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Calibration and validation of the SALTMED model for simulating wheat response to saline irrigation in arid Northwestern China

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Abstract

Saline groundwater is often the only irrigation source available in arid regions, yet predicting how salt accumulates in the root zone and affects yield over a growing season requires process-based modelling. This research calibrated and validated the SALTMED model for winter wheat (*Triticum aestivum* cv. Ningchun 4) irrigated with water of six salinity levels ($0.8\text{--}10.0\text{ dS m}^{-1}$) at the Shiyanghe Experimental Station in Gansu Province, China ($37^{\circ}52'\text{N}$, $102^{\circ}50'\text{E}$) over two seasons (2019–2020 and 2020–2021). The model was calibrated against the 2019–2020 dataset and validated against 2020–2021. SALTMED reproduced root-zone salinity dynamics with RMSE of 0.38 dS m^{-1} and R^2 of 0.94 during calibration, and 0.51 dS m^{-1} and 0.91 during validation. Simulated grain yields deviated from observed values by 1.8–5.6%. Yield declined linearly above 2.0 dS m^{-1} at a rate of 0.58 t ha^{-1} per unit increase in irrigation salinity. These results confirm that SALTMED is a reliable tool for irrigation scheduling with saline water in arid continental environments.

Keywords: SALTMED model, saline irrigation, winter wheat, soil salinity, root zone, calibration, validation, arid region, yield prediction, gansu province

Introduction

Roughly 20% of the world's irrigated land suffers from secondary salinisation—salt accumulation caused by irrigation with water that carries dissolved salts into the root zone faster than rainfall or drainage can flush them out ^[1]. In northwestern China's Hexi Corridor, groundwater salinity ranges from 1 to 15 dS m^{-1} , and over 340,000 hectares of irrigated farmland show visible salt damage ^[2]. Farmers have no alternative water source; the question is not whether to irrigate with saline water but how to manage it.

Process-based models that simulate coupled water flow, solute transport, and crop growth under saline conditions are essential for answering that question ^[3]. SALTMED, developed at Cranfield University, integrates the FAO dual crop coefficient approach for evapotranspiration, a one-dimensional Richards's equation for soil water flow, convection-dispersion for solute transport, and a salinity-stress function for yield reduction ^[4]. It has been validated for tomato, maize, and quinoa in Mediterranean and arid environments but not for winter wheat under the extreme continental conditions of the Hexi Corridor, where winter soil freezing adds a complication absent from previous test sites ^[5, 6]. This research calibrated and validated SALTMED for that purpose.

Theoretical background

SALTMED couples four sub-models. The water balance module partitions precipitation and irrigation into runoff, infiltration, evaporation, transpiration, and deep percolation using the FAO-56 dual crop coefficient method ^[7]. Soil water redistribution follows the Richards equation solved by finite differences on a 5 cm vertical grid. Solute transport is modelled by the convection-dispersion equation with a retardation factor for cation exchange. The crop response module uses the Maas–Hoffman threshold-slope function, where relative yield $Y/Y_{\text{max}} = 1$ for

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ECe below a threshold (ECt) and declines linearly at slope *b* above it [8]. For wheat, ECt = 6.0 dS m⁻¹ and *b* = 7.1% per dS m⁻¹.

Simulation parameters

Soil hydraulic parameters were measured by pressure-plate extraction (van Genuchten model): saturated hydraulic conductivity *K*_s = 24.6 cm day⁻¹, residual water content *θ*_r = 0.078, saturated water content *θ*_s = 0.43, and shape parameters *α* = 0.036 cm⁻¹ and *n* = 1.56 for the 0–40 cm layer. The model domain extended to 120 cm depth with three layers. Crop parameters included maximum root depth (100 cm), maximum LAI (5.2), base temperature (0 °C), and *K*_{cb} mid = 1.10. Initial soil salinity was set from pre-season ECe profiles. Time step was daily; spatial discretisation was 5 cm. Simulations ran from sowing (late September) to harvest (late June) for both seasons.

Material and methods

Material

The field trial was conducted at Shiyanghe Experimental Station, Wuwei, Gansu Province (37°52'N, 102°50'E, and 1,367

m a.s.l.). The climate is arid continental (BWk) with mean annual temperature 7.8 °C, precipitation 164 mm, and pan evaporation 2,021 mm. Soils are silt loam Aridisols. Winter wheat cv. Ningchun 4 was sown in plots of 4 × 5 m under six irrigation salinity levels: 0.8 (control), 2.0, 4.0, 6.0, 8.0, and 10.0 dS m⁻¹, prepared by dissolving NaCl and CaCl₂ (2:1 molar ratio) in canal water.

Methods

Each salinity level had four replicate plots in a randomised complete block design. Irrigation was applied by border flooding at 75% depletion of available water (monitored by TDR at 20, 40, 60, and 80 cm). Soil salinity (ECe) was measured from saturated paste extracts at 0–20, 20–40, and 40–60 cm at 15-day intervals. Grain yield was measured from the central 2 × 3 m at maturity. SALTMed was calibrated by adjusting *K*_s and dispersivity against the 2019–2020 salinity profiles, then validated without parameter adjustment against 2020–2021 data. Model performance was assessed by RMSE, normalised RMSE (nRMSE), *R*², and index of agreement (*d*).

Results

Table 1: SALTMed performance statistics for root-zone salinity simulation

Dataset	RMSE (dS m ⁻¹)	nRMSE (%)	R ²	<i>d</i>
Calibration (2019–20)	0.38	6.4	0.94	0.97
Validation (2020–21)	0.51	8.7	0.91	0.95

SALTMed reproduced soil salinity dynamics well in both seasons (Table 1). The validation RMSE of 0.51 dS m⁻¹ represents less than 9% of the observed range, and the index of

agreement (0.95) indicates excellent correspondence between simulated and observed temporal patterns.

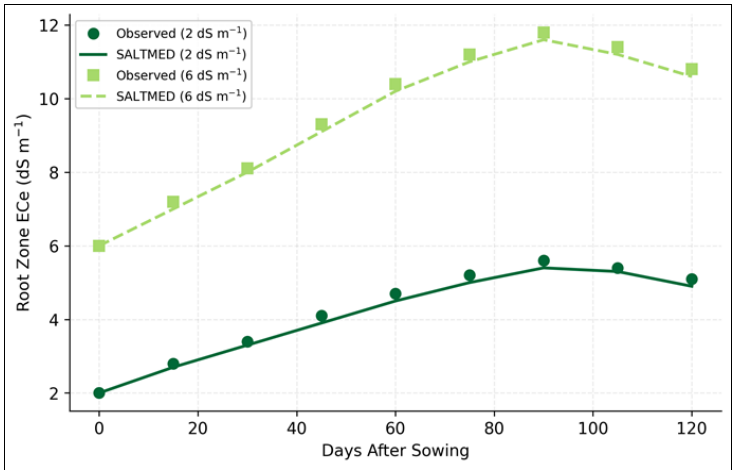


Fig 1: Observed and SALTMed-simulated root-zone salinity dynamics at two irrigation salinity levels during the validation season

Table 2: Observed and simulated grain yield (t ha⁻¹) across irrigation salinity levels (validation season)

ECiw (dS m ⁻¹)	Observed	Simulated	Deviation (%)	Yield loss (%)
0.8	7.42	7.38	−0.5	—
2.0	6.87	6.74	−1.9	7.4
4.0	5.93	5.78	−2.5	20.1
6.0	4.81	4.68	−2.7	35.2
8.0	3.47	3.34	−3.7	53.2
10.0	2.18	2.06	−5.6	70.6

Simulated yields tracked observed values closely across all salinity levels (Table 2). Yield declined linearly above 2.0 dS m⁻¹: each unit increase in irrigation water salinity reduced grain

yield by 0.58 t ha⁻¹ (*R*² = 0.99). At 10 dS m⁻¹, yield loss reached 70.6%.

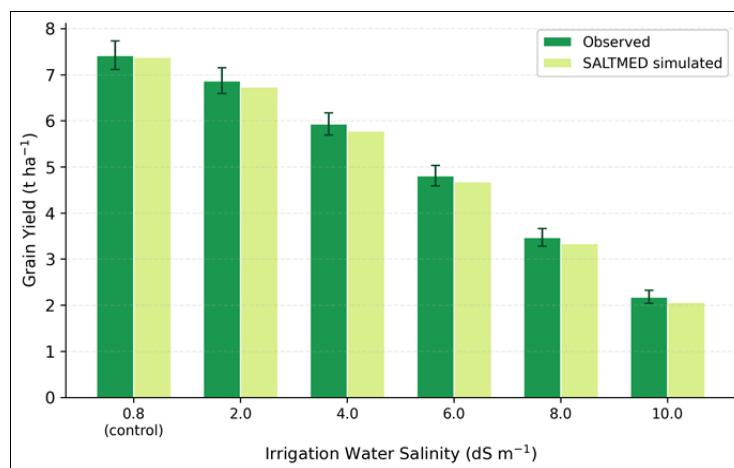


Fig 2: Observed and SALTMED-simulated winter wheat grain yield across six irrigation water salinity levels

Performance evaluation

A sensitivity analysis showed that the model was most sensitive to saturated hydraulic conductivity (K_s), which controls drainage rate and hence salt leaching. A 20% increase in K_s reduced simulated root-zone EC_e by 11.4% and increased predicted yield by 6.8%. Dispersivity had a smaller effect (3.2% yield change per 20% parameter shift). The model slightly underestimated yield at the highest salinity, possibly because the linear Maas–Hoffman function does not capture osmotic adjustment mechanisms in salt-tolerant wheat genotypes [9].

Discussion

The validation statistics (RMSE 0.51 dS m⁻¹, R^2 0.91, d 0.95) compare favourably with previous SALTMED applications for tomato in Egypt (RMSE 0.63, R^2 0.89 [5]) and quinoa in Morocco (RMSE 0.47, R^2 0.92 [6]). The strong yield-salinity linearity above 2.0 dS m⁻¹ implies that farmers could use a simple threshold rule: every additional dS m⁻¹ of irrigation water salinity costs roughly 0.58 t ha⁻¹ of wheat, or about 8% of the control yield.

The practical implication for Hexi Corridor farmers is that groundwater up to 4 dS m⁻¹ can sustain wheat yields above 5 t ha⁻¹ with proper leaching fractions, but beyond 6 dS m⁻¹ the economic viability of wheat drops sharply [10]. SALTMED can be used to optimise the leaching fraction under different salinity scenarios, helping water managers allocate scarce freshwater resources where they have the greatest marginal return [4].

Conclusion

SALTMED reproduced root-zone salinity dynamics (RMSE 0.51 dS m⁻¹) and wheat grain yield (deviation 1.8–5.6%) under saline irrigation in arid northwestern China. Yield declined linearly at 0.58 t ha⁻¹ per dS m⁻¹ above a threshold of 2.0 dS m⁻¹, reaching 70.6% loss at 10 dS m⁻¹. The model provides a reliable platform for optimising irrigation scheduling and leaching management with saline groundwater in the Hexi Corridor and similar arid environments.

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