EGU25-2901
EGU General Assembly 2025

Simulation of Salt and Moisture Dynamics in Agricultural Fields Using HYDRUS: Insights from a Sensor-Based Calibration

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The sustainable management of soil moisture and salinity is a critical challenge for semi-arid regions like the Mahabad Plain in northwestern Iran. This study applies the HYDRUS-1D model, calibrated using sensor-based data, to simulate water and salt dynamics in a 4 HA sugar beet field. The Mahabad Plain, covering 249 km², experiences annual precipitation of 402 mm and evaporation rates of 1,560 mm. Despite its fertile soils, the region faces persistent challenges such as waterlogging, salinity, and unsustainable irrigation practices, exacerbated by agricultural expansion and climate variability. Sensor data were collected every other day from four soil depths (0–25 cm, 25–50 cm, 50–75 cm, and 75–100 cm) in a single sugar beet field between late June 2024 and late July 2024. These measurements were used to calibrate the HYDRUS-1D model, optimizing parameters such as residual and saturated water content, hydraulic conductivity, and dispersion coefficients. Calibration metrics, including RMSE and Nash-Sutcliffe efficiency, confirmed the reliability of the simulations in replicating observed conditions. The results revealed critical inefficiencies in irrigation practices. Over-irrigation was observed, particularly in deeper soil layers, where moisture levels exceeded the optimal range of 18–25% for sugar beet cultivation. Surface layers (0–25 cm) also exhibited frequent waterlogging after irrigation events, with moisture levels surpassing 25%. Electrical conductivity (EC) levels, however, remained within the safe range of 0.6–1.3 dS/m, indicating effective salt leaching and no immediate risk to crop health. Simulations demonstrated that increasing irrigation intervals by 1–2 days could reduce water consumption by 15–30%, prevent excessive soil saturation, and promote healthier root growth. This approach ensures that soil moisture remains within the optimal range while maintaining crop yield and quality. This study is the first of its kind for the Mahabad Plain, offering a novel application of sensor-calibrated HYDRUS-1D modeling. It provides actionable recommendations for addressing water scarcity and improving agricultural sustainability. By integrating field observations with advanced modeling, the research bridges gaps in water resource management and offers replicable solutions for semi-arid agricultural systems worldwide. The findings are especially relevant as the region faces increasing agricultural demands and environmental challenges, including efforts to restore Lake Urmia. By improving irrigation efficiency and reducing agricultural water consumption, more water can be directed toward Lake Urmia, contributing to its restoration and the broader ecological balance of the region.