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# SPRINKLER IRRIGATION OPTIMIZATION FOR SUSTAINABLE CARROT PRODUCTION USING THE AQUACROP MODEL

***Abstract.*** *This study applied the AquaCrop model to optimize sprinkler irrigation management for sustainable carrot production under the soil and climatic conditions of the Tashkent region, Uzbekistan. The model simulated irrigation schedules, soil water balance, crop water stress, biomass accumulation, and yield responses, with seasonal irrigation requirements ranging from 3,782 to 3,934 m³/ha. Model results were compared with field experiments conducted during 2023–2025 on typical sierozem soils, involving sprinkler application intensities of 0.3–0.5 mm/min, operating pressures of 2.5–3.5 bar, and droplet diameters ranging from 1.10 to 2.60 mm. The simulated irrigation requirements closely corresponded to the observed values of 3,822–3,958 m³/ha. These findings demonstrate the potential of AquaCrop as a practical tool for optimizing sprinkler irrigation schedules and improving water management in sustainable carrot production.*

***Key words:*** *AquaCrop model, sprinkler irrigation, irrigation optimization, soil water balance, carrot production, field validation, water-use efficiency.*

## I. INTRODUCTION

Efficient irrigation management is essential for sustainable carrot (Daucus carota L.) production, particularly in arid and semi-arid regions where water availability is limited. Carrot yield and root development are strongly influenced by soil moisture conditions and irrigation scheduling. Previous studies have demonstrated that appropriate irrigation regimes can improve carrot productivity while reducing unnecessary water consumption [1–3]. Recent investigations have also emphasized the importance of optimizing irrigation frequency and water application to maintain crop growth under water-limited conditions [4, 5]. In this context, crop simulation models provide valuable opportunities to evaluate irrigation strategies and predict crop responses before their practical implementation [6].

Among these models, AquaCrop, developed by the Food and Agriculture Organization of the United Nations (FAO), has been widely applied to assess crop growth, biomass production, and yield responses to water availability [7, 8]. The model integrates climatic conditions, soil characteristics, crop development, and irrigation management through a daily soil water balance. Its main simulation processes include canopy development, crop transpiration, biomass accumulation, and yield formation based on the harvest index [9]. Previous applications to potatoes, tomatoes, beans, and wheat have demonstrated the potential of AquaCrop for simulating crop responses under different irrigation regimes and supporting irrigation scheduling decisions [10–13]. The model has also been recognized as a practical tool for improving agricultural water management [14].

Despite these advances, the application of AquaCrop to sprinkler-irrigated carrot production under the typical sierozem soils of Central Asia remains insufficiently investigated. Therefore, this study aimed to evaluate the suitability of AquaCrop for simulating irrigation requirements, soil water balance, biomass accumulation, and yield

responses of carrot under sprinkler irrigation. Model outputs were compared with field observations collected during 2023–2025 in the Tashkent region of Uzbekistan to assess the potential of simulation-based irrigation management for sustainable carrot production.

## II. METHODOLOGY

The study utilized the AquaCrop model to simulate carrot growth under sprinkler irrigation. Key inputs included:

-Soil characteristics: texture, water retention capacity, field capacity, and permanent wilting point.

-Crop parameters: type, growth stages, root depth, and biomass accumulation.

-Water balance components: precipitation, irrigation, evapotranspiration, and infiltration.

-Climatic factors: temperature, solar radiation, and $CO_2$ concentration.

Simulations covered a 104-day growth period, allowing the assessment of soil moisture distribution, transpirational water use, crop stress levels, and yield components.

## III. RESULT AND DISCUSSIONS

The formation of biomass in the AquaCrop model is based on the following fundamental equation:

$$\text{Biomass}=\text{WP}\times\sum(\text{Tr})$$

where *WP* represents the water productivity (kg biomass / mm transpiration / $m^2$), and *Tr* is the amount of transpiration.

At present, the AquaCrop model is widely applied across the world in various scientific studies, including optimization of irrigation systems, assessment of climate change impacts on crop yield, irrigation scheduling, analysis of drought stress, and testing of new crop varieties [15; 16].

AquaCrop is a highly advanced agro-climatic modeling software designed to evaluate crop growth, yield, and water use efficiency under different agronomic and climatic conditions. The model integrates detailed input parameters such as climatic indicators (precipitation, temperature, and $ET_0$), soil physical characteristics,

irrigation regimes, plant phenological phases, and technological management practices.

In this study, under the conditions of sprinkler irrigation for carrot crops, the AquaCrop model was employed to predict yield, total water use (net application), water use efficiency (WUE), potential field yield, and the dynamics of soil moisture.

During the 104-day growth period of the 2025 season (up to August 14), the model simulated and evaluated the growth dynamics of the carrot crop, water use efficiency, the influence of stress factors, and the final yield parameters.

The overall yield results indicate that the biomass yield reaches 42.87 t/ha, while the dry yield amounts to 31.16 t/ha. These results demonstrate that the crop efficiently utilized water. The yield is close to or slightly higher than the average values reported for carrot crops.

The transpiration (Tr) table represents the water consumption by the carrot crop and the contribution from weed competition. Transpiration intensified starting from the 25th day of the growing period and reached its peak between days 40 and 70, corresponding to the active growth phase of the carrot.

DR - Depletion Rootzone (moisture deficit in the root zone) - reflects the soil water distribution profile. Dark blue lines indicate the amount of water in each soil layer (up to 250 mm depth). SAT (Soil Saturation – fully saturated soil), FC (Field Capacity - optimal water content), and PWP (Permanent Wilting Point – water level at which the plant cannot extract moisture) lines define the limits of soil moisture conditions. Simulation results show that optimal moisture levels (within the FC-PWP range) were consistently maintained in the root zone, providing favorable conditions for carrot development.

According to the DR graph, the flowering stage occurred between days 65 and 75. This period represents the most critical stage for yield formation, during which transpiration and water demand reached their maximum. In the graph provided below, the horizontal axis represents time (in days), while the vertical axis shows rainfall amounts (mm) on the left and the depth of root zone water deficit (mm) on the right. This diagram allows a visual analysis of rainfall and soil moisture

dynamics throughout the various growth stages of the crop, particularly before flowering (Figure 1).

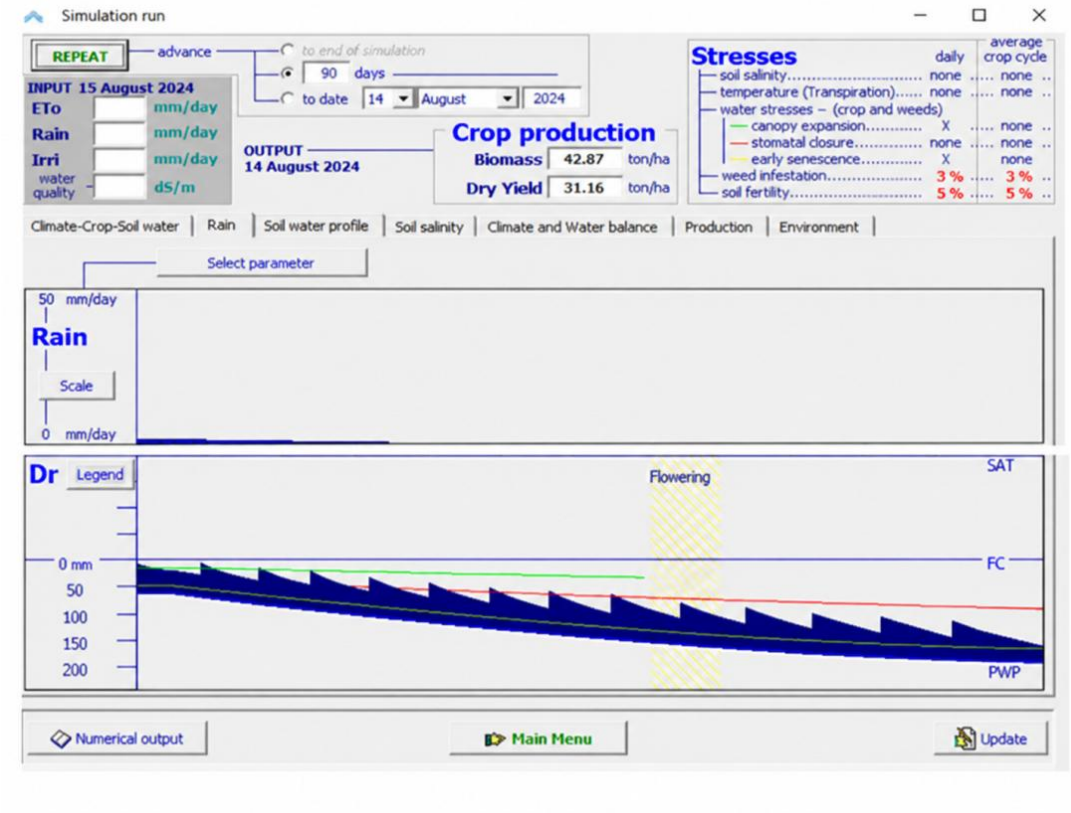



**Fig 1.** Rainfall patterns and soil moisture depletion dynamics in the root zone during the carrot growing season

The rainfall data are presented in the upper part of the diagram as a separate graph and remained very low throughout the entire vegetation period. No significant peaks are observed, indicating that there was almost no considerable rainfall during this period. This suggests an insufficient natural water supply for the crop, making irrigation likely necessary as the primary water source.

The lower graph illustrates the depletion level of water reserves in the root zone. Various colors represent field capacity, permanent wilting point, and full soil saturation limits. Dark blue indicates the degree of soil saturation, and the progressive reduction in this color reflects a decrease in soil moisture. Approaching the flowering stage, a sharp decline in water content is observed, particularly critical during important vegetative phases such as flowering and yield formation, indicating water stress.

Although the soil's water-holding capacity increases with depth, the deeper layers did not accumulate sufficient moisture. The yellow background denotes the onset of the flowering stage, during which water deficit persists and can intensify stress conditions. These stress conditions are also highlighted in the upper right section of the graph under "Stresses," where weed competition reached 25%.

Extremely low rainfall created significant limitations in replenishing water reserves during the vegetation period, increasing the potential risk of yield reduction due to water shortage in the root zone. The diagram clearly illustrates the imbalance between the crop's water demand and the available natural water resources, serving as a crucial source of information for optimizing future agro-technical measures, particularly irrigation scheduling.

The "Soil Water Profile" section visualizes soil moisture in the crop root zone in a vertical cross-section. The vertical axis represents depth from 0.0 m to 1.20 m, corresponding to the extension of crop roots, while the horizontal axis indicates the soil saturation percentage (Figure 2).

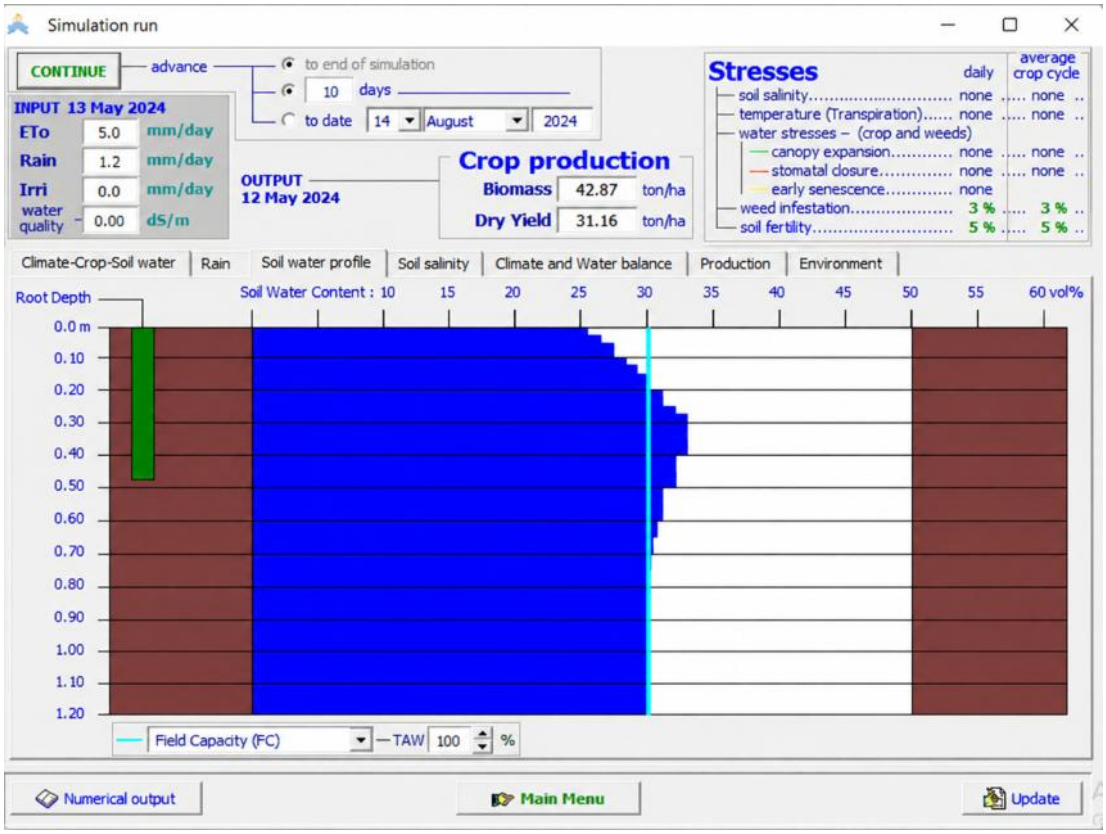


**Fig 2.** Comparison of root zone moisture during the initial growth stage of the crop

The colored cells in the diagram represent soil moisture expressed as a percentage. The layers fully shaded in blue (approximately from 0.00 to 0.70 m depth) indicate soil at field capacity - that is, fully saturated with water. This condition represents optimal water availability for the crop, and no water deficit stress is observed in this region.

In the lower layers (0.70 m to 1.20 m), the cells are unshaded (white), indicating dry soil and the absence of water reserves. Such conditions typically restrict the downward expansion of crop roots or indicate that these layers have not yet been wetted.

A very thin green line on the left side of the diagram represents the depth of the existing root zone. In this case, roots extend to approximately 0.1 m, indicating that the crop is still in its initial development stage. Since the roots have not yet penetrated deeper layers, water availability in the 0.0–0.1 m layer is particularly critical for early growth.

Overall, the diagram demonstrates that water resources required for yield are currently sufficient; however, root depth is limited, and deeper soil layers have not yet been exploited by the plants. This condition is typical for the early stages of crop growth, with the water extraction zone expected to expand as roots deepen.

The agricultural simulation software's "Soil Salinity" section allows the analysis of salinity conditions during crop growth. The primary objective is to determine the vertical distribution of salt concentration within the root zone and deeper layers, assess the potential negative effects on plant growth, and monitor salt balance (Figure 3).

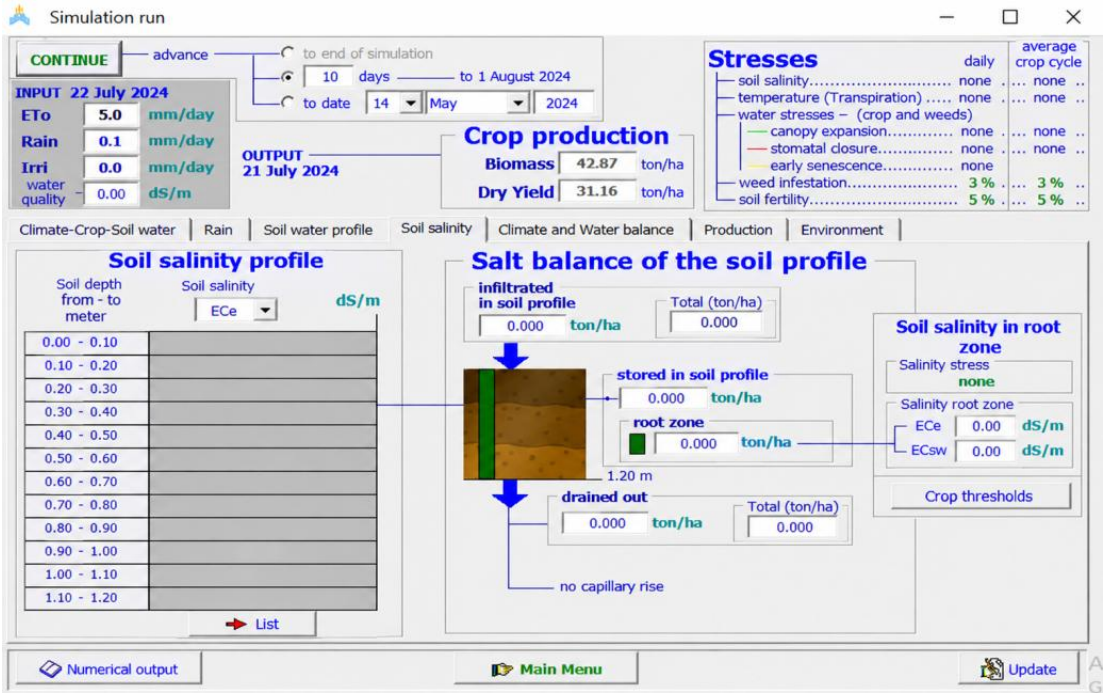



**Fig .3.** Soil salinity profile and salinity stress in the root zone

The “Soil Salinity Profile” diagram represents the electrical conductivity (ECe) of the soil solution along the soil depth. ECe indicates the concentration of dissolved salts in the soil, expressed in dS/m. According to the diagram, from 0.00 m to 1.20 m depth, ECe values across all soil layers are 0.000 dS/m, indicating that there is no salinity present in the soil. Such salinity-free conditions create an optimal environment for crop growth, without limiting root development, water uptake, or nutrient absorption [17].

The section on the right, “Soil Salinity in Root Zone,” shows salinity stress levels. The stress indicator is marked as “none,” confirming the absence of any salinity-related stress in the crop. The ECce value is also 0.000 dS/m, fully corroborating the data observed in the previous graph. This scenario reflects optimal irrigation practices and effective drainage systems under the given agroecological conditions.

Simulation results demonstrate that soil salinity does not pose a threat to crops, the water-salt balance is maintained consistently, and there is no risk of yield loss due to salinity stress. This contributes positively to maintaining crop productivity and implementing long-term

crop rotation strategies. Therefore, controlling soil salinity is crucial for sustaining a stable agro-ecosystem [18].

The “Climate” and “Soil Water Balance” modules of the simulation software allow a comprehensive analysis of crop water balance and climatic conditions. The data presented in the diagram cover the period from May 3, 2025, to August 14, 2025, during which crop growth conditions were evaluated based on available water resources and climatic parameters (Figure 4).

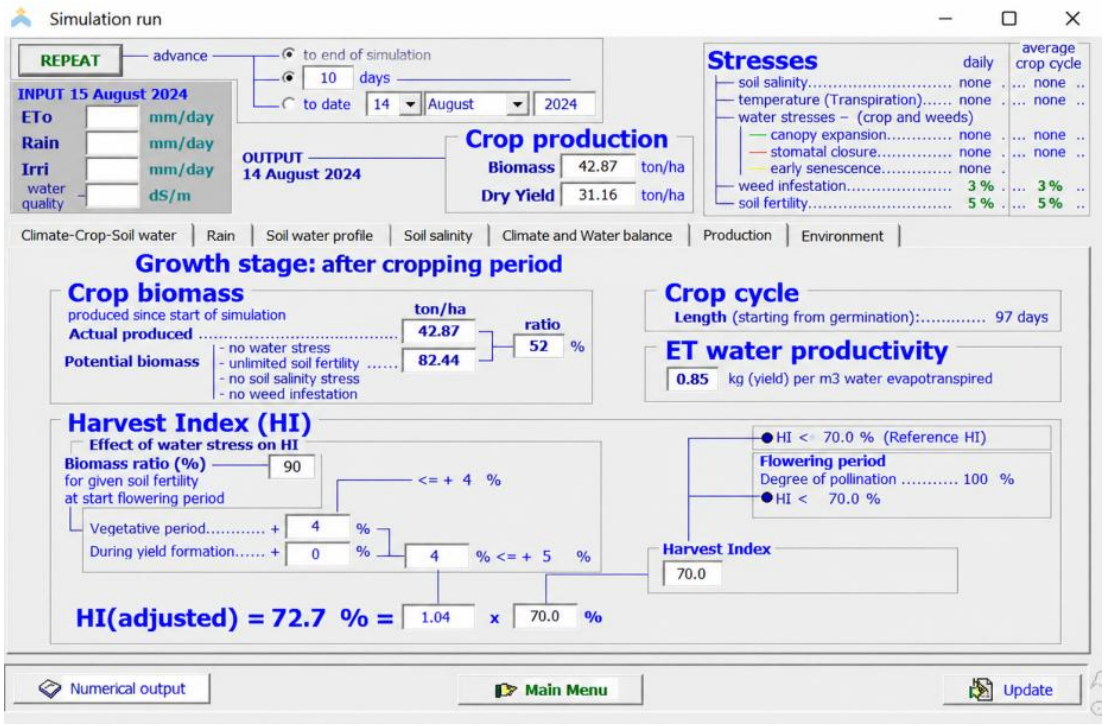



**Fig 4.** Analysis of climate conditions and soil water balance

In the “Climate” module, the average air temperature was 21.6 °C, and the atmospheric $CO_2$ concentration was 420.21 ppm, which is a critical factor influencing photosynthetic activity in plants [84; 50-53]. The reference evapotranspiration (ETo) was 5.0 mm/day, serving as an important parameter for evaluating potential water stress. Precipitation during the period was relatively low, with a daily average of 0.1 mm, totaling 47.6 mm. Irrigation amounted to 288.0 mm, representing the primary source of water supply for the crop.

In the “Soil Water Balance” module, detailed inflow and outflow processes of water are presented. Evaporation accounted for

112.9 mm, while transpiration through the crop reached 174.6 mm, indicating efficient water use. Surface runoff and percolation were negligible, reflecting minimized water losses in the area. The total water infiltrated into the soil was 335.6 mm, which is crucial for replenishing groundwater and maintaining soil moisture. Although 41.4 mm of water was lost via drainage, the absence of capillary rise indicates that water from deeper layers did not return to the root zone.

These data provide a precise assessment of soil water balance, confirming that available water resources are sufficient to meet the crop's demand. The integrated analysis of climate and water balance is essential for optimizing water resource management, developing irrigation schedules, and enhancing the efficiency of agronomic practices. The results indicate that in this region, water supply is largely dependent on irrigation, and soil water resources are adequate to support crop growth, thereby contributing to sustainable agricultural production [19].

The crop biomass indicators reflect the total amount of biomass produced by the plant. The actual biomass reached 42.87 t/ha, which corresponds to 52% of the potential biomass. The potential biomass, calculated at 8.304 t/ha, represents the theoretical yield under optimal conditions without considering stress factors such as water stress, soil salinity, and weed competition. The difference between these values highlights the major agroecological constraints influencing crop growth and productivity [20].

The harvest index, which represents the conversion efficiency of biomass into the final yield, was recorded at 72.7%, indicating a high efficiency of assimilate partitioning into marketable yield. The variation of the harvest index during vegetative growth and reproductive phases provides a more accurate estimation of yield efficiency under varying environmental conditions.

The "Crop cycle" section indicates that the total growth period-from sowing to harvest-lasted 104 days, which is a key parameter for scheduling irrigation, fertilization, and other agronomic operations.

The ET water productivity value was estimated at 0.85 kg yield per $m^3$ of water, which demonstrates efficient utilization of available water resources and an adequate water supply for the crop. This level of

efficiency is consistent with optimized irrigation management practices that minimize water losses and ensure sustainable productivity.

In the “Stresses” section, the impact of weeds is reported at 3%, signifying a moderate but noticeable limitation on crop growth and yield formation. In contrast, no soil salinity or water stress was recorded during the simulation period, confirming the favorable soil-water regime and effective irrigation control.

Overall, this section enables a comprehensive assessment of crop productivity, water use efficiency, and the impact of stress factors. The results provide a strong foundation for optimizing agricultural technologies and improving resource management strategies to enhance sustainable crop production.

**Comparison of AquaCrop Simulation and Field Experimental Results.** The AquaCrop model was applied to simulate irrigation requirements, soil water balance, crop water stress, and biomass development under sprinkler irrigation conditions. The simulations were conducted using climatic data, soil characteristics, and crop growth parameters corresponding to the conditions of the Tashkent region. Particular attention was given to optimizing irrigation schedules and maintaining suitable soil moisture levels throughout the carrot growing season.

The simulation results indicated that seasonal irrigation requirements varied depending on meteorological conditions and crop water demand. The AquaCrop-estimated irrigation requirements were 3,901, 3,934, and 3,782 m³/ha for 2023, 2024, and 2025, respectively. The model also supported the assessment of irrigation frequency and soil moisture management under different growing conditions. These findings highlight the potential of AquaCrop as a decision-support tool for improving irrigation scheduling and water-use efficiency.

To evaluate the model results, field experiments were conducted during 2023–2025 on typical sierozem soils at the experimental farm of TIIAME National Research University in the Tashkent region, Uzbekistan. The experiments were carried out using the Mirzoyi Kizil carrot variety under sprinkler irrigation intensities of 0.3, 0.4, and 0.5 mm/min. The sprinkler system operated at pressures of 2.5–

3.5 bar, with a discharge of 802 L/h at 3.0 bar and a spraying radius of approximately 6 m. Droplet-size analysis considered an initial diameter of 2.60 mm and an estimated diameter of approximately 1.10 mm for smaller droplets distributed across the irrigated area.

The field results demonstrated that an irrigation intensity of 0.4 mm/min provided the highest carrot yields, reaching 28.0, 29.4, and 30.2 t/ha in 2023, 2024, and 2025, respectively. Compared with conventional furrow irrigation, sprinkler irrigation reduced seasonal water consumption by approximately 31–33% while improving crop productivity.

The comparison between simulated and experimental seasonal irrigation requirements showed close agreement. Field-measured irrigation amounts ranged from 3,822 to 3,958 m³/ha, whereas AquaCrop estimates ranged from 3,782 to 3,934 m³/ha. The relative differences between simulated and observed values were approximately 0.6–1.4% across the three experimental years, as presented in Table 1. These findings demonstrate that AquaCrop can provide reliable estimates of seasonal irrigation requirements under the investigated conditions and support the optimization of sprinkler irrigation management for sustainable carrot production.

**Table 1**

Comparison of AquaCrop-simulated and field-observed seasonal irrigation requirements for carrot production (2023–2025)

| Number of irrigations | Irrigation norm, mm | | | | | |
|---|---|---|---|---|---|---|
| | 2023 | | 2024 | | 2025 | |
| | AquaCrop | Field experiment | AquaCrop | Field experiment | AquaCrop | Field experiment |
| 1 | 17.6 | 18.8 | 16.8 | 18.3 | 15.9 | 16.7 |
| 2 | 17.5 | 19.2 | 16.9 | 18.8 | 16.1 | 18.7 |
| 3 | 18.9 | 19.8 | 28.7 | 19.2 | 25.2 | 19.7 |
| 4 | 28.8 | 24.7 | 26.7 | 27.6 | 27.6 | 32.4 |
| 5 | 34.7 | 36.7 | 37.7 | 35.2 | 29.3 | 33.4 |
| 6 | 35.9 | 38.0 | 38.6 | 38.1 | 31.5 | 37.3 |
| 7 | 35.8 | 39.9 | 27.5 | 37.4 | 33.2 | 37.9 |
| 8 | 38.1 | 39.4 | 30.6 | 38.7 | 34.6 | 36.7 |
| 9 | 44.9 | 39.8 | 42.4 | 38.7 | 38.6 | 36.8 |
| 10 | 45.1 | 38.5 | 44.2 | 39.1 | 40.8 | 35.7 |
| 11 | 44.2 | 39.4 | 42.1 | 39.0 | 42.3 | 35.4 |
| 12 | 46.1 | 41.6 | 41.2 | 40.9 | 43.1 | 41.5 |
| **Total:** | **390.1** | **395.8** | **393.4** | **391.0** | **378.2** | **382.2** |

The comparison of AquaCrop-simulated and experimentally observed irrigation requirements revealed close agreement in seasonal irrigation amounts over the three-year study period (Table 1). Based on the reported seasonal totals, in 2023, AquaCrop estimated 390.1 mm compared with the observed 395.8 mm, representing a relative difference of 1.44%. In 2024, the simulated irrigation requirement was 393.4 mm, while the experimental value was 391.0 mm, with a difference of only 0.61%. Similarly, in 2025, the model predicted 378.2 mm compared with the observed 382.2 mm, resulting in a difference of 1.05%. Although some differences were observed between individual irrigation events, the seasonal results showed consistent agreement between model predictions and field measurements. These findings indicate that AquaCrop is a promising tool for estimating seasonal irrigation requirements and supporting efficient sprinkler irrigation management under the soil and climatic conditions of the Tashkent region.

## CONCLUSION

The AquaCrop model demonstrated its effectiveness in simulating carrot growth, irrigation requirements, soil water balance, and crop productivity under sprinkler irrigation conditions. The simulation results indicated a biomass production of 42.87 t/ha, a dry yield of 31.16 t/ha, a harvest index of 72.7%, and water productivity (ET) of 0.85 kg/m³. Seasonal irrigation requirements estimated by AquaCrop ranged from 378.2 to 393.4 mm, highlighting the model's potential for optimizing irrigation scheduling and water-use efficiency. The simulation results were validated against field experiments conducted during 2023–2025 on typical sierozem soils in the Tashkent region of Uzbekistan. Experimental results showed seasonal irrigation depths of 382.2–395.8 mm, closely corresponding to the model estimates. The optimal sprinkler irrigation intensity of 0.4 mm/min achieved a maximum carrot yield of 30.2 t/ha, with water savings of 31–33% compared with furrow irrigation. Overall, the agreement between simulated and experimental irrigation requirements confirms the potential of AquaCrop as a reliable decision-support tool for sustainable sprinkler irrigation management.

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