land

Article

Leaching Efficiency During Autumn Irrigation in China's Arid Hetao Plain as Influenced by the Depth of Shallow Saline Groundwater and Irrigation Depth, Using Data from Static Water-Table Lysimeters and the Hydrus-1D and SIMDualKc Models

Tiago B. Ramos [1,*], Meihan Liu [2], Haibin Shi [3], Paula Paredes [4] and Luis S. Pereira [4]

1 Centro de Ciência e Tecnologia do Ambiente e do Mar (MARETEC–LARSyS), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal
2 State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100190, China; liumeihan@mail.tsinghua.edu.cn
3 College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Huhhot 010018, China; shb@imau.edu.cn
4 LEAF—Linking Landscape, Environment, Agriculture and Food Research Center, Associated Laboratory TERRA, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal; pparedes@isa.ulisboa.pt (P.P.); luis.santospereira@gmail.com (L.S.P.)
* Correspondence: tiagobramos@tecnico.ulisboa.pt

Abstract: The need for controlling salinity in arid zones is essential for sustainable agricultural production and irrigation water use. A case study performed for two years in Hetao, Inner Mongolia, China, is used herein to rethink the contradictory issues of arid lands represented by water saving and controlling soil and water salinity. Two sets of static lysimeters, where water table depths (WTDs) were fixed at 1.25, 150, 2.00, and 2.25 m, were continuously monitored, and soil water and solute data were used to calibrate and validate two models: the soil water balance model SIMDualKc and the deterministic soil water and salt dynamics model HYDRUS-1D. Once accurately calibrated, the models were used to simulate maize water use, percolation, and capillary rise, along with the observed variables for the actual WTD and the autumn irrigation applied. Simulation scenarios also considered agricultural system degradation and dynamic water table behavior. Results have shown that large leaching efficiencies (Lefs) were obtained for large irrigation depths in cases of shallow water tables, but higher Lefs corresponded to high application depths when the water table was deeper. Agricultural system degradation, particularly increased groundwater salinity, lowered Lef, regardless of WTD. Conversely, water savings were minimal and only achievable when considering the dynamic nature of groundwater. These results indicate that there is a need to define different WTDs based on soil characteristics that influence fluxes and root zone storage, as well as the impacts of newly installed drainage systems aimed at salt extraction.

Keywords: arid lands; salts leaching; saline water-table; autumn irrigation; modeling

check for updates

Citation: Ramos, T.B.; Liu, M.; Shi, H.; Paredes, P.; Pereira, L.S. Leaching Efficiency During Autumn Irrigation in China's Arid Hetao Plain as Influenced by the Depth of Shallow Saline Groundwater and Irrigation Depth, Using Data from Static Water-Table Lysimeters and the Hydrus-1D and SIMDualKc Models. *Land* **2024**, *13*, 1797. https://doi.org/10.3390/land13111797

Academic Editor: Paolo Nasta

Received: 6 September 2024
Revised: 23 October 2024
Accepted: 29 October 2024
Published: 31 October 2024

1. Introduction

The Hetao Plain in Inner Mongolia, Northern China, is one of the three major irrigation districts in the country and the largest irrigated area in the upper Yellow River Basin, covering 570,000 ha of irrigated land out of a total of 1.12 million ha. The region faces widespread soil salinization due to both excessive irrigation water application and challenging hydrogeological conditions. This issue affects crop productivity and raises groundwater levels, which in turn may impact the Yellow River's flow regime as irrigation water is sourced from the river and drainage water is returned to it. Additionally, shallow saline water tables, which vary spatially from less than 1.0 m to more than 2.5 m deep during the crop season [1], promote capillary rise and consequent salinity buildup in the root zone [2–4]. As a result, salt accumulation in the upper layers of farmland soil is nowadays observed across over half of the irrigated farmland area [5–8], underscoring the need for continuous efforts to improve agricultural management in the region, particularly regarding crop water use and canal conveyance and distribution [9–12].

Although several water-saving measures have been implemented in the region to reduce river water withdrawals, decrease irrigation water use, and improve canal conveyance and distribution [10–13], these efforts have proven insufficient to effectively mitigate soil salinity issues, as demonstrated by numerous monitoring studies [7,14,15]. In fact, controlling soil salinity often contradicts the general objective of reducing irrigation water use, as it requires adding a leaching fraction to flush salts from irrigation water out of the root zone [16,17]. The presence of shallow saline groundwater tables adds further complexity to the problem as it is crucial to consider the dynamics of the water table, including groundwater contributions and drainage fluxes in and out of the root zone, as well as their effects on soil water availability, crop root distribution and growth, root water uptake, and soil salinity [18]. Finding a balanced solution requires identifying an optimal water table depth (WTD) that effectively controls salinity while supporting crop growth and yield [3,9,19].

While mathematical models are widely regarded as the most effective and commonly used tools for improving agricultural water management [20–22], a review by Liu et al. [23] noted that the application of modeling tools has been limited in studies examining the intrinsic relationships between WTD and soil salinity, as well as the effectiveness and optimization of existing salinity control measures in Hetao. Accurately computing soil water fluxes, particularly capillary rise, remains a significant challenge in agroecosystems with shallow water tables [14,24–26]. The appropriate WTD continues to be a topic of intense discussion [3,9,27,28]. Additionally, the effectiveness of the primary salinity control measure, autumn leaching irrigation, and determining the optimal application depth based on WTD have not yet been fully established [29–32]. As noted in Liu et al.'s [23] review, the literature has been overly focused on developing and implementing water-saving measures in the region, often overlooking the critical role of soil conservation in ensuring the sustainability of local agricultural systems.

Therefore, the main aim of this study is to provide an overview of the key findings from two different modeling studies that were recently conducted in Hetao, which aimed to assess soil salinization risks and evaluate appropriate salinity control measures in the region using data from static water table lysimeters [23,33]. The companion papers focused primarily on evaluating the performance of two modeling tools. This new paper integrates insights from both models while incorporating perspectives on water and soil conservation. Building on previous research, this follow-up study goes deeper into the complex relationship between autumn irrigation and water table depth (WTD), with the goal of advancing new approaches for salt control in the Hetao region. Ultimately, it aims to promote the sustainable use of soil and water resources in this arid area.

2. Materials and Methods

2.1. Site Description

This study was conducted at the Shuguang Experimental Station in the Hetao Plain, Inner Mongolia, China (40°46′ N, 107°24′ E, 1039.6 m a.s.l.), from 2017 to 2018. The region has an arid continental climate, with a mean annual precipitation of 137 mm, mostly occurring in the summer. The average monthly temperature ranges from −10 °C in January to 25 °C in July, and the number of frost-free days ranges from 135 to 150. Figure 1 shows the main weather variables during the study period, obtained from a nearby automatic weather station. The soil is silty loam. The groundwater table is saline, with electrical conductivity (EC_{gw}) ranging from 1.75 to 1.85 dS m^{-1}. Surface basin or border irrigation is the primary irrigation method. Further (and more detailed) data were analyzed by Liu et al. [23,34]. Leaching irrigation is practiced in the autumn after crop harvesting and before the soil water freezes. In addition to controlling soil salinity, this autumn irrigation is crucial for improving the structure of the soil root zone given the multiple occurrences of soil freezing and thawing, particularly in silty soils. It also helps create a soil water reserve usable after winter and before the first irrigation [2,35–37]. However, irrigation depths are often cited in the literature as being excessive [10].

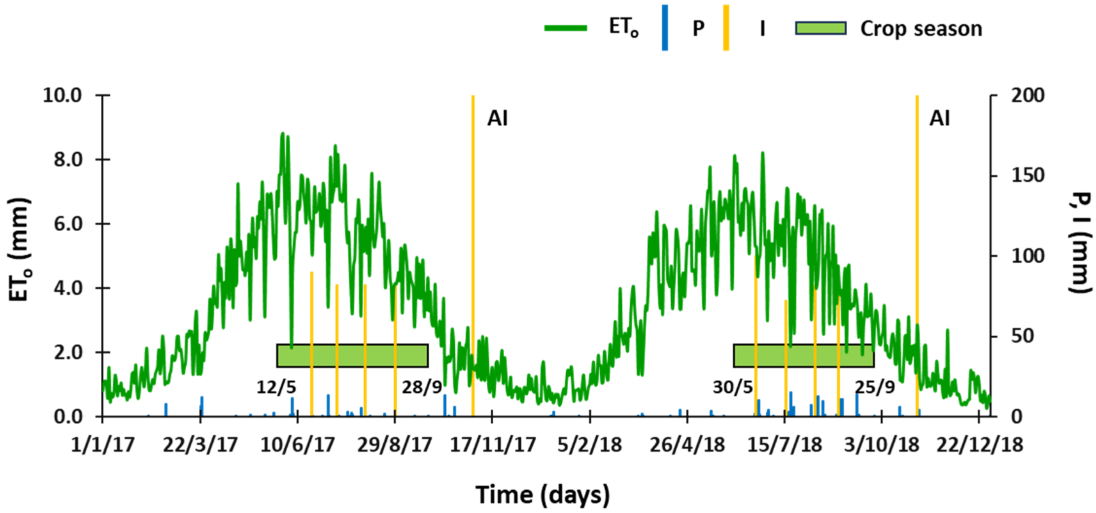

Figure 1. Reference evapotranspiration (ETo), precipitation (P), and irrigation (I) during the 2017 and 2018 growing seasons (AI, autumn irrigation).

2.2. Lysimeter Data

The static lysimeters (3.3 m long × 2.0 m wide × 2.6 m deep) used in this study had water table levels at fixed depths of 1.25, 1.5, 2.0, and 2.25 m throughout both seasons. These depths reflect the range of conditions observed in the region [1]. Liu et al. [23] provided detailed information on the lysimeters, including their field positioning, surrounding conditions (to ensure equilibrium in the surface boundary layer and one-dimensionality of measurements), the equipment used, their operations, and soil surface conditions. Additionally, an automatic rain shelter was used to prevent rainfall from affecting the measurements, enabling a more accurate assessment of the upward fluxes from the different WTDs and their related impacts.

The study crop was maize (Xi-meng 3358) with a planting density of 83,333 plants ha^{-1}. Sowing occurred in early May, and the harvest took place in late September. A 0.2 mm thick transparent polyethylene film mulch was applied along the plant rows, covering 75% of the lysimeter surface (4.95 m^2), to reduce soil evaporation and increase soil temperature. The remaining soil surface was left bare to facilitate the application of irrigation water, fertilizers, and herbicides, with management practices following local recommendations. Four irrigation events were carried out during each maize growing season (Figure 1), based on the surface irrigation practices commonly used by local farmers. Irrigation depths ranged from 72 to 100 mm per event. Additionally, the lysimeters were irrigated in autumn with 200 mm of water, primarily to leach salts from the root zone. Groundwater was used for irrigation purposes.

Soil water content (SWC) was measured every hour using FDR soil moisture sensors (WiTu Agricultural Technology, Shenyang, China). The calibration procedures for these sensors are detailed by Liu et al. [34]. The FDR sensors were installed in all lysimeters at depths of 0.1 m, 0.2 m, 0.4 m, and then at every 0.2 m down to the targeted WTD. Soil salinity was measured at the same depth as the SWC measurement, determined by the electrical conductivity of the 1:5 soil water extract ($EC_{1:5}$, dS m^{-1}), and then converted to the electrical conductivity of the soil saturation paste extract (EC_e) following the method described by Liu et al. [34]. Measurements were taken approximately every 10 days during both growing seasons.

2.3. Modeling Approaches

Two conceptually distinct modeling approaches were considered for computing the soil water and salt balances using static water table lysimeter data and for evaluating the effectiveness of autumn irrigation as a salinity control measure. Liu et al. [23] applied the SIMDualKc model [38] to compute the soil water balance and assess the impact of soil salinity on actual crop evapotranspiration rates. The SIMDualKc model used the dual crop coefficient approach [21,39,40] to estimate crop evapotranspiration (ET_c) by separately computing its components crop transpiration (T_c) and soil evaporation (E_s). In this approach, a basal crop coefficient (K_{cb}), which describes the transpiration characteristics that distinguish a specific crop from the reference grass crop, is used to calculate T_c ($T_c = K_{cb}\ ET_o$). The impacts of water and/or salinity stress on T_c ($T_{c\ act}$) are then accounted for by incorporating a dimensionless stress coefficient (K_s) into the calculation of T_c values ($T_c = K_s\ K_{cb}\ ET_o$), following the methods of Pereira et al. [9] and Rosa et al. [41]. E_s is determined using an evaporation coefficient (K_e) that reflects the difference between the actual soil cover fraction and the full cover provided by the grass reference crop ($E_s = K_e\ ET_o$). This difference is influenced by the fraction of ground shaded by the crop (f_c), the fraction of soil covered by mulch ($f_{r\ mulch}$), and the fraction of soil wetted by rain or irrigation (f_w). The remaining components of the soil water balance equation, namely capillary rise (CR) and percolation (DP), are calculated using the empirical relationships presented by Liu et al. [42]. Runoff is assumed to be negligible in static lysimeters. A detailed description of the equations, data used to run the SIMDualKc model, as well as the calibration and validation procedures are described by Liu et al. [23].

Ramos et al. [33] applied the HYDRUS-1D software package (version 4.17) [20] to numerically simulate one-dimensional water flow and solute transport in variably saturated porous media by solving the Richards equation for water flow and the Fickian-based convection–dispersion equation for solute transport. The unsaturated soil hydraulic properties were described using the van Genuchten–Mualem functional relationships [43,44], while the sink term incorporated the macroscopic approach proposed by Feddes et al. [45]. The Feddes et al. [45] model was chosen to describe the water stress response function, while the effect of salinity stress on root water uptake was modeled using the Maas [46] salinity threshold and slope function. This mechanistic approach also considered the compensated root water uptake mechanism introduced by Šimůnek and Hopmans [47], which accounts for maize's ability to compensate for reduced root water uptake in water/salinity-stressed parts of the root zone by increasing uptake in less stressed soil regions. The solute transport equation considered the electrical conductivity of the irrigation water ($EC_{iw} = EC_{gw}$) and the soil solution (EC_{sw}) as nonreactive tracers, meaning no adsorption in the solid phase was possible [48]. A detailed description of the equations, model implementation, and data used, as well as the calibration and validation procedures, can be found in the work by Ramos et al. [33].

Both models were calibrated using soil water content data, with HYDRUS-1D using measurements from different depths and SIMDualKc integrating the data as soil water storage in the root zone. Capillary rise and actual $ET_{c\ act}$ daily fluxes were also used in the calibration of both models, while HYDRUS-1D additionally incorporated EC_e data measured at various depths. In line with their conceptual approaches, SIMDualKc calibration focused on parameters affecting ET (and K_{cb}, K_e, and K_s), CR, and DP fluxes. In contrast, HYDRUS-1D calibration involved parametrization of soil hydraulic parameters and solute dispersivity within the soil domain, as well as the root adaptability factor for compensated root water uptake. The models were calibrated during the 2018 growing season and validated using independent data from the 2017 season. Several standard goodness-of-fit indicators were used to assess model performance. In this study, only the coefficient of determination (R^2), the normalized root mean square error (NRMSE), and the Nash–Sutcliffe efficiency (NSE) will be reported.

3. Results and Discussion

3.1. Models Performance

The full assessment of SIMDualKc and HYDRUS-1D performance results can be found in the work by Liu et al. [23] and Ramos et al. [33]. Despite their conceptual differences, both models were able to accurately reproduce measured SWC, $ET_{c\ act}$, and CR data during the study period, demonstrating the reliability of their estimates for the various components of the soil water balance [23,33,34]. In both models, soil water content simulations achieved R^2 values between 0.69 and 0.97, NRMSE values between 1.4% and 10.8%, and NSE values ranging from 0.57 to 0.97. Simulations of $ET_{c\ act}$ fluxes produced R^2 values between 0.79 and 0.89, NRMSE values between 26.5% and 30.4%, and NSE values from 0.62 to 0.82. CR daily fluxes were the most challenging to reproduce in both models, with R^2 values ranging from 0.48 to 0.94, NRMSE values between 28.8% and 111.9%, and NSE values from 0.16 to 0.93. The HYDRUS-1D model also satisfactorily simulated soil salinity in the rootzone of different lysimeters, with R^2 values ranging from 0.33 to 0.64, NRMSE from 19.7 to 29%, and NSE from 12.7 to 37.8%. The statistical indicators were deemed satisfactory for the subsequent analysis.

3.2. The Soil Water Balance

The calibrated K_{cb} values for the initial ($K_{cb\ ini}$), mid-season ($K_{cb\ mid}$), and end-season ($K_{cb\ end}$) crop stages, estimated using the SIMDualKc model, were 0.15, 1.15, and 0.2–0.3, respectively, with the latter values depending on grain dryness. The derived K_{cb} data are consistent with the literature [34,39,49], and served as inputs for defining the atmospheric boundary conditions in HYDRUS-1D simulations [33]. The actual K_{cb} ($K_{cb\ act}$) values, either estimated with SIMDualKc or HYDRUS-1D were consistently lower than the potential K_{cb} values due to the combined effects of water and salinity stresses. Crop stress was more pronounced in lysimeters with shallower water tables, where salinity levels were higher. Crop stress was also slightly more pronounced in the estimates provided by HYDRUS-1D compared to SIMDualKc. Consequently, the $T_{c\ act}$ values in SIMDualKc ranged from 398 to 445 mm in 2017 and 442 to 478 mm in 2018, while the corresponding HYDRUS-1D estimates were 396 to 401 mm and 413 to 424 mm, respectively. On the other hand, the K_e values remained relatively low ($K_e < 0.40$) throughout the study, initially due to the plastic mulch, which minimized soil surface exposure to solar radiation during the early crop stages, and later due to increased canopy coverage as the crop developed. Consequently, E_s values were relatively small throughout the crop season ($E_s \leq 26$ mm), with similar estimates produced by both models. During the non-growing season, the values were relatively higher, although they did not exceed 80 mm between the harvest (end of September) and the end of the year (December).

The contribution of groundwater fluxes to actual crop evapotranspiration (GWC) was highly significant in lysimeters with shallower WTDs during the 2017 and 2018 growing seasons, with both models producing similar estimates. According to SIMDualKc, seasonal GWC accounted for 22–39% of $ET_{c\ act}$, while HYDRUS-1D estimated it at 37–38%. In lysimeters with the deepest WTDs, seasonal GWC represented 8–15% of $ET_{c\ act}$ as estimated by SIMDualKc, and 14% by HYDRUS. These estimates align with existing modeling studies assessing groundwater contributions to maize water demand under saline conditions in Hetao [14,24,26].

Lastly, percolation values decreased with increasing WTD, primarily due to the larger, drier root zone under such conditions. However, the estimated values were also influenced by the less efficient irrigation scheduling adopted in the experiment, which involved less timely water applications, reflecting the traditional practices of local farmers and the canal system delivery schedule. Despite the lower efficiency, this approach is beneficial for salt leaching and can be considered desirable. The non-growing period was characterized by high percolation due to the application of 200 mm of water for autumn irrigation, intended to leach the salts accumulated during the previous crop season.

3.3. The Salt Balance and Autumn Leaching

The salt balance was calculated for both growing and non-growing periods using HYDRUS-1D, focusing on the 0.0–1.25 m soil layer to facilitate comparison between lysimeters. Salts were primarily added to the soil through irrigation water, contributing 3.76–3.97 tons ha^{-1} during the crop season and 2.24–2.37 tons ha^{-1} during the autumn irrigation. Additionally, salts were transported via capillary rise from saline groundwater, with shallower WTDs leading to greater salinity build-up in the root zone. For instance, a WTD of 1.25 m resulted in a salt load of 3.49–3.57 tons ha^{-1}, while a WTD of 2.25 m showed a salt load of 1.20 tons ha^{-1} via capillary rise.

Autumn irrigation played a crucial role in removing salts accumulated in the root zone during the previous maize growing season. The WTD significantly influenced the effectiveness of leaching in salt removal. Leaching from autumn irrigation was more effective in lysimeters with shallower WTDs ($\leq$1.5 m; $\geq$6.31 tons ha^{-1}) compared to those with deeper WTDs ($\geq$2.0 m; $\leq$4.75 tons ha^{-1}). This difference was due to the higher salt accumulation and greater soil moisture in the deeper root zone layers of lysimeters with shallower WTDs. The lysimeter with a WTD of 1.5 m exhibited the highest leaching efficiency (83.5–87.5%) compared to the other lysimeters, particularly when compared with the lysimeter having a WTD of 2.25 m, which showed the lowest leaching efficiency (51.3–53.6%).

3.4. Finding an Appropriate Depth for the Water Table

Ramos et al. [33] investigated the effectiveness of autumn irrigation in relation to WTD using the calibrated HYDRUS-1D model. Their simulation scenarios covered WTDs ranging from 1.25 m to 2.25 m and autumn irrigation depths (AID) from 50 to 400 mm, based on values reported in the literature. In the current study, these scenarios were expanded to assess the impacts of agricultural system degradation and dynamic water table behavior on the effectiveness of autumn irrigation as a salinity control measure. One scenario, using the conditions from Ramos et al. [33] (i.e., WTD = 1.25–2.25 m and AID = 50–400 mm), included an increase in groundwater salinity (EC_{gw}) by 0.5 and 1.0 dS m^{-1} compared to present conditions. Another scenario, run for WTD = 1.5 m, which showed the highest leaching efficiency, compared the effects of a static versus dynamic water table. In the dynamic case, the WTD varied from 1.1 m to 1.8 m, becoming shallower during irrigation events and deeper during the non-growing season, while maintaining an average WTD of 1.5 m over the simulation period.

Ramos et al. [33] showed that, for a WTD of 1.25 m, leaching efficiency never exceeded 78%, which was achieved with 200 mm of autumn irrigation (Figure 2). Similarly, the lysimeter with a WTD of 1.5 m exhibited the highest leaching efficiency (83.5–87.5%) with an autumn irrigation depth of 200 mm. In both cases, higher irrigation depths were less effective at salt removal due to increased salt loading in the root zone and poor drainage conditions. These results are consistent with the findings of Minhas et al. [17], who discussed the limited effectiveness of leaching in the presence of shallow and saline water tables unless subsurface drainage is employed. Conversely, for a WTD of 2.0 m, leaching efficiency improved from 67–68% to 86% as the autumn irrigation depth increased from 200 to 250 mm. However, further increases in irrigation depth became less effective for salt leaching. A WTD of 2.25 m showed the most favorable drainage conditions, with a marked increase in leaching efficiency when small increments above 200 mm were applied. With 220 mm of irrigation (+20 mm), leaching efficiency increased from 51–54% to 85–91%. With 250 mm of irrigation (+50 mm), all salts applied during both the growing and non-growing seasons were removed. However, leaching efficiency decreased again to below 100% with 400 mm of irrigation.

The land degradation scenario (Figure 3) showed the same trends as those described earlier. Higher groundwater salinity did not significantly affect the relationship between salt leaching and WTD. However, the increase in groundwater salinity naturally led to more salts being transported to the root zone through irrigation and capillary rise, contributing to salinity buildup. Given that water fluxes remained nearly unchanged, a general decrease in leaching efficiency across all WTDs was expected. Notably, even in the less severe scenario (EC_{gw} + 0.5 dS m^{-1}), conditions where leaching efficiency reached 100% were no longer observed. The highest leaching efficiency (90.3%) occurred with a WTD of 2.25 m and an AID of 250 mm. In the worst-case scenario (EC_{gw} + 1.0 dS m^{-1}), no condition resulted in a leaching efficiency higher than 80%, which is obviously of concern considering the intensification of agriculture in the region.

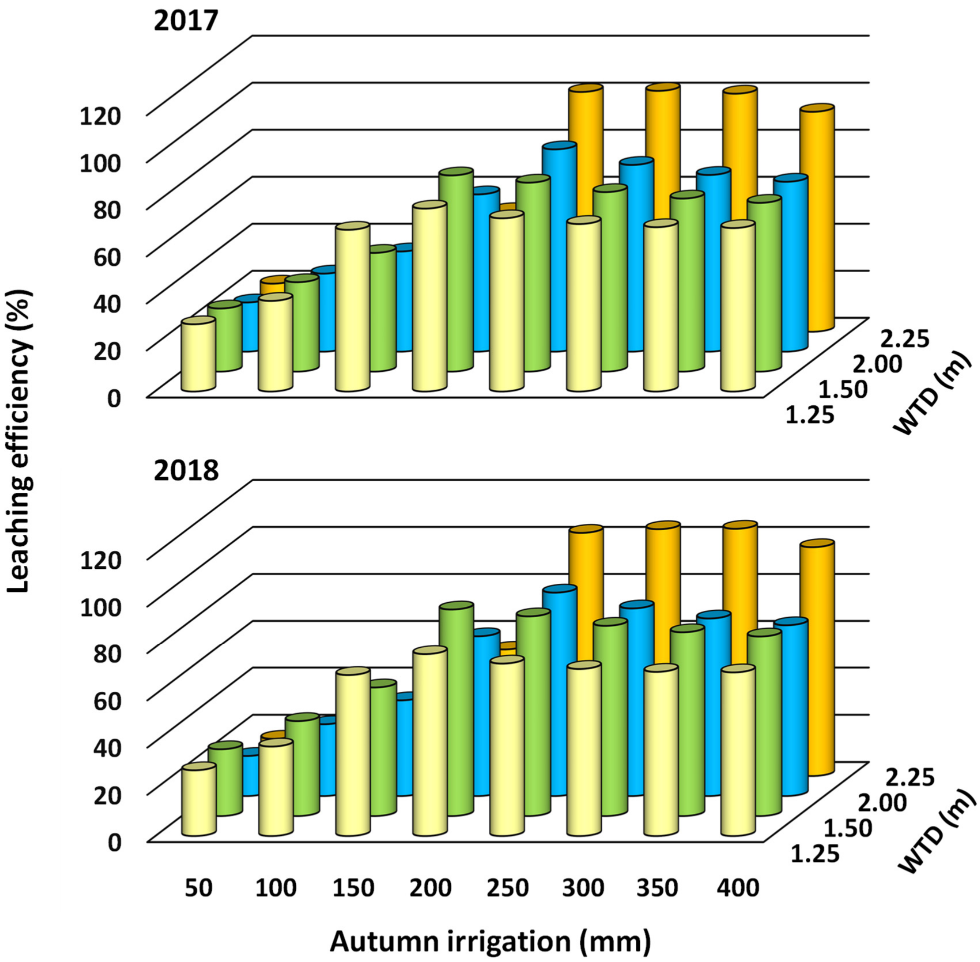

Figure 2. The efficiency of autumn irrigation depth for leaching rootzone salts under variable water table depth (WTD) conditions (adapted from Ramos et al. [33]).

Lastly, the scenario involving dynamic water table behavior revealed some contrasting results (Figure 4). On one hand, the relationship between salt leaching and WTD followed the same trend as before, with leaching efficiency increasing as WTD rose, while higher autumn irrigation depths (AID > 250 mm) did not result in greater leaching efficiencies. On the other hand, compared to static WTD, higher leaching efficiencies were recorded in this variably WTD scenario, reaching 100% with AID above 200 mm. This suggests a significant opportunity for water conservation. However, when AID was reduced to 150 mm, leaching efficiency dropped significantly to 59.4%. To achieve the same leaching efficiency observed for a static WTD of 1.5 m (ranging from 83.5% to 87.5% under experimental conditions with AID = 200 mm), water savings could only be achieved with an AID of 185 mm, representing a mere reduction of 15 mm. While this represents a small decrease, it was realized under a hypothetical scenario of WTD variation. Therefore, considering WTD variability in future studies aimed at identifying effective measures for soil salinity control in the region appears essential.

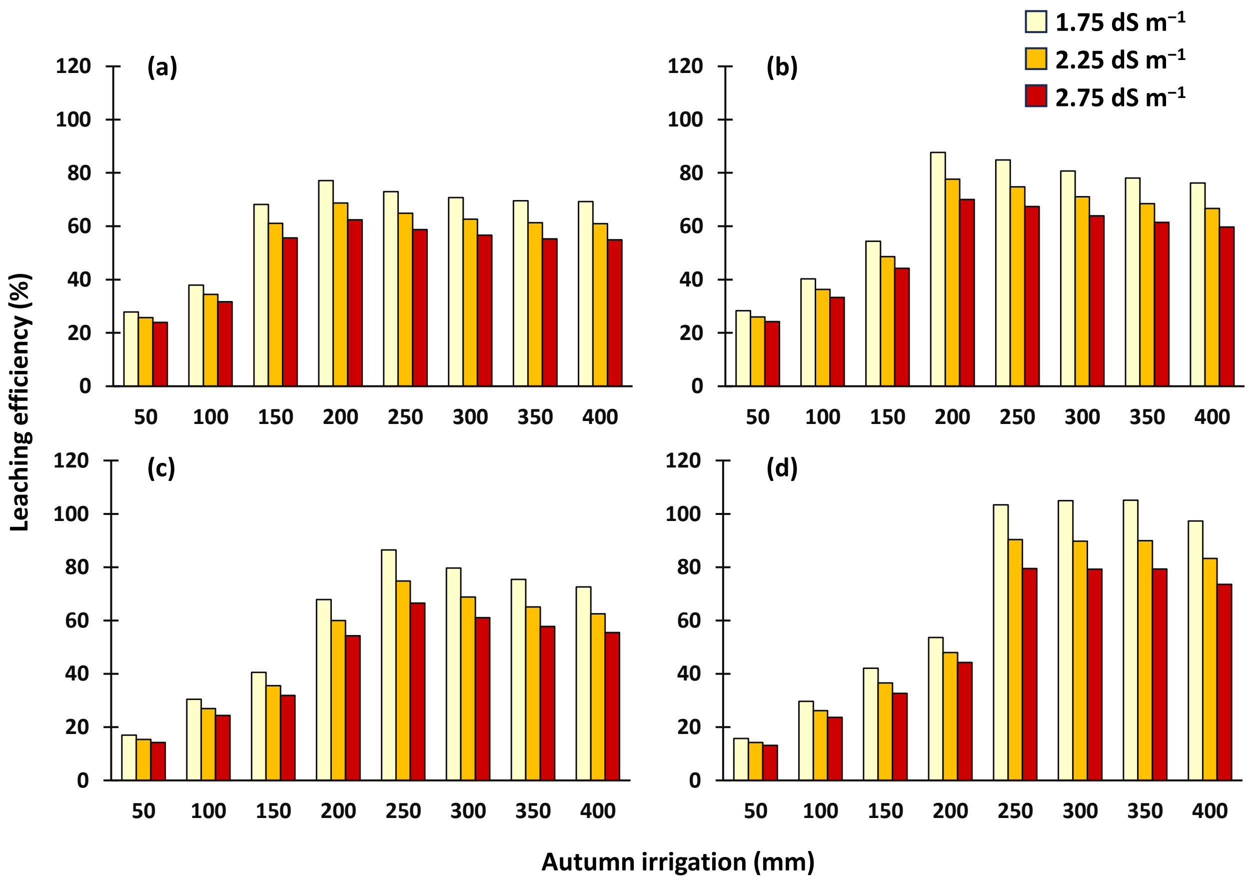

Figure 3. The efficiency of autumn irrigation depth for leaching rootzone salts under variable water table depth (WTD) conditions in a scenario where groundwater salinity (EC_{gw}) increased 0.5 and 1.0 dS m^{-1} compared to present conditions (1.75 dS m^{-1} as observed in 2018). (**a**) WTD = 1.25 m; (**b**) WTD = 1.5 m; (**c**) WTD = 2.0 m; (**d**) WTD = 2.25 m.

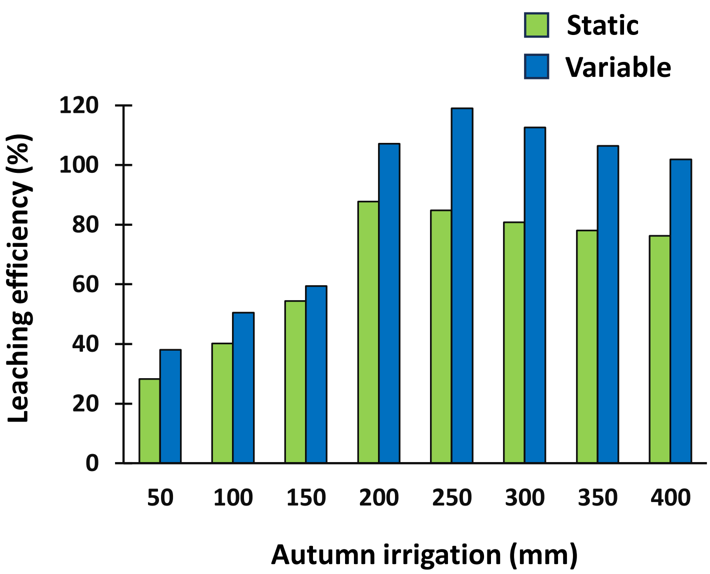

Figure 4. The efficiency of autumn irrigation depth for leaching rootzone salts in scenarios with static and variable water table depths (WTD). For both scenarios, the mean WTD was 1.5 m.

The above results align with previous studies [29,30,32] but contradict several others [31,50], primarily because the methods used in these latter studies were too simplistic for such a complex problem. Model calibration and the consistency of modeling approaches seem critical for the reliability of solutions. Liu et al. [23], using a semi-empirical approach, identified a WTD of 2.0 m as optimal for cropping conditions and lower salinity levels. Shallower WTDs tended to lead to greater salt accumulation in the root zone due to increased upward water fluxes. In contrast, Ramos et al. [33], using a mechanistic approach, determined that a WTD of 1.5 m was most effective for salt control when applying an autumn irrigation depth of 200 mm. Although WTDs of 2.0 m and 2.25 m could also be effective for salt leaching, they would require larger irrigation depths. However, groundwater fluxes, which are crucial for meeting crop water needs in the region, would significantly decrease. Therefore, a balanced approach that incorporates the findings of both Liu et al. [23] and Ramos et al. [33] would be most effective for optimizing crop growth and controlling salinity in the Hetao region.

These findings underscore the importance of mathematical tools for accurately estimating the water balance and optimizing irrigation water use in the region. Regardless of the approach adopted, mathematical tools can provide precise estimates of the various components of the soil water balance, improve irrigation scheduling, and enhance water use efficiency. However, water conservation cannot be the sole focus of agricultural water management, as reducing water application in autumn irrigation, as demonstrated earlier, may lead to increased soil salinity. The new scenarios show that saving water is possible without losing the perspective of soil conservation. The problem is complex, and it is crucial that policy measures aimed at promoting water savings in the region also prioritize soil conservation to ensure the sustainability of local agricultural systems. In this context, physically-based models capable of simulating solute transport are indispensable for assessing soil salinity and complementing irrigation scheduling tools.

In addition to incorporating the dynamic nature of the groundwater table, future studies should also integrate the winter freeze–thaw period into model simulations. This process significantly influences soil water dynamics and solute transport within the soil, thereby impacting the effectiveness of autumn irrigation for salinity control as recently demonstrated by Guo et al. [51].

4. Conclusions

This study highlights the benefits and consistency of using two different modeling approaches to analyze the full complexity of Hetao's agroecosystems. Both soil water balance and mechanistic models used in this study may play a crucial role in assisting farmers and stakeholders in mitigating the impacts of water scarcity, particularly soil salinization, on crop growth and yields. Adopting these models can help develop more efficient irrigation schedules and determine the optimal water table depth, thereby improving the effectiveness of salt leaching in the Hetao region. They are also valuable for helping in the transition from surface irrigation to drip irrigation and for finding the most effective strategies for salt leaching in areas where subsurface drainage systems have been installed. In addition, it is required to find WTD and autumn irrigation depths that better match drainage issues, currently in application.

Author Contributions: T.B.R. and M.L.: manuscript writing and editing; H.S. and P.P.: reviewed and corrected the original draft; L.S.P.: conceptualized, supervised, reviewed, and corrected the original draft. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by national funds through FCT—Fundação para a Ciência e a Tecnologia, I.P., under projects UIDB/50009/2020, UIDP/50009/2020 and LA/P/0083/2020 of LARSyS and UIDB/04129/2020 of LEAF-Linking Landscape, Environment, Agriculture and Food Research Center. This study was further supported by the National Natural Science Foundation of China (grant number: 52269014) and the National Key Research and Development Program of the Chinese Ministry of Science and Technology (grant number: 2021YFD1900602–6). The support of FCT through a grant attributed to T.B. Ramos (CEECIND/01152/2017) is also acknowledged.

Data Availability Statement: The original contributions presented in this study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Xiong, L.; Xu, X.; Engel, B.; Huang, Q.; Huo, Z.; Xiong, Y.; Han, W.; Huang, G. Modeling agro hydrological processes and analyzing water use in a super-large irrigation district (Hetao) of arid upper Yellow River basin. *J. Hydrol.* **2021**, *603*, 127014. [CrossRef]
2. Feng, Z.; Wang, X.; Feng, Z. Soil N and salinity leaching after the autumn irrigation and its impact on groundwater in Hetao Irrigation District, China. *Agric. Water Manag.* **2005**, *71*, 131–143. [CrossRef]
3. Xu, X.; Huang, G.; Sun, C.; Pereira, L.S.; Ramos, T.B.; Huang, Q.; Hao, Y. Assessing the effects of water table depth on water use, soil salinity and wheat yield: Searching for a target depth for irrigated areas in the upper Yellow River basin. *Agric. Water Manag.* **2013**, *125*, 46–60. [CrossRef]
4. Tong, W.; Chen, X.; Wen, X.; Chen, F.; Zhang, H.; Chu, Q.; Dikgwatlhe, S.B. Applying a salinity response function and zoning saline land for three field crops: A case study in the Hetao Irrigation District, Inner Mongolia, China. *J. Integr. Agric.* **2015**, *14*, 178–189. [CrossRef]
5. Wu, J.; Vincent, B.; Yang, J.; Bouarfa, S.; Vidal, A. Remote sensing monitoring of changes in soil salinity: A case study in Inner Mongolia, China. *Sensors* **2008**, *8*, 7035–7049. [CrossRef]
6. Yu, R.; Liu, T.; Xu, Y.; Zhu, C.; Zhang, Q.; Qu, Z.; Liu, X.; Li, C. Analysis of salinization dynamics by remote sensing in Hetao Irrigation District of North China. *Agric. Water Manag.* **2010**, *97*, 1952–1960. [CrossRef]
7. Guo, S.; Ruan, B.; Chen, H.; Guan, X.; Wang, S.; Xu, N.; Li, Y. Characterizing the spatiotemporal evolution of soil salinization in Hetao Irrigation District (China) using a remote sensing approach. *Int. J. Remote Sens.* **2018**, *39*, 6805–6825. [CrossRef]
8. Zhang, T.; Ji, X.; Zhan, X.; Ding, Y.; Zou, Y.; Kisekka, I.; Chau, H.W.; Feng, H. Maize is stressed by salt rather than water under drip irrigation with soil matric potential higher than -50 kPa in an arid saline area. *J. Agron. Crop Sci.* **2021**, *207*, 654–668. [CrossRef]
9. Pereira, L.S.; Gonçalves, J.M.; Dong, B.; Mao, Z.; Fang, S.X. Assessing basin irrigation and scheduling strategies for saving irrigation water and controlling salinity in the upper Yellow River Basin, China. *Agric. Water Manag.* **2007**, *93*, 109–122. [CrossRef]
10. Xu, X.; Huang, G.; Qu, Z.; Pereira, L.S. Assessing the groundwater dynamics and predicting impacts of water saving in the Hetao Irrigation District, Yellow River basin. *Agric. Water Manag.* **2010**, *98*, 301–313. [CrossRef]
11. Xu, X.; Huang, G.; Qu, Z.; Pereira, L.S. Using MODFLOW and GIS to assess changes in groundwater dynamics in response to water saving measures in irrigation districts of the upper Yellow River basin. *Water Resour. Manag.* **2011**, *25*, 2035–2059. [CrossRef]
12. Bai, L.; Cai, J.; Liu, Y.; Chen, H.; Zhang, B.; Huang, L. Responses of field evapotranspiration to the changes of cropping pattern and groundwater depth in large irrigation district of Yellow River basin. *Agric. Water Manag.* **2017**, *188*, 1–11. [CrossRef]
13. Pereira, L.S.; Cai, L.G.; Hann, M.J. Farm water and soil management for improved water use in the North China Plain. *Irrig. Drain.* **2003**, *52*, 299–317. [CrossRef]
14. Gao, X.; Huo, Z.; Bai, Y.; Feng, S.; Huang, G.; Shi, H.; Qu, Z. Soil salt and groundwater change in flood irrigation field and uncultivated land: A case study based on 4-year field observations. *Environ. Earth Sci.* **2014**, *73*, 2127–2139. [CrossRef]
15. Ren, D.; Wei, B.; Xu, X.; Engel, B.; Li, G.; Huang, Q.; Xiong, Y.; Huang, G. Analyzing spatiotemporal characteristics of soil salinity in arid irrigated agroecosystems using integrated approaches. *Geoderma* **2019**, *356*, 113935. [CrossRef]
16. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture*; Irrigation & Drainage Paper 29; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 1998.
17. Minhas, P.S.; Ramos, T.B.; Ben-Gal, A.; Pereira, L.S. Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues. *Agric. Water Manag.* **2020**, *227*, 105832. [CrossRef]
18. Ayars, J.E.; Christen, E.W.; Soppe, R.W.; Meyer, W.S. The resource potential of in situ shallow ground water use in irrigated agriculture: A review. *Irrig Sci.* **2006**, *24*, 147–160. [CrossRef]
19. Hollanders, P.; Schultz, B.; Wang, S.L.; Cai, L.G. Drainage and salinity assessment in the Huinong Canal Irrigation District, Ningxia, China. *Irrig Drain.* **2005**, *54*, 155–173. [CrossRef]
20. Šimůnek, J.; van Genuchten, M.T.; Šejna, M. Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone J.* **2016**, *15*, 1–25. [CrossRef]
21. Pereira, L.S.; Paredes, P.; Jovanovic, N. Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO56 method and the dual Kc approach. *Agric. Water Manag.* **2020**, *241*, 106357. [CrossRef]
22. Heinen, M.; Mulder, M.; van Dam, J.; Bartholomeus, R.; van Lier, Q.J.; de Wit, J.; de Wit, A.; Hack-ten Broeke, M. SWAP 50 years: Advances in modelling soil-water-atmosphere-plant interactions. *Agric. Water Manag.* **2024**, *298*, 108883. [CrossRef]
23. Liu, M.; Paredes, P.; Shi, H.; Ramos, T.B.; Dou, X.; Dai, L.; Pereira, L.S. Impacts of a shallow saline water table on maize evapotranspiration and groundwater contribution using static water table lysimeters and the dual Kc water balance model SIMDualKc. *Agric. Water Manag.* **2022**, *273*, 107887. [CrossRef]
24. Ren, D.; Xu, X.; Hao, Y.; Huang, G. Modeling and assessing field irrigation water use in a canal system of Hetao, upper Yellow River basin: Application to maize, sunflower and watermelon. *J. Hydrol.* **2016**, *532*, 122–139. [CrossRef]
25. Ren, D.; Xu, X.; Ramos, T.B.; Huang, Q.; Huo, Z.; Huang, G. Modeling and assessing the function and sustainability of natural patches in salt-affected agro-ecosystems: Application to Tamarisk (*Tamarix chinensis* Lour.) in Hetao, upper Yellow River basin. *J. Hydrol.* **2017**, *552*, 490–504. [CrossRef]

26. Wu, Z.; Li, Y.; Wang, R.; Xu, X.; Ren, D.; Huang, Q.; Xiong, Y.; Huang, G. Evaluation of irrigation water saving and salinity control practices of maize and sunflower in the upper Yellow River basin with an agro-hydrological model based method. *Agric. Water Manag.* **2023**, *278*, 108157. [CrossRef]
27. Xu, X.; Sun, C.; Qu, Z.; Huang, Q.; Ramos, T.B.; Huang, G. Groundwater recharge and capillary rise in irrigated areas of the Upper Yellow River basin assessed by an agro-hydrological model. *Irrig Drain.* **2015**, *64*, 587–599. [CrossRef]
28. Ren, D.; Xu, X.; Engel, B.; Huang, G. Growth responses of crops and natural vegetation to irrigation and water table changes in an agro-ecosystem of Hetao, upper Yellow River basin: Scenario analysis on maize, sunflower, watermelon and tamarisk. *Agric. Water Manag.* **2018**, *199*, 93–104. [CrossRef]
29. Mao, W.; Yang, J.; Zhu, Y.; Ye, M.; Wu, J. Loosely coupled SaltMod for simulating groundwater and salt dynamics under well-canal conjunctive irrigation in semi-arid areas. *Agric. Water Manag.* **2017**, *192*, 209–220. [CrossRef]
30. Chang, X.; Gao, Z.; Wang, S.; Chen, H. Modelling long-term soil salinity dynamics using saltMod in Hetao Irrigation District, China. *Comp. Electron. Agric.* **2019**, *156*, 47–458. [CrossRef]
31. Sun, G.; Zhu, Y.; Ye, M.; Yang, J.; Qu, Z.; Mao, W.; Wu, J. Development and application of long-term root-zone salt balance model for predicting soil salinity in arid shallow water table area. *Agric. Water Manag.* **2019**, *213*, 486–498. [CrossRef]
32. Cao, Z.; Zhu, T.; Cai, X. Hydro-agro-economic optimization for irrigated farming in an arid region: The Hetao Irrigation District, Inner Mongolia. *Agric. Water Manag.* **2023**, *277*, 108095. [CrossRef]
33. Ramos, T.B.; Liu, M.; Paredes, P.; Shi, H.; Fenz, Z.; Lei, H.; Pereira, L.S. Salts dynamics in maize irrigation in the Hetao plateau using static water table lysimeters and HYDRUS-1D with focus on the autumn leaching. *Agric. Water Manag.* **2023**, *283*, 108306. [CrossRef]
34. Liu, M.; Shi, H.; Paredes, P.; Ramos, T.B.; Dai, L.; Feng, Z.; Pereira, L.S. Estimating and partitioning maize evapotranspiration as affected by salinity using weighing lysimeters and the SIMDualKc model. *Agric. Water Manag.* **2022**, *261*, 107362. [CrossRef]
35. Wang, L.; Akae, T. Analysis of ground freezing process by unfrozen water content obtained from TDR data in Hetao Irrigation District of China. *J. Jpn. Soc. Soil Phys.* **2004**, *98*, 11–19. [CrossRef]
36. Li, R.; Shi, H.; Flerchinger, G.N.; Akae, T.; Wang, C. Simulation of freezing and thawing soils in Inner Mongolia Hetao Irrigation District, China. *Geoderma* **2012**, *173–174*, 28–33. [CrossRef]
37. Liu, S.; Huang, Q.; Ren, D.; Xu, X.; Xiong, Y.; Huang, G. Soil evaporation and its impact on salt accumulation in different landscapes under freeze–thaw conditions in an arid seasonal frozen region. *Vadose Zone J.* **2021**, *20*, e20098. [CrossRef]
38. Rosa, R.D.; Paredes, P.; Rodrigues, G.C.; Alves, I.; Allen, R.G.; Pereira, L.S. Implementing the dual crop coefficient approach in interactive software. 1. Background and computational strategy. *Agric. Water Manag.* **2012**, *103*, 8–24. [CrossRef]
39. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements*; Irrigation & Drainage Paper 56; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 1998.
40. Allen, R.G.; Pereira, L.S.; Smith, M.; Raes, D.; Wright, J.L. FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. *J. Irrig. Drain. Eng.* **2005**, *131*, 2–13. [CrossRef]
41. Rosa, R.D.; Ramos, T.B.; Pereira, L.S. The dual Kc approach to assess maize and sweet sorghum transpiration and soil evaporation under saline conditions: Application of the SIMDualKc model. *Agric. Water Manag.* **2016**, *177*, 77–94. [CrossRef]
42. Liu, Y.; Pereira, L.S.; Fernando, R.M. Fluxes through the bottom boundary of the root zone in silty soils: Parametric approaches to estimate groundwater contribution and percolation. *Agric. Water Manag.* **2006**, *84*, 27–40. [CrossRef]
43. Mualem, Y. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.* **1976**, *12*, 513–522. [CrossRef]
44. Van Genuchten, M.T. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* **1980**, *44*, 892–898. [CrossRef]
45. Feddes, R.A.; Kowalik, P.J.; Zaradny, H. *Simulation of Field Water Use and Crop Yield*; Simulation Monographs Pudoc.: Wageningen, The Netherlands, 1978.
46. Maas, E.V. Crop salt tolerance. In *Agricultural Salinity Assessment and Management*; Tanji, K.K., Ed.; Manual Reports on Engineering Practices; ASCE: Reston, VA, USA, 1990; Volume 71, pp. 262–304.
47. Šimůnek, J.; Hopmans, J.W. Modeling compensated root water and nutrient uptake. *Ecol. Modell.* **2009**, *220*, 505–521. [CrossRef]
48. Ramos, T.B.; Šimůnek, J.; Gonçalves, M.C.; Martins, J.C.; Prazeres, A.; Castanheira, N.L.; Pereira, L.S. Field evaluation of a multicomponent solute transport model in soils irrigated with saline waters. *J. Hydrol.* **2011**, *407*, 129–144. [CrossRef]
49. Pereira, L.S.; Paredes, P.; Hunsaker, D.J.; López-Urrea, R.; Mohammadi Shad, Z. Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. *Agric. Water Manag.* **2021**, *243*, 106466. [CrossRef]
50. Liu, Y.; Zhu, Y.; Mao, W.; Sun, G.; Han, X.; Wu, J.; Yang, J. Development and application of a water and salt balance model for well-canal conjunctive irrigation in semiarid areas with shallow water tables. *Agriculture* **2022**, *12*, 399. [CrossRef]
51. Guo, S.; Li, X.; Šimůnek, J.; Wang, J.; Zhang, Y.; Wang, Y.; Zhen, Z.; He, R. Experimental and numerical evaluation of soil water and salt dynamics in a corn field with shallow saline groundwater and crop-season drip and autumn postharvest irrigations. *Agric. Water Manag.* **2024**, *305*, 109119. [CrossRef]