Can we characterize groundwater reservoirs in central Europe from air-pressure-induced seismic velocity changes?

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Abstract

Given the increasing challenges posed by climate change, especially more frequent and severe droughts experienced globally, effective exploration and management of groundwater resources is essential to ensure a sustainable and resilient society. As part of this effort, it is necessary to acquire a comprehensive knowledge of the distribution of significant and readily accessible fresh water reservoirs on all continents. This outlines the critical need for an efficient and cost-effective imaging method to assess this vital resource. In response, we propose a novel imaging method that utilizes observations of air-pressure-induced seismic velocity changes. As demonstrated in my recent study (Kramer et al., 2023), atmospheric tides and their interaction with the groundwater body are the primary cause of sub-daily seismic velocity changes. Analyzing these velocity changes can reveal valuable information on the hydro-physical properties of the underlying groundwater body. Building on this knowledge, we introduce this imaging method and apply it to the seismic data collected across South and Central Europe.

Sub-Daily dv/v: A proxy for inferring groundwater property

In Kramer et al. (2023), we used passive noise monitoring techniques to investigate the daily and sub-daily seismic velocity variations in the shallow subsurface (southern Germany). The resulting **spectra of the velocity time series** (see **Fig. 1**) show **strong daily and sub-daily behavior.** To some extent, we confirmed the observations and proposed driving forces from earlier studies on short-term seismic velocity variations. In contrast, we **did not observe** a significant **influence of Earth's tides**. Instead, we found a **strong influence of atmospheric tides (atmospheric pressure variations)** on the behavior of seismic velocity variations. We also noted the influence of temperature changes on daily variations, but as a second-order effect. Our proposed explanatory model focuses on the **depth variations of groundwater table** (**Fig. 2**) in response to atmospheric loading and de-loading, linking **atmospheric tides** to **variations in seismic velocity**.

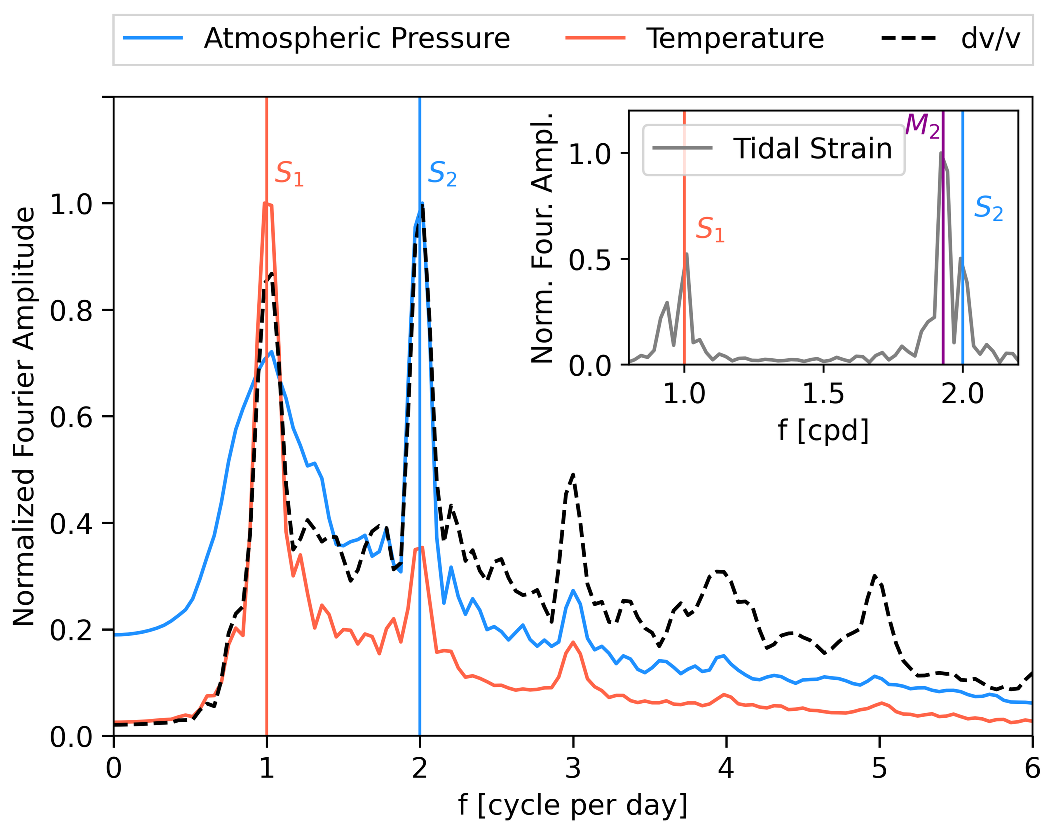

Fig. 1 Spectra of atmospheric pressure (blue line), temperature (red line), and *dv/v* (black dashed line). The inset shows the spectrum of the theoretically determined tidal strain. Vertical lines indicate the main periods in the spectrum of different effects.

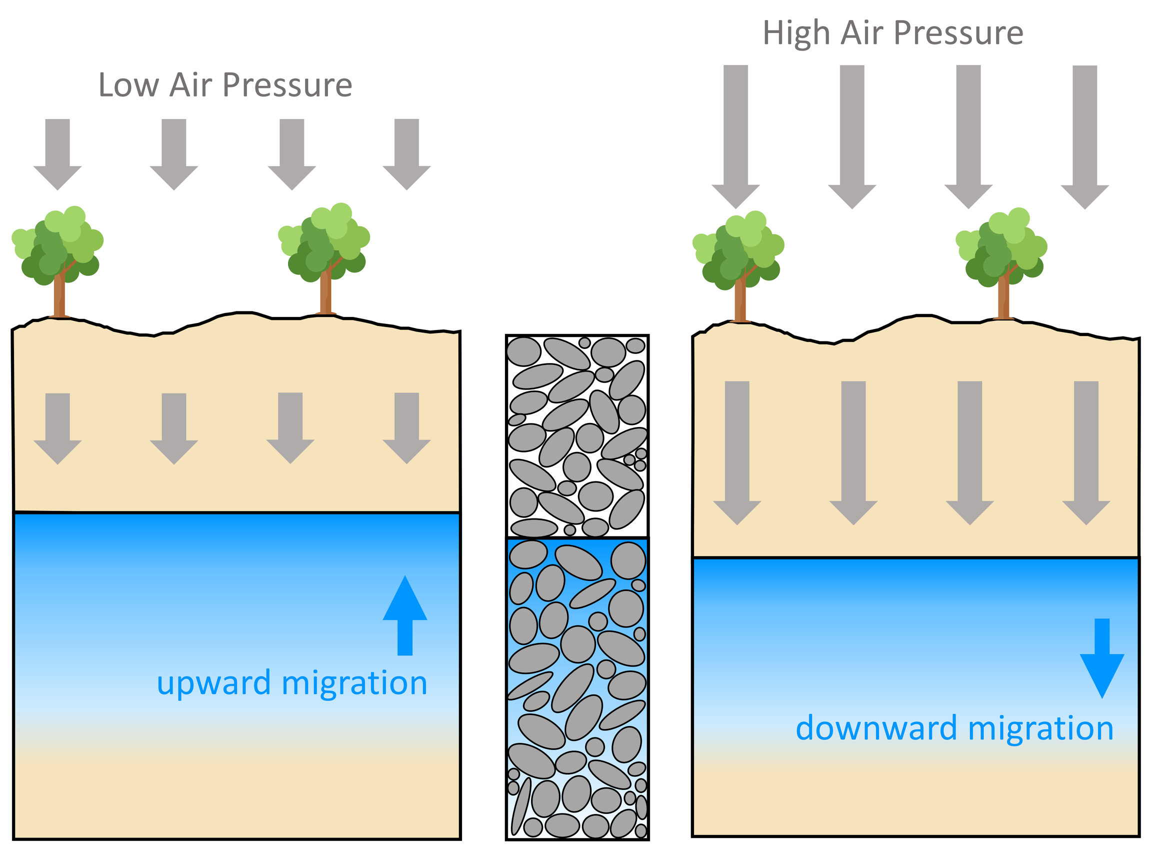

Fig. 2 Schematic representation of the interaction of atmospheric pressure and water table depth. The illustration in the middle shows the pores of the different layers.

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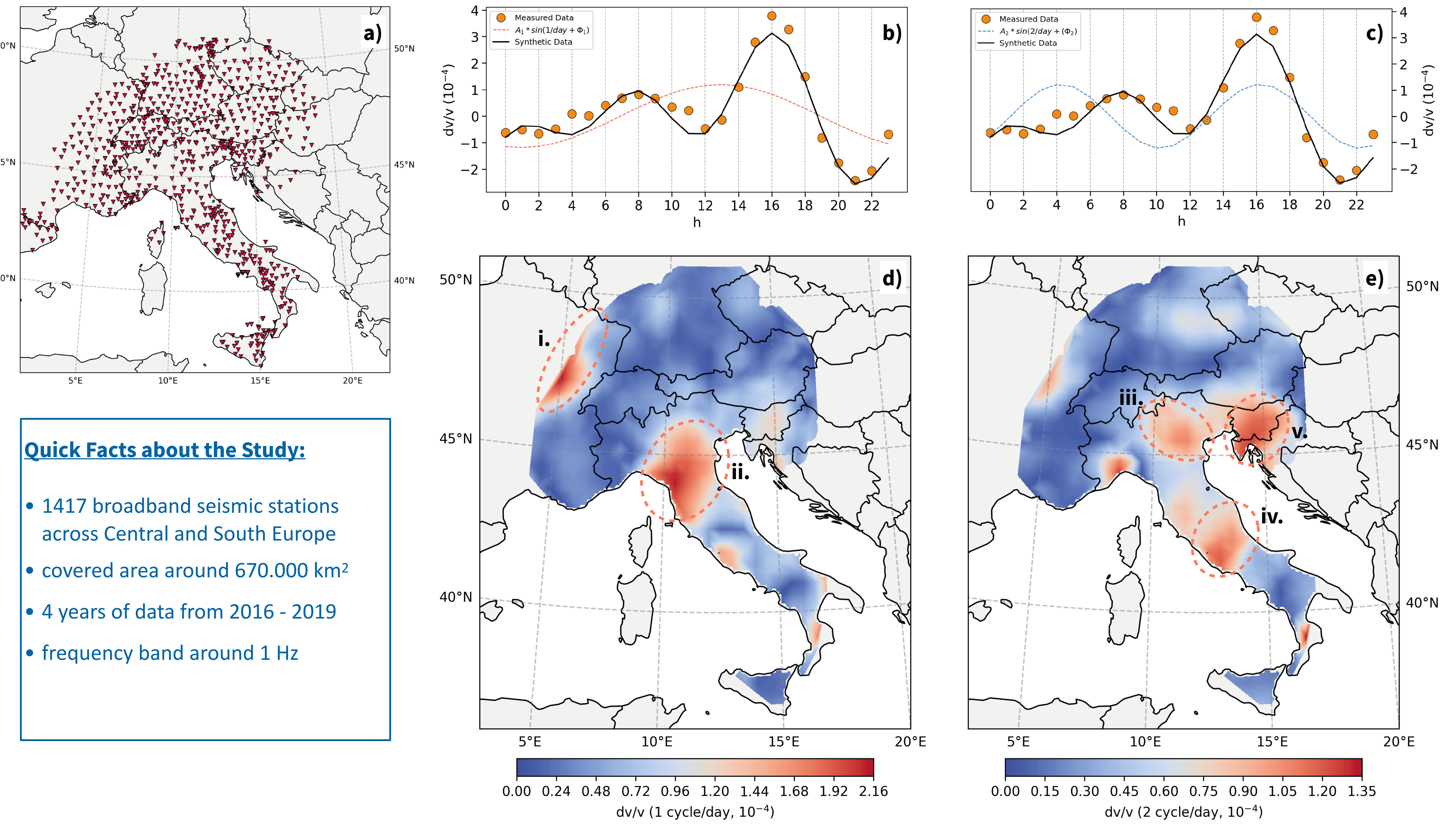
Our findings demonstrated a **strong influence of water/fluids on *dv/v***. While the atmospheric driving force remains similar over a given region, any observed spatial variations in the strength of sub-daily dv/v changes can be primarily attributed to variations in the hydro-physical properties of the groundwater body. This may open up **new perspectives in groundwater geophysics**, for instance, in the characterization of aquifer and geothermal reservoirs. The method benefits from its non-intrusive nature and the possibility to apply it on any spatial scale of interest, provided that seismic sensors are distributed over that scale.

We examine this concept using a large seismic dataset collected from South-Central Europe. The primary objective is twofold. Firstly, we aim to further validate our proposed model for seismic velocity changes on the daily and sub-daily timescales, which we developed based on the analysis of a local array in southern Germany. Secondly, we seek to build a **robust workflow** capable of **imaging and potentially monitoring groundwater resources at the regional scale.** To that end, we will explore a number of methods. Initially, we will assume that the **daily and sub-daily behavior of *dv/v*** follows **similar patterns every day**, **like their driving forces**. This allows us to focus on the *dv/v* of each hour of the day.

Application to Central and South Europe

We used broadband seismic stations distributed over Central and South Europe (see **Fig. 3a**). In a first step, for each station pair, we stacked correlations for each hour of a day over the four-year period of data analysis (24 hourly correlations for each station pair). We measured the relative seismic velocity (*dv/v*) change associated with every hour. The mean *dv/v* changes over all station pairs (see **Fig. 3b/3c** orange dots) clearly shows the expected one-cycle-per-day (S_1; **Fig. 3 b** red line) and two-cycle-per-day (S_2; **Fig. 3 c** blue line) components. The spatial distribution of the strength of the two components S_1 and S_2 are shown in **Fig. 3d** and **3e**.



Quick Facts about the Study:

- 1417 broadband seismic stations across Central and South Europe
- covered area around 670.000 km²
- 4 years of data from 2016 - 2019
- frequency band around 1 Hz

Fig. 3 a) Map of used stations for the study. **b)** Average over all measured station pairs (orange dots), the one-cycle-per-day fit (red dashed line), and the synthetic data (black) after fitting the main frequencies. **c)** Average over all measured station pairs (orange dots), the two-cycle-per-day fit (blue dashed line), and the synthetic data (black line) after fitting the main frequencies. **d)** Spatial distribution of the S_1 amplitude. **e)** Spatial distribution of the S_2 amplitude.

The spatial distribution of S_1 shows two areas with high amplitudes (red dashed lines). One is close to the Vosges mountains (**i**) the other one in the northernmost parts of the Apennines (**ii**). The S_2 shows significant amplitudes (red dashed lines) in the Po Plain (**iii**) and the two Karst areas south of Rome (**iv**) and in Slovenia and northern Croatia (**v**).

Perspectives

Our results (S_2) appear to be particularly sensitive to areas with significant karstification and abundant groundwater resources. Using this study as a starting point, we plan to investigate the temporal evolution of seismic patterns over longer time spans and develop a routine monitoring workflow. We wish to connect with climatologists and hydrogeologists for exploring the implications of these results. The success of this application will shed light on its general applicability in other regions with similar seismic array settings.

References

Kramer, R., Lu, Y., & Bokelmann, G. (2023). Interaction of air pressure and groundwater as main cause of sub-daily relative seismic velocity changes. Geophysical Research Letters, 50, e2022GL101298. https://doi.org/10.1029/2022GL101298

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