Soil Moisture Modeling with Minimal Data for Operational Ag Decision Support

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❑INTRODUCTION

- Rootzone soil moisture (θ_{rz}) is the crop's "water bank" — it controls plant growth, irrigation needs, and drought response but direct measurements are costly and sparse, making it hard to monitor soil moisture across farms and depths
- To overcome these challenges, we use a simple soil water balance (SWB) approach that tracks how water enters, moves through, and leaves the soil profile
- The model uses easily available weather information like rainfall, humidity, net radiation and daily temperature swings — to estimate key processes like soil moisture (θ), drainage (D), evapotranspiration (ET)
- The Diurnal Amplitude of Near-surface Temperatures (DANTE) approach estimates fractional ET dynamics at the field scale

OBJECTIVE

To test whether weather information and daily temperature variations can be used in a SWB model framework to accurately estimate soil moisture for irrigation and drought decision-making.

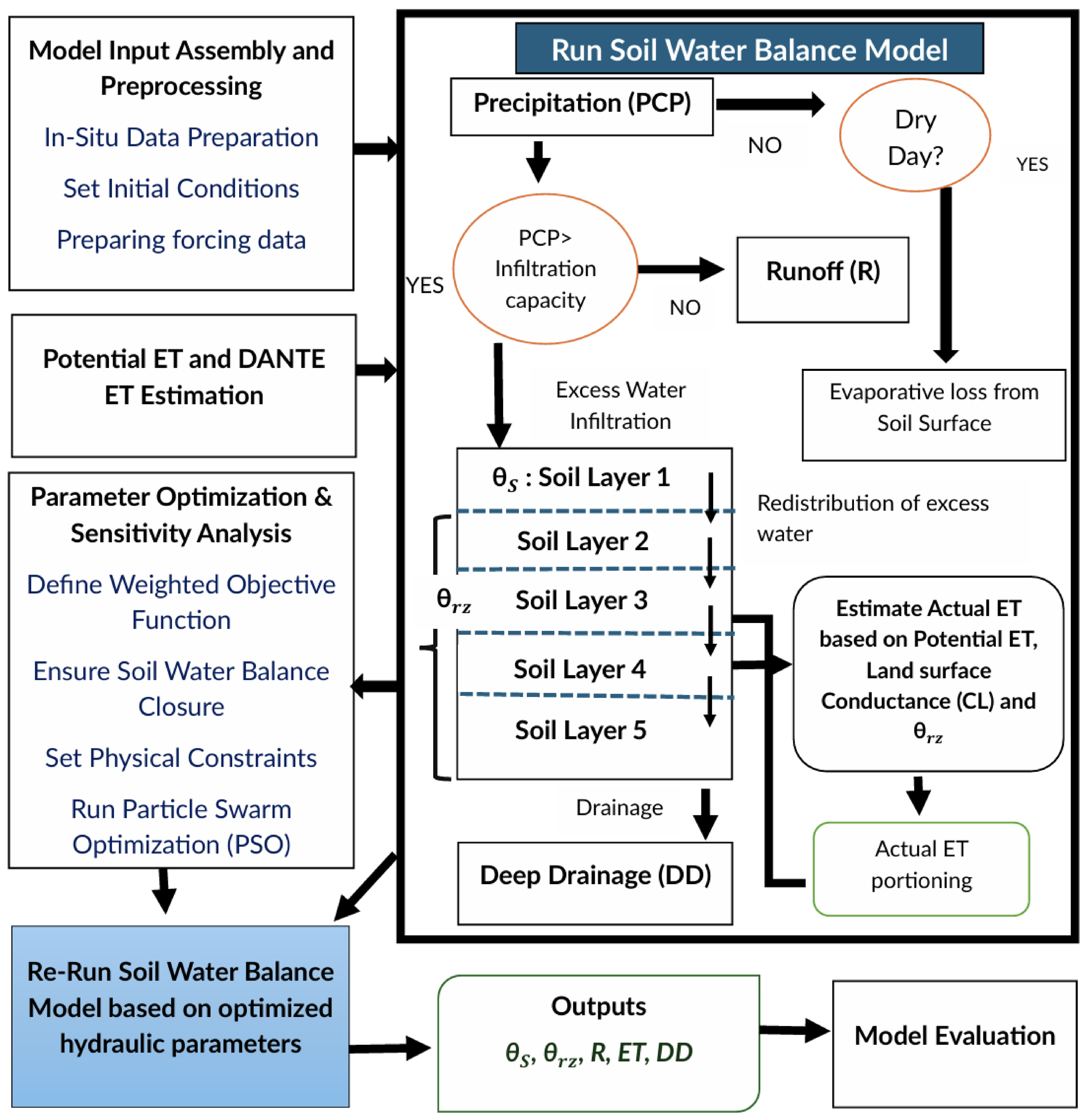
❑DATA SOURCES

- U.S. Climate Reference Network (USCRN)

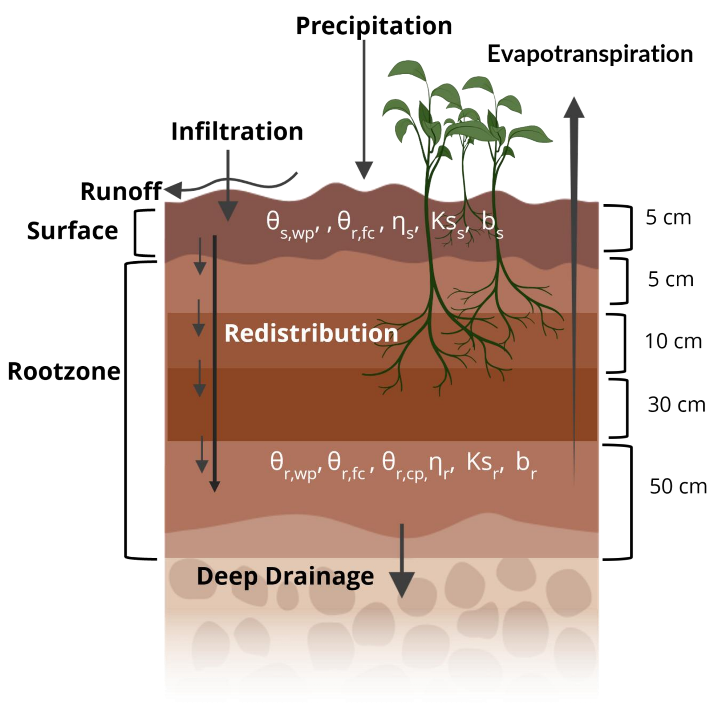
❑METHODOLOGY

- Implemented a multi-layer SWB model simulating , runoff (R), soil moisture, depth-partitioned ET and deep drainage (DD) with mass-conservative updates
- Optimized model parameters using Particle Swarm Optimization (PSO) to minimize a weighted Mean Absolute Error (MAE) of surface soil moisture (θ_s) and ET, with a water-balance closure term and physical/climate-adaptive constraints
- Used USCRN in-situ soil moisture and meteorological data (2015–May 2025), split into 70% training and 30% validation or testing (against observed θ_s, weighted θ_{rz} from USCRN)

❑WORKFLOW OF THE SWB MODEL



SCHEMATIC OF SOIL MOISTURE (θ) DYNAMICS

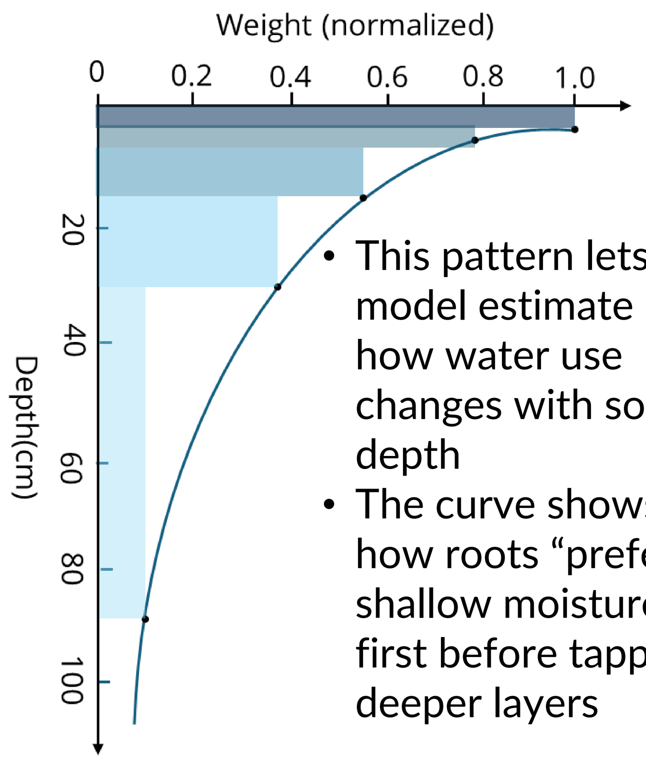


Hydraulic Parameter Set

- $\theta_{s,wp}$= Surface wilting point
- $\theta_{s,fc}$ = Surface field capacity
- η_s= Surface porosity
- Ks_s= Surface hydraulic conductivity
- b_s= Surface drainage exponent
- dstorm = Rainfall duration
- mr = Coupling strength
- $\theta_{r,wp}$= Rootzone wilting point
- $\theta_{r,fc}$ = Rootzone field capacity
- $\theta_{r,cp}$= Rootzone critical point
- η_s= Rootzone porosity
- Ks_r= Rootzone hydraulic conductivity
- b_r= Rootzone drainage exponent
- q = Depth-weighting exponent

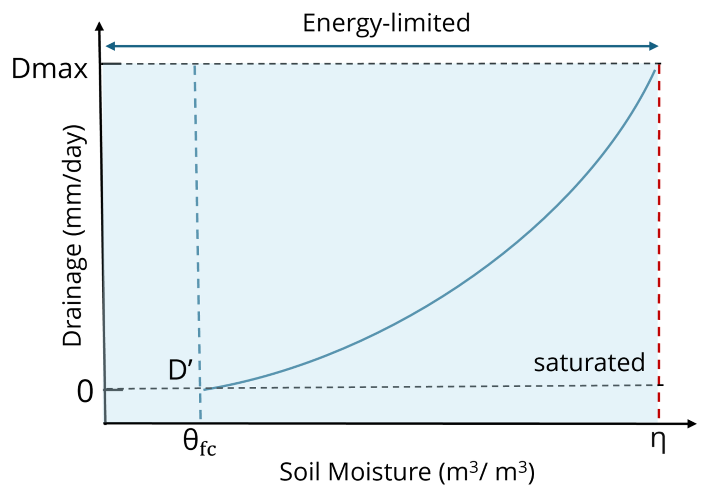
❑HYDROLOGIC RESPONSE FUNCTIONS FOR SOIL–PLANT–ATMOSPHERE COUPLING

Preferential Root-Water Extraction



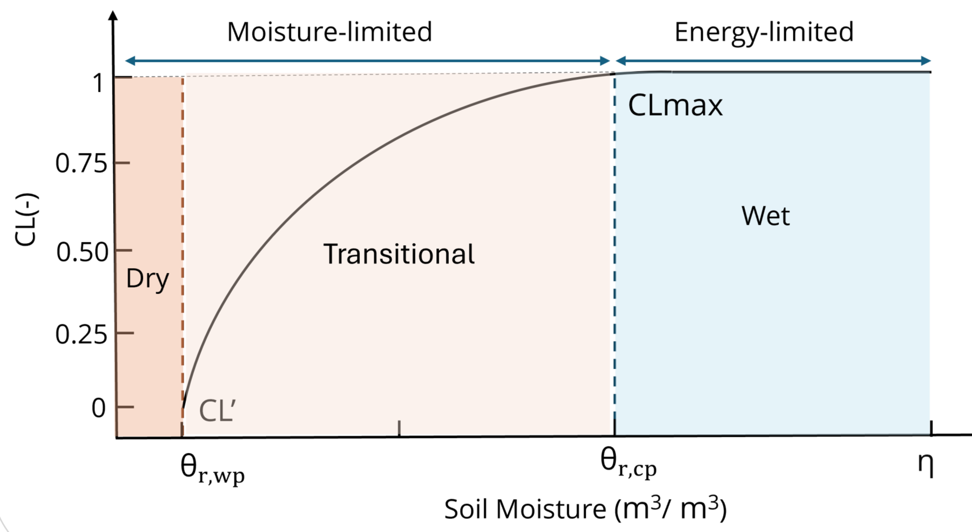
- This pattern lets the model estimate how water use changes with soil depth
- The curve shows how roots "prefer" shallow moisture first before tapping deeper layers
- Captures realistic crop behavior during drying conditions.

Drainage v/s Soil Moisture



- Gravity-driven D begins at saturation (η)
- D decreases non-linearly θ drops toward field capacity (θ_{fc}), as long as θ> θ_{fc}

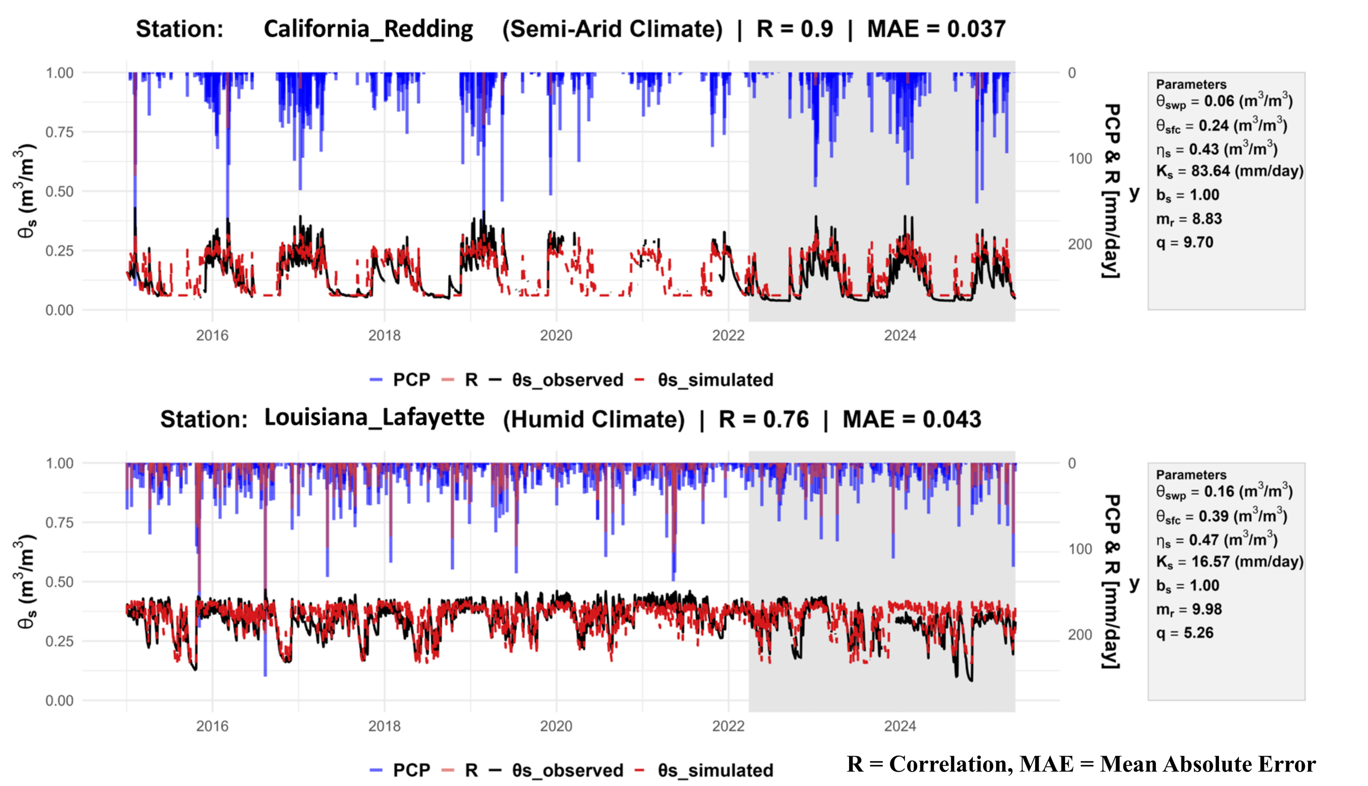
Landscape Conductance v/s Soil Moisture



- CL[t]: landscape conductance governed by θ_{RZ} and ET dynamics
- Increases nonlinearly from moisture- to energy-limited moisture regimes

❑RESULTS

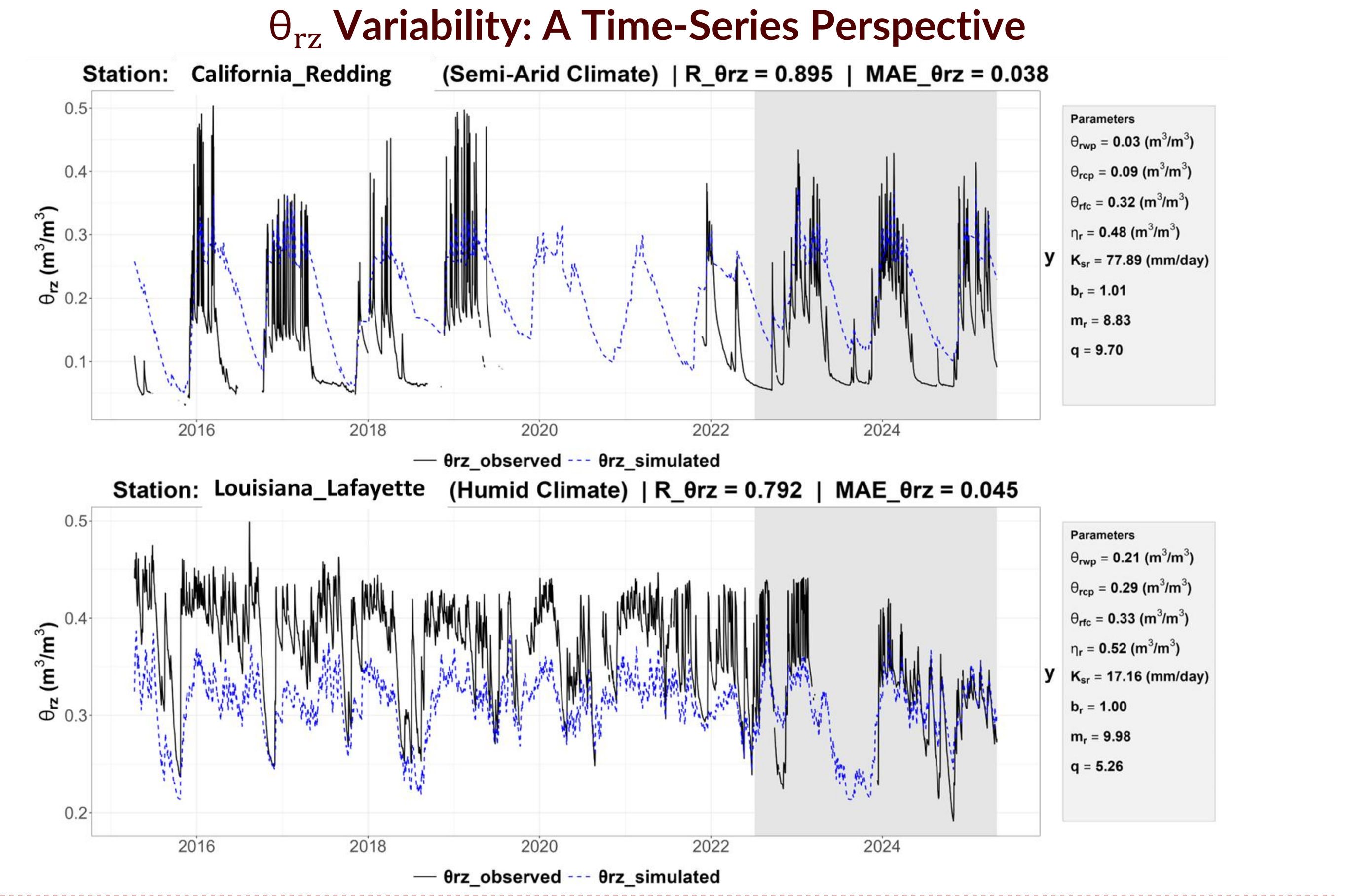
θ_s Variability and Hydrological Forcing: A Time-Series Perspective



The grey-shaded period represents validation data, while the white area denotes training, and statistical metrics are computed from the validation period.

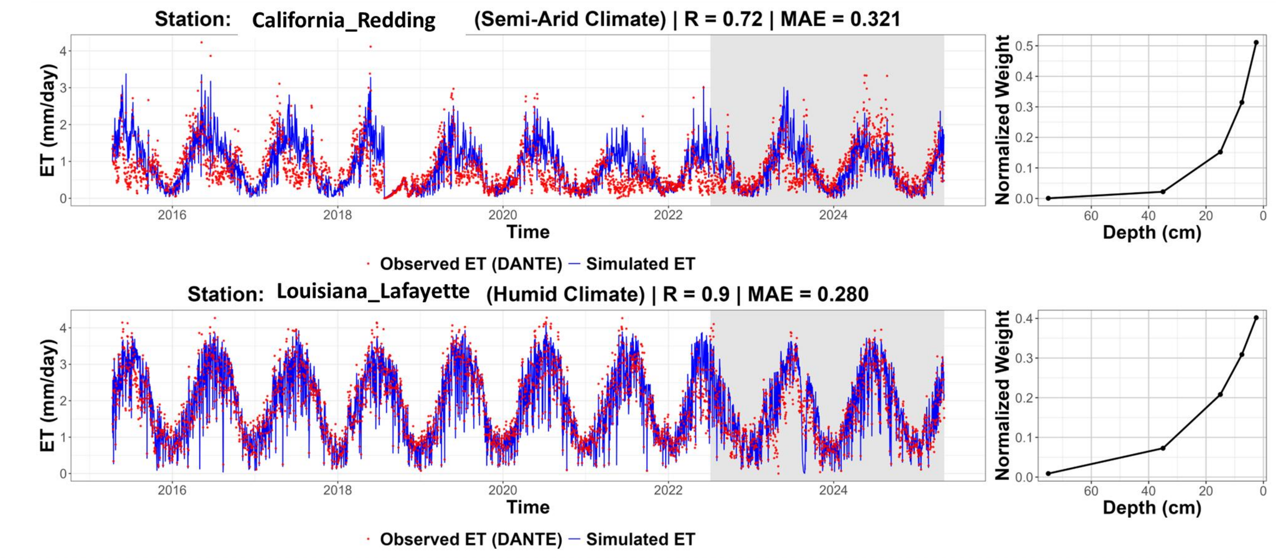
The model reasonably captures seasonal θ_s dynamics across contrasting climates with strong correlations (R ≈ 0.83), demonstrating its robustness and adaptability to diverse hydrologic regimes.

θ_{rz} Variability: A Time-Series Perspective



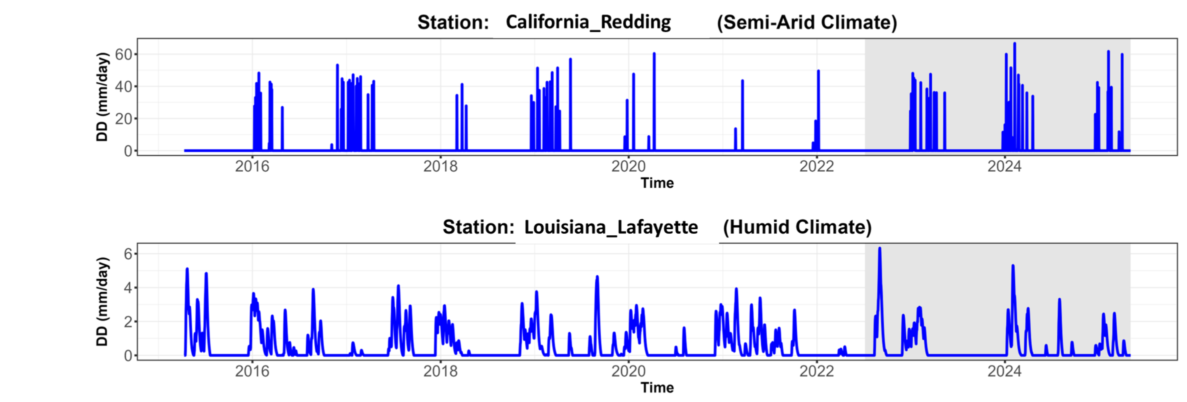
Time-series plots show close alignment between simulated and observed θ_{rz} , across different hydroclimatic regimes , indicating consistent temporal variability captured across multiple soil depths

ET Dynamics Across Climate Zones



Diurnal temperature dynamics capture seasonal ET variations. The accompanying depth-weight curve show the relative influence of soil layers on the temperature signal driving ET dynamics

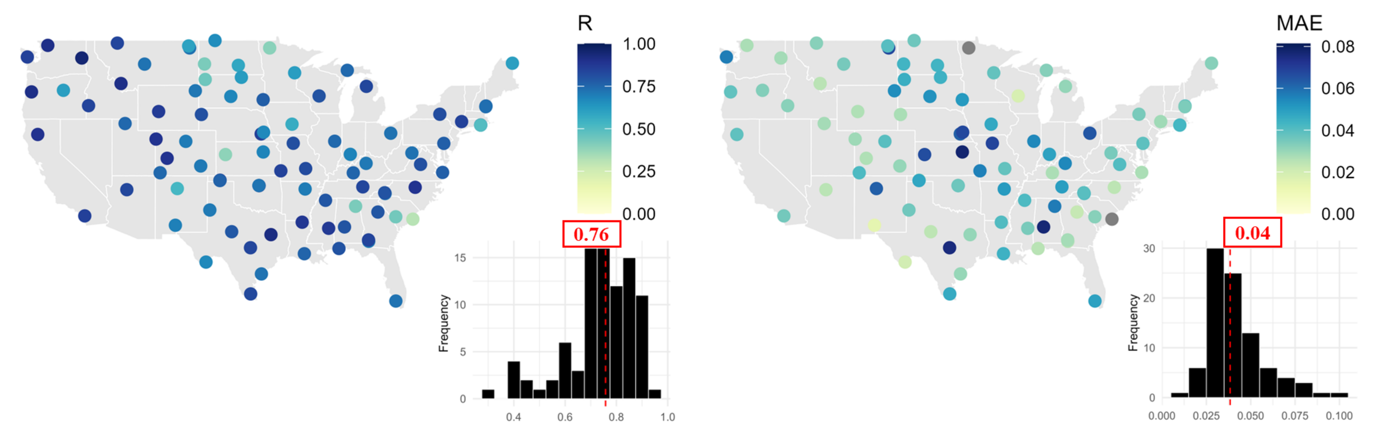
Simulated DD Across Climate Zones



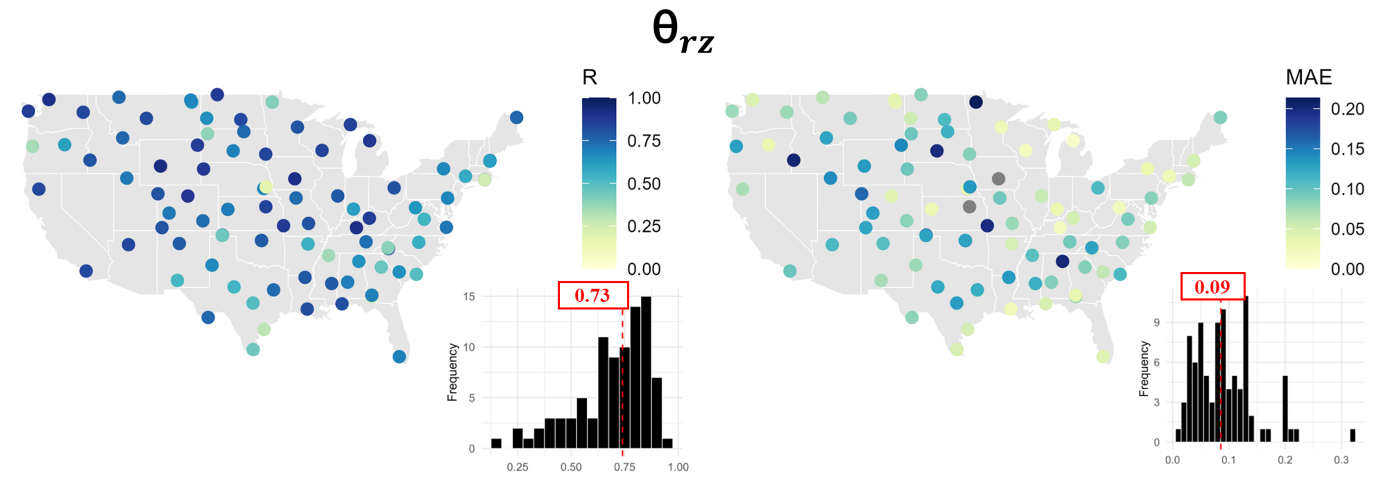
Episodic percolation events that are more frequent and sustained in the humid climate compared to the intermittent pulses in the semi-arid climate.

❑STATISTICAL OVERVIEW OF SOIL MOISTURE ESTIMATES ACROSS U.S.

θ_s



θ_{rz}



Across 91 USCRN stations, the SWB model shows strong correspondence with observations, with median R > 0.7 (indicating strong correlation) and low MAE values (< 0.1) for both θ_s and θ_{rz} estimates, These results indicate robust, though not universally consistent, model performance across diverse climatic and soil conditions

❑ IMPLICATIONS & FUTURE WORK

- The proposed SWB model demonstrates predictive capability to estimate soil moisture and ET dynamics using only basic weather data
- It helps close the gap between limited field measurements and the information needed for field- to regional-scale irrigation and drought forecasting
- The model provides scope for a low-cost, scalable tool for smarter irrigation scheduling, drought preparedness, and climate-smart agriculture across Louisiana and the U.S. CONUS
- **Future work**
  - The approach will extend to Model Parameter Estimation Experiment (MOPEX) catchments and integrate it with satellite datasets (e.g., SMAP) to assess model transferability and enable near–real-time, continental-scale soil moisture monitoring
  - Move towards Self-Calibrated Model

INSPIRED BY

- Sehgal, V., Mohanty, B. P., & Reichle, R. H. (2024). Rootzone soil moisture dynamics using terrestrial water-energy coupling. Geophysical Research Letters, 51(19), e2024GL110342.
- Mbabazi, D., Sehgal, V., & Mohanty, B. P. (2025). Global terrestrial water–energy coupling across scales. Ecohydrology, 18(2), e2743.

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