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The tradeoff between water savings and salinization prevention in dryland irrigation

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ABSTRACT

Soil salinization is a global phenomenon that affects large tracts of arid farmland worldwide. It contributes to the loss of soil fertility, declining yields, and – in the most severe cases – land unsuitability for cultivation. Irrigation water applications are both the main cause of and the solution to, anthropogenic (or 'secondary') salinization because salt typically enters the soil column as dissolved in irrigation water and leaves it through excess water applications (e.g., leaching). Excess leaching, which places additional water costs in areas affected by water scarcity, can be achieved with different irrigation techniques and practices. Here, by complementing a process-based crop water model with a salt balance of the shallow soil, we investigate the tradeoff between root zone salinization and water conservation to limit withdrawals from the water source. We evaluate how such a tradeoff is achieved under different irrigation technology and excess leaching practices. Considering as a case study the cultivation of tomatoes in Egypt, we find that drip and furrow irrigation allows for better control of salt accumulation, thus preventing crop exposure to salt stress. Drip irrigation achieves this goal with minimal water applications because it maintains the soil wetter. Thus, the (rare) rainfall events find more suitable conditions to drain the excess moisture. Conversely, by using more irrigation water (and 'less efficiently'), furrow irrigation allows for higher rates of soil drainage and salt leaching. The irrigation schedule typically adopted with sprinkler irrigation allows for soil drying, thus limiting the ability of rainfall events to drain the soil and leach its salts. Collectively, these results highlight the key role of irrigation technology and practices in the management of secondary salinity in dryland agriculture. Specifically, there is a tradeoff between minimizing water use and preventing salt accumulation in the root zone. Drip irrigation exhibits the co-benefit of achieving both goals, while furrow irrigation limits soil salinity at the cost of requiring greater volumes of applied irrigation water.

1. Introduction

About 20% of the cultivated land is irrigated and contributes to about 40% of global food production (e.g., Rosa et al., 2018). Irrigation is especially important in dryland regions where rainwater alone cannot sustain healthy crop production (Davis et al., 2017). While essential, irrigation also has some environmental impacts, including the depletion of water resources (about 40-45% of the irrigated land (Rosa et al., 2018, 2019, 2020b; D'Odorico et al., 2018) and the deterioration of water quality, subsequently threatening aquatic ecosystems (Asseng et al, 2018; Baharvand and Lashkar-Ara, 2021; Elliott et al, 2014; Gleick and Palaniappan, 2010). Moreover, irrigation can lead to soil salinization – a phenomenon central to the delicate balance between agricultural sustainability and water resources.

Soil salinization, the increases in total dissolved solids (TDS) in soil water such that electrical conductivity of the saturation soil extract (EC_e, dS/m) exceeds 4 dS/m (Richards, 1954), is a major driver of agricultural land degradation worldwide, especially in dryland regions (Hassani et al, 2021). High saline levels cause osmotic stress in vegetation and hinder plant roots' ability to grow and absorb soil moisture, thereby leading to a loss in crop quality and yield (Agrawal et al., 2015; Gorji et al., 2017; Perri et al., 2020; Shahid et al., 2013; Rengasamy, 2010). Saline conditions also inhibit seed germination and growth in crops (Ayers and Westcot, 1985; Horneck et al., 2007). Soil salinization arises

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from natural or human-driven processes (Ghassemi et al., 1995), influenced by factors including soil texture, climate conditions, crop type, and, notably, soil water management. Particularly, irrigation-induced (or 'secondary ') salinization arises from poor-quality irrigation water, inadequate leaching (e.g., due to low hydraulic conductivity or low rainfall rates), and high evaporation rates (D'Odorico et al, 2013; Rengasamy, 2006).

From Inner Mongolia to Australia to Brazil, the occurrence of secondary salinization has been documented for decades, especially since the mechanization of agriculture and expansion of irrigation, underscoring the persistence of this challenge (Dehaan and Taylor, 2002; Singh, 2021; Wang et al., 2019, Nazir, 1965; Zavaleta, 1965; FAO, 1971; Tanji et al., 1986; Kovda, 1980; Pessarakli and Szabolcs, 2019; Dou et al., 2021). Salinization affects 1.0-1.125 billion hectares (ha) across 100 nations, principally in North Africa, Australia, and the Middle East, with approximately 76 million ha attributed to secondary salinization (Sharma and Singh, 2015; Hossain, 2019). Exacerbated by climate change, particularly in arid regions, this issue is increasingly prompting the abandonment of entire agricultural areas, a trend expected to continue through the end of this century (Clarke et al., 2015; FAO, 1971; Hassani et al., 2021). According to the United Nations, 10 million ha of irrigated land are abandoned annually primarily due to secondary salinization (Cherlet et al., 2018; D'Odorico et al., 2019; Francois and Maas, 1999; United Nations, 2022) raising concerns for global food security now and in the future.

Classic salinity management methods (Richards, 1954) focus on the use of suitable irrigation techniques and strategies. The irrigation technique (e.g., furrow, sprinkler, or drip irrigation) determines the return flows, which are the fraction of applied irrigation water that is not evapotranspired by crops but is returned to surface water bodies or groundwater. Return flows are how crucial for salt leaching and soil salinity control (ASCE, 2016). The irrigation strategy determines how much and when irrigation is used (Chukalla et al., 2015). To prevent soil salinity from increasing over time, leaching must exceed salt additions from the applied irrigation water over time (Rhoades and Merrill, 1976; Kitamura et al., 2006; Savva and Frenken, 2002). The amount of leaching required is determined by the crop's salinity tolerance, climate (Corwin et al., 2007; Perri et al., 2022), and the irrigation water quality. Crop types exhibit varying salt tolerances; while tomatoes, moderately salt-sensitive crops, experience declines in production at EC_e levels of 1.7 dS/m (Caro et al., 1991; Maas and Hoffman, 1977), other crops tolerate much higher salinity levels such as rye (up to 11.4 dS/m; Francois et al., 1989) and quinoa (40 dS/m to 400 mM NaCl; Adolf et al., 2013). Since root-zone soil moisture regulates plant growth and ET, the most cost-effective strategy to maintain soil salinity below the crop tolerance threshold is to ensure adequate soil drainage, which is the net downward flow of water and associated salt transport through the root zone. This is especially important as irrigated agriculture expands to areas with low-quality water and over-pumped surface water bodies and aquifers, particularly in coastal areas, where leaching can prevent salt buildup caused by irrigating with slightly saline water (Narayan et al, 2007).

Traditional irrigation models calculate irrigation crop water requirements (CWR) by considering the water amount needed to prevent water stress in vegetation and offset water losses due to soil evaporation (E), crop evapotranspiration (ET_c, mm/day), and drainage (e.g. FAO AquaCrop; Allen, 1998; Chiarelli et al, 2020a). Importantly, they evaluate irrigation efficiency in terms of rates of water withdrawal and consumption and seldom consider the effect of salinization. More complex models (i.e., SWAP, HYDRUS, RZWQM2, ENVIRO-GRO, WATSUIT, SALTMED, OASIS_MOD, Q3D) simulate soil water flows and solute transport using salinity models of root zone salt dynamics (Askri et al., 2010; Corwin et al., 2007; Kroes et al., 2017; Pang and Letey, 1998; Rhoades and Merrill, 1976; Simunek et al., 2005; Team et al., 1998; Ma et al., 2012; Ragab 2002; Zhu et al., 2012). However, most of these models are limited to field-level secondary salinization (Kramer and Mau, 2023) and do not allow for an integrated assessment of the feedback between rainwater (or 'green water', GW – effective precipitation absorbed by soil and plants; Hoekstra et al., 2011), irrigation water from surface or groundwater (or 'blue water', BW) flows, and soil salinity levels.

In this study, we investigate soil salt dynamics driven by the prolonged use of slightly saline irrigation water. To that end, we develop a simple soil salt balance that (1) simulates daily changes in root-zone salt concentration; (2) calculates possible salt-affected crop yields; (3) evaluates long-term soil salinity trajectories associated with different long-term water-management scenarios and irrigation techniques.; and (4) investigates agricultural water management options for preventing, correcting, or delaying the emergence of severe soil salinization by modeling the complex interactions between BW, GW, and root zone salinity.

2. Materials and Methods

2.1. Case Study: Tomatoes in Egypt

Egypt's arid to semi-arid environment is characterized by year-round high solar radiation levels, little precipitation, and high potential ET rates. There is a strong rainfall gradient between the northern coast, with an annual average of 150 mm, and Aswan, located farther south, which receives an annual average of 1 mm (FAO, 2023). ET ranges from 1400 mm in Mediterranean Sea coastal regions to almost 2120 mm in Aswan in the south (FAO, 1984). The Nile supplies 55.5 km^3 of water annually, which provides more than 95% of Egypt's freshwater needs (Gabr, 2022; Moursy et al., 2023). Agriculture covers 8% of the country and uses more than 80% of the nation's water. Among the Mediterranean nations, Egypt has the largest fraction (>95%) of cultivated land that is irrigated (Baudoin et al., 2013). The vast bulk of Egypt's farmed areas are irrigated using an ineffective method of surface irrigation system (Ayyad et al., 2019; Molle et al., 2018), such as furrow irrigation, which is used in 60% of the total irrigated area (Karajeh et al., 2013). Inadequate drainage and salinity harm around 0.3 Mha of land, resulting in agricultural production losses of about 30% of the potential yield (Gabaly, 1977; Richards, 1982). In 1991, approximately 33% of the 2.69 Mha of irrigated land was estimated to be salt-affected (Abu-Zeid, 1991). Fig. 1 highlights the tomato field's spatial distribution within Egypt.

2.2. Crop water requirement

The model developed in this study is a spatially distributed dynamic agro-hydrological model developed with a 0.1-degree grid resolution to solve the vertical water balance and determine root-zone water and salinity conditions. The soil salt balance is coupled with the soil water balance calculated using the crop water model WATNEEDS (Chiarelli et al, 2020, a model inspired by FAO AquaCrop and Allen, 1998) to relate the soil salt balance to irrigation practices. We apply this framework to a case study on tomatoes (*Solanum lycopersicum*) in Egypt, a moderately salt-intolerant crop grown in the drylands, between 2015 and 2021. Tomato is one of Egypt's most widespread vegetable crops, being both a significant source of income and positioning the country as one of the world's top tomato producers (Anriquez et al, 2021). In recent years, the tomato harvested area has decreased from 214,000 to 166,200 ha, with yields ranging from 38.7 to 41.6 tons/ha (FAOSTAT, 2022). Importantly, our study investigates soil water management strategies in a water-scarce agricultural region where a balance must be struck between alleviating water scarcity and preventing salinization through additional water application. This model fills a critical gap in allowing the assessment of various irrigation and soil water management strategies and their influence on soil salinity. It facilitates the exploration of the tradeoff between irrigation efficiency and salinity under different irrigation techniques.

The model uses the FAO56 approach to calculating CWR (mm/yr),

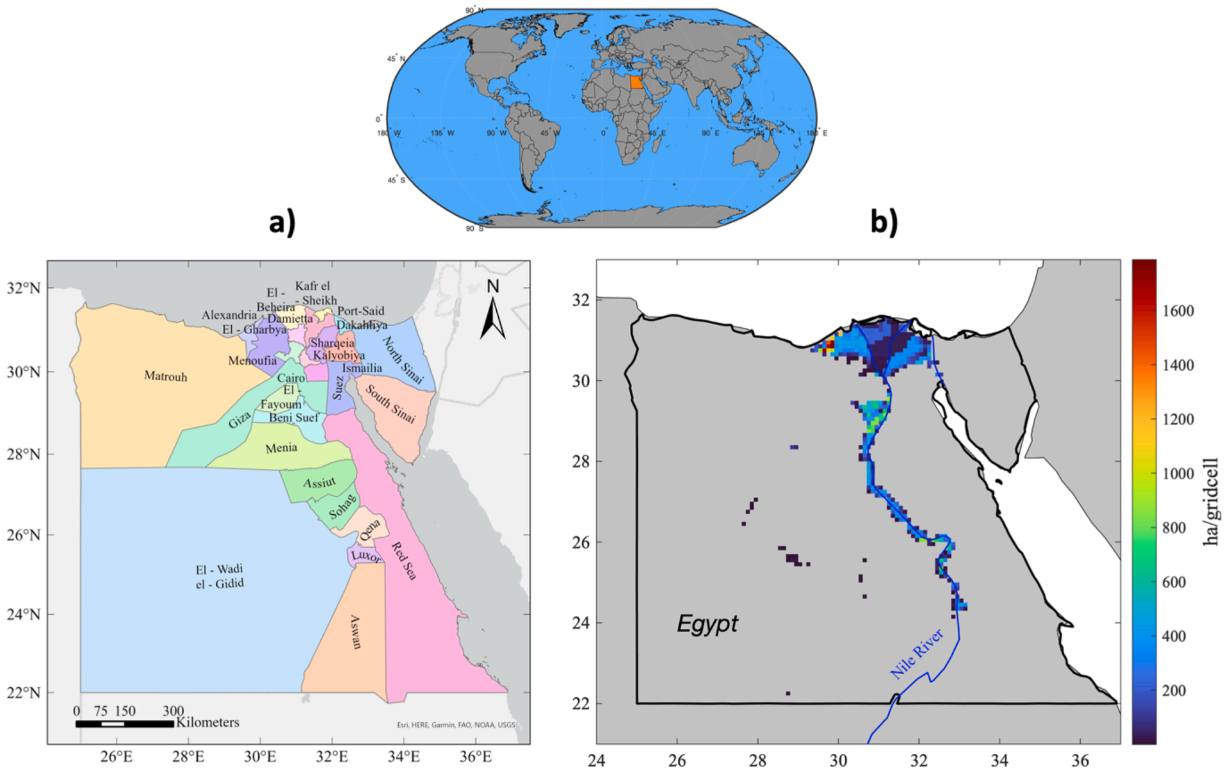

Fig. 1. Maps illustrating (a) the provincial boundaries of Egypt, and (b) the distinct spatial distribution of tomato fields (pixel size of 0.1-degree) in 2000 (Monfreda et al., 2008).

which involves estimating crop ET as $ET_c = K_c \times ET_o$, that is, as the result of multiplying crop specific (K_c) by reference ET (ET_o, mm/day) (Allen et al., 1998). The K_c is a dimensionless coefficient adjusting ET_o, based on the crop type and its growth stage. Four stages mark crop growth: initial, crop development, mid-season, and late-season. The stages and their associated K_c values are in Table 3. We use the well accepted FAO version of the Penman-Montieth model (Eq. 1) (Ahmadi et al., 2022; Allen et al., 1998; Gao et al., 2017) to calculate the ET_o:

$$ET_o = \frac{0.408\ \Delta\ (R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{1}$$

Where R_n is the net radiation over the crop (MJ/m^2.day), and G is the soil heat flux density (MJ/m^2.day), here assumed to be zero at the daily timescale. T is the mean daily air temperature (°C); u_2 is the wind speed at 2 m height (m/s); e_s is the saturation vapor pressure (i.e., 100% relative humidity) (kPa); e_a is the actual vapor pressure (kPa) from the mean dew point (actual amount of water vapor present in the air); Δ is the slope of the saturation vapor pressure curve (kPa/°C) at T (describes how the e_s changes with a change in temperature); and γ is the psychrometric constant (kPa/°C) (relates the partial pressure of water in the air to the air temperature).

2.3. Soil water and salt balances

We monitor the water fluxes entering and leaving the root zone denoted in Eq. 2. The discretized soil moisture in the root zone is calculated across grid cells using a daily soil water balance:

$$\frac{d}{dt}(\theta . Z_r) = P + I - ET_c - DP \tag{2}$$

where θ is the volumetric soil moisture, Z_r is the root depth (mm), P is precipitation (mm/day), I is the rate of irrigation water application (mm/day), and DP is the rate of deep percolation (mm/day). We assume that the capillary rise from the groundwater table is negligible. This formulation of the soil water balance has primarily been used to evaluate green and blue water requirements, hydrological modeling, and agricultural sustainability (Chiarelli et al., 2020b, 2018; Gholami et al., 2023; Rosa et al., 2020, 2018). To simulate salt concentration and soil moisture in the root zone we assume that salt in the root zone instantaneously achieves complete mixing. The salt balance in the root zone control volume is expressed as Eq. (3):

$$\frac{d}{dt}(\theta . Z_r . C_S) = C_I . I - C_S . DP \tag{3}$$

where C_s is the salt concentration in the root zone (mg/L), and C_I is the salinity of irrigation water (mg/L). To be consistent in terms of salinity measurement in both soil and irrigation, we converted TDS into EC values (Eq. (4)), according to the empirical relationship by Rhoades (1996):

$$TDS = k_e \times EC \tag{4}$$

The coefficient k_e ranges from 550 to 800, with 640 utilized for groundwater and surface water (Thorslund & van Vliet, 2020; Atekwana et al., 2004).

2.4. Crop-specific salt tolerance

The effect of soil salinity on crop water stress and the rate of ET can be determined as a function of EC_e, using the yield response factor, K_s (Eq. (5)) (Allen et al., 1998). When salinity stress emerges without water stress, the adverse effect of salt on plant growth, through the yield response factor, is:

$$K_s = 1 - \frac{b}{K_y * 100}\left(EC_e - EC_{e,thr}\right) \tag{5}$$

where $EC_{e,thr}$ is the saturated extract's electrical conductivity at the limit level for crop tolerance (dS/m), b is the yield reduction per % increase in EC_e (%/(dS/m)), and K_y is a yield response factor (-). Table 1 defines the

Table 1
Classification of salt intensity using salinity stress coefficient (K_s).

Class	Mean salinity stress coefficient (K_s)
Non saline	1
Slightly saline	0.9 - 1
Moderately saline	0.7 - 0.9
Strongly saline	0.5 - 0.7
Extremely saline	0 - 0.5

crop specific salinity classification employed in the present study.

2.5. Excess leaching to control salinity

The Leaching Requirement (LR) – the excess water applied beyond the CWR during irrigation to control salinity – is often a percentage of the crop's irrigation need, with higher LR reducing salt buildup (e.g., LR = 50%) (Ayers and Westcot, 1985). Empirical relationships exist to calculate LR based on irrigation water salinity and crop tolerance to soil salinity. The recommended LR (Rhoades 1974; Rhoades and Merrill 1976) used in this study is:

$$LR = \frac{EC_I}{5 * EC_{e,thr} - EC_I} \tag{6}$$

Where LR is calculated using conventional surface irrigation methods (%), and EC_I is the salinity of the applied irrigation water (dS/m). We evaluate the efficacy of Eq. 6 for long-term salinity management across different irrigation strategies.

2.6. Modelling varying irrigation strategies

We explore 8 different irrigation strategies applied with furrow, drip, and sprinkler irrigation methods. We adopt an irrigation schedule that prevents the emergence of water stress in crops during the growing season. Moreover, both the amount of each irrigation application and the time or frequency of irrigation are crucial factors in irrigation scheduling. In the furrow system, irrigation is applied when soil moisture reaches the water stress threshold. Conversely, in the drip system, soil moisture is consistently maintained at or near field capacity. Two approaches are used for the sprinkler technique: (1) irrigation is applied when the soil moisture is nearly at the water stress threshold (hereafter referred to as "sprinkler low frequency (LF)"); and (2) irrigation applications occur when soil moisture is 75% of the total available water (TAW), which leads to more irrigation applications (and of smaller magnitude) ("sprinkler high frequency (HF)"). Conversely, with furrow and sprinkler LF irrigation, water applications begin when the soil moisture in the root zone approaches the readily available water content (RAW). BW withdrawal is then calculated based on the irrigation efficiency – the fraction of applied irrigation water that is taken up and transpired by plants. This value varies with the irrigation technique, and here we assume values of irrigation efficiency of 60%, 75%, and 90% for furrow, sprinkler, and drip methods, respectively (Brouwer et al., 1985). To assess the effectiveness of the suggested LR in managing salt accumulation, the estimated LR from Eq. (6) is also added to the applied water as the required EL. Table 2 summarizes the 8 irrigation strategies considered. We assume that during the first ten days, the root apparatus has access to the top 25 cm of soil (Raes et al., 2012) and then the root zone is assumed to grow linearly in time, reaching a depth of 110 cm.

2.7. Off-season

In the modeling of the off-season (or outside growing season), ET is limited to only evaporation from bare soil, and no irrigation is applied. During this period, careful consideration is given to the entering and exiting fluxes such as precipitation, evaporation, and deep percolation. The control volume for salt concentration is then computed within an effective depth of the initial root zone length (0.25 m).

Table 2
Comparison of irrigation strategies for salinity simulation in tomato production.

Irrigation Method	Irrigation Strategy	Irrigation Efficiency	Excess Leaching (EL) for Egypt
Furrow	Irrigation applied when soil moisture reaches water stress threshold	60%	No
Furrow + EL			Groundwater: 8%, Surface water: 3.5% in winter and 5% in spring
Sprinkler LF		75%	No
Sprinkler LF + EL			Groundwater: 8%, Surface water: 3.5% in winter and 5% in spring
Sprinkler HF	Irrigation applied when soil moisture is 75% of the Total Available Water (TAW)	75%	No
Sprinkler HF + EL			Groundwater: 8%, Surface water: 3.5% in winter and 5% in spring
Drip	Soil moisture consistently maintained at or near field capacity	90%	No
Drip + EL			Groundwater: 8%, Surface water: 3.5% in winter, 5% in spring

Bare soil evaporation (E_s) is computed at the daily time scale as $E_s = K_e \times ET_o$ using the dual FAO-56 K_c method (Allen et al. 2005), where K_e is the daily evaporation coefficient. This method accounts for the two stages of evaporation: stage 1 evaporation happens when the rate of evaporation is restricted by energy. The primary equation for K_e in stage 1 is Eq. (7):

$$K_e = \left(K_{c,max} - K_{cb}\right) \tag{7}$$

$K_{c,max}$is the maximum crop coefficient for a fully vegetated or entirely moist surface, while K_{cb} is the basal crop coefficient (Allen et al. 2005, 1998). In fact, K_{cb}exclusively describes plant transpiration, which is below $K_{c,max}$. In stage 2, a decrease in evaporation rate occurs as the topsoil layer dries out. Therefore, in stage 2 the coefficient K_e accounts for a dependency on soil water content and is expressed as Eqs. (8) and (9):

$$K_e = K_r \times \left(K_{c,max} - K_{cb}\right) \tag{8}$$

with

$$K_r = \frac{TEW - D_e}{TEW - REW} \tag{9}$$

Where K_r is a dimensionless evaporation reduction coefficient that depends on the total amount of soil water that can be evaporated from the soil surface layer (or 'depth of water drawn down'). total evaporable water (TEW) (Eq. (10)) is the greatest depth of water that may evaporate from the top layer of soil once the soil has been at field capacity (mm). The readily evaporable water (REW) measures the total, cumulative evaporation during stage 1 drying. REW typically varies from 5 to 12 mm, with higher values being associated with fine-grained soils (Ritchie 1972; Ritchie et al. 1989). D_e is the cumulative evaporation during stage 1 and 2 from the soil's top layer (mm). A detailed explanation of bare soil evaporation models is provided by Mutziger et al. (2005). According to ASCE (2016) and Allen et al., (2005), the highest value of TEW that may be evaporated over a whole drying cycle is:

$$TEW = (\theta_{FC} - 0.5\theta_{WP})Z_e \tag{10}$$

Field capacity θ_{FC} and wilting point θ_{WP} are expressed in (m^3/m^3) and Z_e is the effective depth in (mm) of the surface soil subject to drying by way of evaporation to the $0.5\theta_{WP}$ level. Often, a value of 0.1 m or 0.15 m is chosen for Z_e. A shift in Z_e to a depth of 0.2 to 0.25 m may be necessary for evaporation durations longer than three or four weeks in order to depict the soil depth contributing more accurately to total evaporation (Allen et al., 2005; Raes et al., 2009). Thus, in our model, Z_e is considered the top 0.25 m.

Each year, we model the growing and off-season water and salt balance through December 31st. Then, the year's end values for EC and soil moisture are used as the initial conditions for January 1st of the following year. For the off-season, the simulation continues until the planting date for the next growing cycle. This approach offers a realistic and continuous modeling of the agricultural system, adeptly capturing the critical dynamics of water and salt balances.

2.8. Parameterization for the Case of Egyptian Tomatoes

The general model is then parameterized and applied to the case of tomatoes in Egypt. We specify planting to begin on January 15th and the off-season to begin on May 30th (or May 29th for leap years, like 2016 and 2020) to roughly align with local crop calendars (FAO, 2023). $EC_{e,thr}$ for tomato is 1.7 dS/m, b is 9%, and K_y is 1.05 (ASCE, 2016; Rhoades et al., 1992).

The initial soil EC for 2015 is established using the global dataset of soil properties in a vertical profile, segmented into eight layers down to a depth of 2.3 meters (Shangguan et al., 2014). Based on the expected growth of the mean tomato root zone to 1.1 meters (Allen et al., 1998), we compute the average EC of the top seven layers to represent the initial EC for 2015. For the initial soil moisture condition, we apply 20 mm (about 2-5%) as the initial BW consumption to maintain the soil field capacity condition within the root zone.

For EC_I of Nile River irrigation water, we use the seasonal mean EC values reported by Abdel-Satar et al. (2017), which are 0.399, 0.286, 0.276, and 0.350 (dS/cm) for winter, spring, summer, and autumn, respectively. In pixels located far from the Nile River, irrigation quality is characterized with EC_I=0.646 dS/cm, which is the salinity of groundwater, while we use the value of 0.251 dS/cm (Engelen et al. 2019) in the Nile Delta Aquifer.

From Eq. 6, we find LR is 3.5-5% for areas irrigated by the Nile River and 8% for areas using groundwater. This LR is added as Excess Leaching (EL) for furrow, drip, and sprinkler systems. Sites within 100 km of the Nile River and canals use surface water, while areas like Siwah, Bahariya, Farafra, Dakhla, and Kharga rely on groundwater.

The remaining parameters for evapotranspiration and evaporation (i. e., K_c, K_e, K_{cb}, K_b, TEW, REW, θ_{FC},andθ_{WP}) are taken from Allen et al., (1998). Salinity related parameters (i.e., $EC_{e,thr}$, b, and K_y) are retrieved from Rhoades et al., (1992). The parameters and datasets used in this research for crop, salinity, climate, and soil conditions are summarized in Tables 3 and 4. Fig. 2 depicts the simulation procedure employed in this study.

Table 3
Tomato parameters used in this study related to evapotranspiration, evaporation, and salinity.

Parameters	Values	Unit	Source
$K_{c,\ ini}$	0.6	-	
$K_{c,\ mid}$	1.15	-	
$K_{c,\ end}$	0.8	-	Allen et al. (1998)
K_{cb}	0.15	-	
K_e	1	-	
$EC_{e,thr}$	1.7	dS/m	
b	9	%/(dS/m)	Rhoades et al. (1992)
K_y	1.05	-	
Initial period	30	day	
Development period	40	day	
Mid-season period	40	day	
Late-season period	25	day	
Growing period	135	day	FAO (2023)
Planting date	January 15th	-	
Off-season starting date	May 30th	-	
Off-season period	230	day	

Table 4
The climate and soil datasets used in this study.

Variable	Source
Maximum, minimum, dew temperature, precipitation, cloud cover, wind	Boogaard et al. (2020)
Irrigation EC (River)	Abdel-Satar et al. (2017)
Irrigation EC (groundwater)	Engelen et al. (2019)
Extraterrestrial radiation	Calculated based on the FAO manual (Allen et al., 1998)
Soil characteristics	Hiederer and Köchy (2011)
Soil initial EC_e	Shangguan et al. (2014)
Tomato harvested area	Monfreda et al. (2008)
Elevation	JISAO (2023)

3. Results

3.1. Crop, blue, and green water requirement

The cumulative annual GW consumption for tomato production was consistently larger for furrow and sprinkler LF irrigation than for sprinkler HF and drip irrigation throughout the study period (Fig. 3). This was due to the soil moisture dynamic difference among irrigation strategies. In furrow and sprinkler LF, soil was allowed to become drier compared to sprinkler HF and drip. As a result, when rainfall occurs, drier soil had a higher capacity to hold water before reaching field capacity, which resulted in higher GW consumption. In sprinkler HF, irrigating at 75% of TAW decreased the soil's ability to absorb rainfall due to the presence of irrigation water. Therefore, BW consumption was expected to be slightly larger for drip and sprinkler HF than for furrow and sprinkler LF irrigation. This pattern was reversed when considering BW withdrawals (Fig. 3), which were largest for furrow and smallest for drip irrigation due to the different efficiencies of these irrigation systems, as noted earlier. Because of the dry climate, GW on average met a small fraction (<5%) of the CWR for the entire country, with regional variation. The highest GW was found in Izbat Al Khadra, where in 2019, GW was equal to 93.6 mm and accounted for 18.1% of CWR (517.8 mm) with the furrow irrigation method (see Fig. 4. for a map). As noted, GW values were lower when drip irrigation was used.

On the other hand, the highest total BW withdrawal (2005.6 Mm^3 in 2015) was found when the furrow irrigation plus EL was used. In this system, the highest BW per square meter was 1726.9 mm, which was consumed in Kom Umbu (in the Aswan governorate in upper Egypt) during the 2018 growing season, while the west part of Izbah Al Muwazanah (located in Al Buhayrah) had the lowest BW using the drip irrigation method (about 462.5 mm) in 2019. The mean CWR (per unit area) of tomatoes ranged from 649.9 mm (2015) to 693.1 mm (2021). In general, the CWR and the amount of BW needed to meet such a requirement for tomatoes were higher in South Egypt, particularly in areas not located along the Nile River because of the drier and hotter climate conditions, and lower in North-Western Egypt (cooler and wetter). Fig. 4 illustrates the average BW and GW calculated across Egypt for various irrigation strategies.

3.2. Electrical conductivity simulation

Model simulations of water and salt in the root zone from 2015 to 2021 reveal the ability of farmers in certain regions to contribute to or prevent the emergence or aggravation of secondary salinization. The simulations showed that many regions, especially the Al Wadi Al Jadid and Al Jizah areas, were significantly affected by soil salinity, depending on the irrigation method used and the soil characteristics (sandy vs. clay). For example, in Alexandria (29.8° Long, 30.9° Lat), tomato production is particularly intense. At the onset of the 2015 growing cycle, the EC was recorded at 0.30 dS/m. By the end of the 2015 growing cycle, the EC roughly tripled or more based on irrigation method, reaching 1.71, 1.60, 1.07, 1.01, 0.97, 0.92, 0.91, and 0.88 dS/m for sprinkler LF,

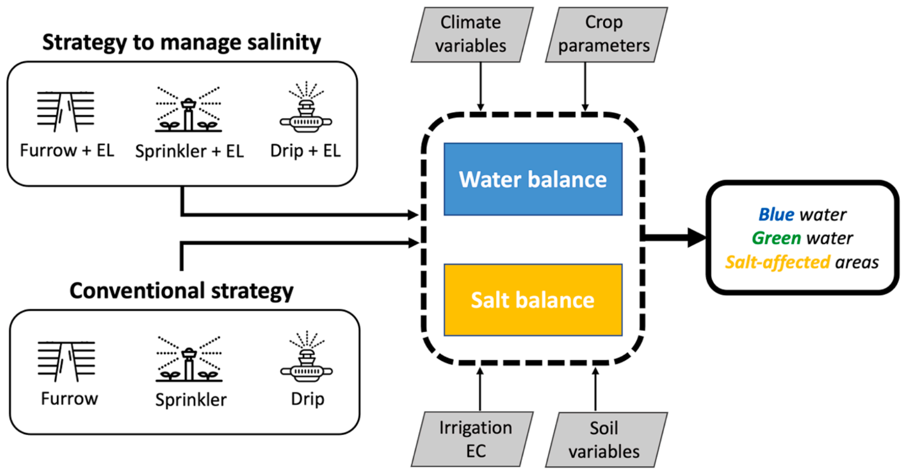

Fig. 2. The flow diagram of the simulation process implemented in this study.

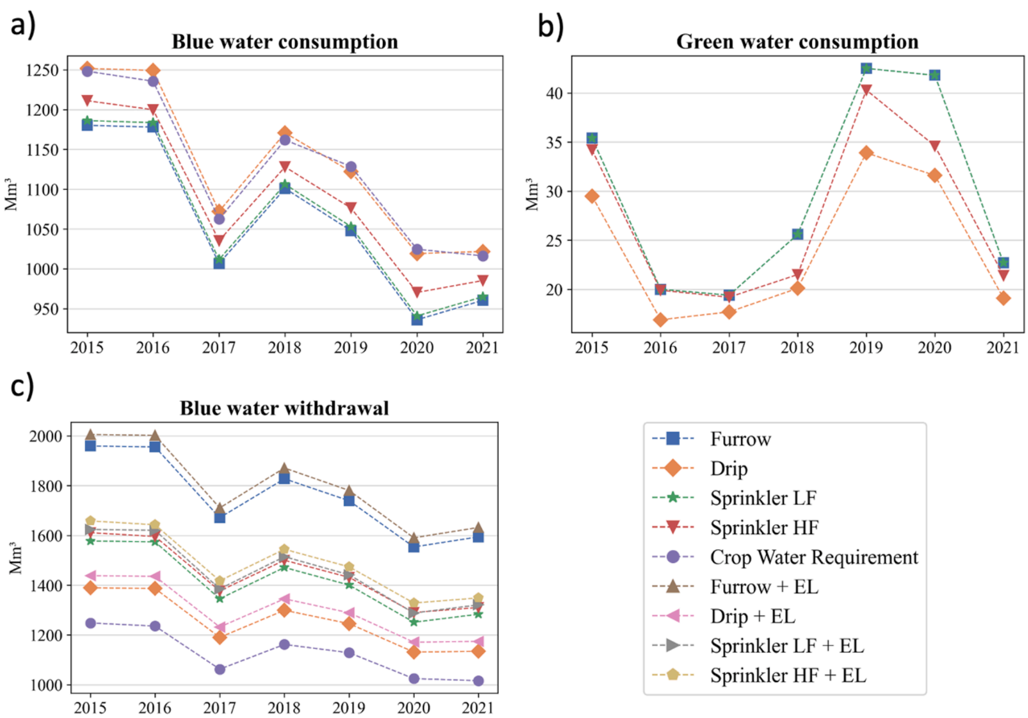

Fig. 3. Water consumption and withdrawal for tomato crop in Egypt (2015–2021): a) Blue water consumption, representing surface and groundwater use; b) Green water consumption, reflecting rainwater utilization in soil; c) Blue water withdrawal, indicating fresh surface water and groundwater extraction.

sprinkler LF + EL, sprinkler HF, sprinkler HF + EL, furrow, drip, furrow + EL, and drip + EL, respectively. In such an area, the long-term outcome will depend on whether farmers are able to properly manage the soil and water resources at the farm scale.

Encouragingly, in north-western Egypt, the salinity levels in tomato fields did not require additional farmer interventions (e.g., water applications) to meet leaching requirements because of the higher precipitation rates characteristic of that region. For example, in 2020 in the north-western region, the highest precipitation rate was 310.7 mm, while the mean precipitation across the tomato fields in the entire country was 79.4 mm (i.e., in northern Egypt rainfall was almost 3.9 times more than the average). A similar pattern was seen in the driest year, 2017, when the highest precipitation was 90.1 mm in the north, and the country-mean precipitation across tomato croplands was 20.6 mm. Our results show that the mean annual EC_e of most tomato fields remained non-saline (i.e., EC_e<4 ds/m) with no soil salt buildup through time when furrow or drip irrigation was used (Fig. 5). These results are compatible with findings from Kubota et al. (2017). By the end of each year, soil salinity remained below 4 dS/m when the recommended LR (i.e., 8% for groundwater and 4% for Nile River water) was adopted in furrow and drip irrigation systems. However, soil salt built up when no EL was adopted. Likewise, sprinkler HF brought the soil EC below 4 dS/m after four years when managed with EL. Conversely, sprinkler LF significantly accumulated salt regardless of the use of EL additions and the initial soil EC. Fig. 6 illustrates the distribution of BW with six combinations of irrigation method water applications, and the corresponding EC for every pixel within tomato cultivated areas. These results show that in most years and locations, furrow, drip, and sprinkler HF irrigation systems managed with EL can maintain EC<4 dS/m and in many locations, EC was also within the tolerance threshold for tomato (EC<1.7 dS/m). Interestingly, furrow and drip irrigation systems tended to perform better – in terms of salt management – than sprinkler HF. The

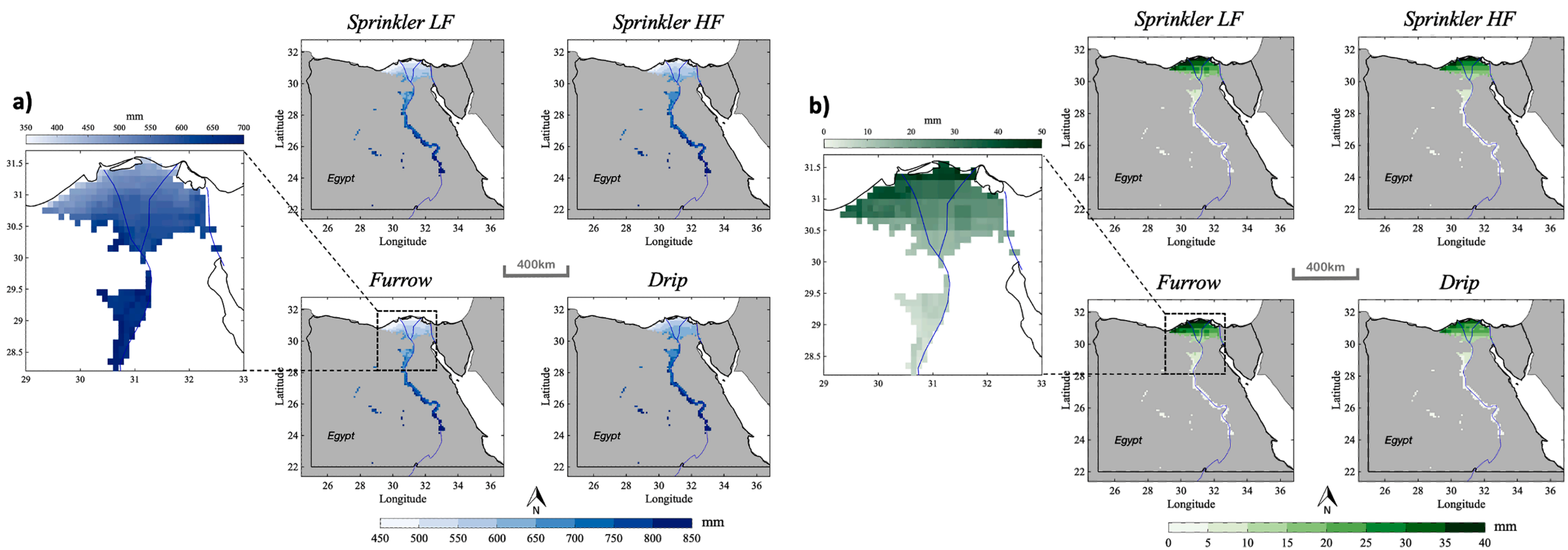

Fig. 4. Average (a) Blue Water, and (b) Green Water distribution in tomato fields of Egypt when sprinkler LF, sprinkler HF, furrow, and drip irrigation methods are used for the period 2015 - 2021. Interestingly, in the case of Egypt, crop water requirements are met for the most part by blue water. This fact highlights that in this region, crop production strongly relies on irrigation, while green water consumption is roughly 20 times less than blue water consumption.

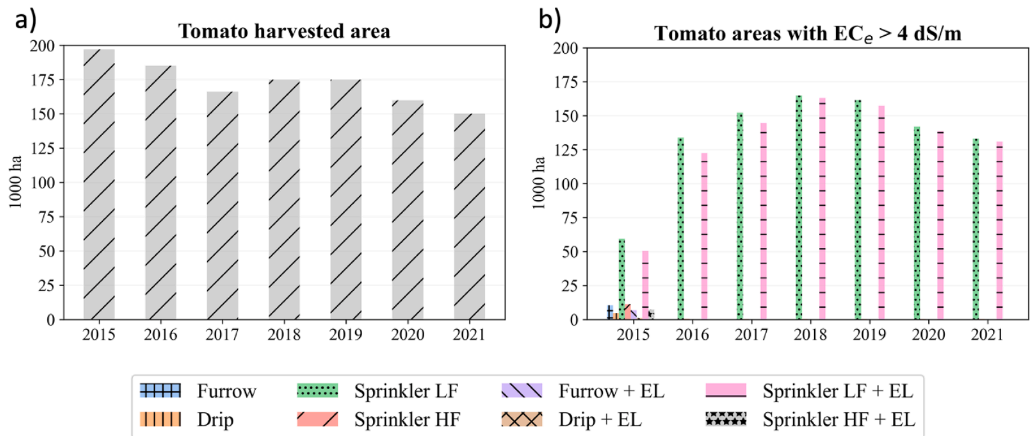

Fig. 5. a) The total harvested area of tomato in Egypt, and b) the effect of irrigation techniques on soil salinity management across tomato fields in Egypt, expressed as areas with EC higher than 4 dS/m. Excess leaching substantially reduces the area affected by soil salinity.

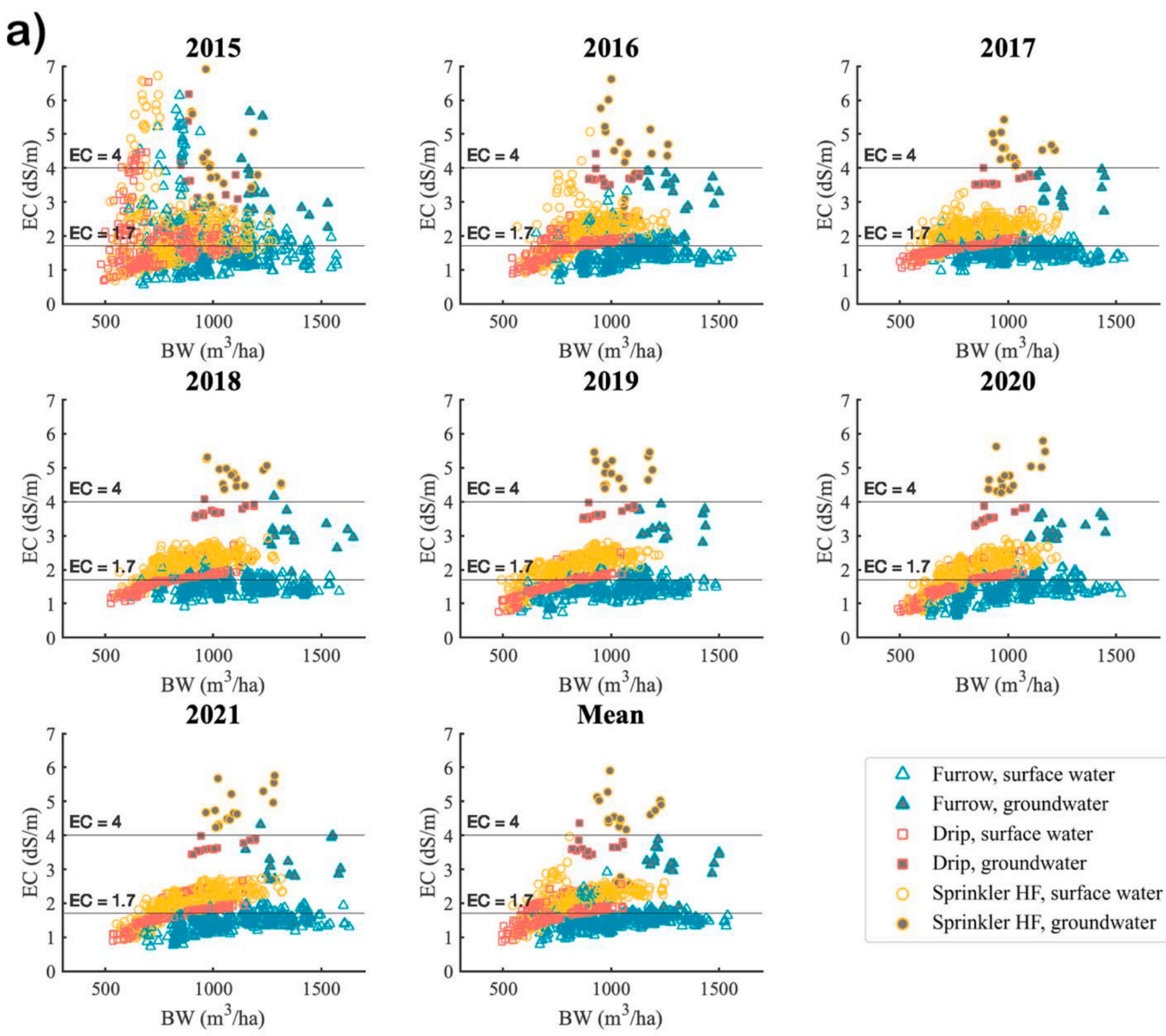

Fig. 6. Mean annual (including growing and off-season) electrical conductivity of root zone soil water (EC_e) as a function of applied Blue Water (BW) under (a) furrow, drip, and sprinkler HF (b) furrow, drip, and sprinkler HF with Excess Leaching (EL) for all pixels (pixel size of 0.1-degree) across tomato cultivated areas in Egypt.

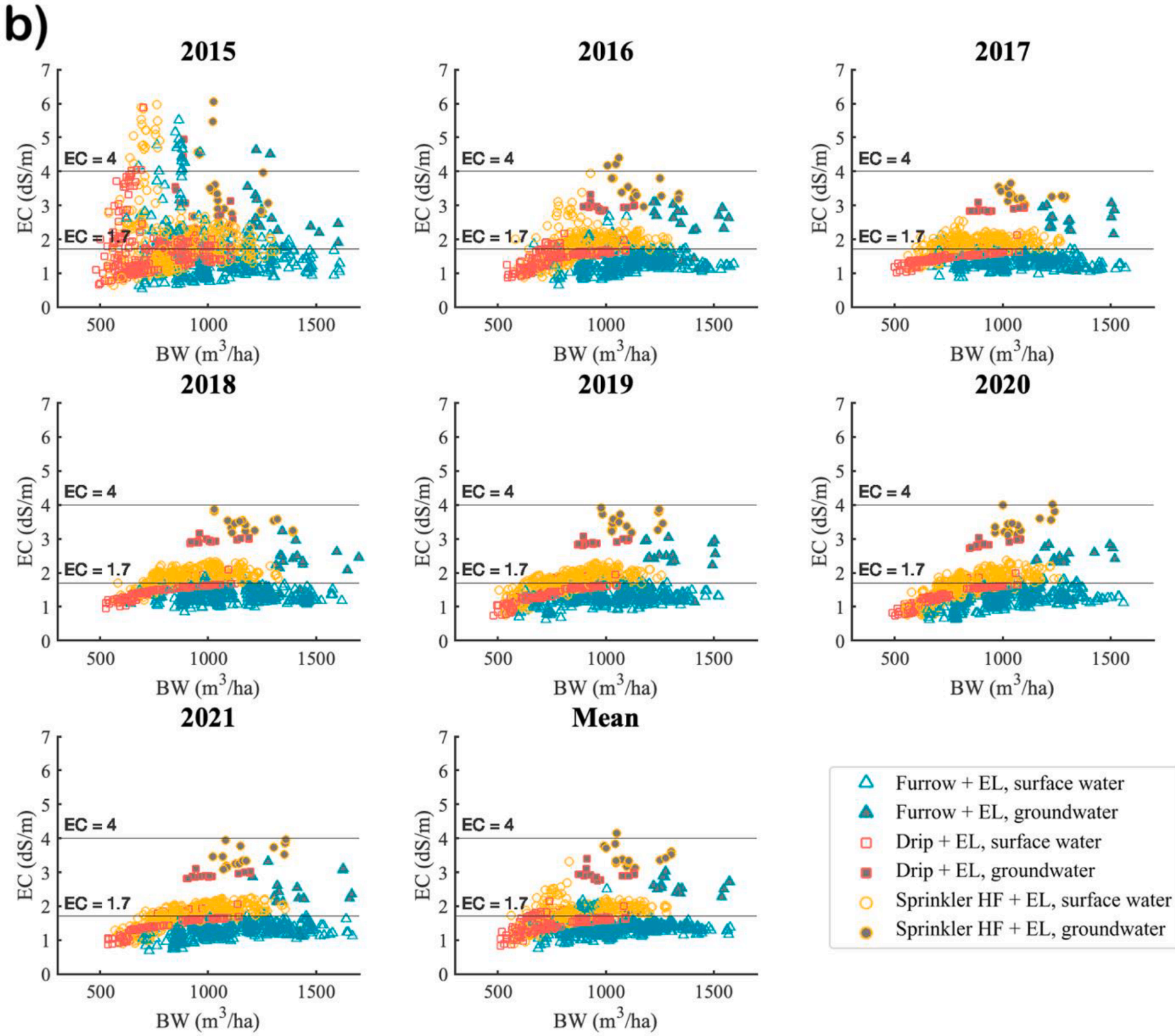

Fig. 6. (*continued*).

scatterplots of EC vs. BW consumption (Fig. 6) show that in locations with low BW (i.e., cumulated irrigation water volumes), EC was small and in many cases below 1.7 dS/m. Low BW values corresponded to locations with more abundant rain and, thus, a stronger reliance on GW for tomato growth. In these areas the more abundant rainfall allowed for soil leaching, while the smaller irrigation water applications ensured smaller salt inputs from irrigation water. Locations with high soil EC were typically irrigated with groundwater (Fig. 6), suggesting that higher leaching requirements should be adopted in those areas.

3.3. Salt-affected areas of tomato production

The results show that avoiding secondary salinization in Egypt requires a delicate balance that is ripe with tradeoffs, beginning with the irrigation method. Drip systems had the best performance among irrigation strategies because they avoided the uncontrolled increase in soil salinity, while requiring low BW withdrawal. Their performance was enhanced when the recommended LR was added to the irrigation water requirements for crop growth (Fig. S.1). In these irrigation management conditions, 93.5% of the tomato cultivated areas showed no adverse effect of salinity on yield by 2016 despite initial (2015) conditions exhibiting 69.2% of the tomato cultivated areas affected by salinity. Therefore, these areas reached a steady-state condition with reduced soil salinization after one year of using the drip irrigation strategy with EL rates equal to LR. Likewise, the furrow irrigation system was still effective overall in controlling root-zone soil water salinity. With this irrigation system, the salt-affected areas oscillated between 49.0% to 25.3% of the irrigated area for tomato production from 2015 to 2021 with no monotonic downward trend. However, when the EL was added, the salt affected areas exhibited a downward trend, shrinking to 32.4% in 2015 and they further contracted to 8.7% in 2021. Lastly, sprinkler LF irrigation led to salt accumulation in the root zone, causing severe secondary salinization. Thus, sprinkler LF irrigation led to the largest fraction of irrigated land affected by 'extreme' salinity and reduction in crop yield (169.3 thousand hectares in 2018, accounting for 96.9% of tomato cultivated areas) because of the low precipitation in the previous years (i.e., 20.6 mm (about 0.81 in) in 2017) and poor salt management of sprinkler irrigation (see discussion). The trend of salt accumulation was slowed in the sprinkler HF system, which maintained higher soil moisture levels. The consequently higher irrigation frequency in sprinkler HF created favorable plant-soil-water conditions with salt concentrations in the wetted root zone close to those of the irrigation water. This minimized both water and salinity stress in crops.

The source of irrigation water was also an important determinant of salinization. Fig. 7 maps the salinity levels in the case of furrow irrigation in the areas cultivated with tomato. It shows that the areas that are not close to the Nile River suffer from secondary salinization due to groundwater use, which has lower water quality (higher EC) than

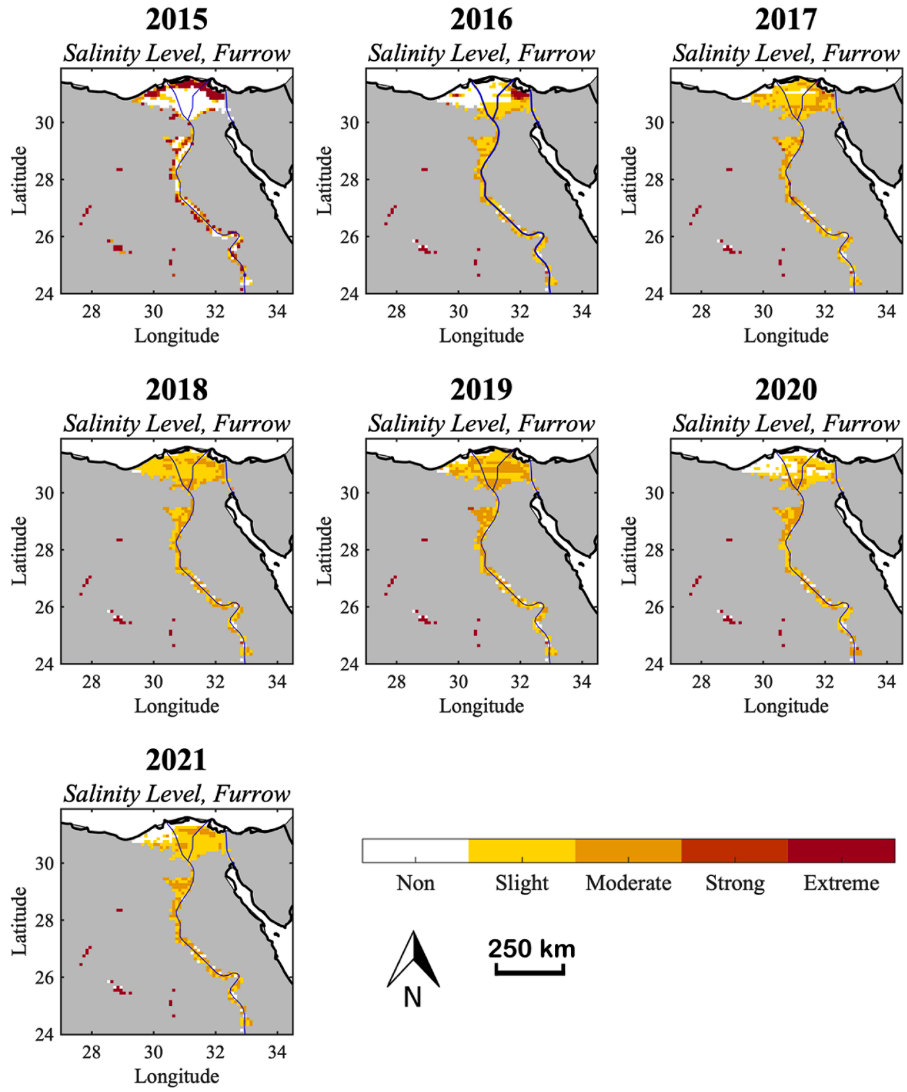

Fig. 7. Soil salinity map for the case of furrow irrigation, including spatial distributions and the severity level of crop-specific salt-affected soils for tomato production in Egypt.

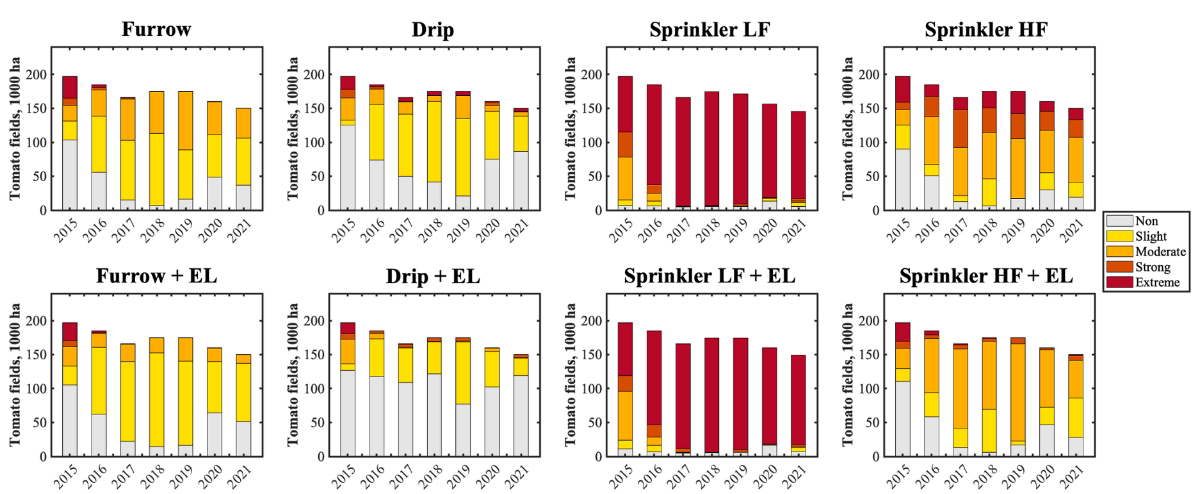

Fig. 8. Areas of tomato-cultivated land affected by no, slight, moderate, strong, and extreme salinity.Discussion

surface water. This result was also found when the recommended LR (i.e., 8%) was added to the most efficient irrigation system (i.e., the drip system, Fig. 7, 8 and S.1), pointing at potential persistent challenges of groundwater-based irrigation agriculture in Egypt. In soils with high sand content, a high frequency of irrigation events occurs due to poor water holding capacity which leads to proper salinity management despite using groundwater with higher EC as the irrigation source.

The interplay between background precipitation and irrigation method also played a critical role in determining intervention needs. In Northeastern Egypt, the higher precipitation allowed for salinity to be effectively managed if drip irrigation with the recommended LR was met. However, the recommended LR was not always adequate in less rainy regions where irrigation used groundwater. Sprinkler LF irrigation enhanced irrigation-induced salinity because the drainage rate was insufficient to leach the salt. This system resulted in a 12,000 ha/year increase in tomato-cultivated areas affected by soil salinity. Conversely, the higher irrigation frequency in sprinkler HF reduced the salt accumulation rate over time. Video 1 (available on the electronic version of the article) illustrates a comparison of water and salt flux dynamics within the root zone across different irrigation strategies: Sprinkler LF + EL, Sprinkler HF + EL, Furrow + EL, and Drip + EL during the 2015 growing season.

4. Discussion

4.1. Modeling emphasizes the need for dynamic management

Even when using water of good quality, arid regions still face moderate challenges in preventing, correcting, or delaying the emergence of severe soil salinization (Brandt et al., 2003; Van-Camp, et al., (2004). In these cases, the model demonstrates its potential to assess location- and circumstance-dependent irrigation strategies to identify ones that sufficiently flush salts and avoid waterlogging, which can be detrimental to crop output (Russ et al., 2020).

Our analysis shows that a drip irrigation intervention was the best at consistently preventing secondary salinization, while sprinkler irrigation exhibited the worst performances, consistent with the literature (Pasternak and De Malach, 1995; Dehghanisanji et al., 2006; Hanson el al., 2008, 2009; Pereira et al., 2009; Roberts et al., 2009; Minhas et al., 2020). These results can be explained by the interaction between rainfall and irrigation water management within the irrigation strategies. Drip irrigation is relatively continuous in time and maintains root zone soil moisture close to field capacity. Therefore, the few rainfall events that occur take place in conditions favorable for the emergence of soil drainage because even small rainfall amounts are sufficient to exceed field capacity, thereby triggering gravity drainage and the displacement of saline water with higher quality precipitation. Conversely, with sprinkler irrigation, water applications take place episodically when soil moisture reaches the threshold value of acceptable water stress conditions. In the period between two consecutive water applications, soil moisture decreases from field capacity to the acceptable water stress level. Therefore, when rainfall occurs, it is much less likely that the soil moisture exceeds field capacity, explaining the accumulation of salt shown in the model's simulations.

In certain regions, we observe that soil salinity remains low, even when the proposed leaching requirements by Rhoades (1974) are not consistently met. This phenomenon is particularly evident in sandy soils and in arid zones with infrequent precipitation and limited soil water holding capacity. Our research reveals that in arid and semi-arid regions, leaching plays a more pivotal role in salinity management than the dilution effects of sustaining soil moisture near field capacity. This emphasis on the significance of leaching aligns with observations from humid subtropical regions in Northern Argentina (Jayawickreme et al., 2011; Perri et al., 2022). These soils quickly reach their water stress thresholds, leading to more frequent irrigation, mimicking the drip irrigation approach. While the concentrated volume of the root zone is susceptible to increased solute concentration, the soil's EC is primarily influenced by the irrigation water's conductivity. As a result, the salinity within the root zone remains below the threshold value, signifying low salt concentrations, even in the absence of precipitation. These findings underscore the importance of a comprehensive approach to managing secondary salinization, taking into account irrigation water quality, soil characteristics, and irrigation scheduling.

The methodology herein is effective in the Egyptian context and has parallels in the literature. For instance, Minhas and Gupta (1992) highlighted the advantage of leaching practices prior to the advent of rains, aimed at amplifying pre-rainfall moisture levels and curtailing salinity in soils, even when confronted with saline waters. This is further corroborated by Forkutsa et al. (2009) who emphasized the superiority of pre-season leaching compared to mid-season approaches, especially in regions with shallow water tables. Analogously, in North China, there is a prevailing trend of administering irrigation during autumn, principally to facilitate salt removal while concurrently enhancing soil structure and reserving water for crops in the subsequent spring (Feng et al., 2005; Pereira et al., 2007).

While this study dynamically models the impact of different irrigation methods on salinity in space and time, it has some limitations. The model does not consider the effect of salinity on fertilizer uptake rate by plants nor the impact of irrigation schedule on soil fertilizer application. Additionally, the model only accounts for the vertical flow of water and not the lateral flow. We considered salt inputs only through irrigation water and did not account for other processes associated with the presence of shallow water tables. Salinity problems in irrigated agriculture, however, may be strongly influenced by a shallow water table (<2 meters of the surface) because capillary rise brings water up from the water table to close to beneath the ground surface (exfiltration process) where it evaporates, leading to salt accumulation (D'Odorico et al, 2013; Runyan and D'Odorico, 2010). This phenomenon can be controlled with additional soil leaching. Thus, controlling the effects of a shallow water table (through soil drainage) is critical to successful salinity management and long-term sustainability of irrigated agriculture. Higher salinity water necessitates significant additional water for leaching, compounding a potential water table drainage problem and making long-term irrigated agriculture nearly impossible to achieve without adequate drainage. Further, seawater intrusion into coastal aquifers has been identified as a significant factor in the long-term salinization trends of arid coastal areas (Bear et al., 1999; Jasechko et al., 2020). However, our results do not reflect this, given our assumption that the Nile Delta predominantly utilizes water from the Nile River, which is characterized as having a moderate salinity hazard (Daliakopoulos et al., 2016). Despite these limitations, the model can be applied to study the impact of irrigation management practices in regions with intensive agriculture with relatively deep (e.g., >2m) water tables (e.g., the Central Valley in California, USA).

4.2. Salinization vis-à-vis sustainable irrigation in arid regions

Control of secondary salinization in arid regions via excess leaching sits somewhat paradoxically as a solution in the sustainable irrigation space. Sustainable irrigation is typically evaluated based on the extent to which irrigation water consumption takes place without causing groundwater depletion, loss of environmental flows in water bodies, or lake desiccation (Rosa et al, 2018). Yet, in arid regions like the Southern Mediterranean Basin, characterized by minimal rainfall, significant evapotranspiration (Koutroulis et al., 2013), shrinking water resources, and overall drier conditions (Koutroulis et al., 2011), sustainable irrigation must also consider excess irrigation applications to combat rising salinity. While rainfall events can typically beget soil leaching and thereby offset salinization, rainfall in arid regions is often insufficient to leach the salt out of the root zone. Thus, farmers need to increase the amount of irrigation water applied to sustain soil drainage, leading to a seemingly inefficient irrigation practice (i.e., low consumption-to-withdrawal ratios) that nevertheless maintains salinity. This practice requires an increase in water withdrawals for irrigation in regions that are often affected by water scarcity, where finding water for soil leaching through excess irrigation can be a challenge and may require re-allocating it from another use (including leaving some land fallow to maintain the overall water use). Alternatively, farmers can switch to more salt-tolerant crops to maintain local sustainable water resources. The increase in water for soil leaching could also be offset by an irrigation strategy transition such as from sprinkler to drip irrigation, which reduces the consumptive water footprint of crop production without impacting the yield (Chukalla et al., 2015). The case study of tomato production in Egypt shows that excess irrigation is indeed needed to prevent soil salinization, and at varying amounts depending on the quality of the irrigation water source. Water amounts between 3.5-8% of the crop's irrigation requirement are generally sufficient to sustain adequate leaching rates with surface (furrow) and drip, but not with sprinkler LF irrigation. In these cases, water use must be carefully managed to avoid secondary salinization while maintaining overall water consumption within sustainable limits.

Given the similar arid climates, the advancements in irrigation made in California can offer invaluable insights for Egypt. In two decades, California underwent a notable transition from surface irrigation to pressurized methods, especially drip irrigation. Specifically, there was a 38% increase in drip systems and a 37% decline in surface methods (Taylor and Zilberman 2017; Tindula et al., 2013). This shift was catalyzed by factors such as rising water costs, increased yields, and specific soil types, making it especially advantageous for high-value crops (Hopmans et al., 2021). However, drip irrigation is not without challenges. There is the issue of soil surface salt accumulation (Roberts et al., 2009). Potential solutions to combat this include preseason flood irrigation, shifting drip lines every few years, or alternating crop rows between seasons (Hanson and May 2011). Additionally, in regions like the San Joaquin valley, soil salinity adversely impacts root growth and nutrient absorption. The intricate relationship between soil salinity and nitrate-water application has been emphasized by Vaughan and Letey (2015) and Libutti and Monteleone (2017). While drip irrigation systems, along with sprinklers, allow for exact water and fertilizer control, they require consistent water availability. Research indicates that drip irrigation is superior, while sprinklers can cause leaf burn (Hopmans et al., 2021). However, it also flags potential risks associated with this method, like infrastructure demands, the need for specialized knowledge and maintenance, and the vulnerability to soil degradation or crop failures (Assouline et al., 2006). Contrastingly, gravity-driven surface irrigation methods, such as furrow irrigation, necessitate precise soil leveling to ensure even water distribution. They tend to over-use water to achieve complete field saturation, leading to the need for effective drainage. This drainage, be it through ditches or perforated tubes, helps prevent salt buildup. However, it also introduces challenges related to water quality downstream and the possibility of groundwater being contaminated by agrochemicals (Hopmans et al., 2021).

4.3. Future research directions

The future of agricultural sustainability will rely on cutting-edge models that capture the dynamic interplay of soil-plant-atmosphere interactions (Minhas et al., 2020). This study's model begins to address these needs, being capable of appraising the role of irrigation methods and excess leaching at a subnational, policy-relevant scale. The methodology employed in this study is adaptable for various crops and regions since the crop parameters have been extensively established in existing literature (Allen et al., 1998; Rhoades et al., 1992). Leveraging global datasets and widely recognized crop parameters, it offers potential for a comprehensive global assessment of the water-salinity interface in precision agriculture, which could address the global assessment research gap highlighted by Kramer and Manu (2023). While our study aimed to ensure a non-water-stress condition through irrigation design, further optimization in scheduling is crucial to counter the detrimental effects of water and salinity on crop evapotranspiration and potential yield loss. For instance, Nicolas et al.'s study (2023) tested varying salinity levels and irrigation rates on tomato crops in California to determine crop profitability but did not consider an optimized irrigation system approach, which, if applied using a multi-objective water and salinity simulation, could yield vastly different profitability outcomes. Future research should further explore how salt buildup on the soil surface, which alters the soil's hydraulic conductivity, may impact the results. Research should also account for the impact of salinity and sodicity on soil hydraulic conductivity, as these factors can influence effective precipitation, runoff, and soil moisture in the root zone. Incorporating the hysteresis module and swelling process into the model can enhance its accuracy as well (Kramer et al., 2021; 2022; Kramer and Mau, 2023). Additionally, in this study, irrigation strategies were designed to prevent water-stress conditions. Future research might use this model to explore the impact of deficit irrigation on BW, GW, and soil salinity. Finally, highly variable sowing and growing periods that span different months of the year, along with a cropping cycle ranging from 110 to 180 days, have been documented in Egypt. Optimizing these parameters may serve as an effective strategy to mitigate salinity in tomato fields. Therefore, models such as the one developed here could be updated to inform real-time best management practices, balancing optimal crop yield with minimized environmental impacts (Hopmans et al., 2021).

5. Conclusions

This study demonstrates that proper irrigation management practices are crucial for ensuring sustainable tomato production in Egypt. By utilizing the modeling framework, we were able to investigate the complex dynamics of soil salt accumulation and its impact on crop yields under different irrigation methods. The results highlight the effectiveness of drip irrigation systems in minimizing soil salinity while requiring relatively low blue water consumption. This is further improved by adding the recommended leaching requirement to the irrigation water requirements for crop growth, resulting in a significant reduction of salt-affected areas and steady-state conditions with reduced soil salinization.

The study also reveals the effectiveness of furrow irrigation in controlling root-zone soil water salinity, which shows no monotonic downward trend in salt-affected areas but exhibits a downward trend when excess leaching is added. On the other hand, sprinkler LF irrigation leads to irrigation-induced saline conditions in the soil, causing extreme salinity and a reduction in crop yield. However, sprinkler HF irrigation performs better in salt management and maintains higher soil moisture levels, creating favorable plant-soil-water conditions and minimizing both water and salinity stress in crops.

The implications of this study are far-reaching, providing valuable insights for future research and policy interventions in water resource management and agricultural practices. The adoption of drip and furrow irrigation systems with excess leaching allows for sustainable tomato production, while mitigating soil salinity issues. This is especially crucial for areas grappling with low quality groundwater. The results emphasize the utmost significance of proper irrigation management techniques in preventing soil salinization and sustaining crop productivity. By doing so, it contributes to the larger goal of improving water resource management and agricultural practices, thereby strengthening the resilience of the agricultural sector.

CRediT authorship contribution statement

Saeed Karimzadeh: Conceptualization, Writing – original draft, Investigation, Methodology, Software. **Sarah Hartman:** Conceptualization, Writing – original draft, Methodology. **Davide Danilo Chiarelli:** Conceptualization, Investigation, Methodology, Software. **Maria Cristina Rulli:** Conceptualization, Methodology, Supervision. **Paolo**

D'Odorico: Conceptualization, Writing – review & editing, Methodology, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Paolo D'Odorico reports financial support was provided by National Science Foundation. Saeed Karimzadeh reports financial support was provided by Polytechnic University of Milan. Sarah Hartman reports financial support was provided by National Science Foundation. The corresponding author, along with a co-author, serves on the Editorial Board of the Journal of Advances in Water Resources.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2023.104604.

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