Simulation of seasonal water table dynamics across North America using the Water Table Model (WTM)

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community surface dynamics modeling system

1. Background

Groundwater is a vital resource for ecosystems, agriculture, and human consumption, particularly in North America, because of its extensive agricultural and industrial lands and diverse climate. However, short term water table behavior remains poorly described at the continental scale; most models assume steady state conditions and neglect the centuries long transient changes that control the response of aquifers to modern precipitation and drought. Here, we use the Water Table Model (WTM) to provide a monthly, continent wide map series of natural water table variability for 2020. Our simulation features a transient, millennial scale spin up, followed by monthly, high resolution snapshots of natural groundwater variability for the modern era. This result is important for several reasons, including:

- Groundwater buffers >60 % of North America's fresh water supply, yet short term (seasonal to annual) fluctuations are poorly quantified.
- Climate driven recharge / droughts are accelerating; decision makers need high resolution forecasts, not long term steady state averages.
- Existing continental models ignore millennial memory in aquifers; they miss the lagged response that controls today's water table trends.

2. Methods

Water Table Model (WTM): The Water Table Model (WTM)uses a coupled approach to simulate groundwater and surface water (lake water) systems. To do so, the WTM solves the 2D groundwater flow equation for a heterogeneous, horizontally isotropic medium, using PETSc's SNES component, and it uses Fill-Spill-Merge to simulate dynamically changing lake levels.

We forced the model using palaeo-climate simulations and modern climate re analysis, applying strict bias correction and spatial downscaling so that every input field aligns on a uniform 30 arc second (~1 km) grid. This workflow lets the Water Table Model (WTM) resolve monthly water table dynamics while honouring the very slow memory of continental aquifers.

Model spin-up: In previous work, we ran a transient simulation of North American water table from 21 ka to 1500 CE (500-year time-steps; forced with TraCE-21ka climate data and GEBCO-2020 topography modified using a GIA model).
Here, we use this result to initialize a spin-up to finer temporal resolutions.

- **Climate forcing**
  1500-1900: TraCE 21 ka paleo re analysis (decadal).
  1900-1970: TraCE 21 ka paleo re analysis (annual).
  1970-2000: CMIP6 historical climate variables (seasonal).
  2000-2020: CMIP6 historical climate variables (monthly).
- **Validation**
  56,200 USGS wells + 645 FLake bathymetries (2000-2020).
  Performance: $\mathbf{R^2} = 0.95 \pm 0.002$; **NSE** $= 0.94 \pm 0.002$ (monthly).

3. Results

The transient monthly water table run exhibits a clear north–south gradient: shallow water tables across the Great Lakes and Canadian Shield vs. more than 50 m depths in the arid Southwest (Fig 2). Spring recharge elevates levels by up to 1 m, while late-summer drought compels ~0.8 m drops in the Pacific-Coastal and Colorado River basins (Fig 1). Precipitation-minus-evaporation maxima are echoed three months later in water table levels, quantifying the lag in seasonal-scale response times (Fig 3). Watershed-scale plots show that most basins end 2020 with higher water tables, but the Pacific- and Gulf-Coastal aquifers see lower water tables, signaling drought-sensitive hot-spots (Fig 4).

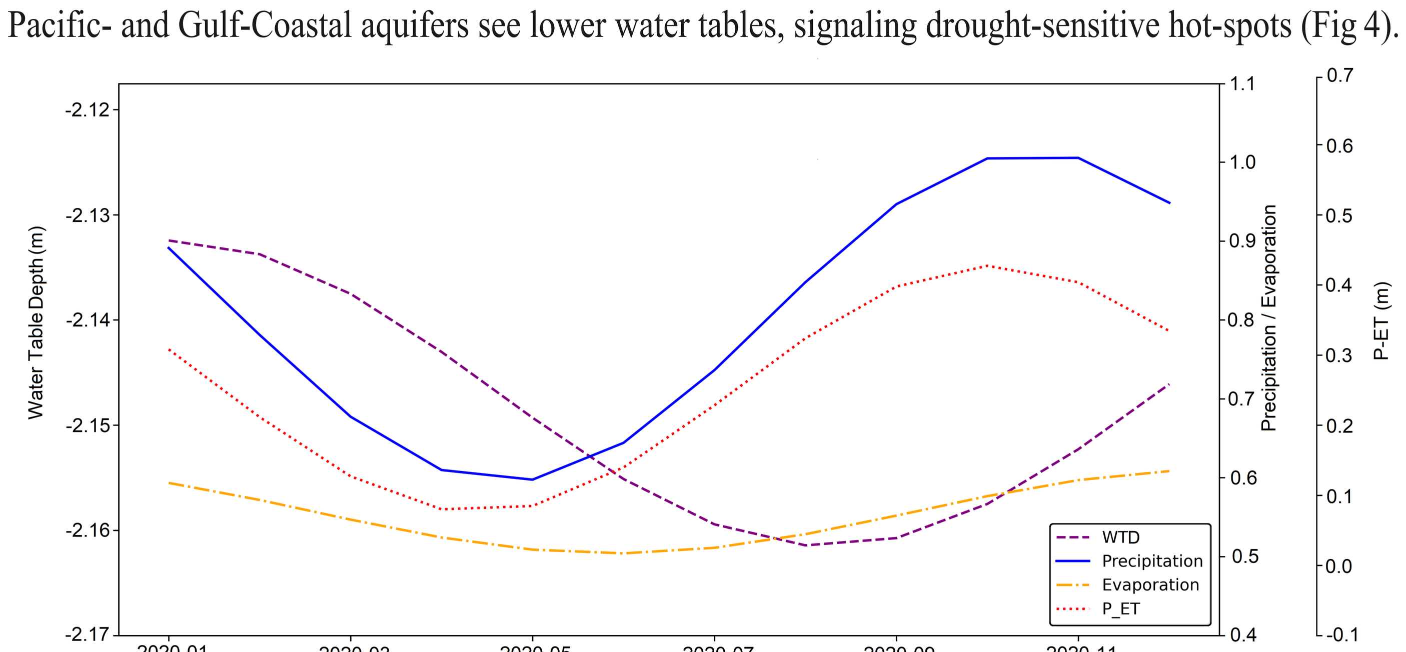

Fig. 3. Monthly Water table trends for the year 2020. Note the three-month lag in the effects of changing precipitation and evaporation on water table depth.

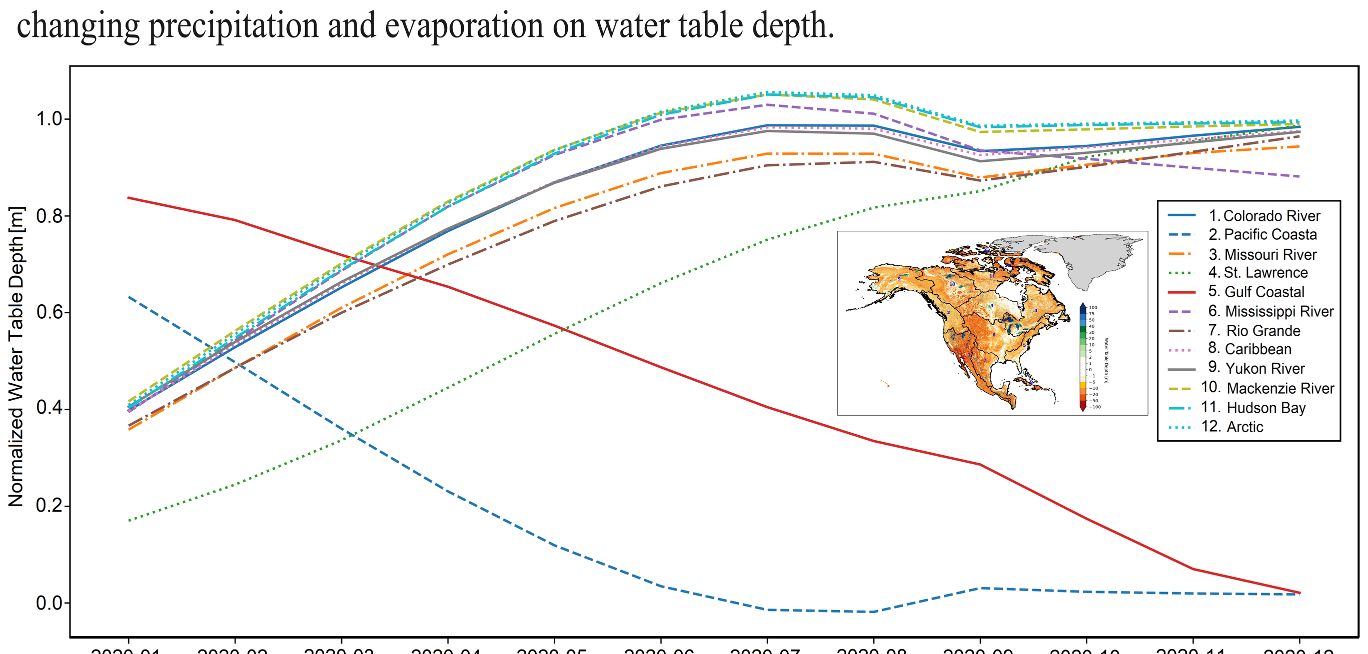

Fig. 4. Normalized monthly change in water table depth for each major watershed in North America. Water tables rise across most of the continent, but the average water table depth decreases over the continent as a whole (see Fig. 3). This highlights the dramatic decreases in water table depth seen in the Gulf Coastal and Pacific Coastal watersheds.

3. Results

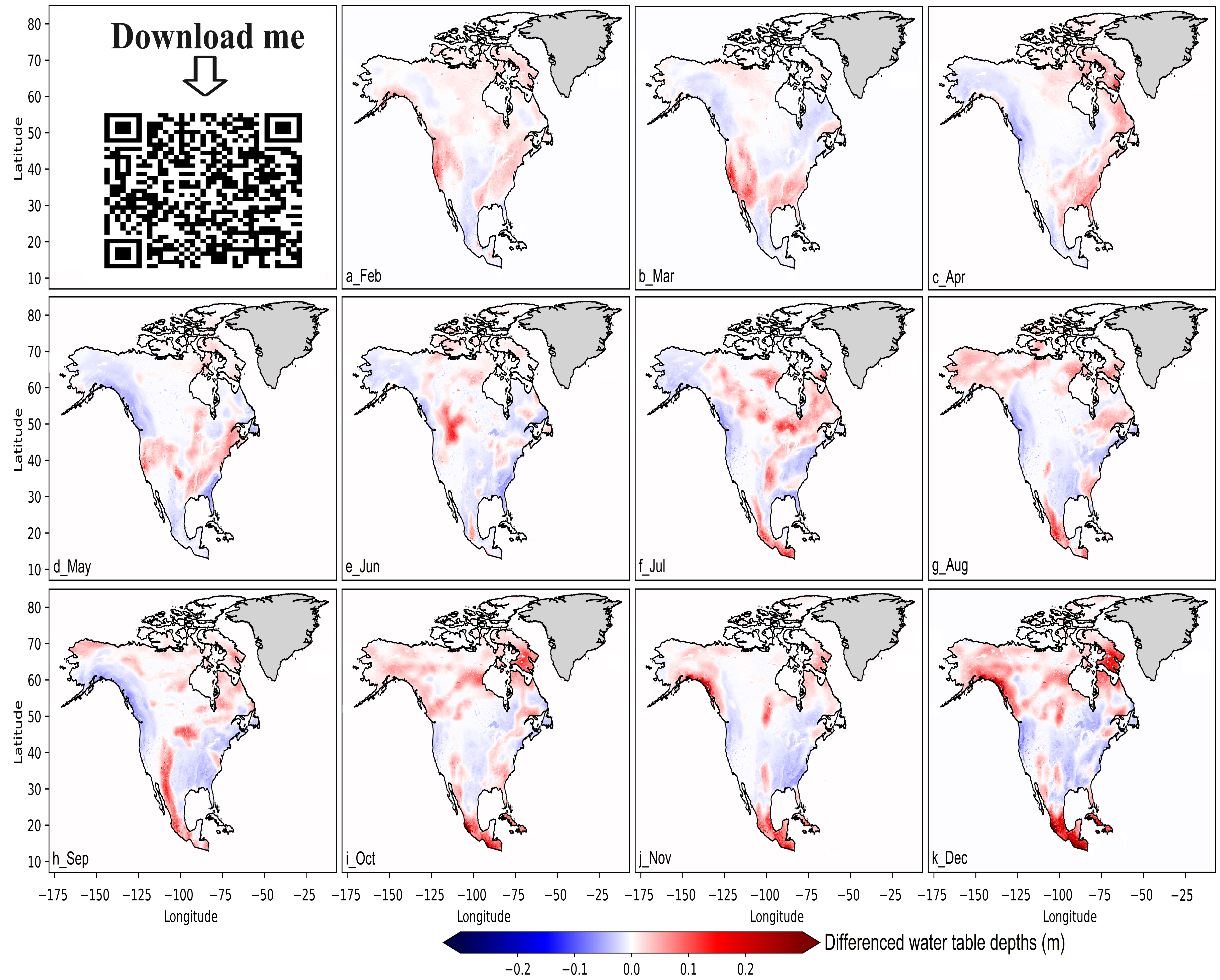

Fig. 1. Monthly water-table anomalies for 2020 (30-arc-sec grid). Panels (a–k) progress from February to December, each showing the depth change to water table relative to January. Blues indicate a shallower (rising) water table, reds a deeper (falling) one. Late winter–spring (a–c) is marked by extensive rises across the Great Plains, Midwest, and boreal Canada, and summer (e–g) by as much as 0.8 m decrease in water-table elevation in the Pacific-Coastal, Colorado River, and Gulf-Coastal basins. Fall (h–j) refills northern elevations to some degree, but December (k) confirms ongoing deficits along the Pacific coast and Mexico, highlighting strong seasonal and regional groundwater contrasts illustrated by the transient run.

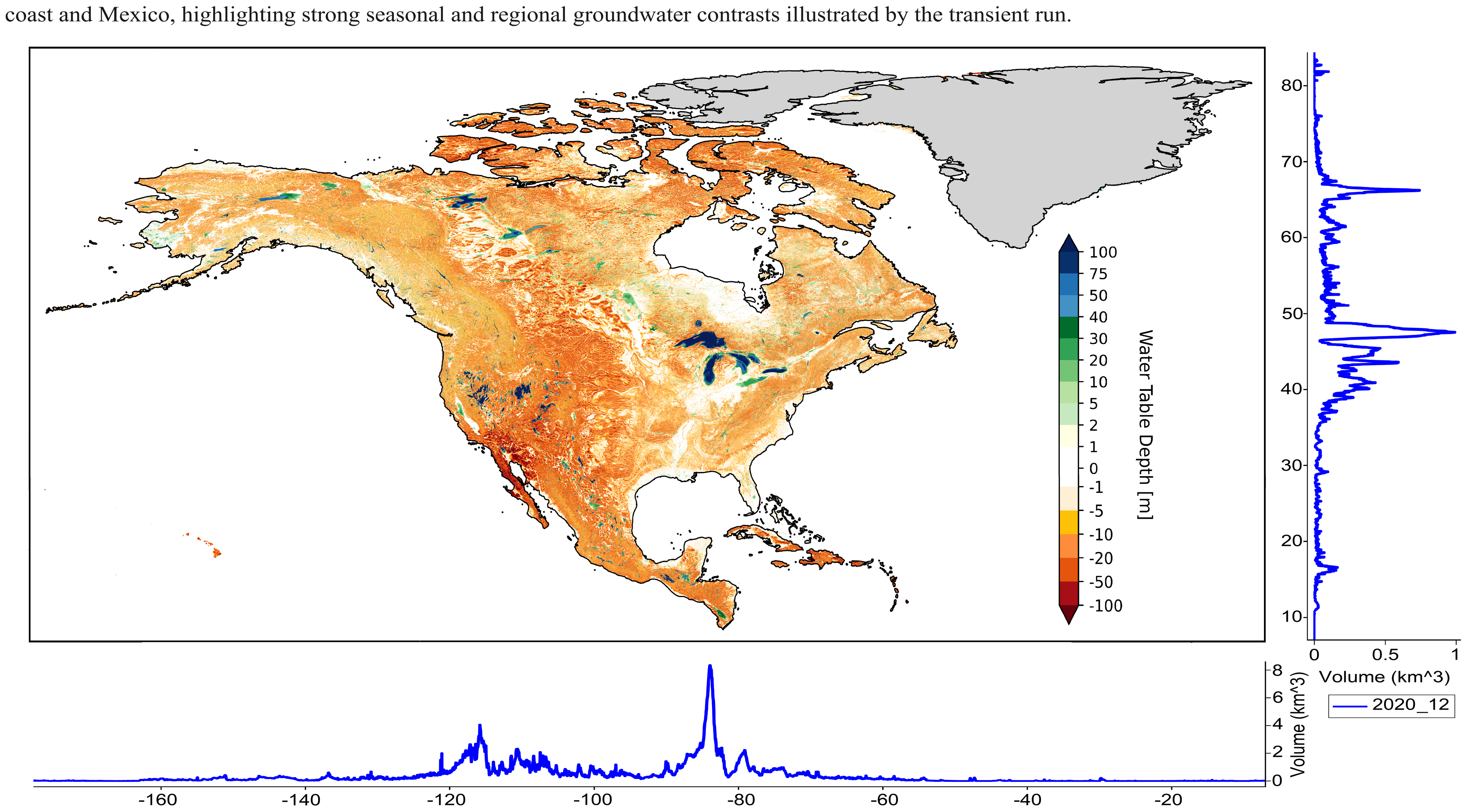

Fig. 2. Spatial distribution of water table depth across North America (December 2020), showing areas where the water table is below (negative values) or above (positive values) the land surface. The western and southwestern regions exhibit a lower water table (deeper depths), while the northern and northeastern regions display a higher water table (shallower depths). The color bar represents water table depth in meters. The line plots show the surface water volume [km3] at each latitude and longitude

4. Conclusion

1. Transient matters: A millennial spin-up plus monthly forcing captures the 3-month lag in water table response time and seasonal swings that steady-state models miss.
2. Sharp regional contrasts : Results show the shallow, rising water tables across the Great Lakes and boreal zones, but more than 0.8 m drops in Pacific- and Gulf-Coastal basins.
3. Natural baseline established: Good-skill ($R^2 \approx 0.94$) maps provide a climate-only reference against which human pumping impacts can now be isolated.
4. Scalable framework: WTM's HPC-ready workflow can integrate CMIP6 futures, enabling scenario testing for groundwater sustainability under climate change.

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