, and field conditions [21, 45, 33]. Several models have been developed to simulate the water-nitrate dynamics in the soil profile. However, the management program requires an obvious determination of the soil hydraulic properties because each soil has its unique soil hydraulic phase [46, 47]. Understanding the nitrate dynamics in the Iraqi soil profile under various irrigation systems and watering rates becomes indispensable for developing appropriate practices of water-nitrate management [7, 17]. Therefore, this study discovered the possibility of achieving an appropriate irrigation management practice for reducing the soil nitrate accumulation out of the effective crop root zone in Iraqi field conditions.

Estimating soil water-nitrate dynamics at a high temporal resolution and their impacts on crop growth can be important for creating a successful field management system [20, 28, 29]. Agricultural models are a helpful tool for investigating and enhancing field management practices because of their capability to investigate new knowledge gaps such as the water-nitrate dynamics under different irrigation systems and watering rates [15, 18, 36–38]. Root Zone Water Quality Model (RZWQM2) is a widely used agricultural management model to investigate the impacts of field management on water dynamics and plant development [1, 2, 21]. It can integrate many field processes to estimate the influence of management practices on soil water-nitrate dynamics and plant development at a temporal resolution that costs a lot if it is manually measured in the field [4, 19, 40, 44]. [17] used HYDRUS to simulate the responsibility of maize production and water-nitrate dynamics in several irrigation and nitrogen fertilization scenarios under drip irrigation; the study concluded that the HYDRUS model is a good and reliable tool for determining the optimal fertigation practice under both deficit and sufficient irrigation. RZWQM2 was used in the North China Plain to simulate the soil water dynamics and wheat yield under different practices of field tillage and irrigation; this study demonstrated that the no-tillage practice can enhance soil water dynamics and crop water production if it is combined with delayed irrigation [12]. Also, in northwest China, [32] investigated the impacts of several methods of irrigation and nitrogen applications on the dynamics and distribution of soil nitrate under maize crop; the study showed that the alternate furrow irrigation with conventional nitrogen supply resulted in better spatial distribution and little leaching of soil nitrate.

Application rates of irrigation and fertilization often increase the accumulation and leaching of soil nitrate because their application rates exceed crop requirements [22]. Unfortunately, the traditional application rate of water and nitrogen in Iraq is much higher than the crop requirements, which defiantly affects the quality of groundwater. In this study, sprinkler and surface irrigation systems with different irrigation rates were used under wheat (*Triticum aestivum* L.) to develop an irrigation and nitrate management program that increases crop growth and production, with reducing nitrate leaching. Therefore, the objective of this study is to discover the best management practice of the interaction between irrigation systems and watering rates to prevent the leaching and accumulation of soil nitrate out of the effective plant root zone.

MATERIALS AND METHODS

Study area and measurements. The study was applied at Al-Raeeid Research Station, which is a specialized research station affiliated with the Environmental Studies Department/National Center for Water Resources Management. The station is located 20 km Western Baghdad, Iraq, at longitude 44°24 N, latitude 33°22 E, and an altitude of 34 m above sea level. The site has a semi-arid climate with a mean annual rainfall of 133.4 mm based on 12-yr (2009–2021) weather data. The average air temperature during the growing season was 16°C (Fig. 1). The soil of the study site is Entisol soil order, which is classified as Typic Torrifluvents, according to the Soil taxonomy, USDA (2014) [42], or Calcisols according to the WRB. It has a texture of silty clay loam at surface depths and silty clay at deeper depths, and low soil organic matter of less than 1%. The field study took place in about 1 hectare. The soil properties were determined by opening a soil profile in the study site (Table 1). Table 2 presents the groundwater depth from the surface which was between 110–170 cm depth and the NO_3 concentration for the groundwater during the study period. The groundwater was monitored in several field wells around the experimental site.

Wheat was planted on 1 November 2020 and harvested on 30 April 2021. The irrigation treatments were to apply three levels of irrigation water depletion (30, 50, and 70%) of available water, using surface and sprinkler irrigation systems. (Irrigation depletion is the amount of soil water allowed to be extracted by the crop from the effective root zone between irrigation events). The experimental surface irrigation system was designed as a randomized complete block design (RCBD), and crops were grown in 9 plots, each treatment has been replicated three times, and each plot

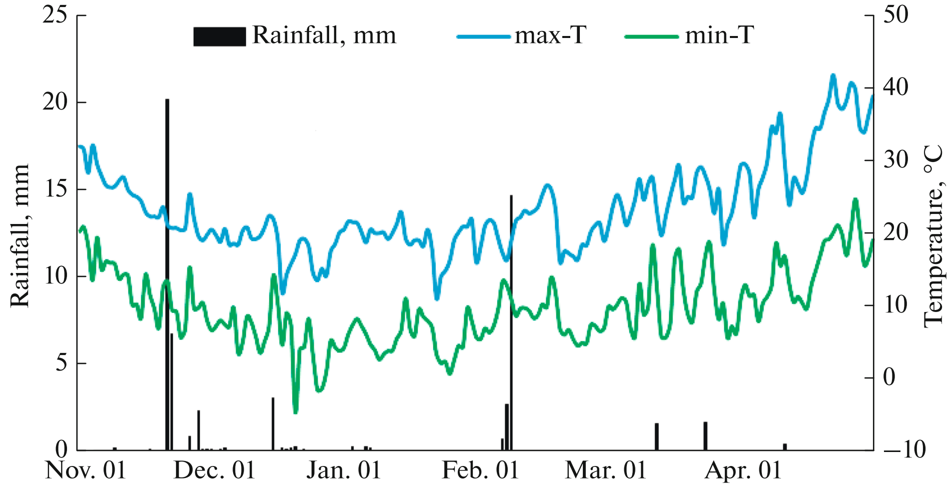

Fig. 1. Daily Rainfall and maximum and minimum air temperature during the wheat growing season of 2020–2021.

has an area of 45 m^2 (5 × 9 m). Treatments of sprinkler irrigated have three replicates, each replicate has an area of 170 m^2 (17 × 10 m). The total number of sprinklers used in the experimental sprinkler irrigation system was 18. The sprinkler system was operated under a pressure of 1.5 bar to achieve the best irrigation uniformity.

The fertilization was split across two applications regarding the local fertilization cultural practice. The first application occurred at the beginning of the season with diammonium phosphate fertilizer (DAP) added at the rate of 75 kg P/ha; It includes 18 kg N, 46% P_2O_5, and 0% K_2O. The second fertilizer application was applied after 45 days with 146 kg N/ha in the form of urea. Both applications were applied following the surface broadcast method.

A total water amount of 678, 544, and 517 mm/season was applied through surface irrigation at 30, 50, and 70% depletion levels, respectively. The applied water amounts were divided into 11, 8, and 6 irrigation events for the 30, 50, and 70% depletion levels, respectively. The total water amount of 541, 520, and 504 mm/season were applied through sprinkler irrigation at 30, 50, and 70% depletion levels, respectively. The applied water amounts were divided into 16, 12, and 9 irrigation events for the 30, 50, and 70% depletion levels, respectively.

The soil moisture was measured each 2–3 days for each treatment using the gravimetric method to apply the irrigation water requirement until the water contents reaches the field capacity. These measurements were carried out at three depths (0–15, 15–30, and 30–50 cm), and the irrigation was scheduled depending on the average measured soil water content of all depths. Soil water content was measured about (21, 17, and 22) times for surface irrigation at depleted water (30, 50, and 70%) of the available water, respectively; and (22, 25, and 24) times for sprinkler irrigation at depleted water (30, 50, and 70%) of the available water, respectively. In both irrigation systems, there was no water runoff because the applied water was just to rise the soil water content to the soil moisture level of field capacity. The data of measured soil water content were used to calculate the actual evapotranspiration (ETc) of wheat, which was computed for each 3–10 day period using the soil water balance equation.

Table 1. Physical and hydraulic properties of the soil profile at the research station; these properties are model input parameters

Soil depth, cm	Soil texture, %			Bulk density, gm/cm^3	Saturated hydraulic conductivity, cm/hr	Soil water content, cm^3/cm^3			Available water, %
	sand	silt	clay			0 kPa	33 kPa	1500 kPa	
0–25	12	53	35	1.39	0.15	51.4	32.0	14.7	17.3
25–50	11	52	37	1.42	0.09	52.9	31.6	15.1	16.5
50–75	10	52	38	1.46	0.1	53.2	32.3	15.4	16.9
75–100	10	53	37	1.48	0.07	54.0	32.1	15.8	16.3

*Kpa = kilopascal.

Table 2. Water table depths and NO_3 concentration in drainage water during the wheat growing season under the impact of sprinkler and surface irrigation systems

Water table depths		NO_3 Concentration in drainage water	
date	depth, cm	date	NO_3, mg/L
Dec. 17, 2020	167	Jan. 4, 021	5
Jan. 4, 2021	149	Jan. 19, 2021	3
Jan. 27, 2021	130	Jan. 27, 2021	2.3
Feb. 7, 2021	115	Mar. 2, 2021	3.4
Feb. 24, 2021	112	Apr. 8, 2021	1.6
Mar. 2, 2021	120		
Mar. 11, 2021	125		
Mar. 28, 2021	110		
Apr. 7, 2021	120		
Apr. 18, 2021	124		

The grain yield, plant area cover, and the number of branches were measured at the end of the wheat growing season for all treatments. In addition, soil samples were collected for four horizons (0–25, 25–50, 50–75, and 75–100 cm) with a soil auger. The collected soil samples were dried, and ground to pass through a 2-mm sieve, extracted with distilled water, and analyzed for NO_3 concentration using HANNA HI 83200 photometer. The soil NO_3 in the soil profile was measured three times at 0–25, 25–50, 50–75, and 75–100 cm depths during the crop growing season. The nitrate concentration was also analyzed for the irrigation and drainage water samples. Soil texture was determined with the sieving and pipette method. As well as saturated hydraulic conductivity was determined in the field using the borehole permeameter method. The soil bulk density was measured in the field using the core method.

Simulation of water-nitrate dynamics in the RZWQM2. The RZWQM2 model has been explained with sufficient detail in many articles such as [1, 4, 25, 36, 37]. Therefore, this study is focused on the processes of estimating the soil water-nitrate dynamics. RZWQM2 model processes the soil water dynamics based on the Richards equation which is applied for the redistribution of soil water, especially, the water flux at the upper and lower soil boundary, and between irrigation or rainfall events. While the soil infiltration during precipitation and irrigation events is processed by the Green-Ampt equation [1]. The soil hydraulic properties are explained with the modified Brooks and Corey (1964) equation [1, 3]. The Nimah-Hanks equation (1973) estimated the crop water uptake from the soil profile and was also used to calculate the actual crop transpiration [30]. The Richards soil water dynamics equation is also used for calculating the actual soil evaporation [2]. However, the potential crop transpiration and soil evaporation rate are computed using the extended Shuttleworth and Wallace (1985) equation [10, 39].

Soil nitrate dynamics occur in the soil matrix and soil macropores. The nitrate dynamics in the soil matrix introduce a form of preferential flow transport. While the dynamics in the microporosity are based on the amount of soil water content that occurs at the 2-bar section [4]. During the infiltration process, the nitrate dynamics in the saturated soil layers is changing the soil solution concentration. Therefore, diffusion occurs between soil pores, and nitrate concentrations in each soil layer are appropriately adjusted [16].

The RZWQM2 model was calibrated for the sprinkler irrigated winter wheat under the impact of water depletion at 30% of available water to obtain the corresponding model parameters carried out during the growing season of 2020–2021. While The model validation was under the impact of water depletion at 30, 50, and 70% of the available water under the surface irrigation system and 50 and 70% of the available water under the sprinkler irrigation system during the same growing season and location. Model calibration and validation processes were operated as mentioned in many articles such as [23, 24, 26, 27, 34, 35]. Table 1 presents the measured soil hydraulic properties for the field experiment, which were used as model input parameters for model simulations. Calibrated model input parameters of the wheat crop are presented in Table 3, which are the parameters of crop development and production such as the optimum temperature required to complete the crop vernalization process, and standard kernel size of the wheat under the optimum field conditions.

The model simulation results were evaluated using the most common statistics equations to give adequate accuracies of simulated results compared to the measured results. The Root Mean Squared Error (RMSE) reflects the average difference between measured and

Table 3. The model calibrated input parameters of wheat crop

Parameters of wheat Cultivar	
P1V: Days at the optimum vernalizing temperature required to complete vernalization	40
P1D: Percentage reduction in development when the photoperiod is 10 h less than the threshold (P1DT = 20 h) relative to that at the threshold	45
P5: Grain filling (excluding lag) phase duration (degree C day)	400
G1: Kernel number per unit canopy weight at anthesis (#/g)	18
G2: Standard kernel size under optimum conditions (mg)	23
G3: Standard,non-stressed dry weight (total, including grain) of a single tiller at maturity (g)	1.5
PHINT: Interval between successive leaf tip appearances (degree days)	80

simulated data. The normalization of RMSE (NRMSE) indicates the goodness of the model performance. The Mean Bias Error (MBE) refers to the systematic bias (positive or negative) of the simulation results. The criteria for accepting the model accuracy and performance are the low values of statistical equations [8, 28]:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi - Oi)^2}\,, \quad (1)$$

$$\mathrm{MBE} = \frac{1}{n}\sum(Pi - Oi), \quad (2)$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{O_{\mathrm{avg}}}, \quad (3)$$

$$\%E = \left(\frac{P_{\mathrm{avg}} - O_{\mathrm{avg}}}{O_{\mathrm{avg}}}\right)\times 100, \quad (4)$$

where Oi is the field observed data, Pi is the model simulated data, O_{avg} and P_{avg} are the averages of the field observed and simulated data, and n is the number of data pairs.

RESULTS AND DISCUSSION

The outcomes of the model calibration under the impact of the watering rate of 30% and sprinkler irrigation system showed a good model performance. The statistical values of the RMSE were 0.06 cm^3/cm^3 and 1.7 mm/day for simulated soil water content and actual crop evapotranspiration, respectively. Moreover, the statical values of the MBE were –0.03 cm^3/cm^3 and –0.96 mm/day for the soil water content and the actual crop evapotranspiration, respectively (Figs. 2, 3). These results are comparable to the finding of [35]. In addition, the crop yield was simulated under the calibration treatment with an error of 7% kg/ha. These statistical values display the goodness of the RZWQM2 for simulating the impacts of field management practices under Iraqi conditions.

Figure 2 presents the field measured and daily model estimations of soil water content during the wheat growing season for three watering rates and two irrigation systems. The model simulated soil water content satisfactorily with appropriate statistical values of NRMSE, RMSE, and MBE for all soil depths. Surface irrigation yielded higher soil water content for all soil depths compared with sprinkler irrigation. In addition, the irrigation at a 30% rate yielded higher soil water content in the soil profile than the other watering rates and the lower values of soil water content in the soil profile were found at a 70% rate. The differentiation between soil water contents of watering rates was larger in the surface irrigation than the sprinkler irrigation due to the short time of applied water irrigation in the surface system. The required application events of sprinkler irrigation are more than the required application events of surface irrigation. The required amount of water was applied in a short time for the surface irrigation system which increased the soil water infiltration.

The soil water content simulations under the surface irrigation were slightly better than the simulation of the sprinkler irrigation at a soil depth of 0–15 cm. However, at the other soil depths (15–30 and 30–50 cm), the model presented better simulations under sprinkler irrigation. The soil water content was overestimated for the surface irrigation as shown in the statistical values of NRMSE, RMSE, and MBE values.

The actual evapotranspiration (ETc) of wheat was computed for each 3–10 day period by using the soil water balance equation. The comparison between field-calculated and model-estimated ETc of three watering rates and two irrigation systems is presented in Fig. 3. The ETc was simulated with RMSE value between 1.5 to 2 mm/day for all watering rates and systems. Generally, RZWQM2 simulated the ETc of sprinkler irrigation with RMSE values lower than the values of surface irrigation. The RZWQM2 underestimated the ETc for both irrigation systems. Moreover, the MBE values of sprinkler irrigation were lower than the MBE values of surface irrigation by about 0.5 mm/day. The 30% rate presented higher ETc values than the other watering rates. The model simulations of ETc were statistically very close to the finding results of [2, 36, 37, 50].

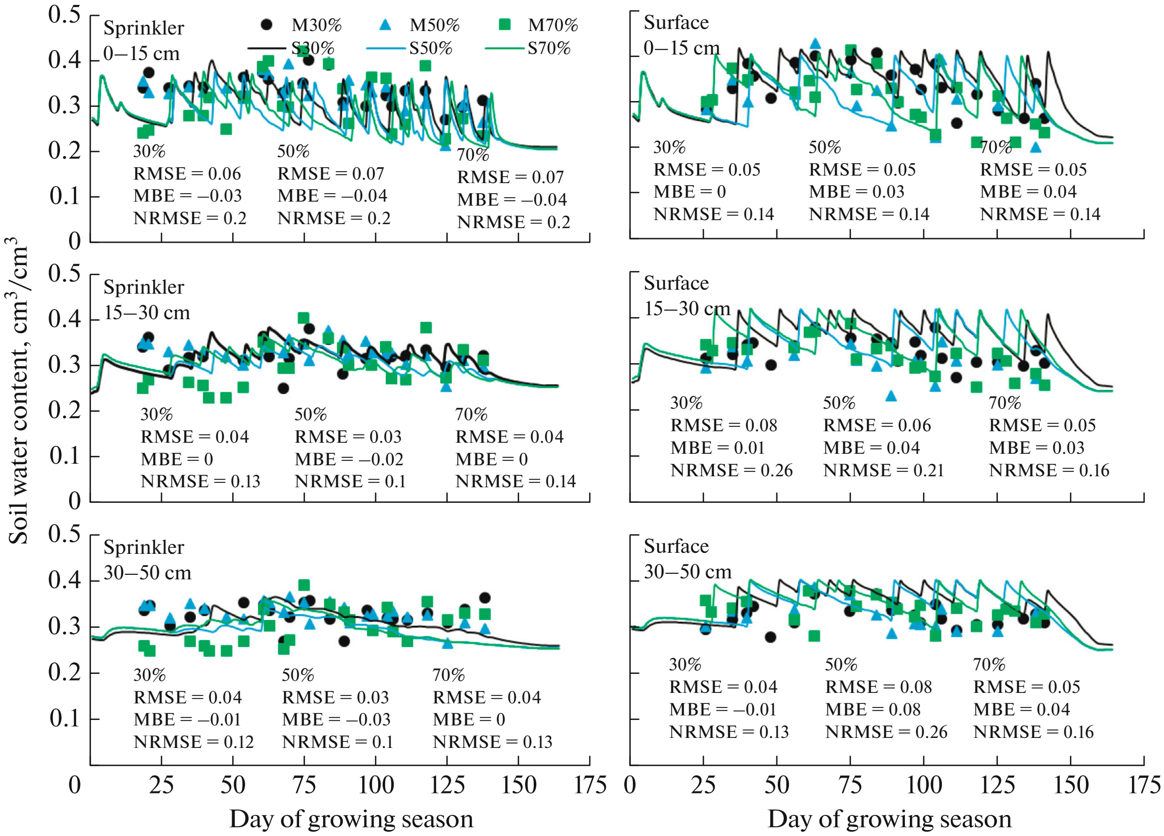

Fig. 2. Field-measurements vs. model-simulations of soil water content with time for three soil layers (0–15, 15–30, and 30–50 cm) and three irrigation rates (30, 50, and 70%) under the sprinkler and surface irrigation systems; during the wheat growing season.

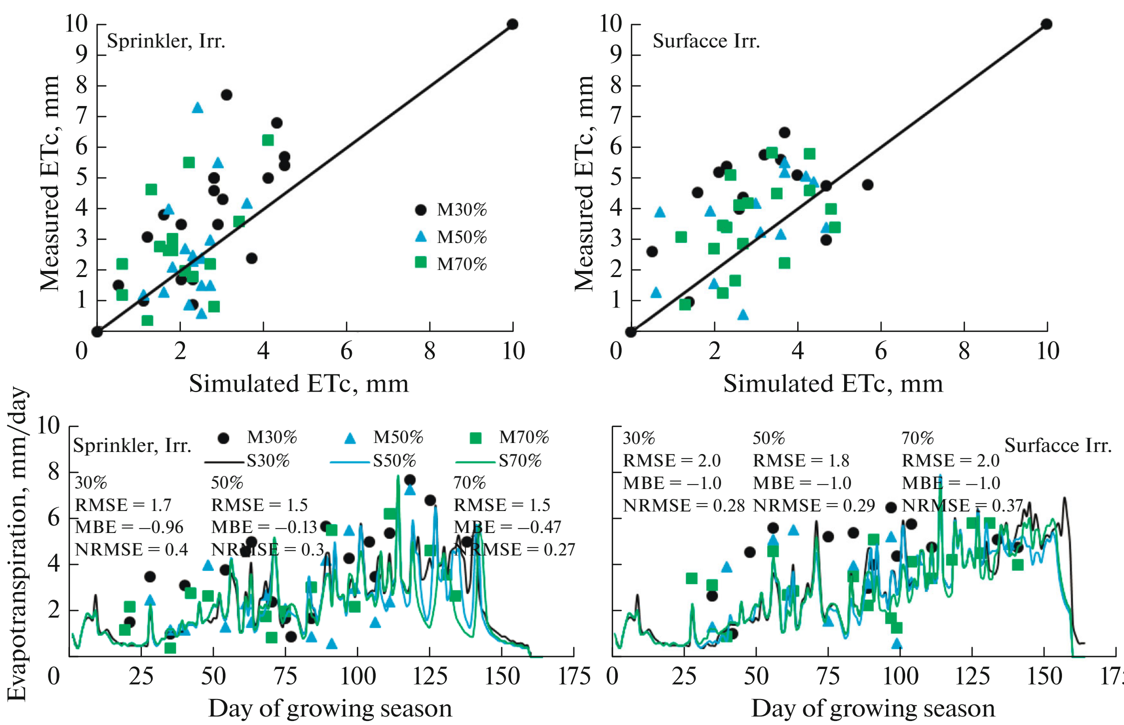

Fig. 3. Measured vs. simulated crop evapotranspiration with time for three irrigation rates (30, 50, and 70%) and two irrigation systems (sprinkler and surface irrigation); during the wheat growing season.

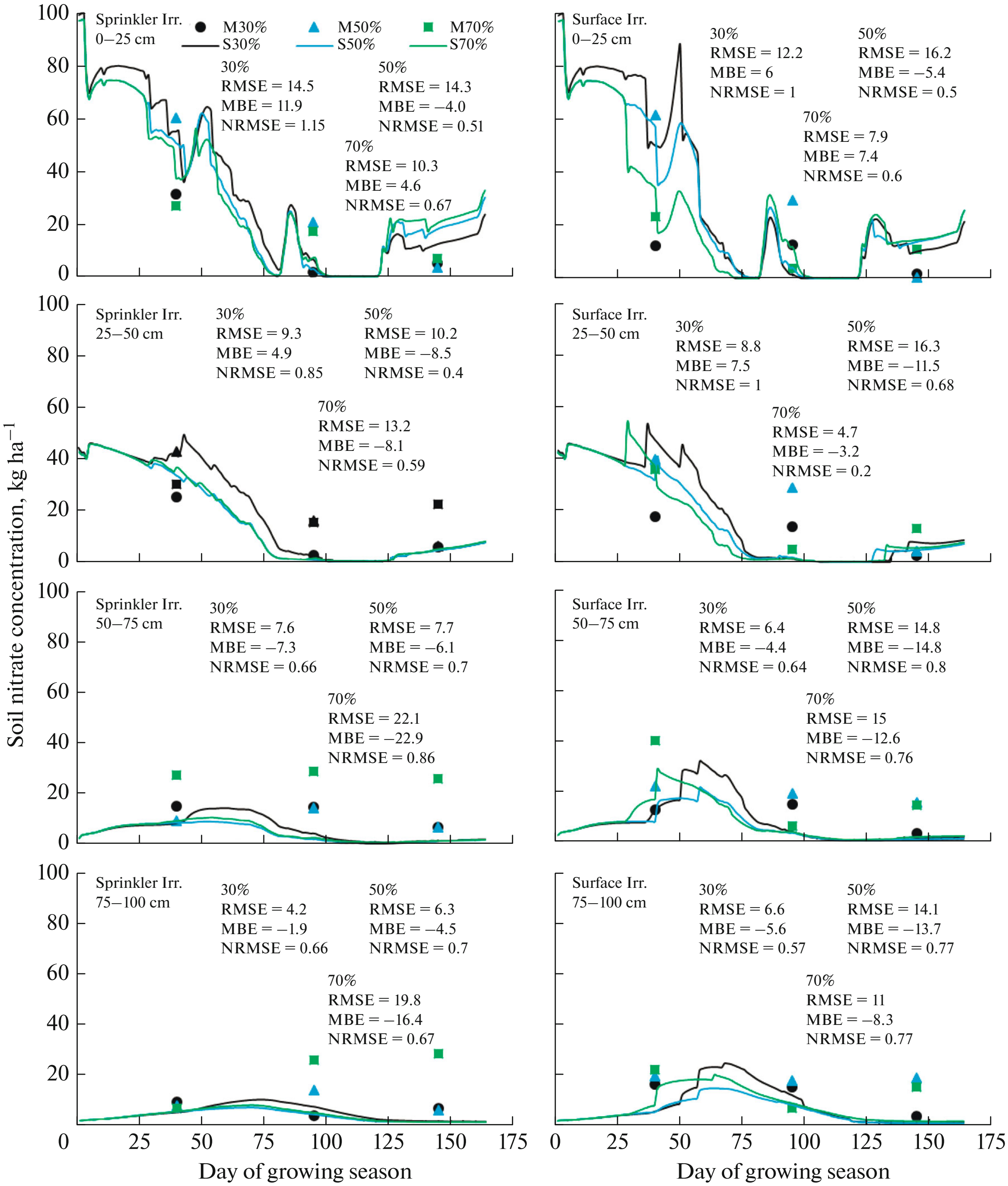

Fig. 4. Field measurements vs. model simulations of soil NO_3 with time for four soil layers (0–25, 25–50, 50–75, and 75–100 cm) and three irrigation rates (30, 50, and 70%) under the sprinkler and surface irrigation systems; during the wheat growing season.

Figure 4 shows the field-observed and model-estimated soil NO_3 for the crop growing season at four depths (0–25, 25–50, 50–75, and 75–100 cm). Soil NO_3 was estimated with NRMSE values of 0.4–1 and RMSE values of 6–22 kg N/ha, at different soil depths, for both irrigation systems and all watering rates. These results were better than the finding of [43]. However, [13] presented better NO_3 simulations compared to the finding of this study. The model inputs of field management practices have highly affected the estimated dynamics of soil C/N [4] which is the main reason behind the high fluctuation in NO_3 simulations.

During the first half of the growing season, the watering rate of 30% yielded higher NO_3 concentra-

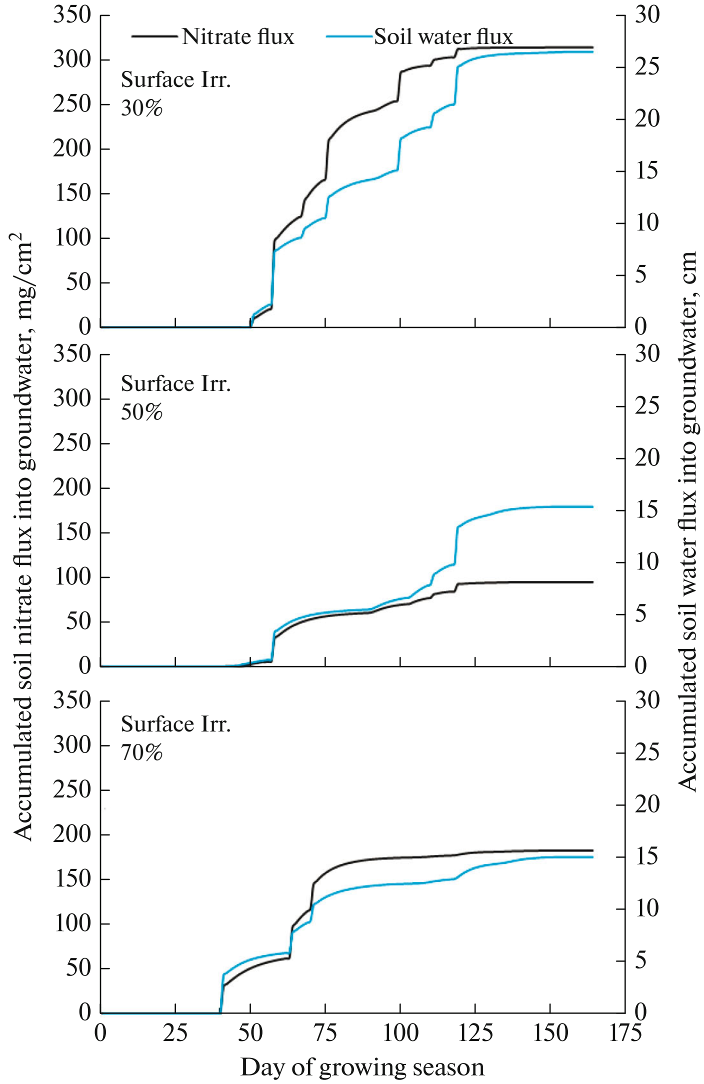

Fig. 5. Accumulated NO_3 and water flux into groundwater with time under three irrigation rates (30, 50, and 70%) and two irrigation systems (sprinkler and surface irrigation); during the wheat growing season.

tions in the soil profile than the other watering rates, especially, under the impact of surface irrigation. While the watering rate of 70% presented the lowest amount of NO_3 in the same depth of soil profile. However, during the second half of the growing season, the results were contrary, where the watering rate of 30% presented the lowest values of NO_3 in all soil depths. The reason behind that could be the impact of crop development (Fig. 6). During the growing stage of ripening, the soil NO_3 was increased because of that the crop no longer extracted NO_3 from the soil, while the NO_3 was still produced by the mineralization process in all soil depths. The differentiation between soil NO_3 results of sprinkler and surface irrigation was very low probably due to the irrigation management, where the irrigated water amount was added for each treatment as scheduled and required to reach the field capacity.

Naturally, the soil nitrate is moved toward the groundwater. This movement depends on the amount of applied irrigation water as well as on the soil texture and structure. Figure 5 shows the impact of applied watering rates and systems on the water-nitrate flux into groundwater. The accumulated soil nitrate out of the crop root zone was very low under sprinkler irrigation for all watering rates, which was less than 10 mg/cm^2 for the wheat growing season. However, under the impact of surface irrigation, the nitrate flux into groundwater was much higher because the required water was applied in a short time. The leached nitrate into groundwater was affected by the applied irrigation rate; the accumulated nitrate flux was about 300, 100, and 150 mg/cm^2 under the 30, 50, and 70% rates, respectively. The watering rate of 50% presented lower nitrate flux than under all other water-

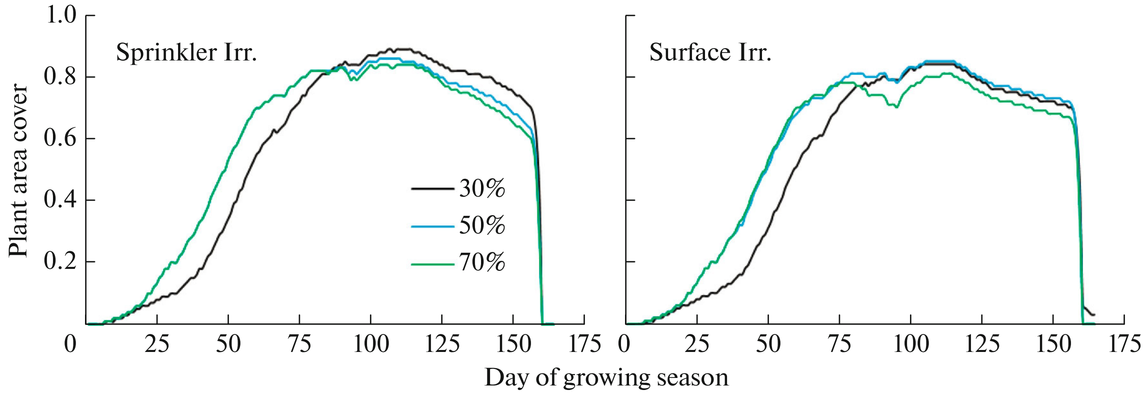

Fig. 6. The simulated plant area cover for three irrigation rates (30, 50, and 70%) and two irrigation systems (sprinkler and surface irrigation); during the wheat growing season.

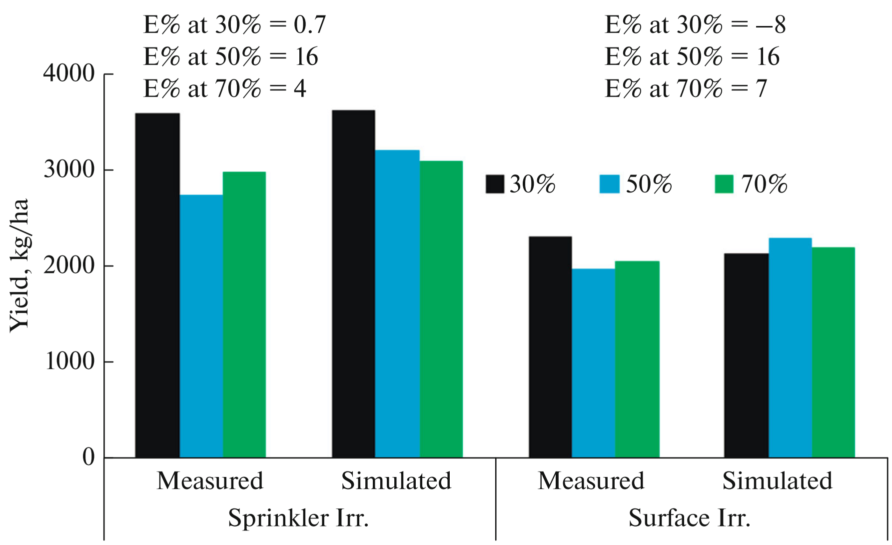

Fig. 7. Measured vs. simulated wheat grain yield for three irrigation rates (30, 50, and 70%) and two irrigation systems (sprinkler and surface irrigation).

ing rates probably due to the impact of crop growth and development. The 50% rate yielded better crop growth and yield (Figs. 6, 7), appropriate crop growth requires more nitrate uptake from the soil profile. The nitrate flux toward the groundwater was proportionally affected by increasing the water flux into the groundwater, and the water moving toward the groundwater was proportionally influenced by the applied irrigation amount.

Sprinkler irrigation produced a higher crop grain yield than surface irrigation by an average of 30% for all watering rates. The high differentiation between grain yield results of sprinkler and surface system is due to the impact of watering rate on the nitrate concentration in the soil profile; applying a high water amount with a short time leaches the nitrate out of the crop root zone and consequently, the plant may not take sufficient nitrogen for its growth and development. The RZWQM2 model produced satisfactory simulations of crop yield with an error between 0.7 to 16 kg/ha for both irrigation systems and watering rates. Sprinkler irrigation presented better crop yield simulations than surface irrigation for the 30 and 70% rates.

Figure 8 shows the water and nutrient stress for the crop growing season. At the beginning of the growing season, water stress appeared for both irrigation systems. However, at the ripening and maturity stages, sprinkler irrigation yielded crop water stress; while surface irrigation yielded water stress during the maturity stage. Both irrigation systems presented nutrient stress, but it was higher under the impact of surface irrigation for all watering rates because soil nitrate leached out of the effective crop root zone. Water and nutrient stress are the most controlled fac-

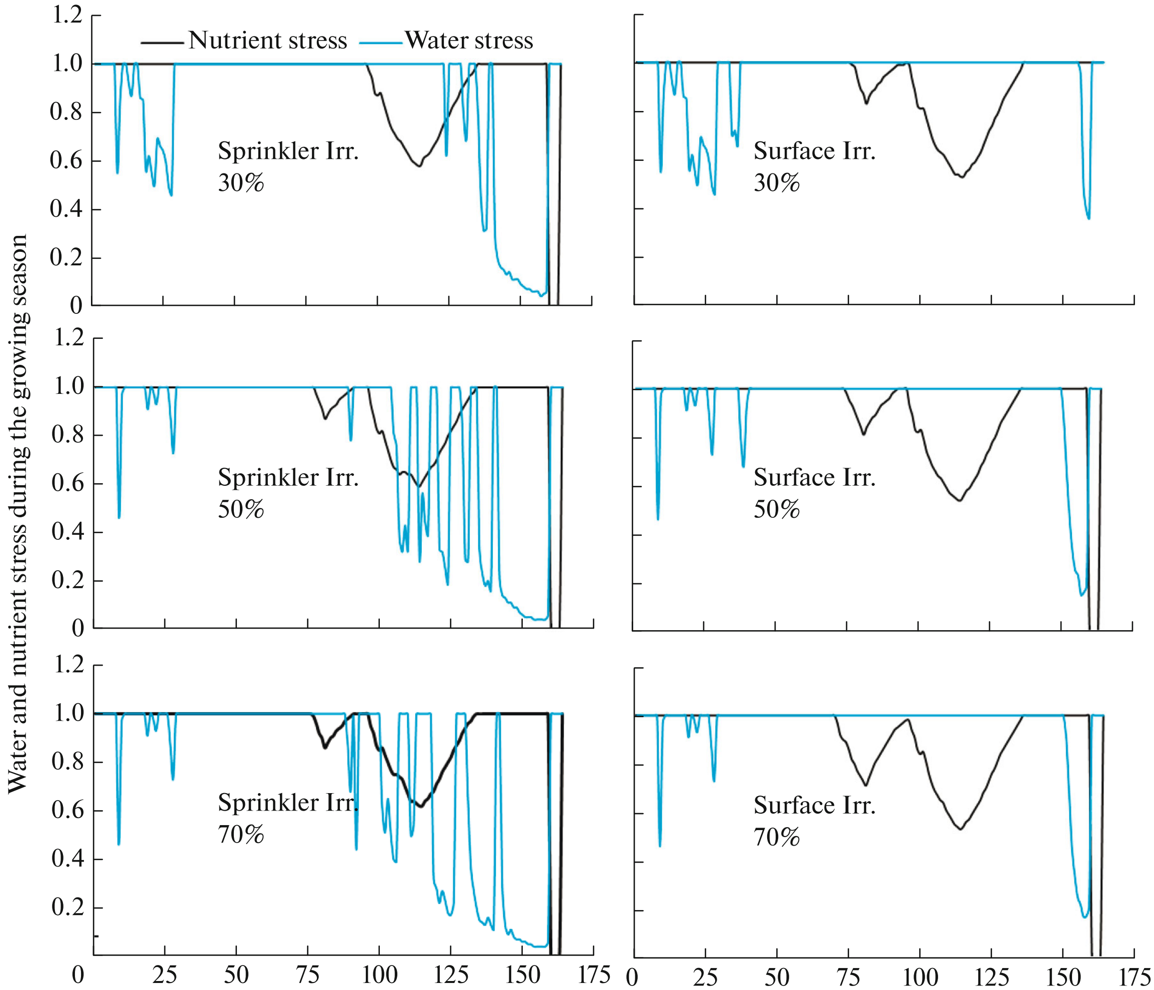

Fig. 8. Simulated water and nutrient stress for three irrigation rates (30, 50, and 70%) and two irrigation systems (sprinkler and surface irrigation); during the wheat growing season.

tors for crop growth. When water and nutrient stress appeared at any growing stage, crop growth is considerably affected [49].

CONCLUSIONS

Modeling the effects of irrigation practice management (irrigation systems and watering rates) on wheat growth and water-nitrate dynamics at different soil depths were examined in a field of wheat in central Iraq. The results showed that, the RZWQM2 satisfactory simulated the Iraqi field conditions and assessed the impacts of irrigation management practices on soil nitrate dynamics and crop production. Sprinkler irrigation with an watering rate of 30% exhibited the highest grain yield, soil water content, and soil nitrate concentration. The outcomes of our modeling and simulation results for the Iraqi field conditions are supporting the concept of considering a specific field management practice of irrigation and nitrogen application for each field condition. Therefore, Increasing the number of irrigation schedules with a low watering rate can be the best irrigation strategy for the local area of high temperatures to achieve a balance of high crop yield and low nitrate flux out of the root zone. Notwithstanding, more studies on different Iraqi soils and crops are an important need in the future for building further confidence in the findings of this study and improving agroecosystem sustainability.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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