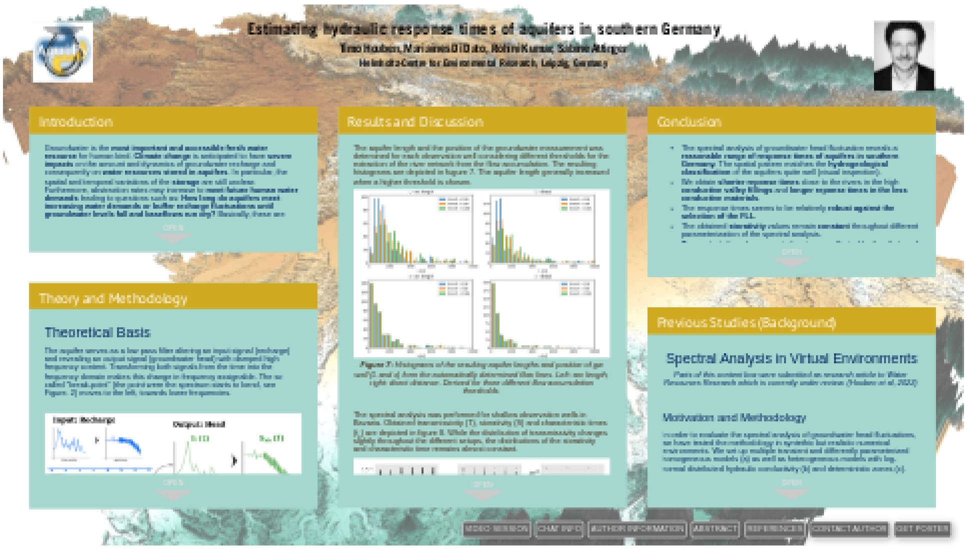
Estimating hydraulic response times of aquifers in southern Germany



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PRESENTED AT:

INTRODUCTION

Groundwater is the **most important and accessible fresh water resource** for human kind. **Climate change** is anticipated to have **severe impacts** on the amount and dynamics of groundwater recharge and consequently on **water resources stored in aquifers**. In particular, the spatial and temporal variations of the **storage** are still unclear. Furthermore, abstraction rates may increase to **meet future human water demands** leading to questions such as: **How long do aquifers meet increasing water demands or buffer recharge fluctuations until groundwater levels fall and baseflows run dry?** Basically, these are questions about hydrological response times of aquifers!

The **aquifer response time t_c of hydrogeological systems** has been widely used, is well known in hydrogeology and describes the temporal response of the aquifer towards perturbations. It depends on aquifer properties such as **transmissivity**, **storativity** as well as on the **length the signal has to travel**. The interpretation of transient pumping tests give e.g. estimates of local response times.

In this work, we focus on **response times** of **regional aquifer systems** making use of spectral analysis of groundwater head time series and determine the response time with the help of **semi-analytical solutions** and transfer functions for the spectral domain. We hypothesize that the spectral approach can be used to infer **regionally valid and reliable aquifer response times** with the aim to estimate the vulnerability of groundwater resources against changing climatic conditions.

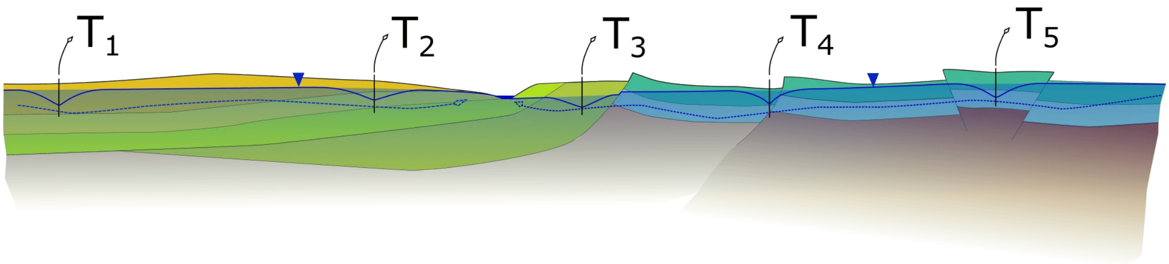


Figure 1: *Schematic represantation of a heterogeneous, layered aquifer. Each groundwater observation well reveals a different transmissivity value when investigated via classical pumping tests but the regional information content of each time series can only be revealed without disturbing the natural fluctuations, i.e. with the spectral analysis.*

THEORY AND METHODOLOGY

Theoretical Basis

The aquifer serves as a low pass filter altering an input signal (recharge) and revealing an output signal (groundwater head) with damped high frequency content. Transforming both signals from the time into the frequency domain makes this change in frequency assignable. The so called "break-point" (the point were the spectrum starts to bend, see Figure. 2) moves to the left, towards lower frequencies.

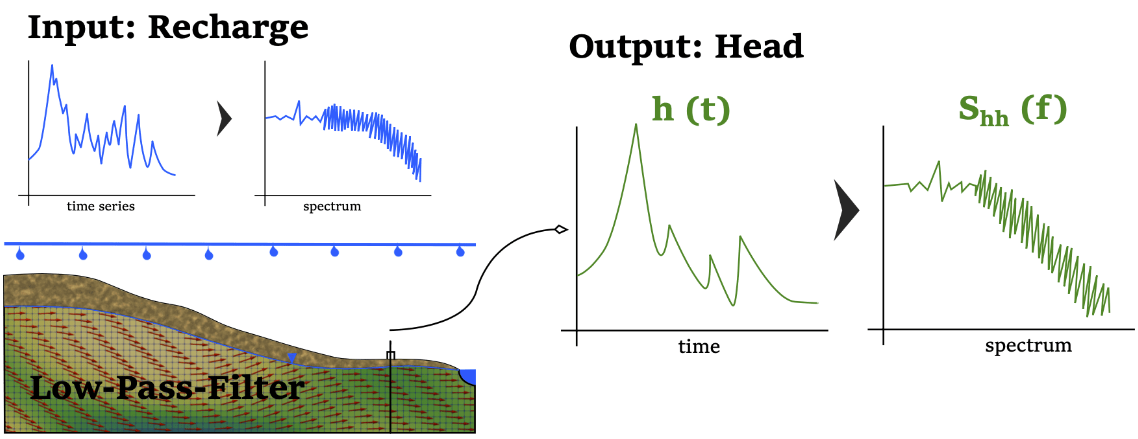
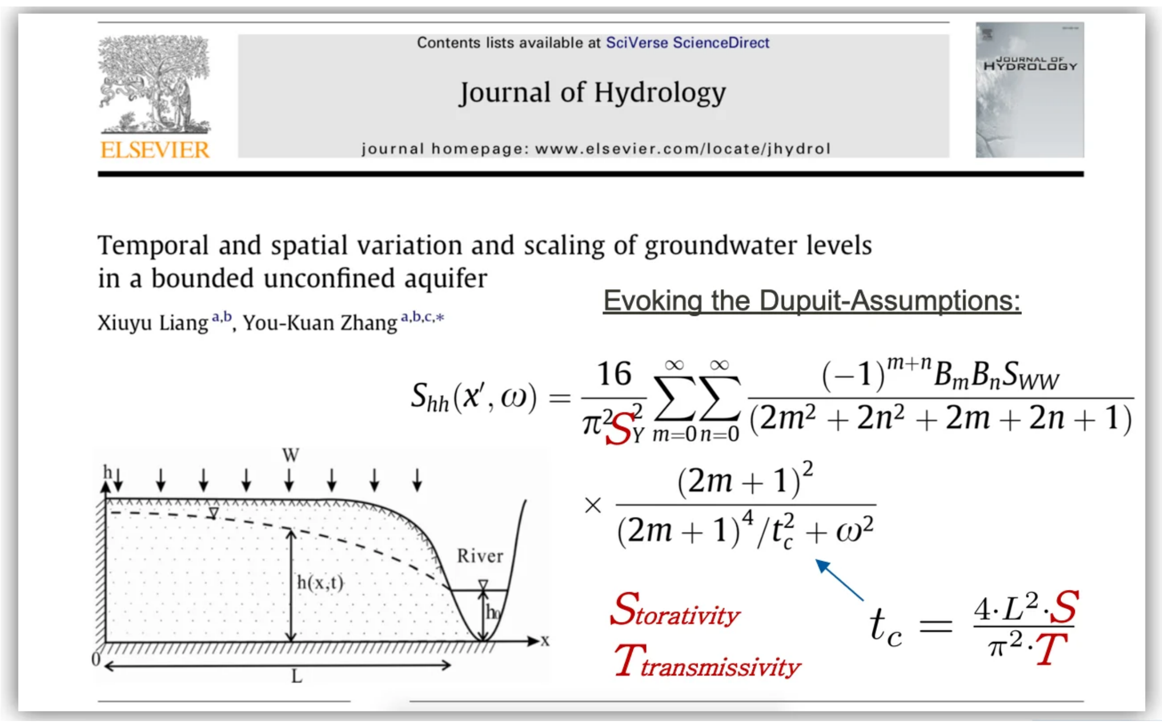


Figure 2: *Schematic representation of a signal filtered by an aquifer. The aquifer serves as a low pass filter and eleminetes the high frequency content of the signal.*

The strength of the filter depends on the magnitude of the properties such as the transmissivity (T) and storativity (S) of the aquifer. Liang and Zhang (2013) derived a semi-analytical solution for the head spectrum including these parameters. We use this equation, fit it to the power spectrum of measured head time series and optimize the parameters T and S as well as the response time (= characteristic time) t_c.



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ELSEVIER

Temporal and spatial variation and scaling of groundwater levels in a bounded unconfined aquifer

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Evoking the Dupuit-Assumptions:

$$S_{hh}(x',\omega) = \frac{16}{\pi^2 S_Y^2}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{(-1)^{m+n}B_m B_n S_{WW}}{(2m^2+2n^2+2m+2n+1)} \times \frac{(2m+1)^2}{(2m+1)^4/t_c^2+\omega^2}$$

Storativity

Ttransmissivity

$$t_c = \frac{4 \cdot L^2 \cdot S}{\pi^2 \cdot T}$$

Figure 3: *The publication from Liang and Zhang (2013) and their analytical solution of the head spectrum based on a linearized Boussinesq equation.*

In our previous studies, we have shown that the determined aquifer parameters by spectral analysis contain regional information of the aquifer system under investigation (see box "Previous Studies"). Here, we select several hundred groundwater head time series from shallow wells and present groundwater response times for the southern part of Germany.

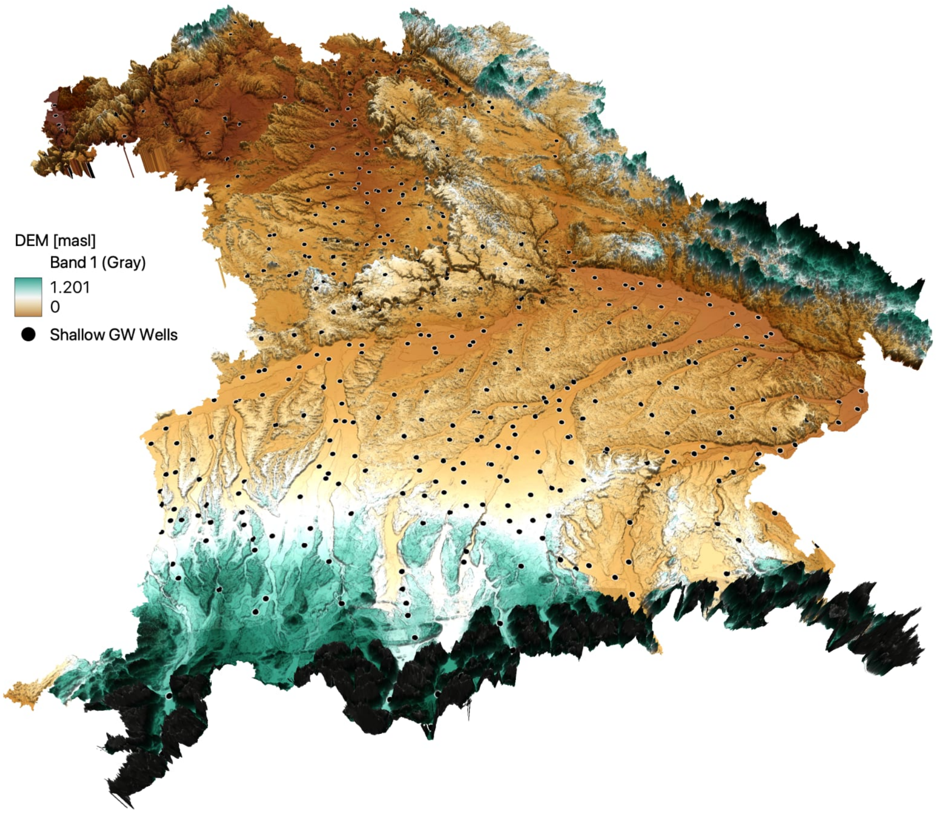

Figure 4: *3D tilted view of the state of Bavaria (southern Germany) with a digital elevation model and the shallow groundwater observation wells. The groundwater data is freely available under license CC BY 4.0 and was downloaded from the online service of the Bavarian State Office for the Environment (https://www.gkd.bayern.de/de/grundwasser/oberesstockwerk).*

Methodological Workflow

In order to be able to optimize the analytical solution for T, S and t_c we need to provide L and x, i.e. the length of the aquifer and the position of the groundwater measurement. Since we want the methodological procedure to be operated almost automatically, we determine the parameters L and x via an algorithm. Based on a DEM (digital elevation model) the flow direction is calculated. Starting at the location of the groundwater observation well the path of the water particle is traced in upgradient and downgradient direction. The algorithm takes the flow direction of each cell and follows it downgradient till it reaches a river and vice versa, i.e. upgradient till it reaches a plateau. The river is derived from a flow accumulation map based on a user defined threshold.

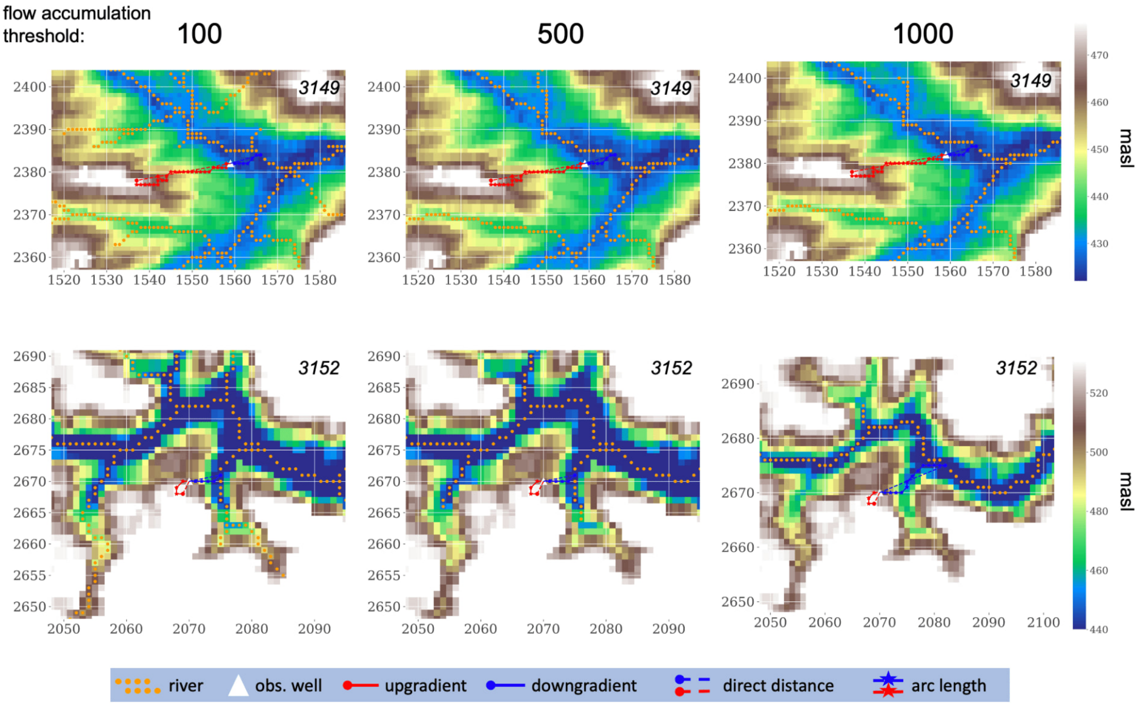

Figure 5: *Results of the automatic flow line length (FLL) determination for two groundwater wells and different thresholds of flow accumulation, depicted on top of a digital elevation model (SRTM, resolution: 30 m). X and Y coordinates represent the cell index (not spatial coordinates). Top: groundwater well 3194, bottom: groundwater well 3152.*

The groundwater head time series of the observation wells are transformed into the frequency domain and the power spectrum of heads are obtained (S_{hh}). The analytical solution is fitted to the head spectrum (S_{hh_fit}).

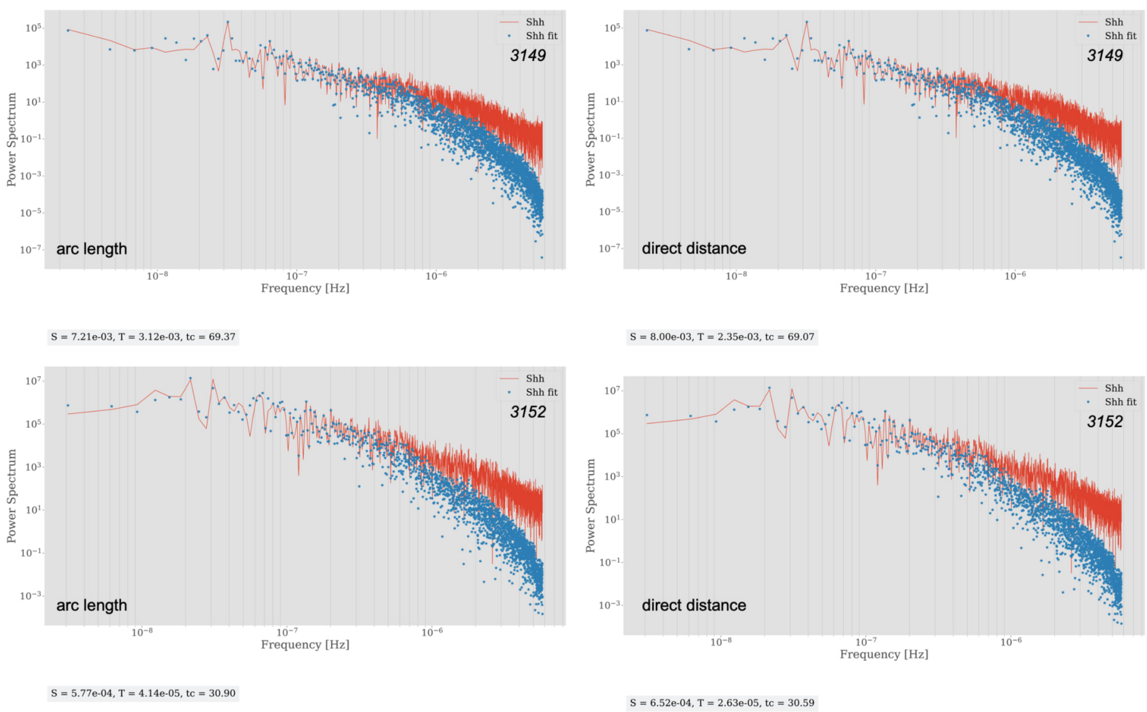

Figure 6: *Observed and fitted spectrum of two observation wells for the arc length and the direct distance of the FLL. Optimzed aquifer parameters T, S and t_c are added below each figure.*

RESULTS AND DISCUSSION

The aquifer length and the position of the groundwater measurement was detemined for each observation well considering different thresholds for the extraction of the river network from the flow accumulation. The resulting histograms are depicted in fugure 7. The aquifer length generally increased when a higher threshold is chosen.

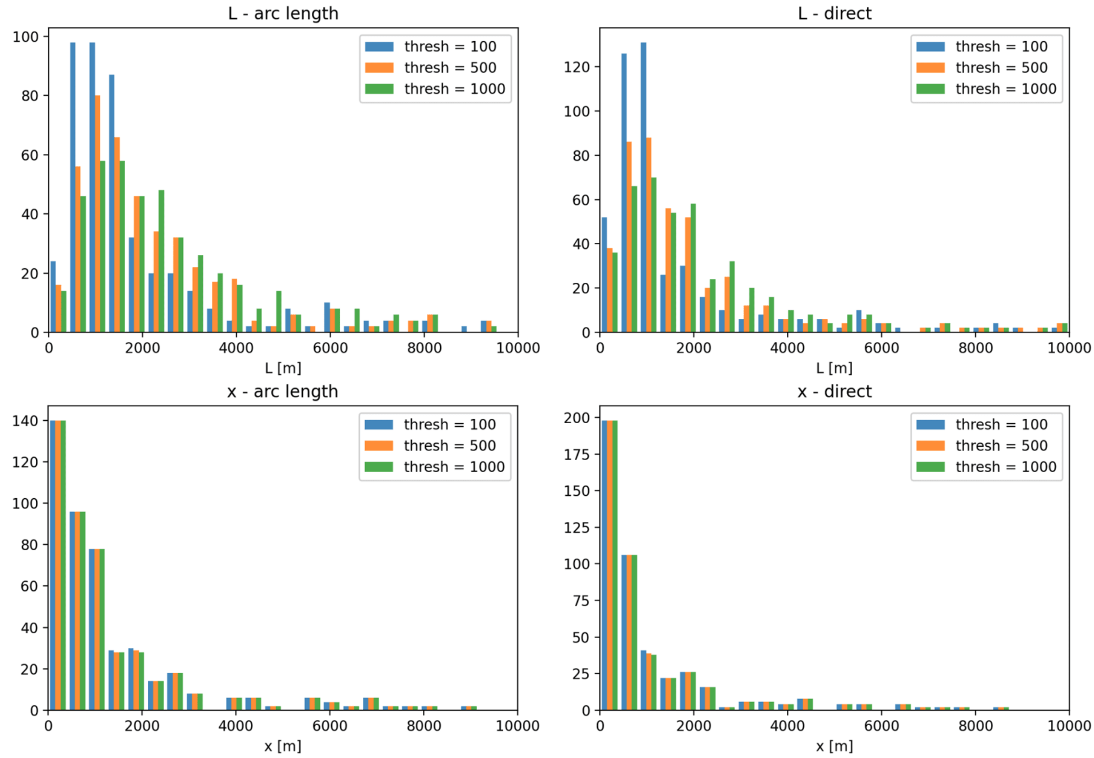

Figure 7**:** *Histograms of the resulting aquifer lengths and position of gw well (L and x) form the automatically determined flow lines. Left: arc length, right: direct distance. Derived for three different flow accumulation thresholds.*

The spectral analysis was performed for shallow observation wells in Bavaria. Obtained transmissivity (T), storativity (S) and characteristic times (t_c) are depicted in figure 8. While the distribution of transmissivity changes sightly throughout the different setups, the distributions of the storativity and characteristic time remains almost constant.

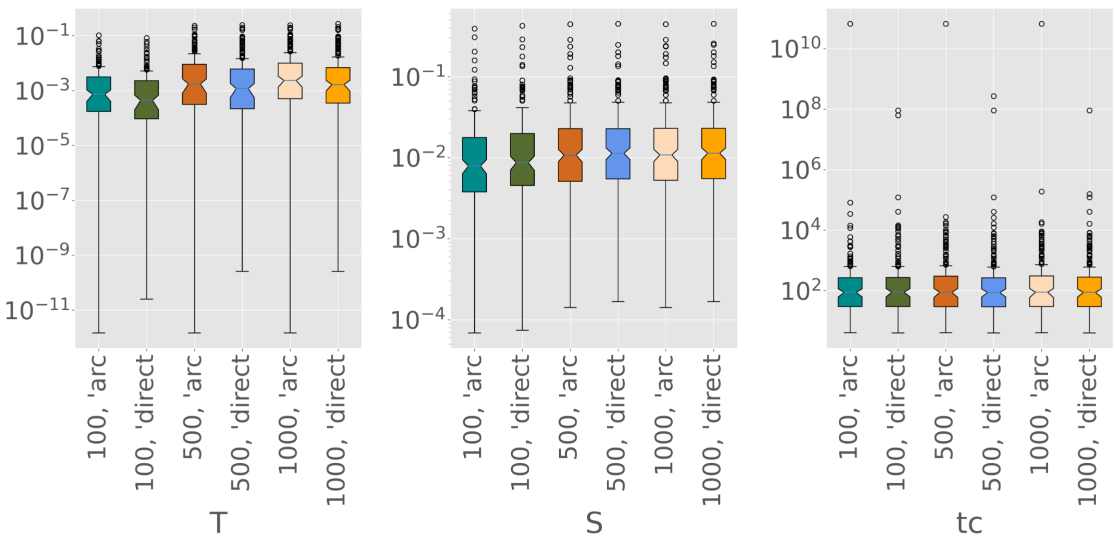

Figure 8: *Resulting optimized transmissivity (T), storativity (S) and characteristic times (t_c) for ~ 200 observation wells in Bavaria obtained from FLL based on different flow accumulation thresholds and distances (arc length vs direct distance).*

The spaital distribution of tc is depicted in figure 9. Most of the observation wells show response times in the range of a few to 100 days, in some areas up to 300 - 400 days. Some outliers have response times up to a few years.

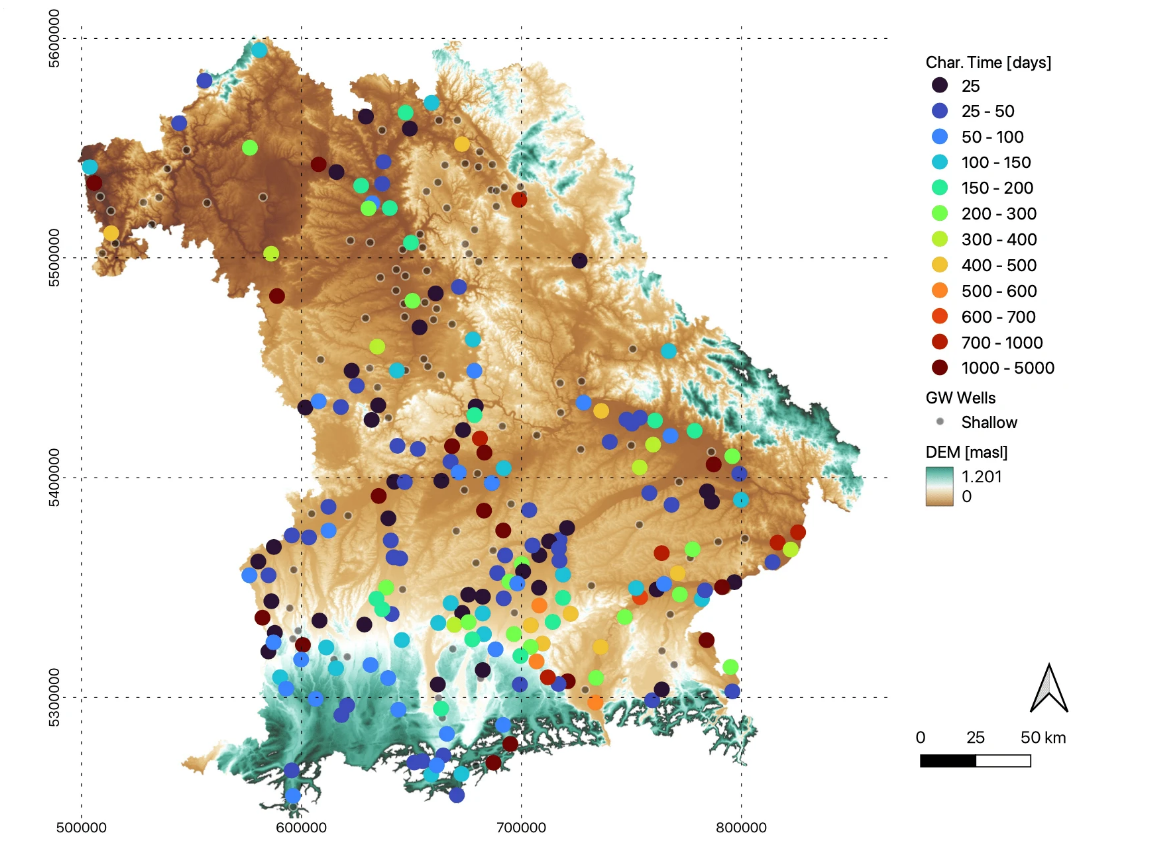

Figure 9: *Spatial distribution of t_c in Bavaria plotted for every observation well (threshold 1000, direct distance). Grey dots mark locations where the spectral analysis failed (e.g. because of to short observation period).*

In addition to the characteristic time also the transmissivity and storativity where plotted on a map. The storativity is spatially relatively constant whereas the transmissivity in the south is roughly 1-2 orders of magnitude higher than in the north.

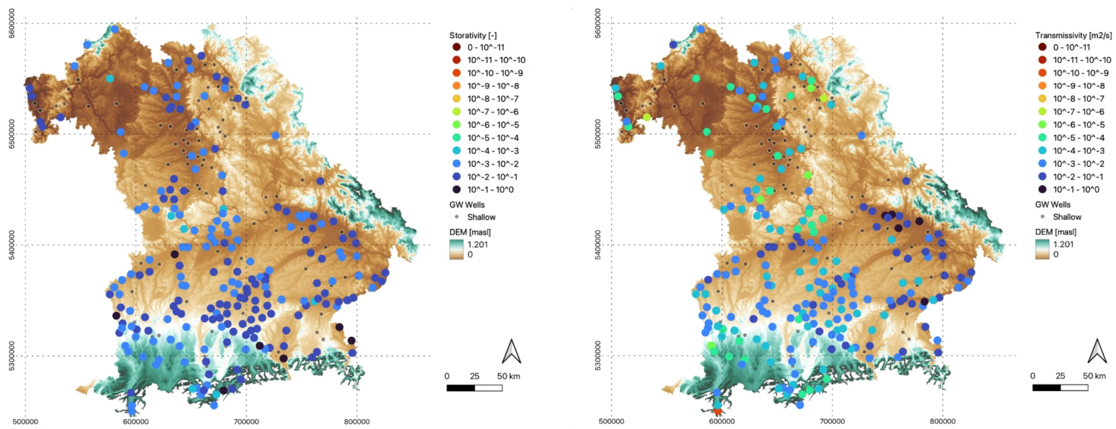

Figure 10: *Obtained storativities (left) and transmissivities (right) from the spectral analysis (threshold 1000, direct distance).*

The response times plotted on a map with approximate hydraulic conductivities of the rocks on the surface. Higher conductive materials seem to have shorter response times than lower conductive materials.

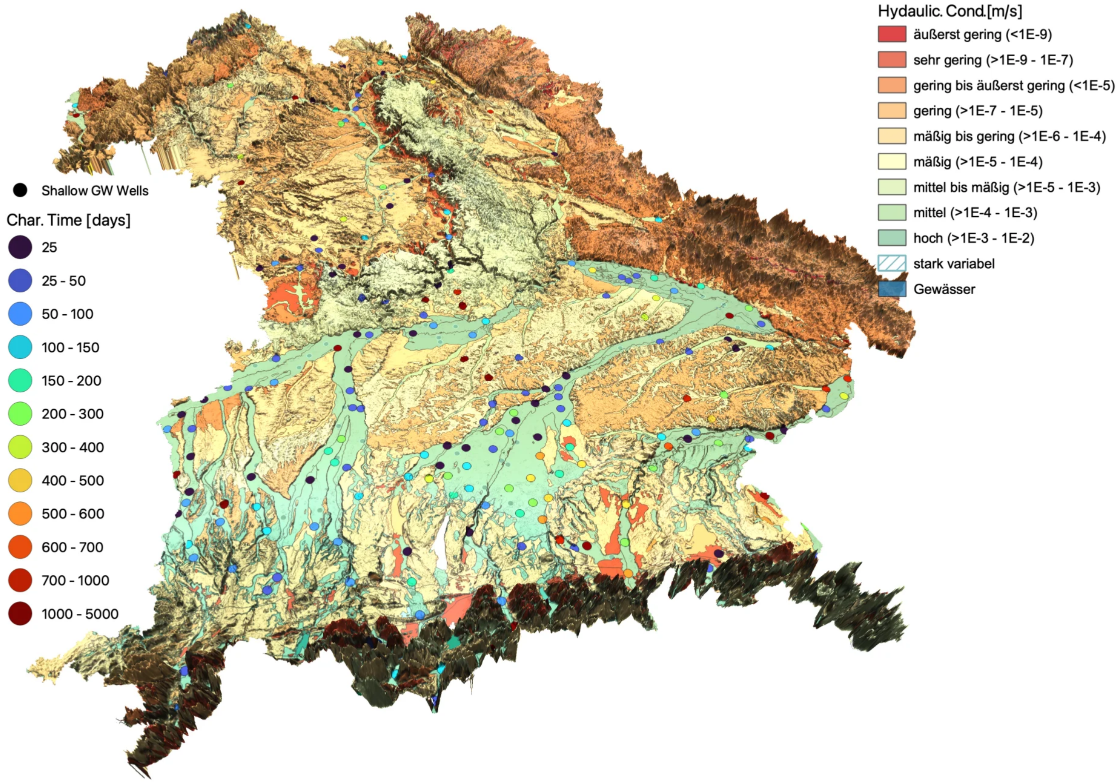

Figure 11: *Characteristic times plotted on a 3D map of Bavaria (SRTM based) which is colored according to the hydraulic conductivity (threshold 1000, direct distance). The values where taken from the hydrological overview map of Germany (HUEK 200, BGR, https://produktcenter.bgr.de/terraCatalog/Start.do).*

To visualize the correlation of the obtained transmissivity values to the hydraulic conductivity values from the Federal Institute for Geosciences and Natural Resources, we have plotted them on the same map as the response times.

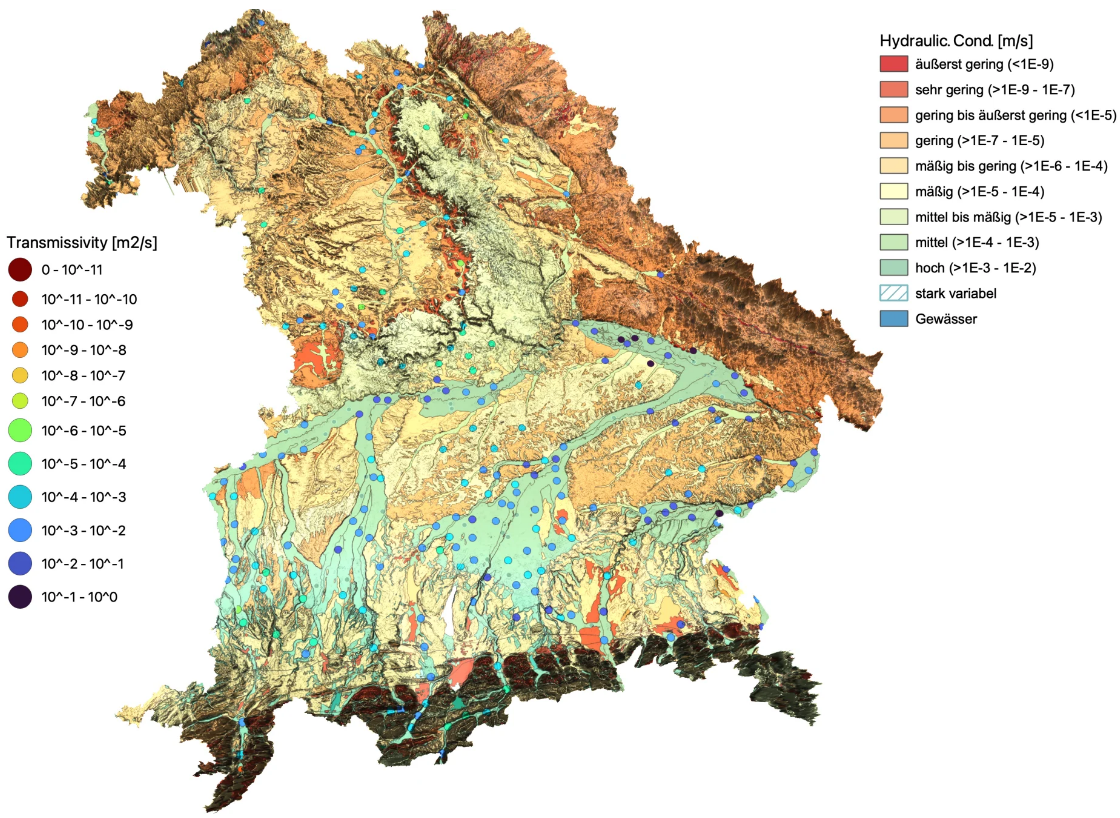

Figure 12: *Transmissivity plotted on a 3D map of Bavaria (SRTM based) which is colored according to the hydraulic conductivity (threshold 1000, direct distance). The values where taken from the hydrological overview map of Germany (HUEK 200, BGR, https://produktcenter.bgr.de/terraCatalog/Start.do).*

CONCLUSION

- The spectral analysis of groundwater head fluctuation reveals a **reasonable range of response times of aquifers in southern Germany.** The spatial pattern matches the **hydrogeological classification** of the aquifers quite well (visual inspection).
- We obtain **shorter reponse times** close to the rivers in the high **conductive valley fillings** and **longer reponse times in the less conductive materials**.
- The response times seems to be relatively **robust against the selection of the FLL**.
- The obtained **storativity** values remain **constant** throughout different parameterization of the spectral analysis.
- **Transmissivity** values seem to be stronger affected by the **choice** of the **FLL** but generally **follow the spatial distribution of hydraulic conductivity values**.
- Further statistical evaluations are required in order to proof the **significance of correlation** of different **environmental features** and the results of the spectral analysis.

Outlook

- in depth statistical correlation analysis of different features (**geology, time series length, soil map, hydraulic conductivity, aquifer type, etc.**) in relation to the target features T, S and t_c to validate the results of the spectral analysis
- **spatial correlation analysis** of T, S and t_c
- **machine learning supported analysis** for ungauched aereas

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The scientific results have (in part) been computed at the High-Performance Computing (HPC) Cluster EVE, a joint effort of both the Helmholtz Centre for Environmental Research - UFZ (http://www.ufz.de/) and the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig (http://www.idiv-biodiversity.de/).

PREVIOUS STUDIES (BACKGROUND)

Spectral Analysis in Virtual Environments

Parts of this content box were submitted as research article to Water Resources Research which is currently under review. (Houben et al, 2022)

Motivation and Methodology

In order to evaluate the spectral analysis of groundwater head fluctuations, we have tested the methodology in syntethic but realistic numerical environments. We set up multiple transient and differently parameterized homogeneous models (a) as well as heterogeneous models with log-normal distributed hydraulic conductivity (b) and deterministic zones (c).

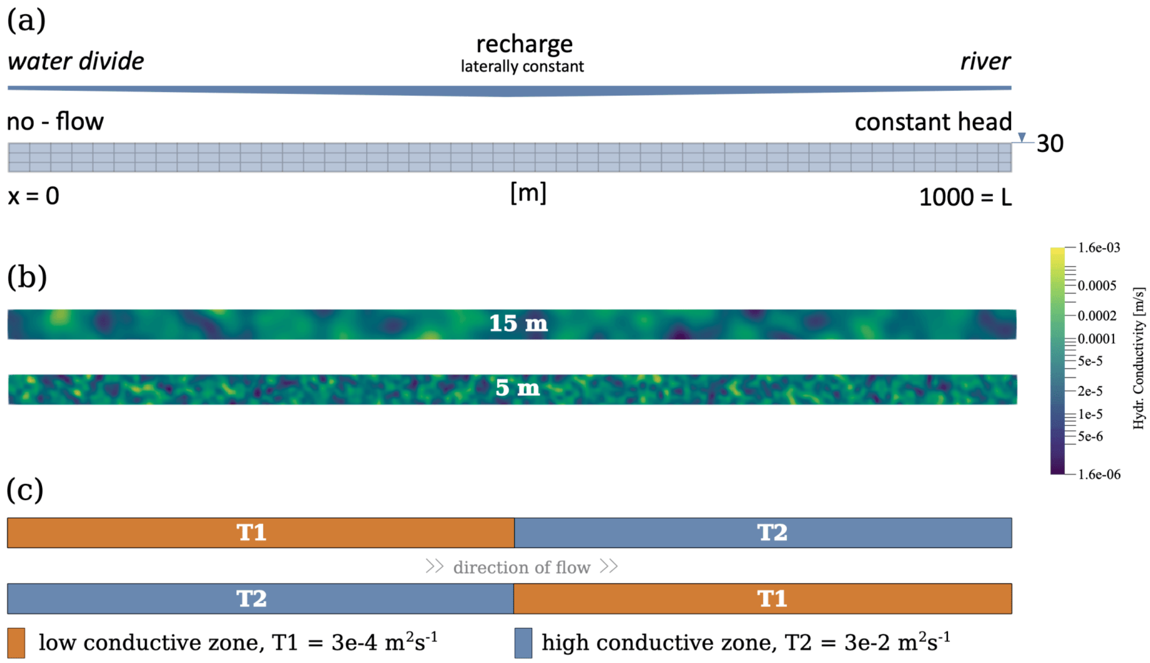

Figure 13: *(a) Aquifer geometry, forcing and boundary conditions for all setups (b) One realization of each correlation length of an isotropic, log-normally distributed hydraulic conductivity field generated from a Gaussian covariance model with variance 1. Top: 15 m, bottom: 5 m correlation length. (c) Deterministic block aquifer with two zones of hydraulic conductivity. The position of the boundary between the zones was varied throughout the investigation.*

Results and Conclusion

We compared the model input parameters with the results of the spectral analysis of the transient groundwater head fluctuations from the numerical model. In the homogeneous models we were able to match the model input parameters almost exactly for different parameterizations as long as the duration of the observation (modelling period) is long enough.

The analysis of 200 realizations of a stochastic aquifer showed a small variance in the derived aquifer parameters for locations far away from the river. When approaching the river, the variance increased.

Performing the spectral analysis in deterministic aquifers revealed the regional component of the groundwater head signal. Comparing the model input parameters with the results of the spectral analysis a deviation could be identified. This deviation is related to the gradient of the adjacent zones. Transmissivities in a low conductive zone was influenced by the adjacent high conductive zone and vice versa.

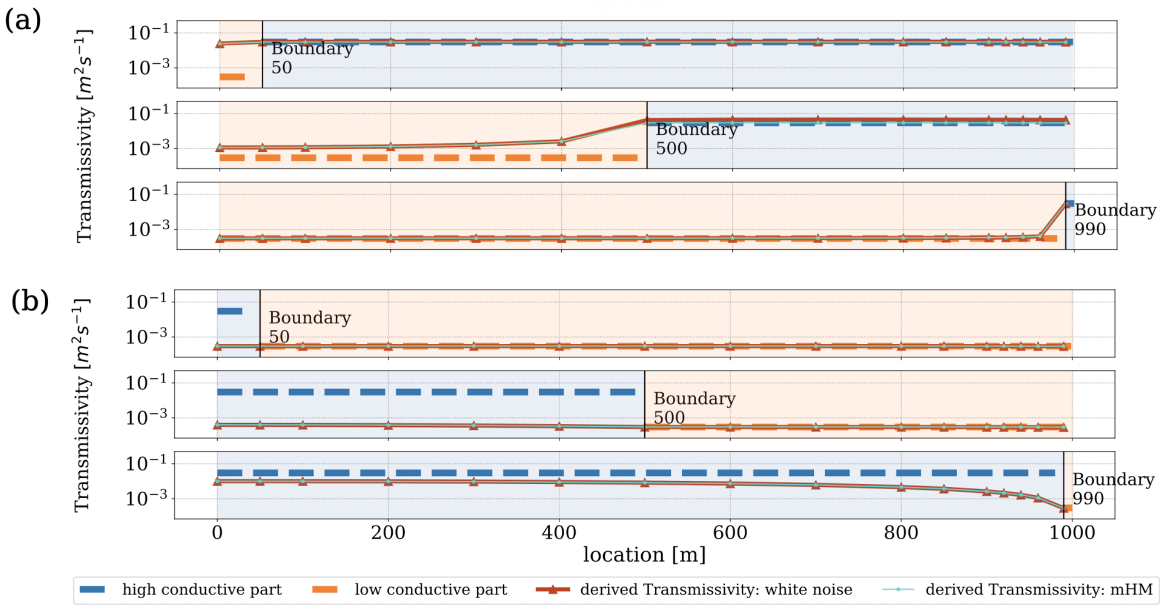

Figure 14: *Input (numerical model) and output (spectral analysis) transmissivity for six different deterministic aquifers. A white noise and a realistic, temporally correlated recharge generated by mHM was assigned to the numerical model. a) A low conductive zone in the upstream part of the aquifer and a high conductive zone at the outlet. b) A high conductive part upstream and a low conductive part downstream.*

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ABSTRACT

Groundwater is the most important and accessible fresh water resource for human kind. Climate change is anticipated to have severe impacts on the amount and dynamics of groundwater recharge and consequently on water resources stored in aquifers. In particular, the spatial and temporal variations of the storage are still unclear. Furthermore, abstraction rates may increase to meet future human water demands leading to questions such as: How long do aquifers meet increasing water demands or buffer recharge fluctuations until groundwater levels fall and baseflows run dry? Basically, these are questions about hydrological response times of aquifers!

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In our previous studies, we have shown that the determined aquifer parameters by spectral analysis contain regional information of the aquifer system under investigation. Here, we select several hundred groundwater head time series from shallow and deeper wells and present groundwater response times for the southern part of Germany. Based on these response times we evaluate the aquifer's capability to buffer the impact of groundwater recharge dynamics under climate change.

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