Hybrid AI Framework for Soil Moisture Forecasting: Towards Sustainable Water Use in Agriculture

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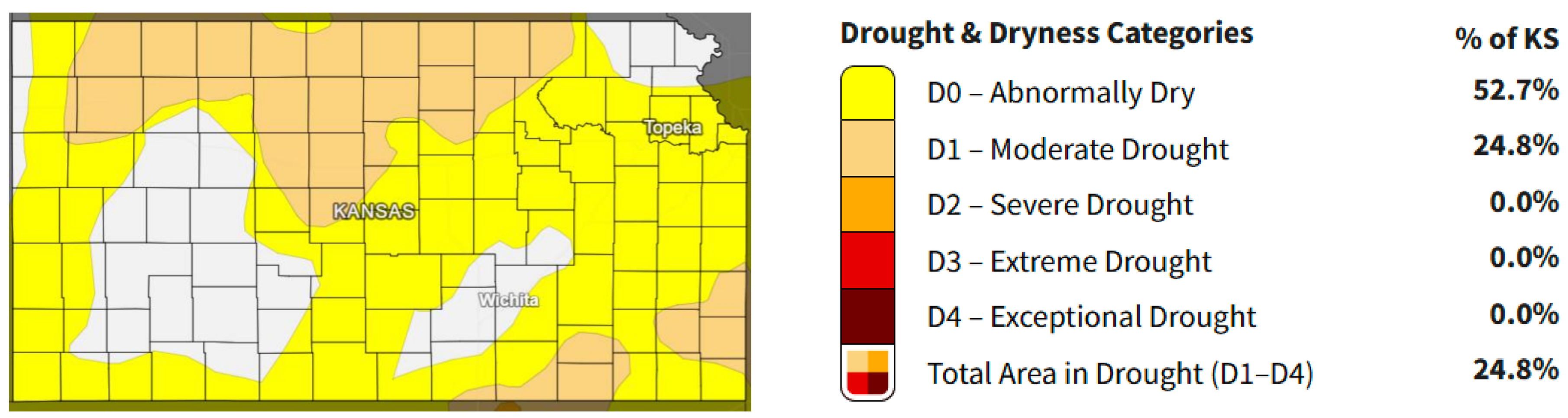
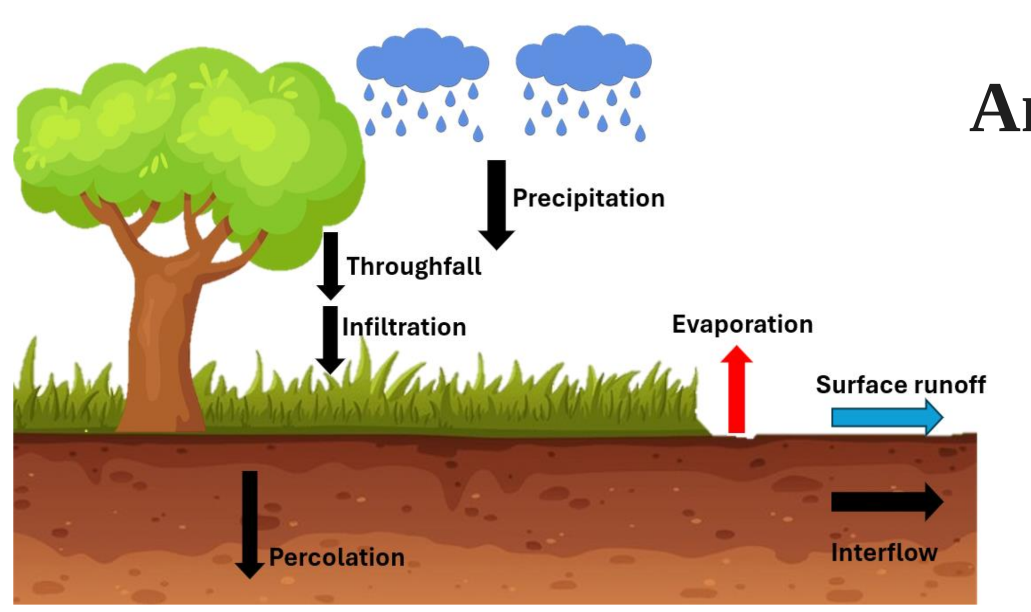
Background and Motivation

- **Agriculture accounts for ~80% of consumptive water use in the U.S.**
- **Improving soil moisture retention reduces irrigation demand and associated energy consumption.**
- **Kansas experiences recurrent droughts and declining groundwater levels.**



Monitoring and Modeling Soil Moisture

- **Soil moisture is the water stored in the soil profile.**
- **Accurate monitoring and modeling strengthen drought resilience.**
- **Conventional models often fail to adapt to changing soils and weather.**



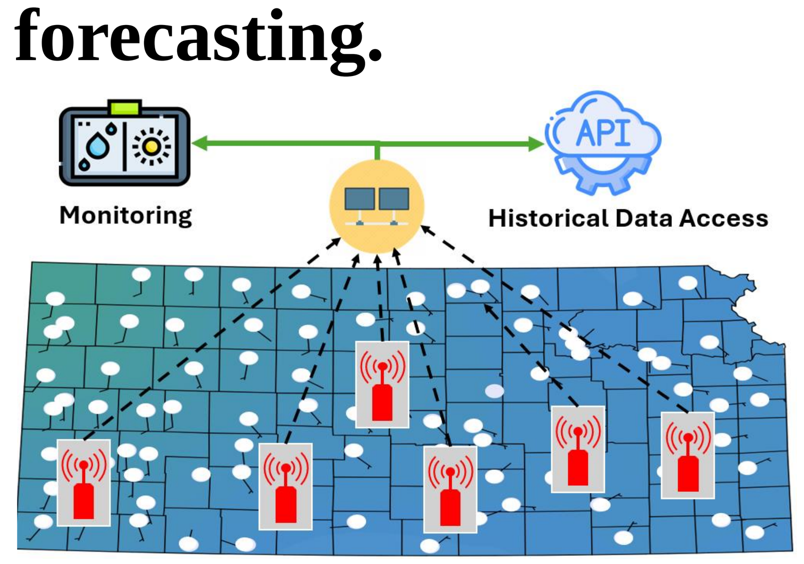
Antecedent Precipitation Index (API) Model

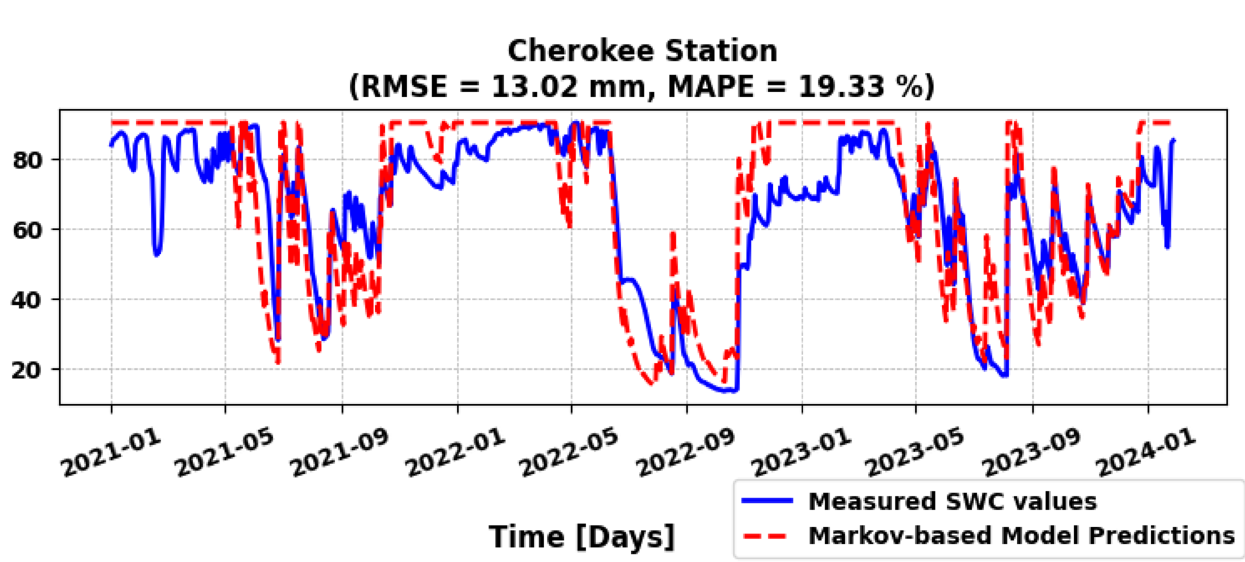
$$S_t = min\left(\begin{matrix}(S_{min}+\alpha(S_{t-1} - S_{min}) \\ +P_t),\ S_{max}\end{matrix}\right)$$

$$\alpha = c + (1 - c)\ cos\left(2\pi\ \frac{DOY - \phi}{365}\right)$$

Kansas MesoNet and API

- **Statewide network of automated weather stations providing real-time meteorological data.**
- **API leverages historical observations to support data-driven prediction and forecasting.**



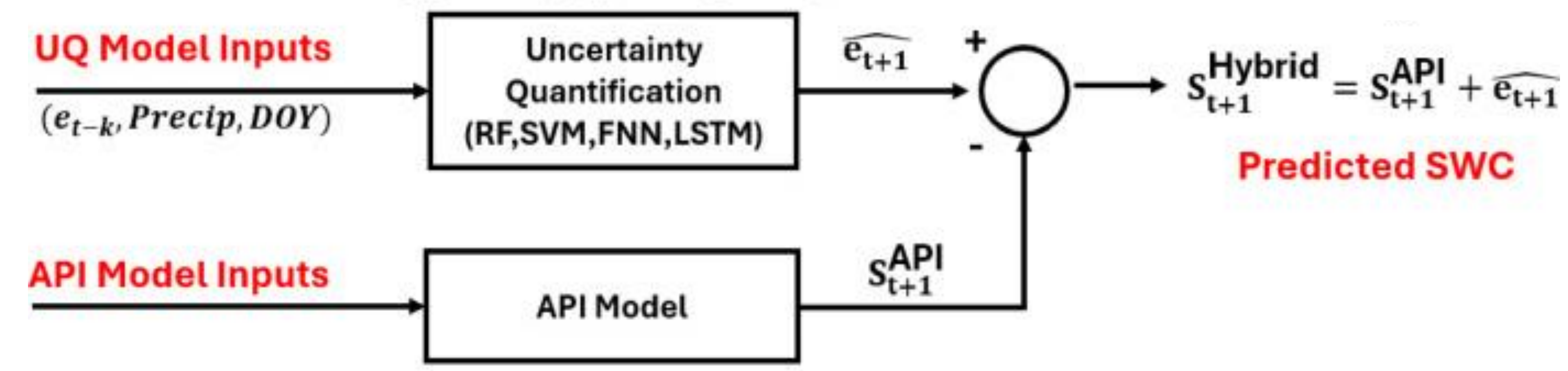


Hybrid AI Framework for Soil Moisture Modeling

1) Hybrid Uncertainty Quantification (UQ)

✓ **ML observer corrects systematic errors in the API baseline model.**

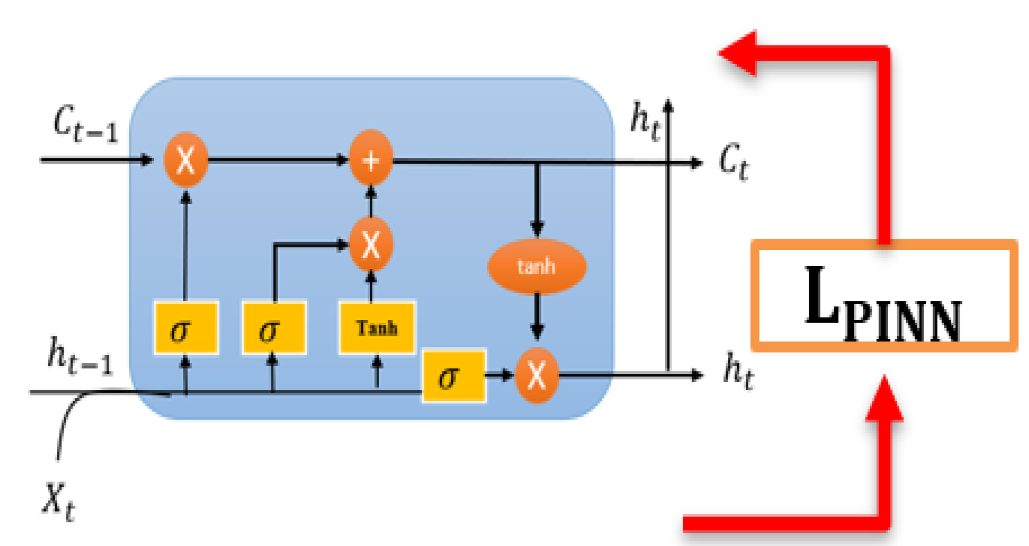
$$e_{t+1} = UQ(e_{t-k}, Precip, DOY)$$



$$S_t = \min(S_{min} + \alpha(S_{t-1} - S_{min}) + P_t,\ S_{max})$$

2) Physics-Informed Neural Networks (PINNs)

✓ **PINN training rule integrates the API model with Kansas Mesonet data.**



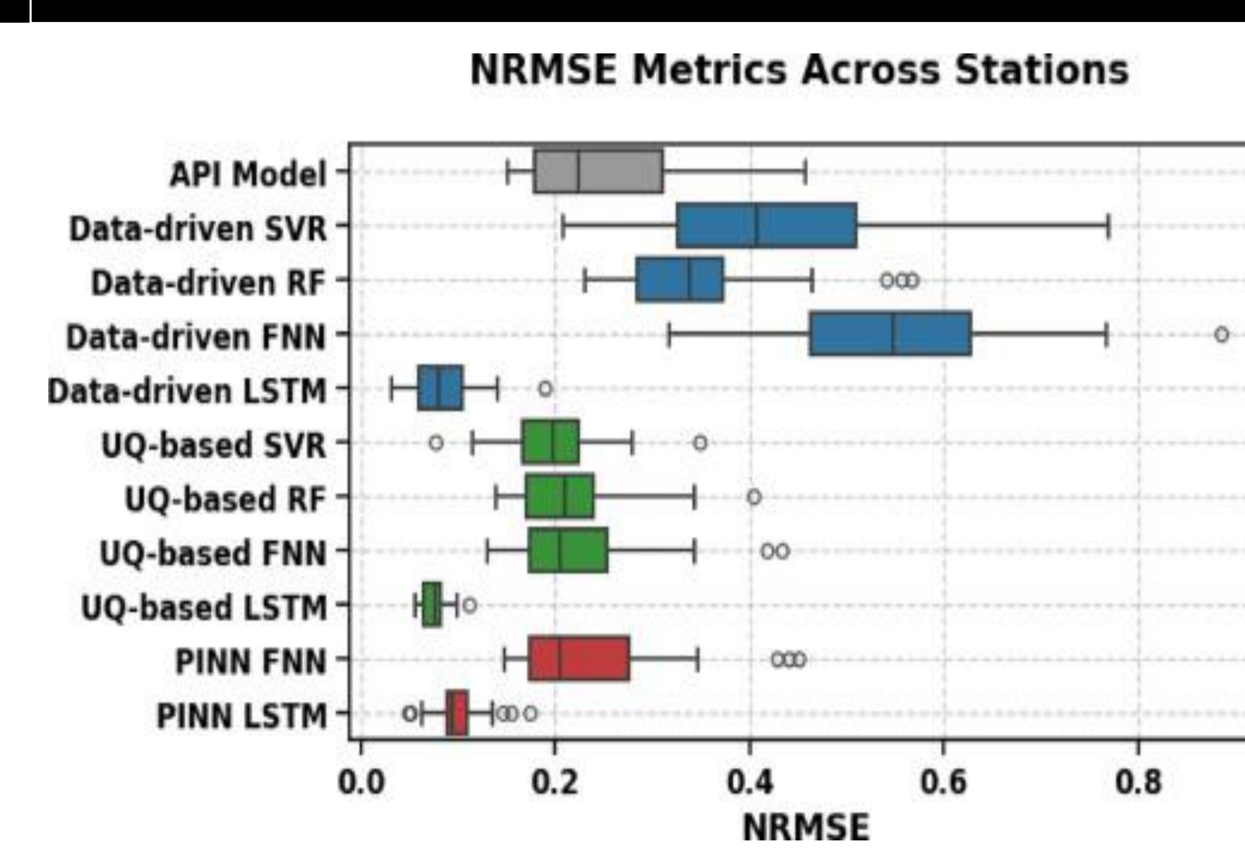
$$L_{data} = \frac{1}{N}\sum_{i=1}^{N}(S_t - \hat{S}_t)^2$$

$$L_{Physics} = \frac{1}{N}\sum_{i=1}^{N}(S_{m,t} - \hat{S}_t)^2$$

$$S_{m,t} = min(S_{min} + \alpha(S_{t-1} - S_{min}) + P_t, S_{max})$$

$$L_{PINN} = \gamma L_{data} + \beta L_{physics}$$

Results and Impacts



- **Hybrid AI achieved the highest predictive accuracy.**
- **PINN provided the best overall performance.**

Impacts:

1. **Enable smart agricultural planning.**
2. **Protect groundwater resources.**
3. **Improve drought resilience (aligned with NIDIS)**

Bagheri A. et al. "A hybrid time series and physics-informed machine learning framework to predict soil water content." *EAAI*, 144 (2025): 110105.