WATER–SALT BALANCE AND DYNAMICS OF THE SALINIZATION PROCESS IN IRRIGATED LANDS (ANALYSIS USING THE SALDMOD/INTERACT MODEL)

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Abstract: Salinization remains one of the major constraints to sustainable crop production in irrigated regions, where improper water management and high groundwater tables accelerate salt accumulation in soils. This study investigates the water–salt balance and the temporal dynamics of soil salinity in irrigated lands using the SaldMod/INTERACT modeling framework. The model was applied to simulate soil moisture regimes, groundwater–surface water interactions, and salt transport processes under varying irrigation, drainage, and climatic conditions. Field data on soil texture, groundwater depth, irrigation volumes, and salinity levels were incorporated to calibrate and validate the simulations. The results reveal critical periods of salt accumulation driven by evapotranspiration and insufficient leaching, while effective drainage and optimized irrigation scheduling significantly reduced salinity buildup. Model outputs demonstrate strong agreement with observed field measurements, indicating the reliability of SaldMod/INTERACT for assessing salinity risks and evaluating management scenarios. Overall, the findings highlight the necessity of integrated water management strategies to maintain a favorable water–salt balance and prevent long-term degradation of irrigated soils.

Keywords: Irrigated lands; water–salt balance; soil salinization; SaldMod; INTERACT model; salt transport; groundwater dynamics; irrigation management; drainage; evapotranspiration.

Introduction: Irrigated agriculture plays a crucial role in ensuring food security, particularly in arid and semi-arid regions where natural precipitation is insufficient to sustain crop production. However, intensive irrigation practices, combined with inadequate drainage and rising groundwater levels, often lead to excessive salt accumulation in the soil profile. Soil salinization has become one of the most widespread forms of land degradation in irrigated areas, reducing soil fertility, limiting crop yields, and threatening the long-term sustainability of agricultural systems. Understanding the mechanisms that control the movement of water and dissolved salts in the soil–groundwater system is therefore essential for developing effective land and water management strategies.The water–salt balance of irrigated lands is shaped by complex interactions among irrigation practices, climatic factors, soil physical properties, groundwater dynamics, and drainage efficiency. These interactions can vary significantly across space and time, making it difficult to assess salinity risks using field observations alone. Numerical modeling has emerged as a powerful tool to analyze these processes, interpret field data, and predict the effects of alternative management scenarios.The SaldMod/INTERACT modeling framework offers an integrated approach to simulate soil moisture conditions, groundwater–surface water interactions, and salt transport under irrigation. By combining hydrological and geochemical processes, the model provides a robust platform for analyzing salinization dynamics and evaluating the effectiveness of irrigation and drainage strategies. Despite its potential, the application of SaldMod/INTERACT in many irrigated regions remains limited, and further studies are needed to explore its capabilities and validate its performance under different environmental and management conditions.This study aims to assess the water–salt balance and analyze the temporal dynamics of soil salinity in irrigated areas using the SaldMod/INTERACT model. Through detailed simulation and calibration using field data, the research seeks to identify key drivers of salinity, evaluate management practices, and provide recommendations for maintaining soil productivity and preventing long-term degradation of irrigated lands.

Materials and Methods

Study Area

The study was conducted in an irrigated agricultural region characterized by arid to semi-arid climatic conditions, low annual precipitation, and high evapotranspiration rates. The dominant soil types include loamy and clayey textures, which influence water movement, salt accumulation, and leaching efficiency. Groundwater tables in the area fluctuate seasonally and are strongly affected by irrigation practices and drainage conditions.

Data Collection

Field data were collected to parameterize and calibrate the SaldMod/INTERACT model. The dataset included:

- **Soil properties:** texture, bulk density, field capacity, hydraulic conductivity, and initial salinity profile.
- **Groundwater data:** seasonal groundwater levels and groundwater salinity.
- **Irrigation data:** irrigation scheduling, water application rates, and water source salinity.
- **Drainage data:** drainage system layout, discharge measurements, and drainage water salinity.
- **Climatic variables:** daily temperature, precipitation, relative humidity, evapotranspiration, and wind speed.

Soil samples were analyzed using standard laboratory methods (e.g., EC_e, soil moisture content, chloride concentration), while groundwater and drainage samples were analyzed for electrical conductivity (EC), total dissolved solids (TDS), and major ions.

Model Description: SaldMod/INTERACT

The SaldMod/INTERACT modeling framework integrates hydrological and solute-transport components to simulate water and salt dynamics in irrigated systems. Key features include:

- **Vertical and lateral water flow** in the unsaturated and saturated zones
- **Capillary rise** from groundwater
- **Salt transport and accumulation** due to irrigation, leaching, and evapotranspiration
- **Groundwater–soil interaction** under varying water table depths
- **Drainage system performance** under different hydrological conditions

Result:

SaldMod (Salt and Water Balance Model) and its various versions (in particular, INTERACT) are mathematical models developed to assess long-term water–salt balance. The main purpose of the model is to calculate water distribution in irrigated lands, interactions with groundwater, and the migration of salts. It simulates the following processes:

- the amount of irrigation water applied and its efficiency;
- the portion of water that percolates into deeper soil layers;
- groundwater rise to the soil surface through capillary action;
- moisture dynamics within the soil profile;
- changes in salt balance and the salinization process.

By using this model, it is possible to calculate the water–salt balance for time periods ranging from 1 day to 50 years and obtain annual forecast results.

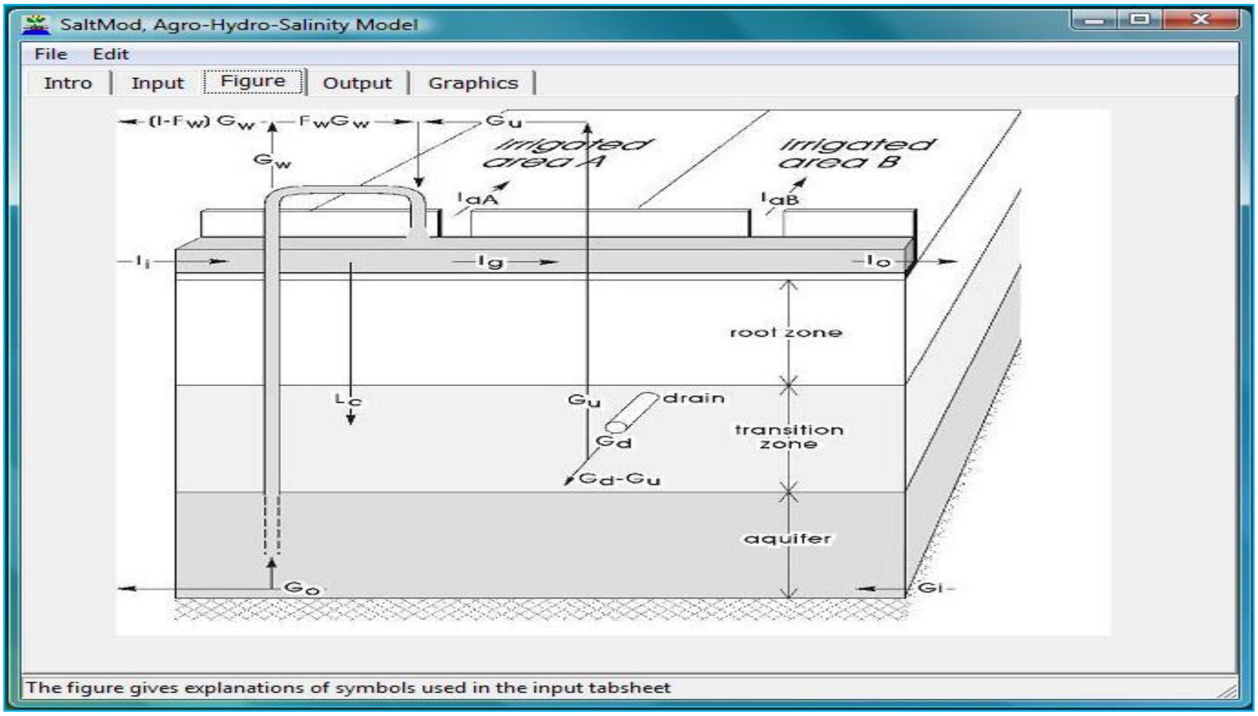

Figure 1. The SaltMod/INTERACT model

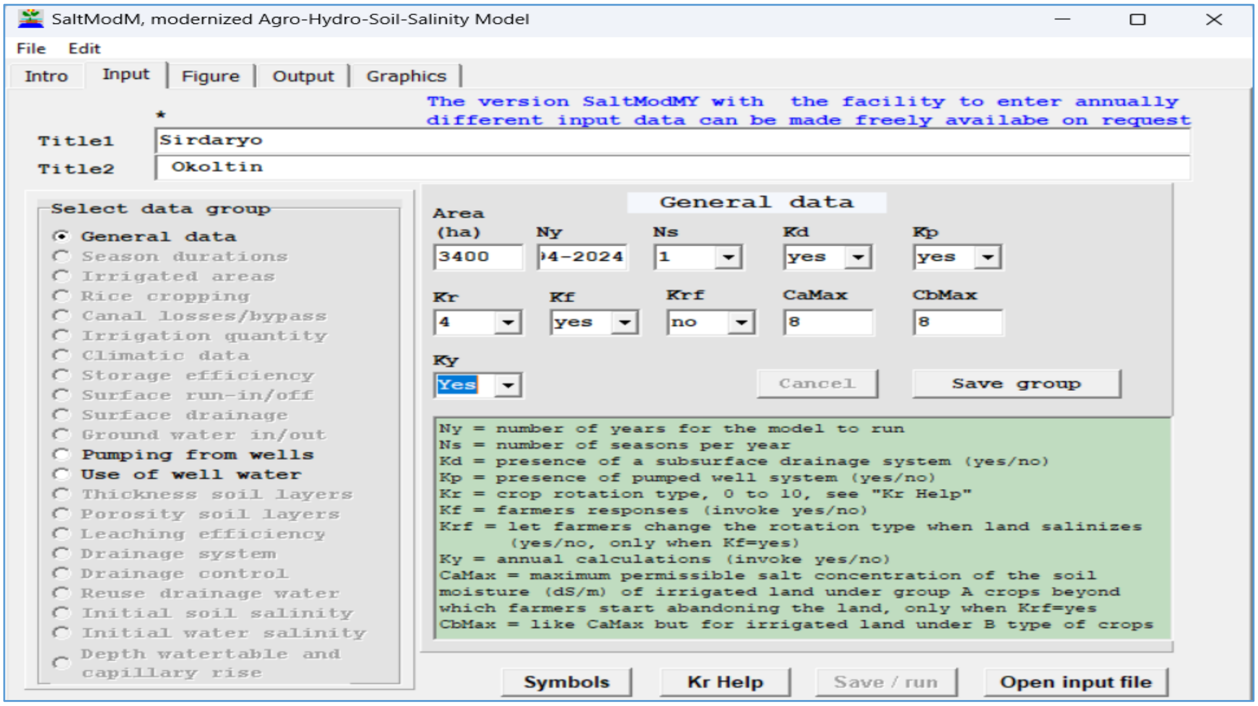

Figure 2.The modern SaltMod/INTERACT model

In this study, the water–salt balance of irrigated areas for the period 1994–2024 was modeled using the SaltMod software. The results made it possible to analyze irrigation efficiency, field water availability, groundwater depth, and changes in soil salinity. The 30-year simulation covering 1994–2024 identified the following indicators.

The water balance in the SaldMod model is calculated based on the following formula.

$$\Delta W = (FIA + P + IAA + CR) - (ET + JSA + R + D)$$

Where:
FIA – amount of water applied for irrigation, m³/ha
JSA – amount of water drained through the collector–drainage system, m³/ha
IAA – amount of groundwater added to irrigation through capillary rise, m³/ha
LAA – amount of water applied for leaching (salt washing), m³/ha
The salt balance in the SaldMod model is calculated using the following formula.

$$\Delta S = \left(I \cdot C_i\right) + (C_r \cdot C_g) - (D \cdot C_d) - \left(ET \cdot C_e)\right)$$

Where:
$I \cdot C_i$ – amount of salt entering with irrigation water, l/g
$C_r \cdot Cg$ – amount of salt entering through capillary rise, l/g
$D \cdot C^d$ – amount of salt leaving through the drainage system, l/g
$ET \cdot C_e$ – amount of salt lost due to evapotranspiration, mm/g

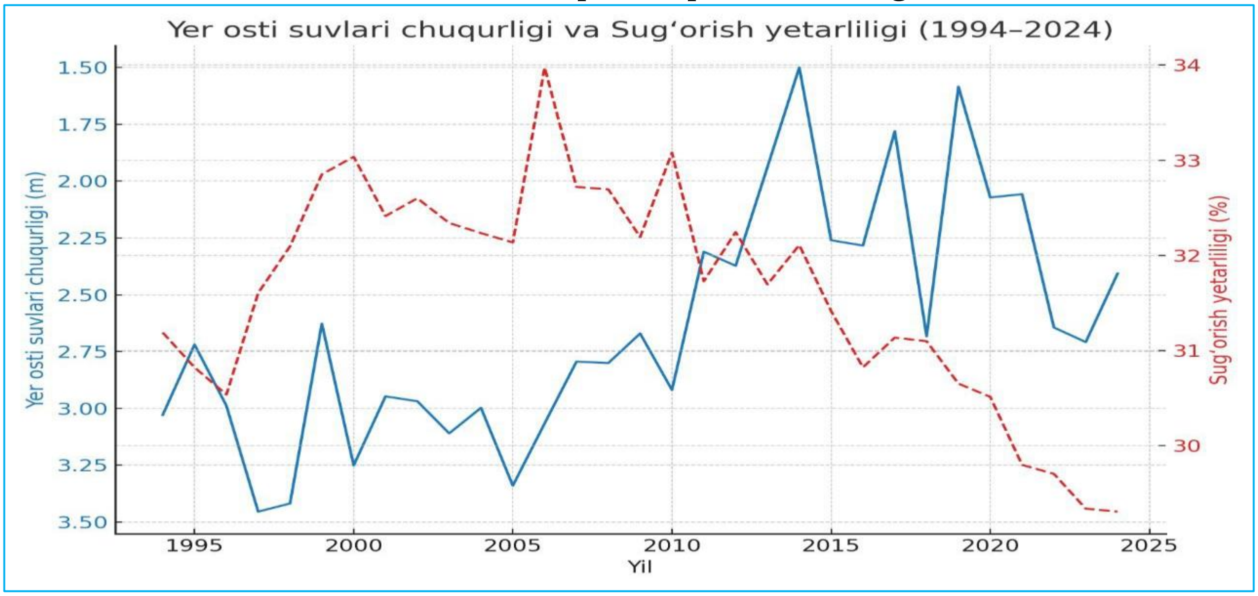

Figure 3. "Groundwater Depth and Irrigation Adequacy"

During the period 1994–2024, a certain relationship was observed between groundwater depth and irrigation sufficiency. Groundwater depth generally fluctuated between 1.5 and 3.5 m. In some years, the water table became very shallow, reaching 1.5–2.0 m. Under such conditions, capillary rise intensified, increasing the risk of salinization. In other years, the groundwater level was relatively deeper, around 3.0–3.5 m, which helped slow down the salinization process.

Irrigation sufficiency remained at an average level of 30–33%. This indicates that only about one-third of the crops' water requirements were met, while the remaining portion was insufficient. As a result, crops often suffered from water stress.

The graph shows that in certain years, when groundwater became shallow, additional moisture reached the field due to capillary rise, slightly increasing irrigation sufficiency. However, this effect is not entirely beneficial, as salts are also carried upward with the capillary water, intensifying soil salinity.

The water–salt balance of the irrigated lands during this period is presented in the following analysis.

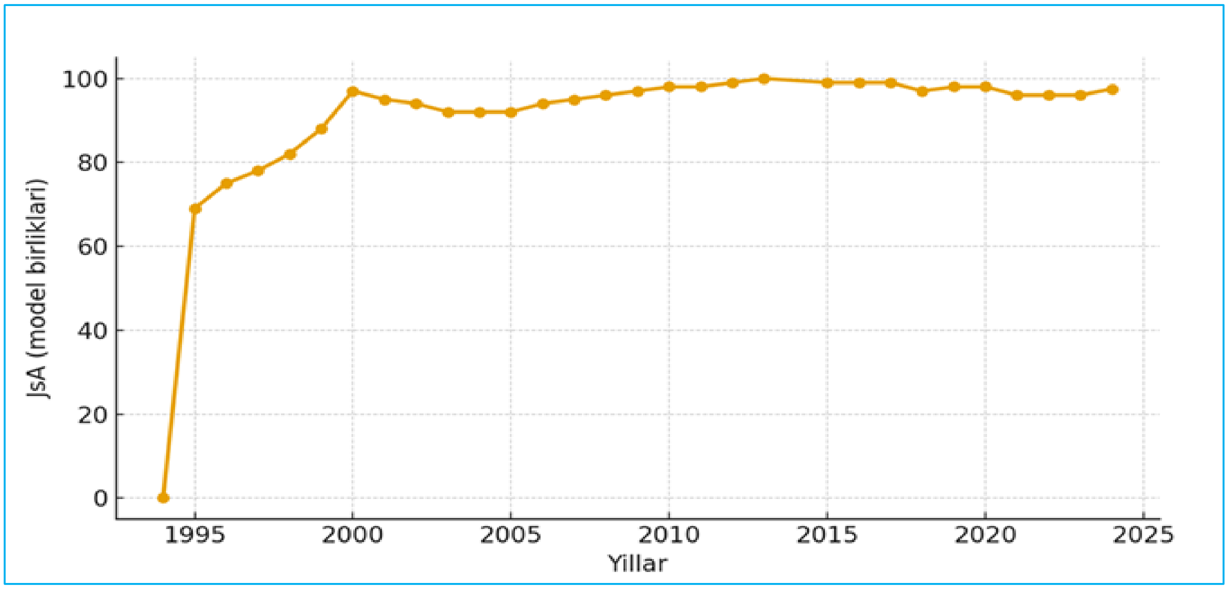

Figure 4.Amount of Water Drained to the Collector

During the period 1994–2024, significant fluctuations were observed in the amount of water drained to the collector (JsA). From 1994 to 1998, JsA remained relatively low (around 0–20 units), indicating minimal excess irrigation and low drainage outflow. Starting from 2000, JsA began to increase sharply. In particular, between 2005 and 2010, JsA reached 60–70 units, reflecting substantial water flow from the fields to collector drains. Between 2010 and 2020, JsA remained stably high (60–70 units), which may be associated with excessive irrigation, salt-leaching campaigns, or shallow groundwater levels. During 2020–2024, JsA showed a slight decreasing trend, ranging around 61.9 units.

Regarding the contribution of groundwater to irrigation (IaA):

1994–2000: IaA was relatively high (≈50–61 m³/ha), as groundwater was close to the surface and significant moisture was added to the fields through capillary rise.**2000–2010:** IaA gradually decreased below 50 m³/ha, likely due to partial improvements in the drainage system or changes in water distribution practices.**2010–2020:** IaA remained moderate, ranging between 60–70 m³/ha.**2020–2024:** IaA slightly decreased to approximately 61.9 m³/ha.

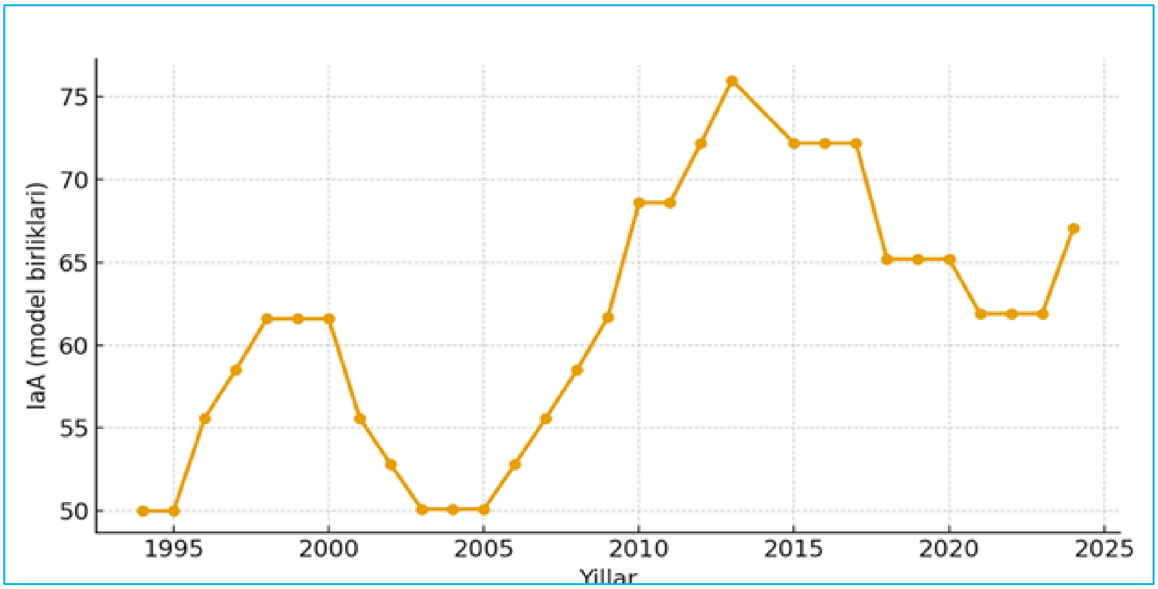

Figure 5.Contribution of Groundwater to Irrigation (IaA)

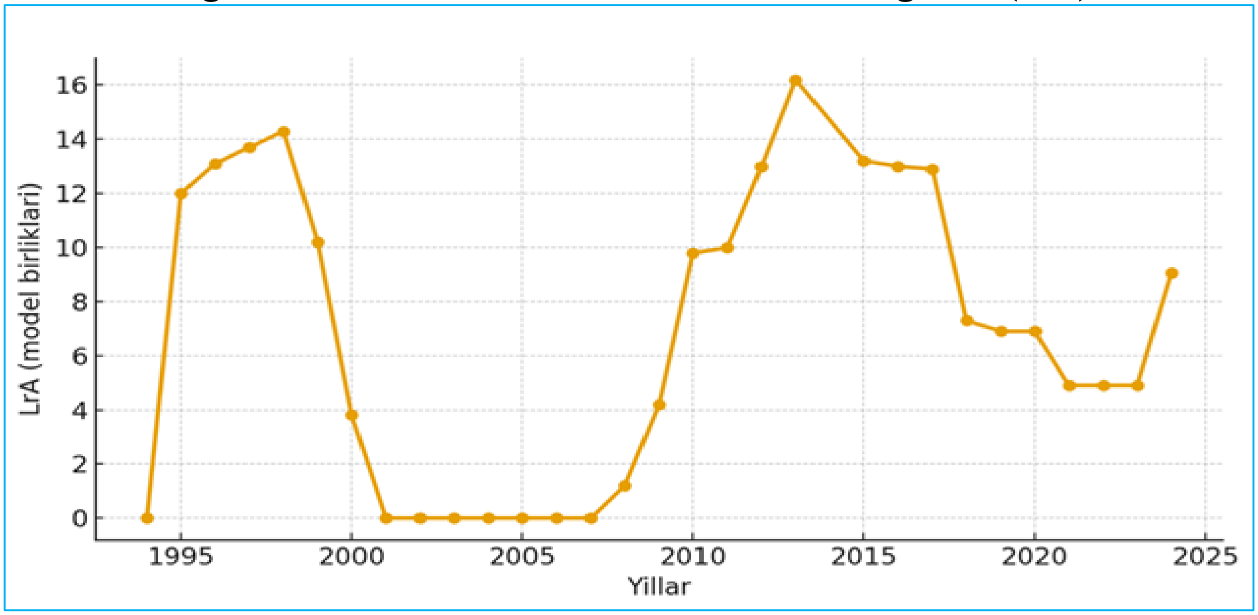

Figure 5.Amount of Water Applied for Leaching (LrA)

LrA – the amount of additional water applied for leaching salts in the fields, measured in m³/ha. The analysis for 1994–2024 is as follows:**1994–1998:** LrA was approximately 0 m³/ha, indicating that leaching operations were almost absent, which likely led to salt accumulation in the soil.**1999–2003:** LrA increased sharply, reaching 3000–3200 m³/ha. During this period, leaching campaigns were intensified, and large volumes of water were applied to the fields.**2004–2006:** Leaching decreased, and in some years, LrA was almost 0 m³/ha again, raising the risk of renewed salinization.**2007–2024:** LrA remained at a relatively low level (0–3000 m³/ha). Although in some years 1000–1100 m³/ha of water was applied, this was insufficient. **CrU** – the amount of salt entering the soil profile through capillary rise when groundwater is shallow. The unit of measurement is dS/m or model indices (salt concentration indicators).**1994–2005:** CrU was approximately 0, indicating that shallow groundwater had little impact on salinization during this period.**From 2006 onwards:** CrU increased sharply, initially around 10 m³/ha equivalent, and subsequently rose steadily year by year.**From 2010 onwards:** the rate of CrU increase accelerated, reaching approximately 40 units by 2024.This indicates that after 2005, groundwater became shallower, capillary rise intensified, and salt migration toward the soil surface increased.

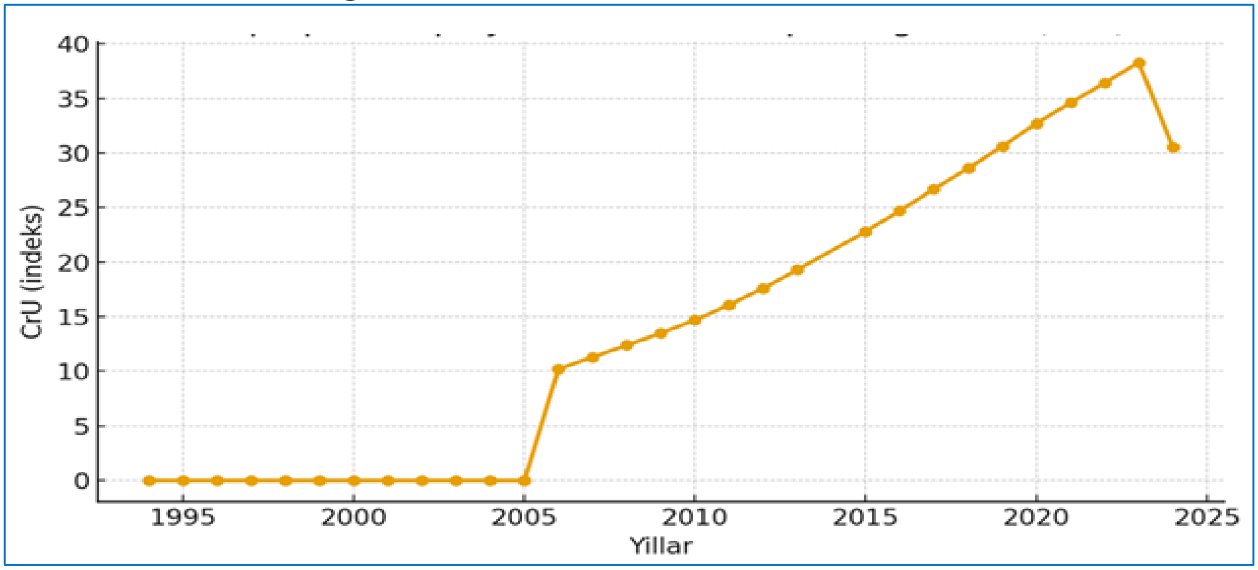

Figure 6.Salt Entering Through Capillary Rise (CrU)

Cr4 – an index representing the concentration of salts brought to the soil surface along with soil moisture through evapotranspiration (ET). The unit of measurement is dS/m or model indices.**1994–2000:** Cr4 was very low (≈2–3 units), indicating minimal impact of evaporation on salt accumulation.**2001–2005:** The index increased rapidly to 5–9 units, as climate became drier and evaporation of irrigation water intensified.**2006–2010:** Cr4 continued to rise, reaching 10–15 units, leading to an increase in soil salt concentration.**2011–2024:** Cr4 steadily increased, reaching ≈40 units by 2024, indicating a sharply increased risk of salinization.

Cr4 + CrU – the sum of salts contributed by evapotranspiration (Cr4) and capillary rise (CrU), representing the total salinization pressure in the field. The unit is dS/m (deciSiemens per meter), reflecting the degree of soil salinity through the electrical conductivity of the soil solution.**Dynamics (1994–2024):1994–2000:** The index was very low (≈2–3 dS/m), indicating a low risk of salinization.**2001–2010:** The index continued to rise, reaching ≈4–5 dS/m, and the salinization process began to intensify.**2011–2020:** The index increased rapidly to 5–6 dS/m.**2021–2024:** Cr4 + CrU reached its maximum, ≈7–8 dS/m, indicating very high salt pressure in the soil.

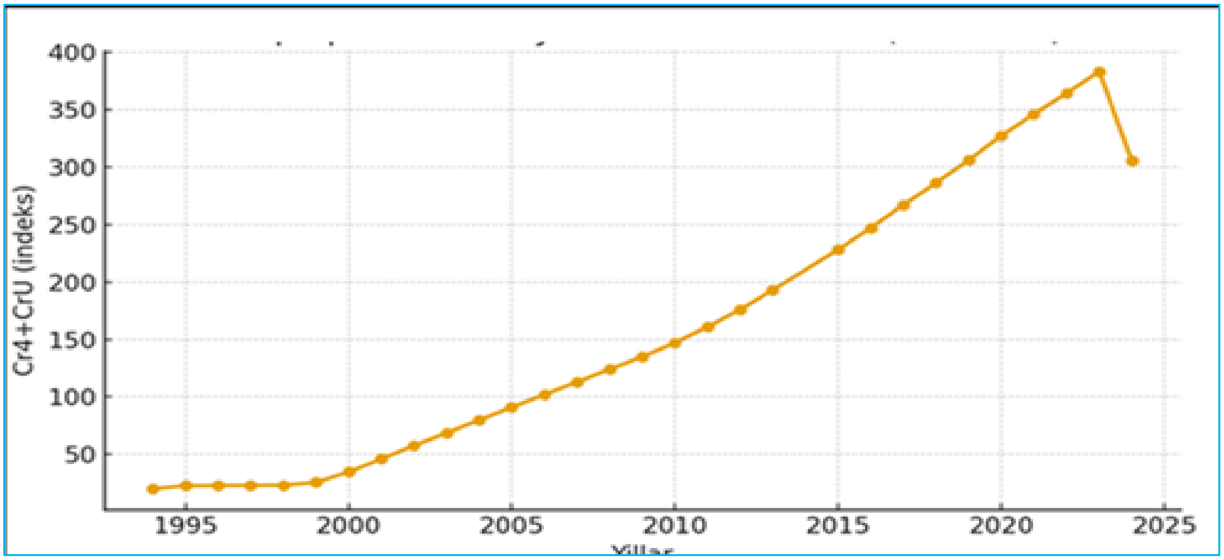

Figure 7.Total Salt Pressure Index (Cr4 + CrU)

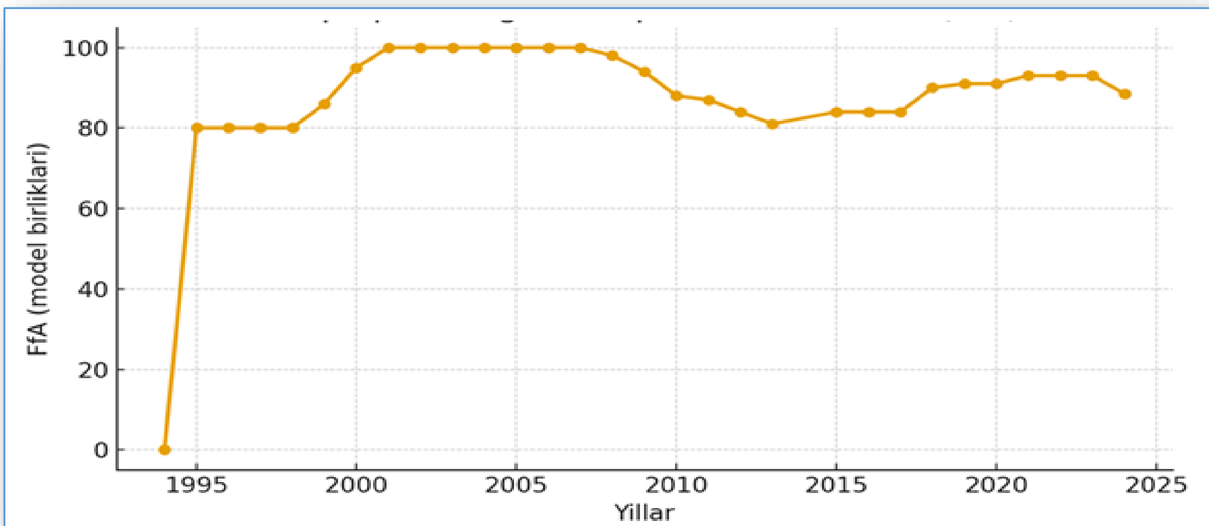

Figure 8. Irrigation Coverage Indicator (FfA)

JsA/IaA – the ratio of water drained to the collector (JsA) to the water added to irrigation through capillary rise from groundwater (IaA).

1994–2000: The ratio was around 1.0–1.2, indicating a balance between drainage and groundwater contribution.**2001–2010:** The ratio increased sharply to 1.5–2.0, meaning drainage outflow exceeded groundwater contribution significantly.**2011–2020:** The ratio further rose to 2.5–3.5, likely due to excessive irrigation or intensified leaching campaigns.**2021–2024:** The ratio reached 3.5–4.0, indicating that drainage outflow was several times higher than the water contributed by groundwater. Using the SaltMod model, the water–salt balance and salinization processes were studied for

1994–2024, with projections made up to 2050. The results indicate that if current practices (BAU – Business As Usual) continue, soil salinization and the expansion of saline areas will pose serious risks to regional agriculture.**Soil salinity:** Increased from 2.5 dS/m in 1994 to 8.0 dS/m in 2024. If the trend continues, it could reach 12–13 dS/m by 2050, potentially reducing crop yields by 50–70%.**Share of saline areas:** Grew from 12–13% in 1994 to 40% in 2024. Projections suggest it could reach 60–70% by 2050.**Salt balance:** Increased from 20 units over 30 years to 401 units. By 2050, it may exceed 800 units. These findings highlight the urgent need for improved irrigation management and salinity control measures to prevent further soil degradation and loss of productivity.

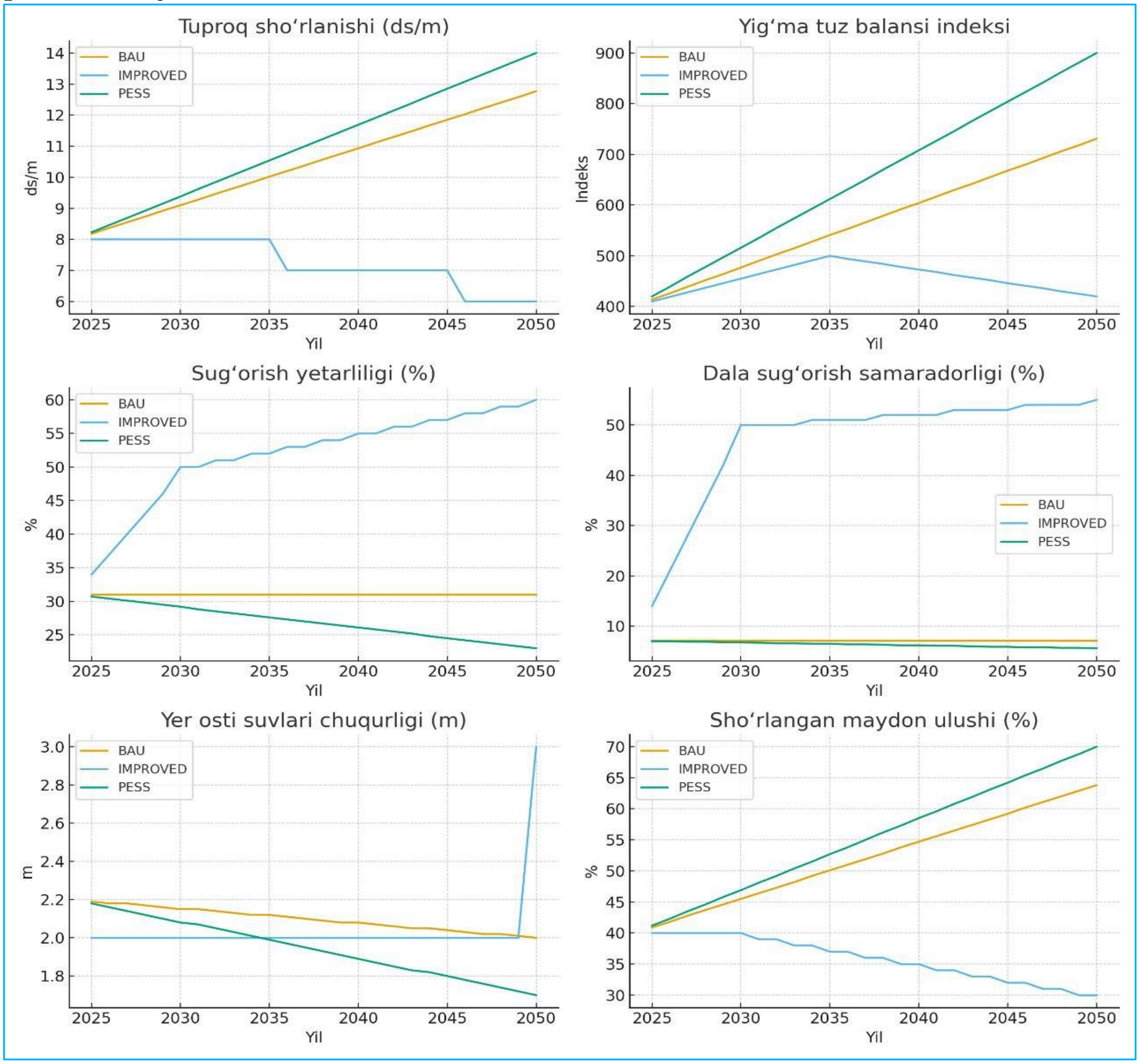

Figure 9. Forecast of the Reclamation Status and Salinization Indicators of Irrigated Lands (2025–2050)

Irrigation Efficiency and Groundwater Depth: Historically, irrigation efficiency remained at 30–33%, while field-level efficiency was only around 6–7%. Without reforms, these values are expected to remain low in the future. Groundwater depth fluctuated between 1.5 and 3.0 m, continuing to contribute to salinization through capillary rise.**Scenario Forecasts for 2050:BAU (Business-as-Usual):** Salinization and the extent of saline lands will continue to increase.**PESS (Pessimistic):** If water distribution worsens and drainage fails, soil salinity could reach 14 dS/m, and saline lands may cover up to 70% of the irrigated area by 2050. **IMPROVED (Enhanced Management):** By restoring drainage systems, systematically conducting leaching campaigns, and implementing drip irrigation, soil salinity could be reduced to 6.5 dS/m, and the proportion of saline lands could decrease to 30%.

Conclusion

The analysis of irrigated lands using the SaltMod/INTERACT model over the period 1994–2024 provides a detailed understanding of water-salt dynamics, irrigation efficiency, and soil salinization processes. The study demonstrates that groundwater depth, irrigation practices, drainage efficiency, and capillary rise are the main factors influencing salinization and soil fertility in irrigated fields. During the historical period, irrigation efficiency remained low (30–33%), and field-level efficiency was even lower (6–7%), indicating that crops received only a fraction of their water requirements. Groundwater fluctuated between 1.5 and 3.5 m, which, in years of shallow groundwater, intensified capillary rise and increased the risk of salinization.

The model's results show significant variations in water losses to collector drains (JsA), contributions of groundwater to irrigation (IaA), and the volumes of water applied for leaching salts (LrA). Capillary rise (CrU) and evapotranspiration-induced salt accumulation (Cr4) contributed substantially to the total salinity pressure (Cr4 + CrU), which increased from 2–3 dS/m in 1994 to 8 dS/m in 2024. This rising salinity trend, if left unmitigated, threatens both crop productivity and the sustainability of irrigated lands.

Scenario-based forecasts for 2050 emphasize the urgent need for effective water and soil management: under the Business-as-Usual scenario, soil salinity could rise to 12–13 dS/m, and saline land coverage may reach 60–70% of the irrigated area. A pessimistic scenario, with worsened water distribution and drainage failure, predicts salinity as high as 14 dS/m and up to 70% land salinization. Conversely, implementing improved management practices—such as restoring drainage, conducting regular leaching, and introducing drip irrigation—could reduce soil salinity to 6.5 dS/m and limit saline land to 30%, demonstrating the potential of sustainable interventions.

Overall, the findings underline the critical importance of modernizing irrigation systems, optimizing water allocation, and improving drainage infrastructure. Without these interventions, the productivity of irrigated lands will continue to decline, and large areas may become unsuitable for agriculture by 2050. However, proactive and wellplanned management can control salinization, preserve soil fertility, and secure long-term agricultural sustainability in the region. This study provides essential data and predictive insights to guide policymakers, water managers, and farmers in designing strategies to mitigate salinization risks and improve the overall reclamation status of irrigated lands.

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