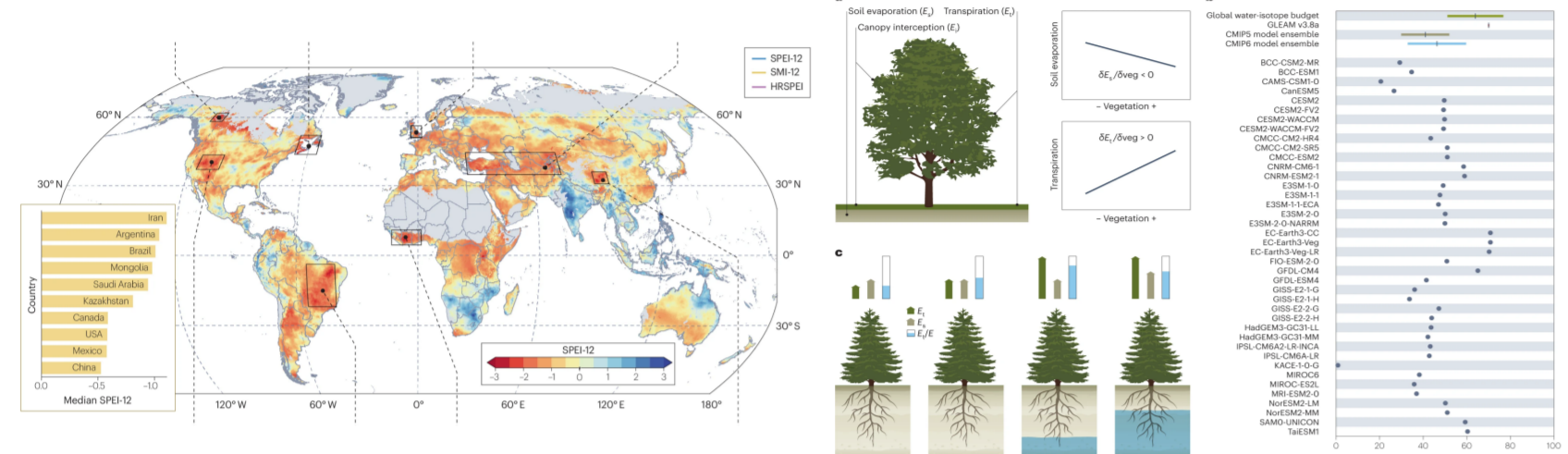


1. What role does groundwater play in Earth System Modeling?

- Increasing research indicates that as the increase of groundwater, not only regulate soil evaporation (E) and vegetation transpiration (T), it significantly enhance **the proportion of vegetation transpiration**.
- Hydrology in ecosystem model is often depicted as one-dimensional (1-D, vertical), neglecting the three-dimensional (3-D, vertical + lateral) movement.
- Vegetation and water are tightly coupled—but often modelled separately.
- Coupled models reveal feedbacks that are otherwise missed, improving both understanding and projections.

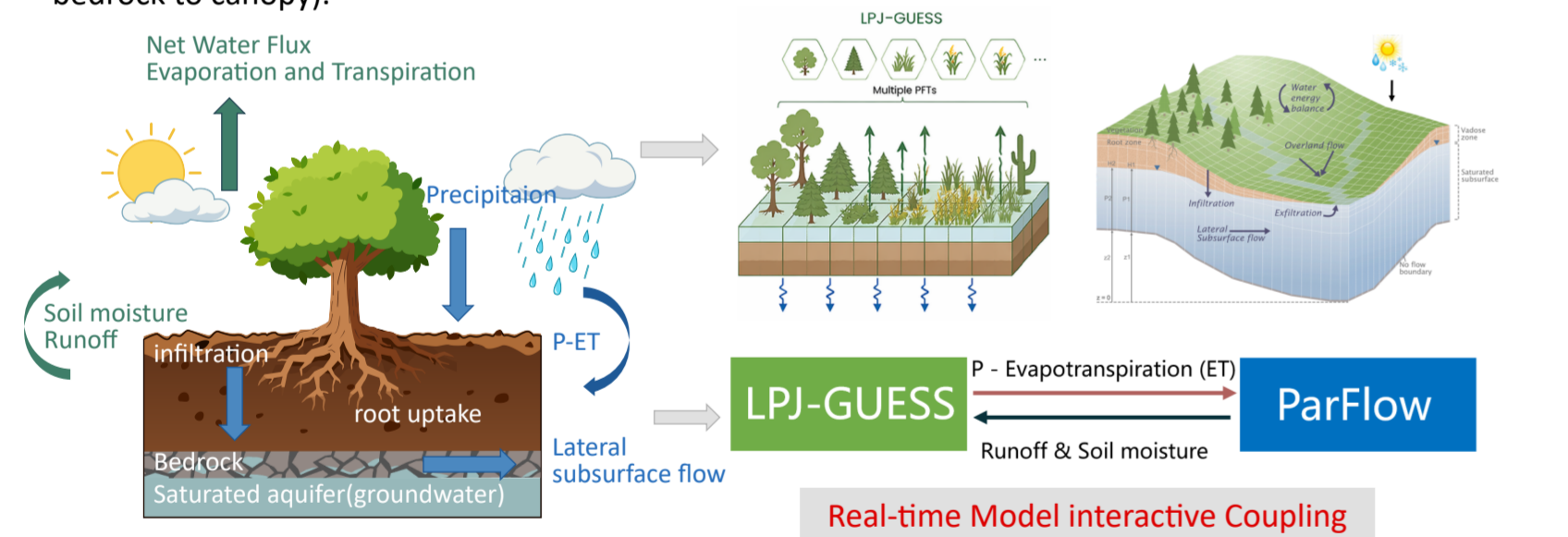


Groundwater processes can **strongly regulate** ecosystem resilience, especially under **drought**

ET is **underrepresented** in Earth System Models because of the absence of groundwater

2. We coupled dynamic vegetation model with 3-Dimensional hydrology model

- An MPI-based internal coupler was added to facilitate communication between LPJ-GUESS and ParFlow.
- Each timestep, LPJ-GUESS send the net water input (Precipitation minus Evapotranspiration, P-ET) as an upper boundary condition to ParFlow, which solves the 3-D Richards equation for variably-saturated flow and returns updated soil moisture and surface runoff to LPJ-GUESS.
- This coupling enables the simulation of surface water, groundwater, and dynamic vegetation processes (the bedrock to canopy).



Model Validation: Streamflow Performance

- The coupled model ParFlow-LPJ-GUESS (PF-LPJG) improves streamflow simulation without any parameter calibration.
 - Biases in low flows during spring snowmelt and peak flows during summer rainfall are notably **reduced**.
- More than 80% of gauging stations achieve **KGE > 0.5** and **Spearman's rho > 0.8**.

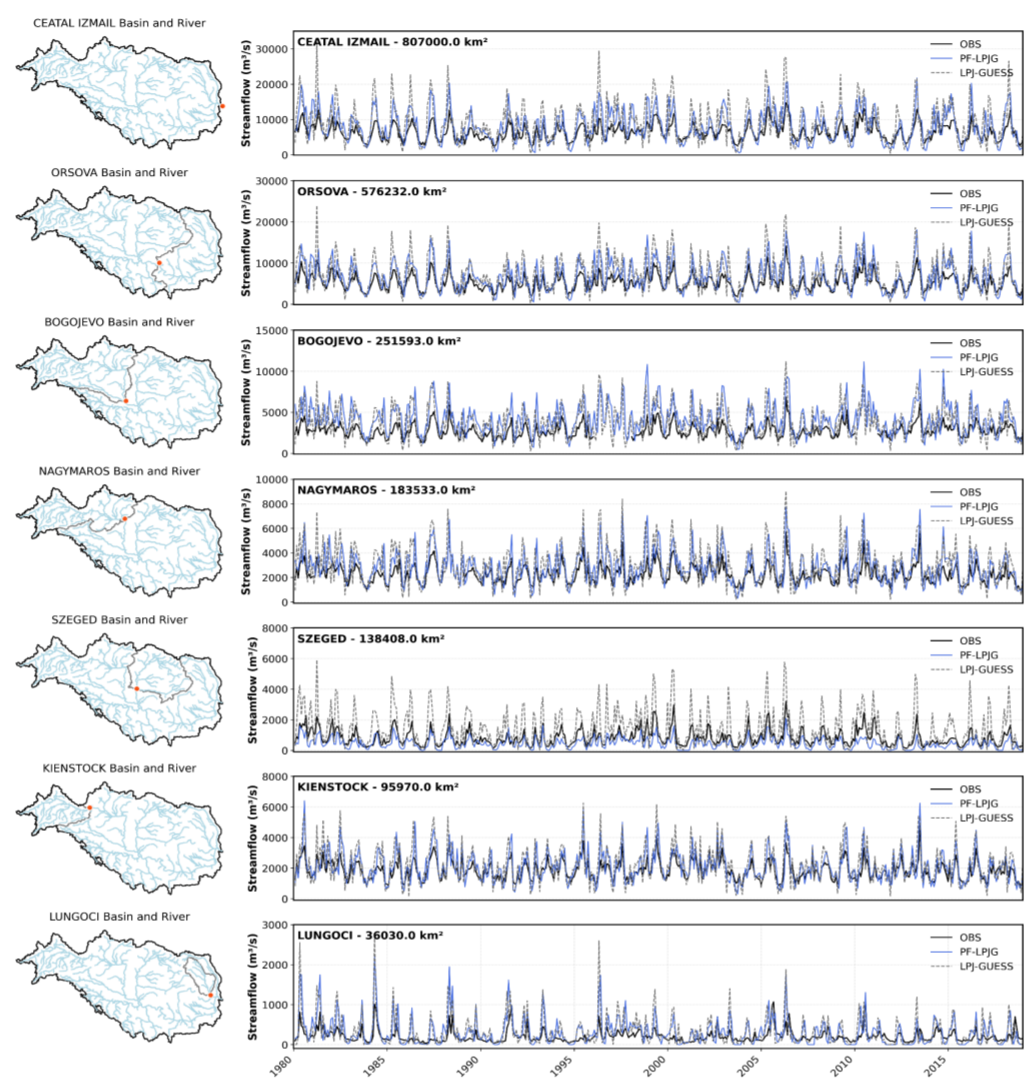


Figure 3. Cumulative distribution function (CDF) of WTD as simulated by PF-LPJG and Fan's model with observed WTD data.

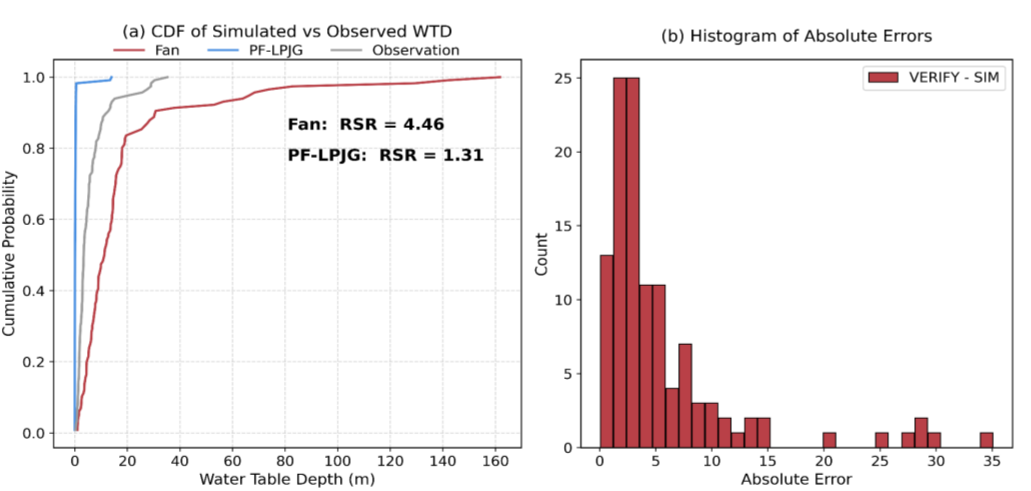


Figure 4. Spatial distribution of mean annual ET (a-c), inter-model differences (d-f), Histogram of mean annual ET (g) and Cumulative distribution function (CDF) comparison of seasonal E (h) for the period 1980-2018 as simulated by the coupled model PF-LPJG, the stand-alone model LPJ-GUESS, and the GLEAM 4.2 datasets across the Danube River Basin.

3. Results

Model Validation: Evapotranspiration, Soil Moisture

- PF-LPJG significantly improves the simulation of soil moisture and groundwater dynamics (particularly within the 0-5 m range), with the most pronounced gains **under drought conditions**.
- PF-LPJG better reproduces spatial patterns of evapotranspiration broadly consistent with GLEAM observations.

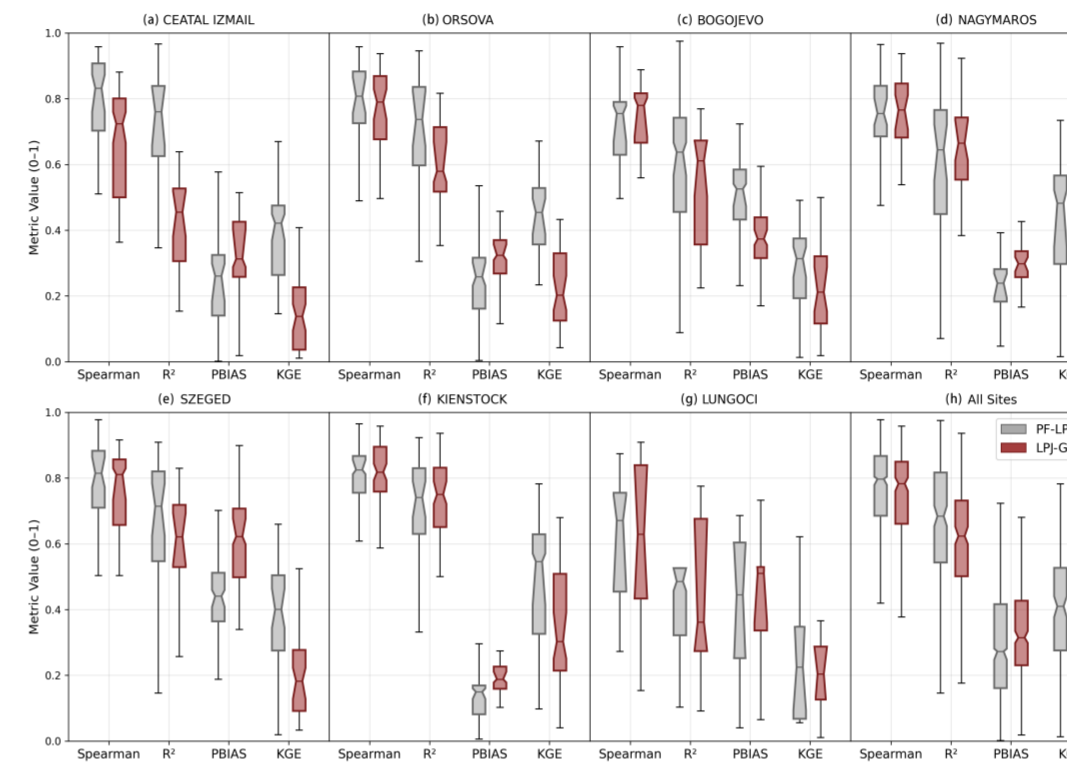


Figure 5. Interannual Precipitation Anomalies and Vegetation-Hydrology Responses

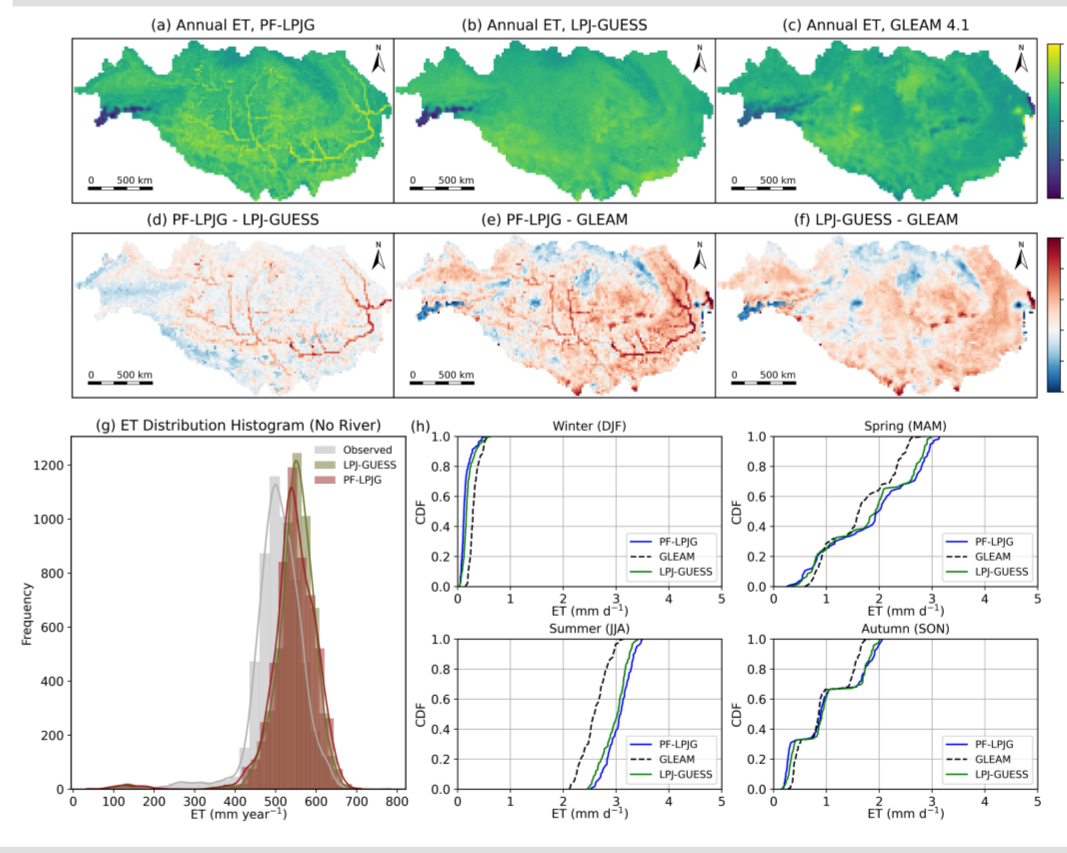


Figure 6. Scatter plot of Delta LAI Response to Hydrological Drivers in Drought Years

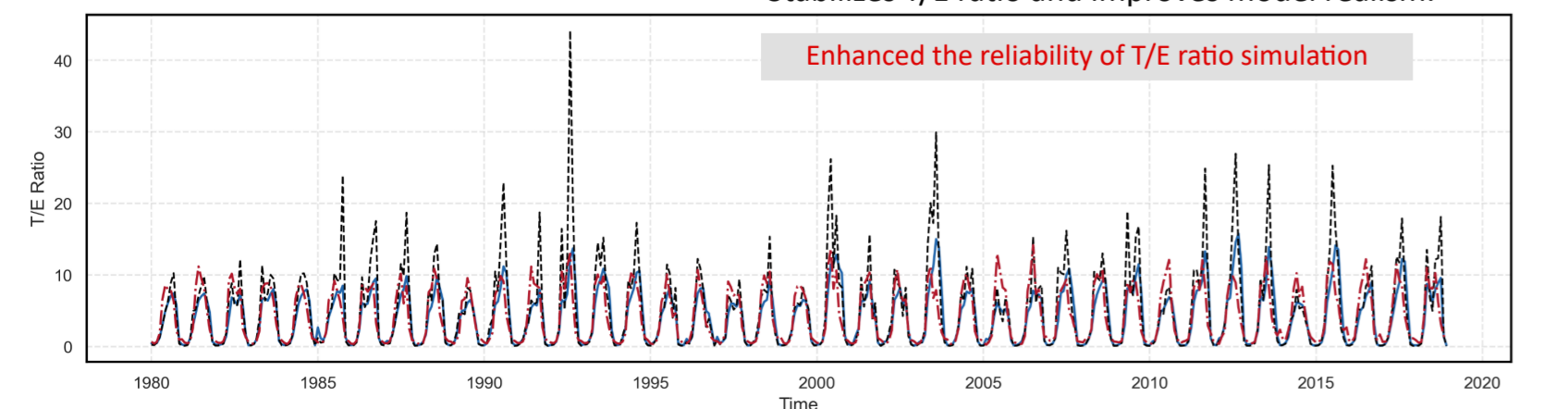
4. Groundwater supply stabilizes Transpiration/Evaporation ratios

LPJ-GUESS limitations:

- Lacks upward water flux from groundwater, causing **abnormally high** transpiration/evaporation (T/E) ratios.
- Strictly 1-D vertical hydrology, lateral flow redistribution entirely absent.

PF-LPJG improvement:

- Incorporates physically based 3-D groundwater process.
 - Enhances **surface moisture supply**, especially in dry/hot periods.
 - Supports plant available water and bare-soil evaporation.
 - Stabilizes T/E ratio and improves model realism.



Enhanced the reliability of T/E ratio simulation

6. Conclusion

Technological:

- We developed an **internal coupler** that seamlessly integrates the dynamic vegetation model LPJ-GUESS with the three-dimensional surface-sub-surface hydrological model ParFlow.
- This integration allows vegetation processes (growth, competition, carbon cycling simulated by LPJ-GUESS) to interact directly with water dynamics across the landscape—from soil moisture to groundwater flow (from ParFlow).

Changes Introduced by coupled model PF-LPJG:

- The coupled model enables more **realistic simulations** of hydrological fluxes : Improved runoff simulations addressed the limitations of LPJ-GUESS in modeling terrain gradients (slope) .
- Enhanced transpiration** in areas influenced by groundwater contribution, incorporates the groundwater table depth (WTD) dynamics into LPJ-GUESS.
- These changes have profound implications for understanding **groundwater-vegetation feedbacks** in climate change.

5. Lateral flow drives vegetation greening

- Anomalous greening persists in drought years despite **precipitation deficits**.
 - Delta LAI peaks in **notably dry years** (2009, 2011, 2013, 2015), while precipitation anomaly shows no significant relationship with Delta LAI ($\rho = -0.224$, ns).
 - Delta ET remains elevated or even peaks in dry years (1990, 2007), with precipitation explaining little variance in Delta ET.
 - Lateral flow sustains ET during drought, **decoupling** vegetation water use from local rainfall.
- At **equal drought intensity**, pixels with stronger lateral flow show larger Delta LAI - lateral flow, not precipitation, drives greening.



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Research Focus: Ecohydrological Modeling. We are looking for candidates who: Have backgrounds in ecology, hydrology, or related fields, are passionate about modeling.