Deep learning shows declining groundwater levels in Germany until 2100 due to climate change

Andreas Wunsch¹, Tanja Liesch¹, Stefan Broda²

¹KIT, ²BGR
Current Situation in Germany

- Germany is generally water rich\(^1\)
  - water availability per year: 188 billion m\(^3\)
  - less than 13% are used
- 70% of drinking water supply from GW and springs\(^2\)
- Hot and dry summers in recent years (esp. 2018-2020)
  - ongoing exceptional droughts (few recharge and declining groundwater levels)
  - severe consequences for agriculture and ecology

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1 UBA, 2020
2 DESTATIS, 2016
Long-Term Climate

Simulation of groundwater levels based on climate projection ensemble:
- 118 sites all over Germany
- RCP2.6, RCP4.5, **RCP 8.5 ("business as usual")**
- 5-6 bias corrected and downscaled projections (5x5 km²) per scenario
- 80%-90% of total ensemble spread covered by selected models

Until 2100:
- Total annual precipitation (left): no trend or slight increase except for one projection
- Annual avg. Temperature (right): substantial increase
Methods: Model building

1. Site-specific **1D-CNN Models** to predict GWL using (only) P and T

2. **Train, optimize and validate** Models in the past (observed climate data), select highly performing models

3. **Plausibility checks** (artificial extreme climate scenario (T + 5°C, P x 4) and SHAP values)
Limitations and Assumptions

- Highly Performing Models in the past
  - sites mainly influenced by climate
- Only climatic influences are taken into account
- Basic input-output relationships remain unchanged
- Secondary, mainly anthropogenic effects are neglected!
- We simulate **direct** climate change effects on GW
Results: Individual Site, 6 different results

Individual projection results 2070-2100 (partly diverging)

Simulations of complete period as heatmap

Annual cycle
Results: Individual Site, 6 different results

Wet periods (blue): shorter and less wet
Dry periods (red): longer and drier

Especially critical: Succession of several dry years

Upper part of annual cycle does not necessarily decrease in absolute height (blue tones remain)
Results: linear trend analyses

Significant (p<0.05) relative changes [%] until 2100 - compared to 2014 (start of sim.) and normalized on individual historic range.

Linear trend is based on Mann-Kendall test and Theil-Sen slope.
Results: Annual Mean

Significant (p<0.05) relative changes [%] until 2100 - compared to 2014 (start of sim.) and normalized on individual historic range;

- 54% significant trends (p<0.05)
- different developments depending on projection
  → median change between -23% (p1) and -6.6% (p6)
  → absolute numbers: -0.1 m to -0.4 m
- more and stronger negative trends in northern and eastern Germany
- some opposite trends at single sites

Linear trend is based on Mann-Kendall test and Theil-Sen slope

Significant Relative Changes of the Mean in 2100 (p < 0.05)
Results: Annual 2.5% Quantile

- 64% significant trends
- all but one single result: downward trends
- trends down to -81%
- median changes (depending on the projection) between:
  - -38% and -10%
  - absolute: -0.1 m to -0.7 m
Results: Annual 97.5% Quantile

- >70%: non-significant
- also increasing trends up to 20%
- clear spatial pattern: constant or increasing trends except eastern Germany (declining trends)
- Opposing trends compared to other quantiles → increasing variability
Summary

- Clear tendency of declining groundwater levels until 2100 in Germany
- Emphasized existing trends: stronger declines in eastern Germany
- Absolute values mostly seem small: order of tens of centimeters
  - nevertheless critical
  - amplified by secondary factors (only direct influence projected)
- Only linear trends: obscured patterns of successive dry years, likely to have serious consequences
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- [https://github.com/AndreasWunsch](https://github.com/AndreasWunsch)
- [https://www.linkedin.com/in/andreaswunsch/](https://www.linkedin.com/in/andreaswunsch/)
- [https://hydro.agw.kit.edu/21_172.php](https://hydro.agw.kit.edu/21_172.php)
- [https://www.researchgate.net/profile/Andreas-Wunsch](https://www.researchgate.net/profile/Andreas-Wunsch)
- ORCID: 0000-0002-0585-9549

Email: andreas.wunsch@kit.edu