GLOBGM PROGRESS

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(with the contributions from Jarno Verkaik, Nicole Otto, Daniel Zamrsky, and Anna Hoogeveen)

In short: Why this research?

- Climate change & excessive pumping are threatening worldwide (fresh) groundwater reserves
- Higher-resolution groundwater models are required for better estimates & projections
- Going to a higher-resolution is motivated by:
  - The increasing resolution of global datasets
  - The increasing computing power
- However, the resulting runtimes & memory usage easily go beyond the possibilities of a single computer
- That’s why we require high performance computing

Image credit: wikipedia

Image credit: USGS

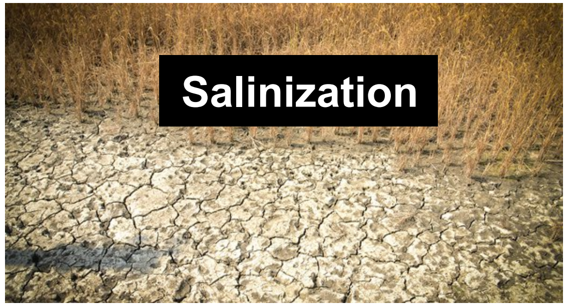

Image credit:India Water Portal

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What are PCR-GLOBWB and GLOBGM?

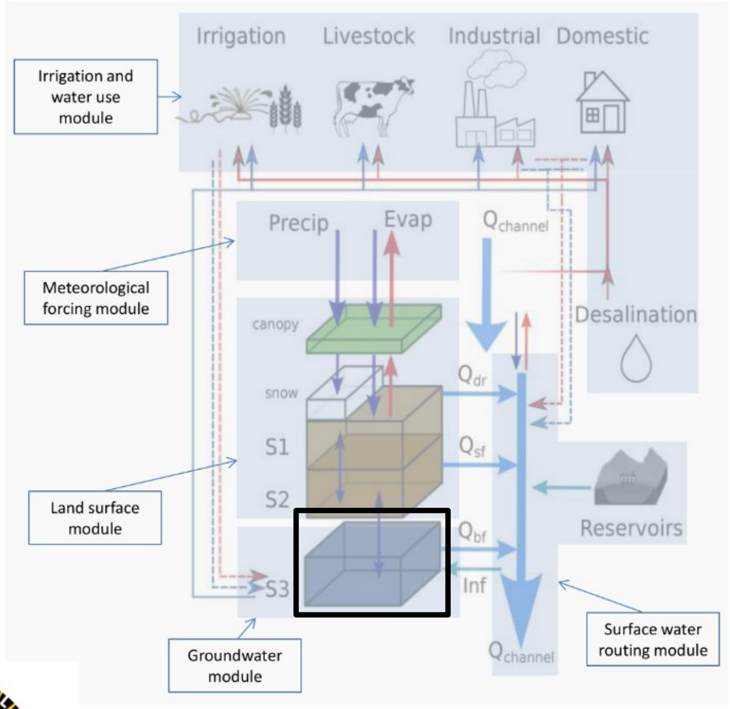
PCRaster **GLOB**al **W**ater **B**alance model (Sutanudjaja et al., 2018, GMD)

- Global-scale hydrology and water resources model
- Being developed at Utrecht University for > one decade
- Current version has 5’ cells (~10 km @ equator)
- No Greenland & Antarctica

GLobal **G**roundwater **M**odel (Verkaik et al., 2022, GMD-D)

- Replace S3 (groundwater) with GLOBGM (lateral flow)
- Two model layers: confining layer (upper) + aquifer (lower)
- Previous: MODFLOW-2005 ; Now: switch to MODFLOW-6
- **This presentation is about the refined version having 30″ cells (~1 km @ equator)**

PCR-GLOBWB



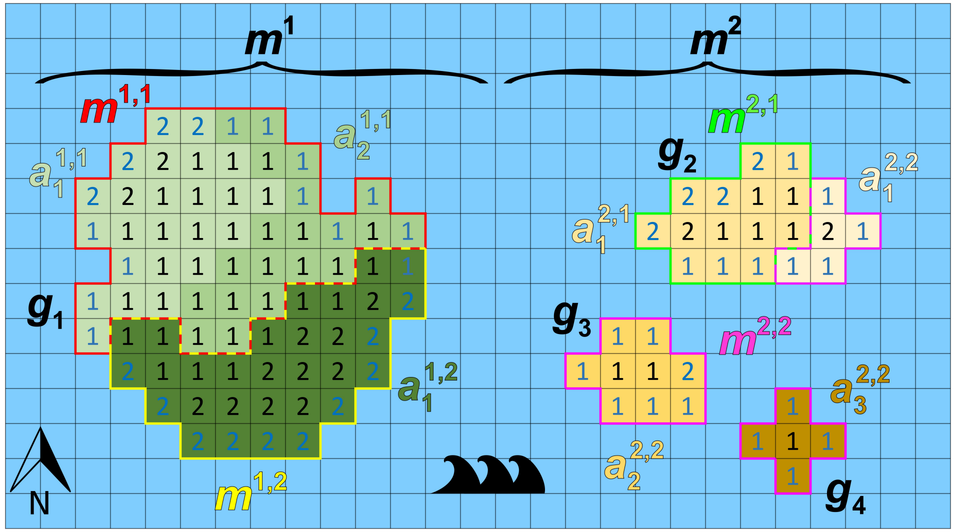
Universiteit Utrecht

Sutanudjaja et al., GMD2018
(https://doi.org/10.5194/gmd-11-2429-2018)

Outline of this presentation

- Computing parallelization – PhD of Jarno Verkaik
- GW dependent ecosystem (an alternative for validation approach) – PhD of Nicole Otto
- Developing a better geological model (working progress) – Postdoc of Dr. Daniël Zamrsky
- 1 km Senegal groundwater model (application example) – MSc of Anna Hoogeveen

Computing parallelization



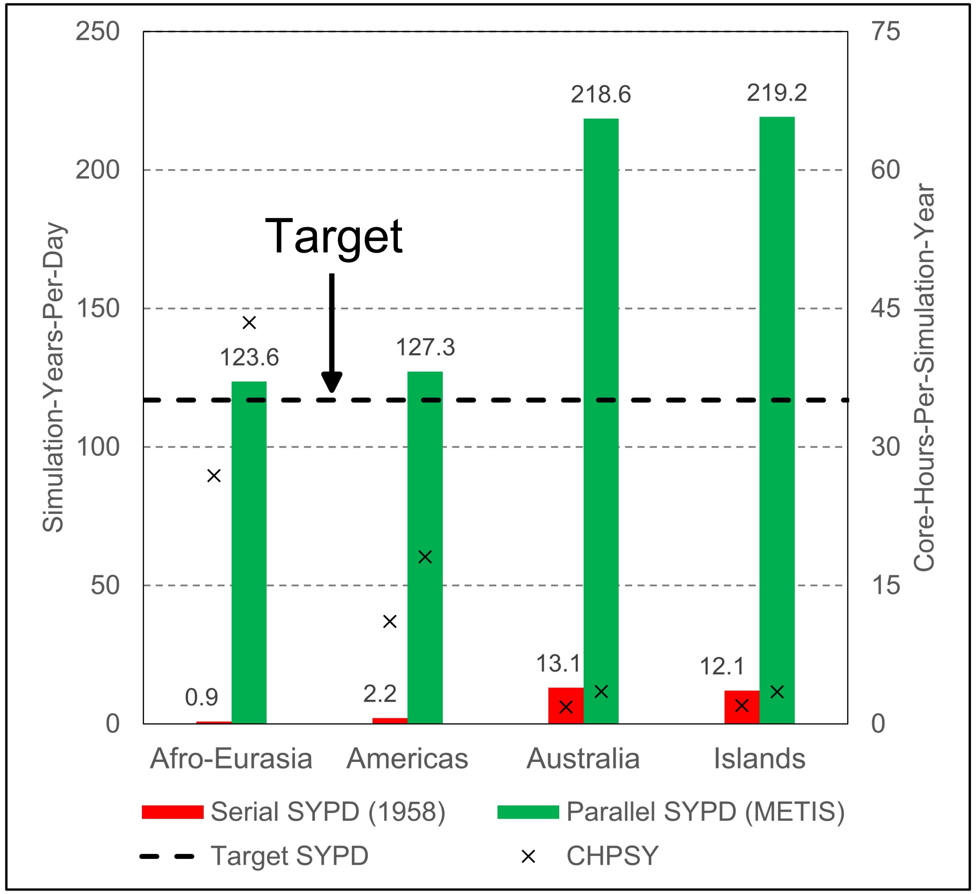
- Partitioning based on sub-catchments
  - For future online coupling to surface water.

- Experimental setup:
  - **Main purpose: To develop and test our parallelization approach**
  - 30 arcsec model (1 km).
  - Offline coupling, forced with the existing output of PCR-GLOBWB (Sutanudjaja et al., 2018)
    - Recharge and abstraction at 5 arcmin (no downscaling).
    - Discharge: Accumulating 5 arcmin runoff through 30 arcsec drainage network.
  - Other input fields at 30sec resolution (e.g. based on MERIT and GLiM).

Parallel performance results, 1958-2015

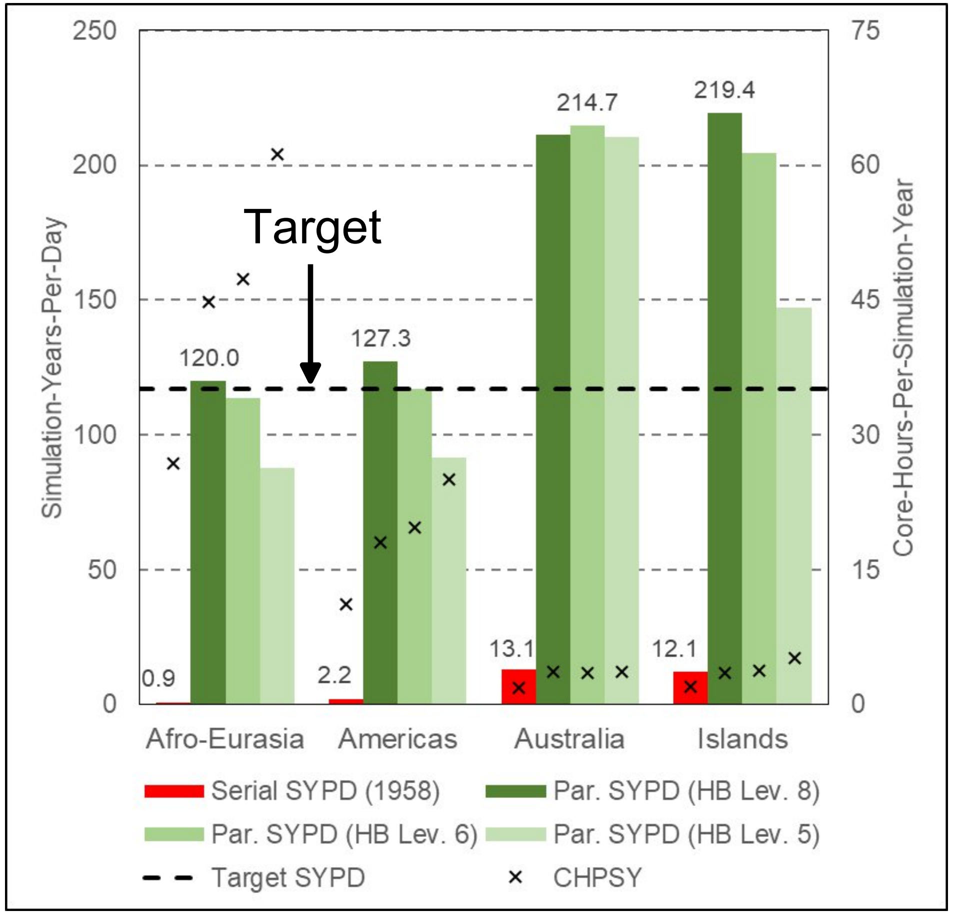
- Our target: Simulating 1958-2015 (20 year spin-up + 58 year simulation) within 16h (5 PM-9 AM).
- Target = 117 SYPD

- Target is achieved for all models
- Afro-Eurasia:
  - 87 days (0.9 SYPD) ☾ 15 hours (123.6 SYPD)



Parallel performance results, 1958-2015 (cont.)

- Catchment partitioning
- HydroBASINS Pfafstetter levels: 8 (275k), 6 (40k), 5 (28k)
- Target is achieved for level 8
- Up to level 6 performance is still good



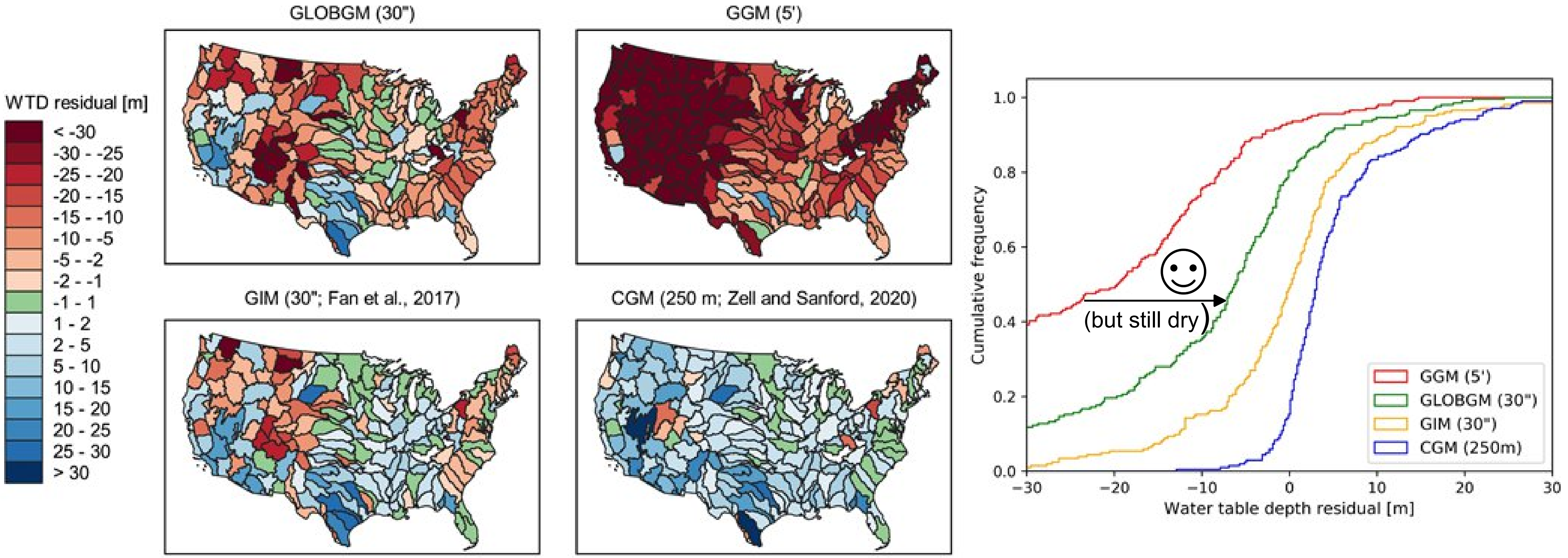
In general:

- Parallel performance is good enough for its purpose
- However, there is still room for improvement:
  - Reduce number of (linear) iterations
  - Reduce number of non-contiguous partitions
  - Improve processor core utilization (memory contention)

Steady-state evaluation for the CONUS

- Under natural conditions (no groundwater pumping)
- Comparing to measurements from the USGS National Water Information System (NWIS) database
- Aggregated to watersheds for spatial representation
- Comparing the GLOBGM to three other models:
  - **Previous version**:
    5’ PCR-GLOBWB-MODFLOW groundwater model of de Graaf et al.
    (HESS-2015, https://doi.org/10.5194/hess-19-823-2015)
  - **GIM**:
    30” global-scale inverse plant root depth model of Fan et al.
    (PNAS-2017, https://doi.org/10.1073/pnas.1712381114)
  - **CGM**:
    250 m CONUS model of Zell & Sanford (USGS)
    (WRR-2020, https://doi.org/10.1029/2019WR026724)

Steady-state evaluation for the CONUS

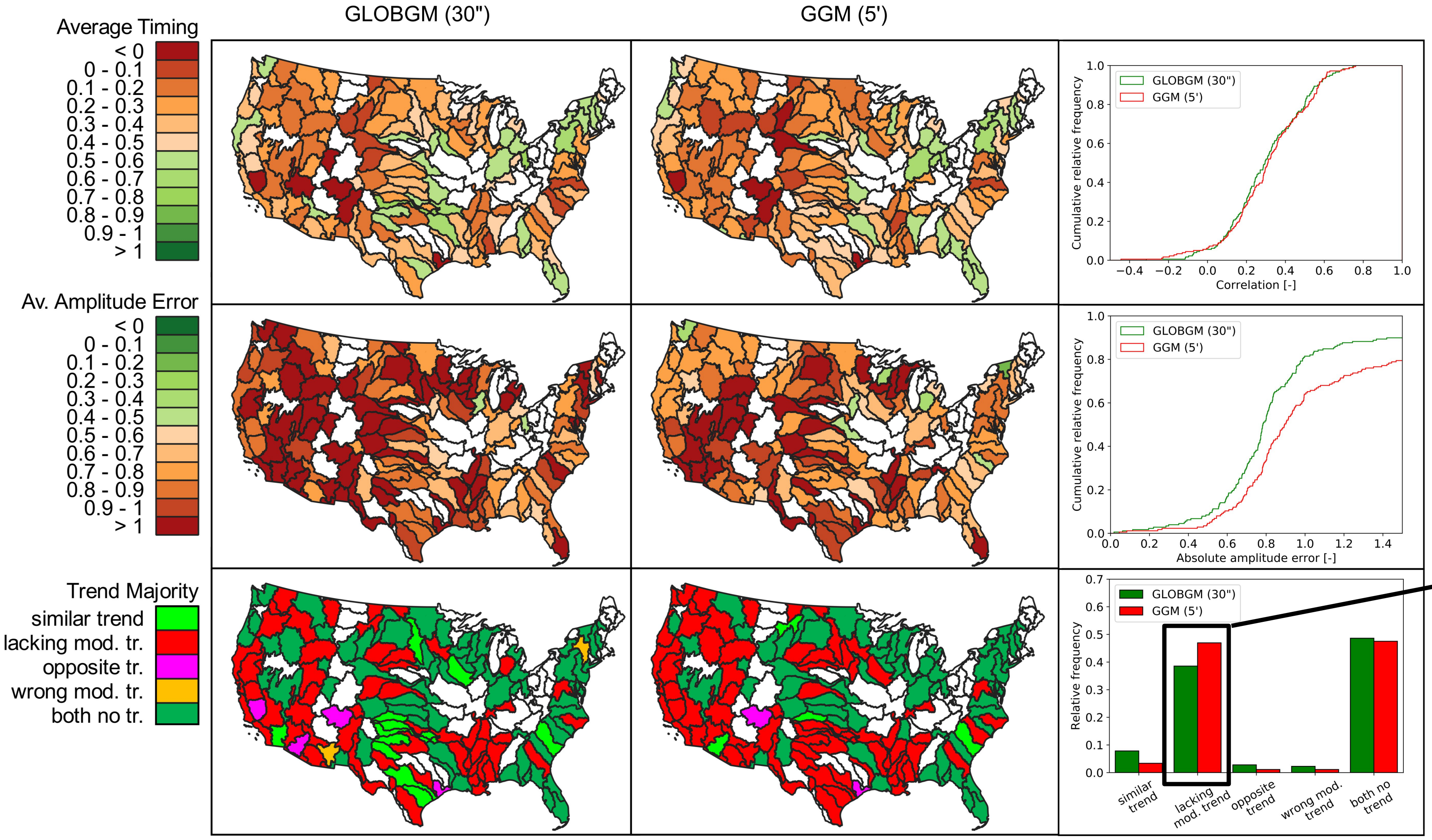


Transient evaluation for the CONUS, 1958-2015

- Including abstraction wells (non-natural)
- Comparing the GLOBGM to the 5’ GGM only (monthly averaged heads)
- Considering three statistics of time-series:
  1. **Timing**: sample cross correlation coefficient
  2. **Amplitude**: interquartile range error $IQRE_{mo} = |IQR_m - IQR_o| / IQR_o$
  3. **Trend**: year-averaged slope of simple linear regression function; trend exists if $|b_y| > 0.05$ m/y

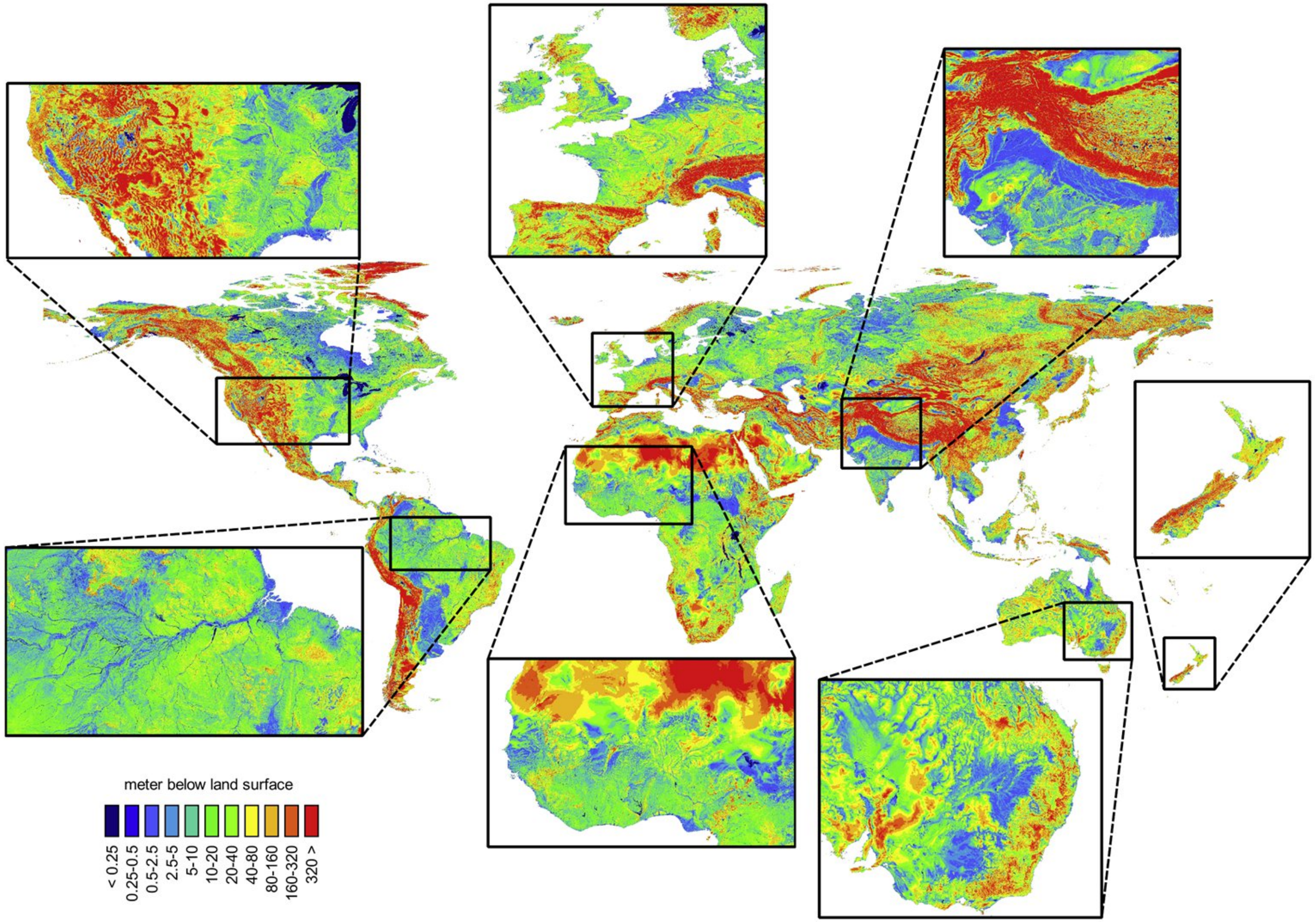
- Applied filtering to 900k NWIS sites:
  - Unconsolidated sedimentary systems only
  - Selection for contiguous periods for 5 consecutive years
  - Layer selection using correlation with soil moisture time-series
  - Resulting in ~12k time-series
  - Aggregated to HUC4 surface water boundaries for spatial representation

Transient evaluation for the CONUS, 1958-2015

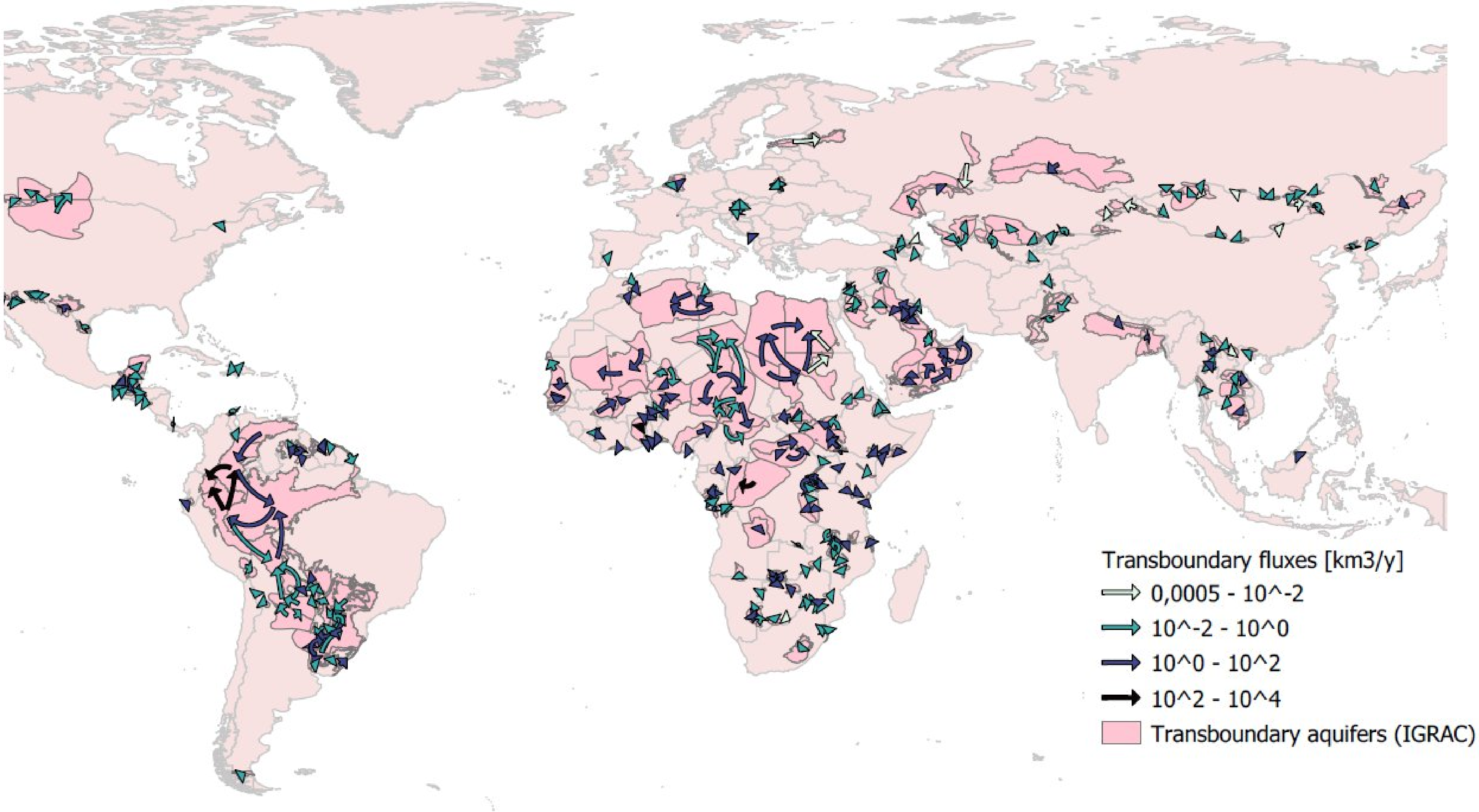


Model does not capture trend

Example of global-scale steady-state result

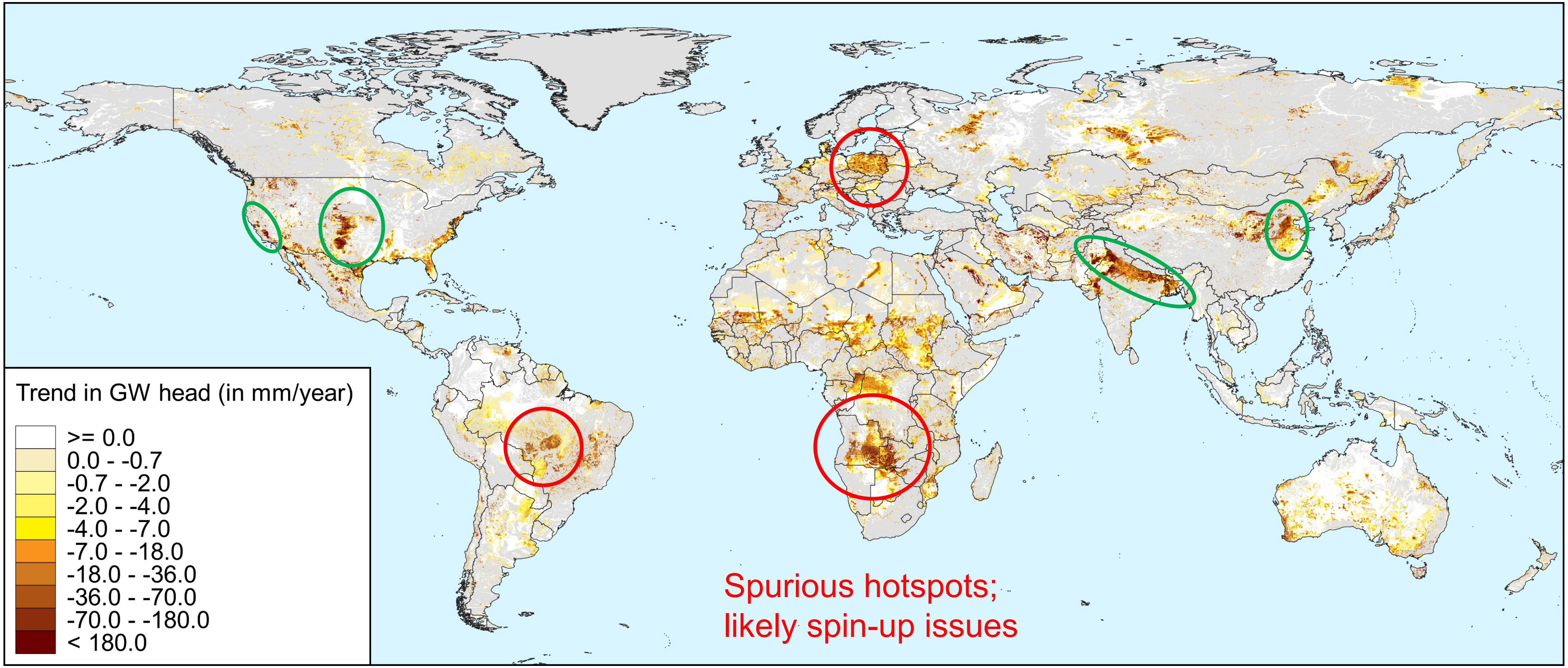


Example of global-scale steady-state result (cont.)



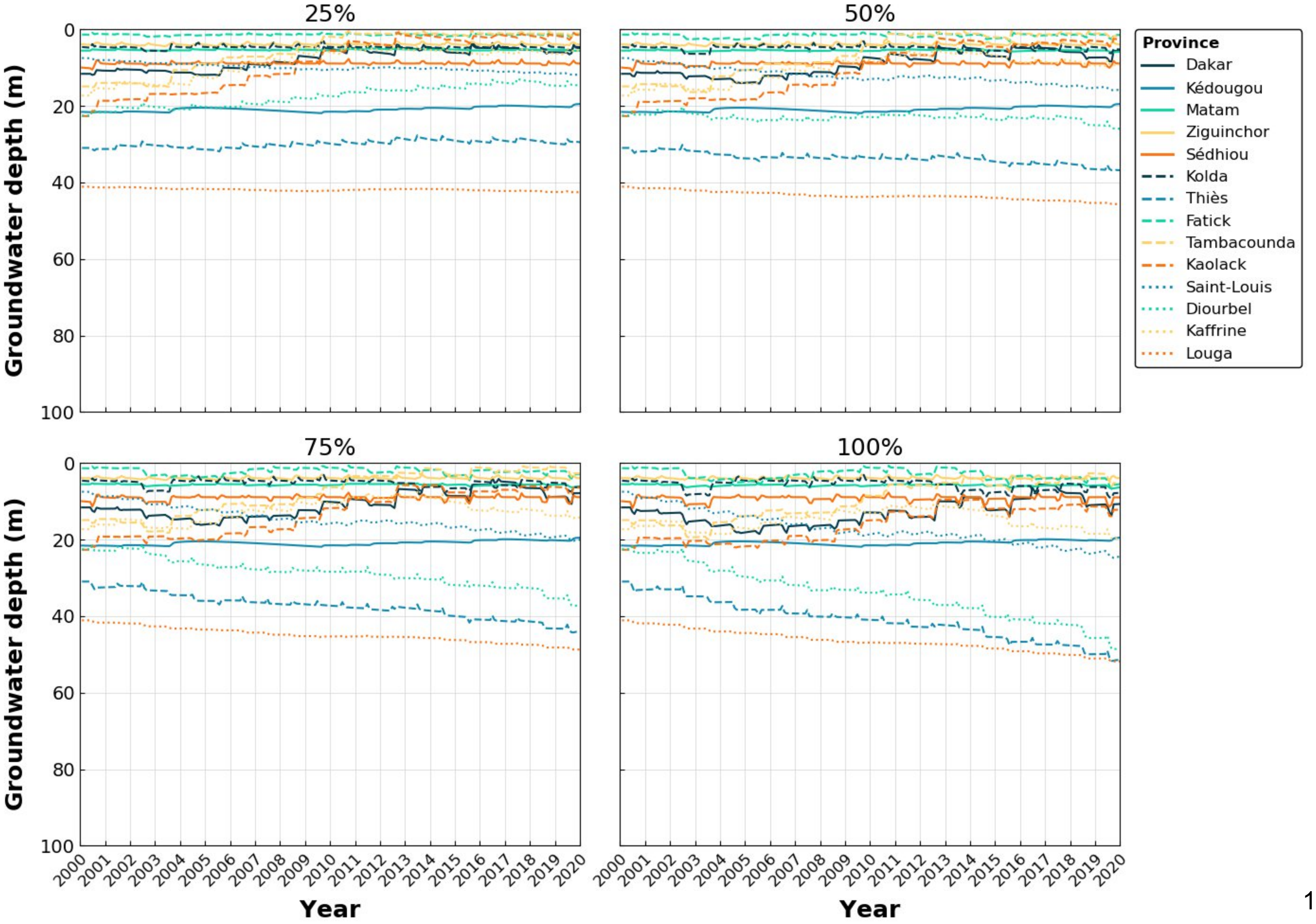
(Map created by Joeri van Engelen)

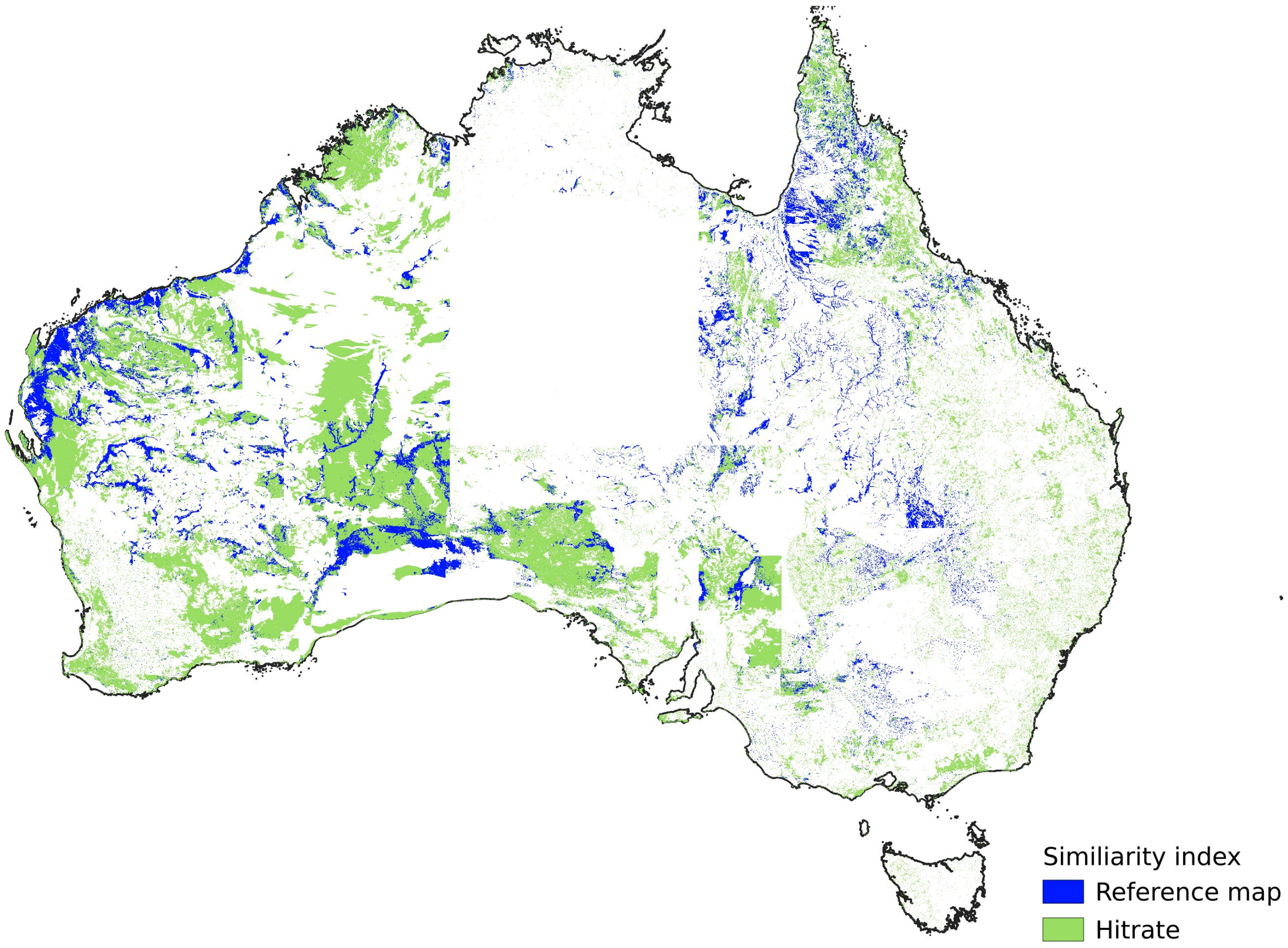
Example of global-scale transient result



1 km GLOBGM for Senegal

Assessment of groundwater head declines for various scenarios for covering water gaps (25%, 50%, 75% and 100%)





Validation to groundwater dependent ecosystem (based on database in Australia)

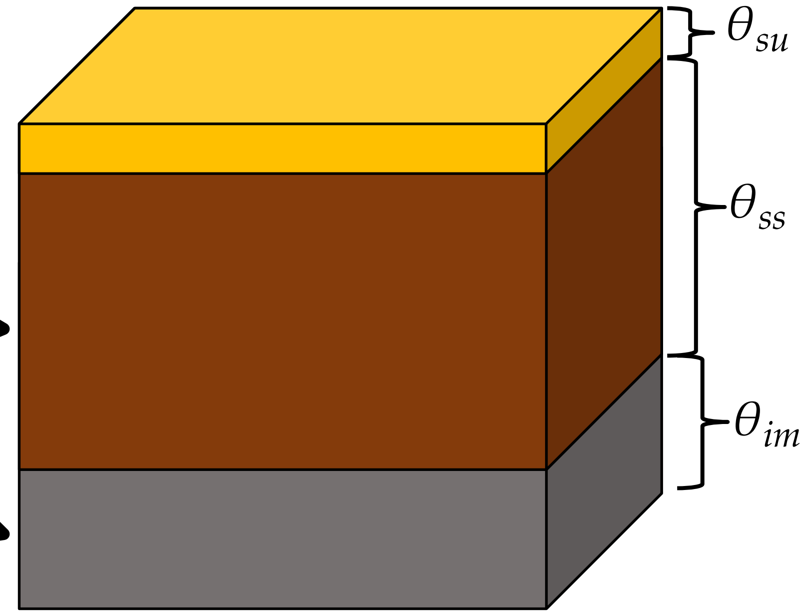
- GDE: if rooting depth > groundwater depth
- Rooting depth based on Fan et al., 2017.

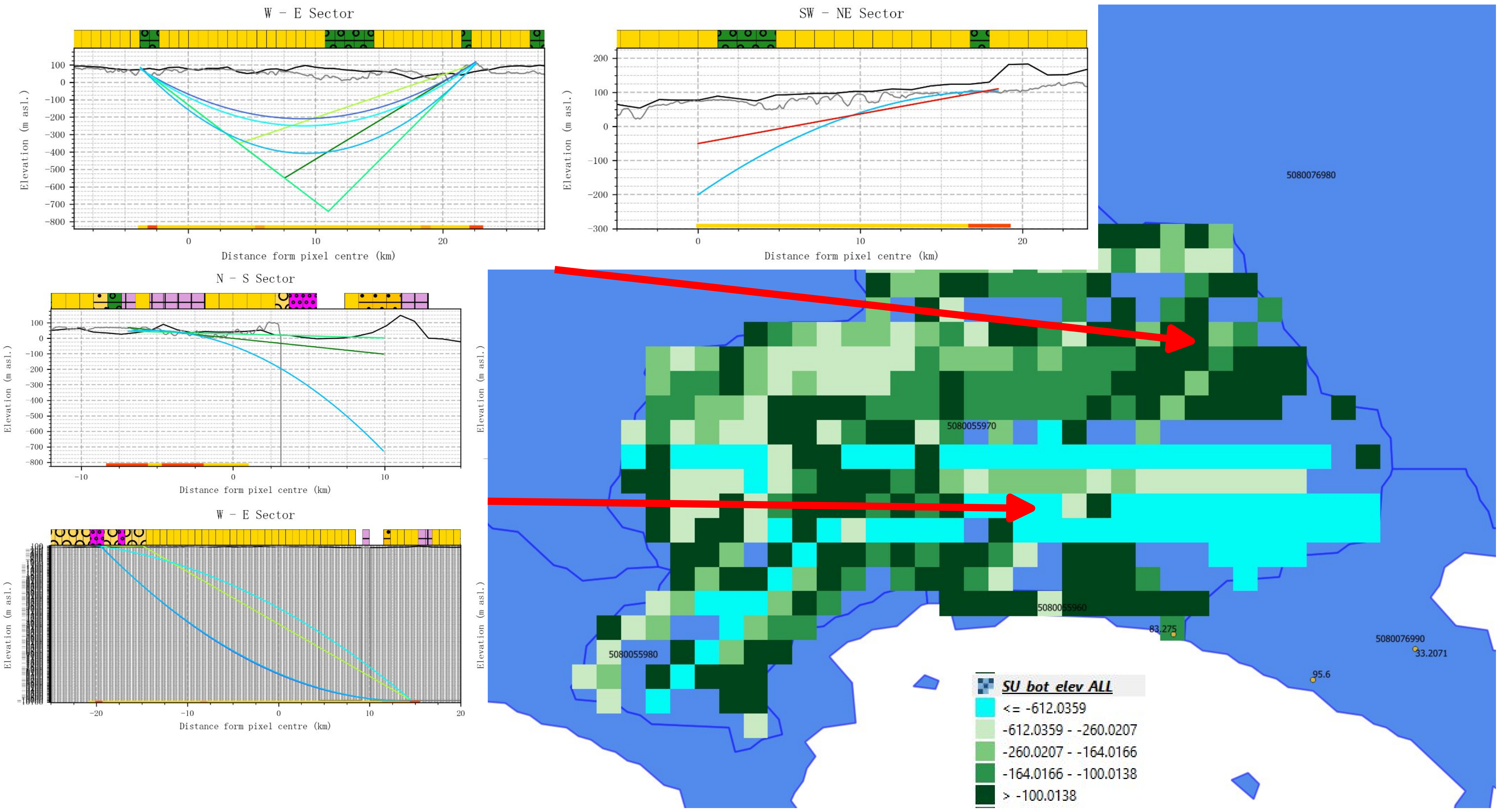
- Hit rate = 77%
- Critical success index =77%

- We missed mainly riparian areas (which we classified in another class, e.g. the aquatic type of GDE).
- The simplified geological model may also be the reason, see e.g. the northern part of Great Artesian basin.

A better geological model (HYGS, working progress)

- Global 30'' (1km * 1km) grid
- Split geology into (at least) 3 main layers
  - Unconsolidated sediments
  - Sedimentary rocks (differentiate siliclastic vs karstic) – CRUST 1.0
  - Fractured igneous and metamorphic rocks
  - Max thickness (10km?)
- Define geometry (thickness - θ) of these layers in each 1km cell





W - E Sector
Elevation (m asl.)
Distance form pixel centre (km)
SW - NE Sector
Elevation (m asl.)
Distance form pixel centre (km)
N - S Sector
Elevation (m asl.)
Distance form pixel centre (km)
W - E Sector
Elevation (m asl.)
Distance form pixel centre (km)
5080076980
5080055970
5080055960
5080055980
5080076990
83.275
33.2071
95.6
SU bot elev ALL
<= -612.0359
-612.0359 - -260.0207
-260.0207 - -164.0166
-164.0166 - -100.0138
> -100.0138

Conclusions

- We successfully implemented the GLOBGM,
  a transient, global groundwater model at 30” (1 km) resolution
- Using parallel pre-processing and parallel MODFLOW 6,
  we demonstrated the effectiveness of our parallelization
- A relatively limited number of cores were required on Snellius (~384 cores)

- From our limited evaluation for the CONUS, we conclude that:
  - The 30″ steady-state results are better than the 5’ results
  - Transient results are comparable to the 5’ results
  - In general, there is much room for further model improvement:
    e.g. geology could be improved, and parameters such as well abstraction rates and locations