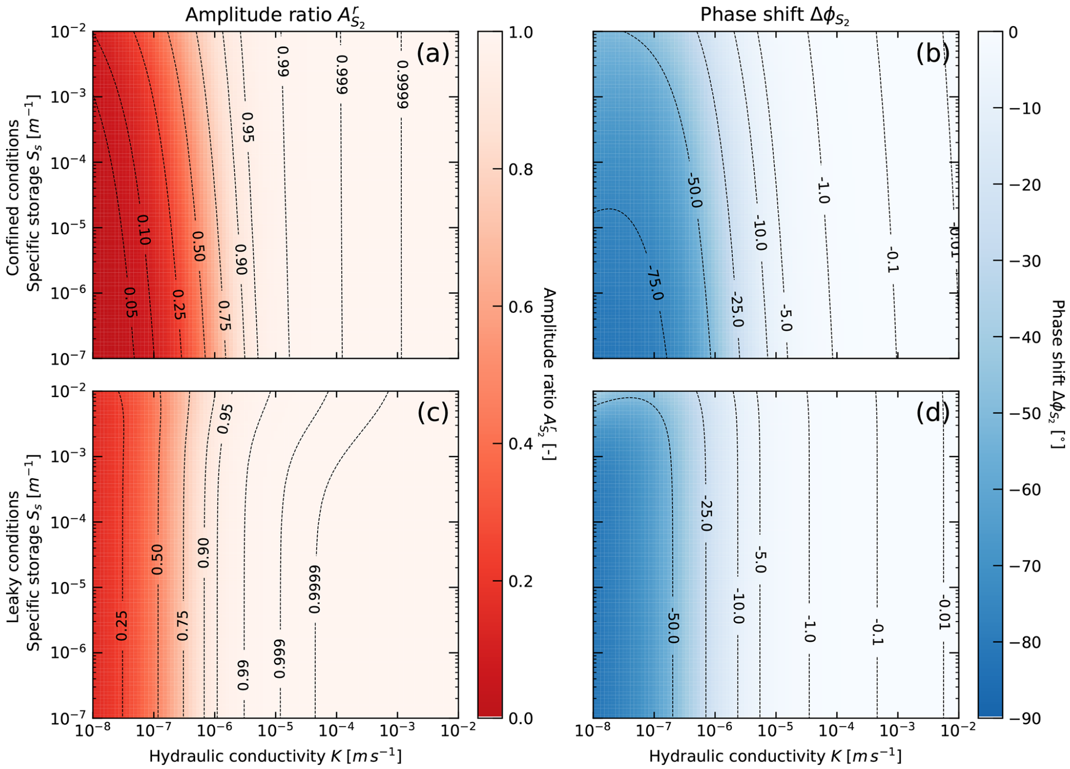

Figure 1. Amplitude ratio and phase shift relationship between subsurface pore pressure and well water level for harmonic forcing under fully confined conditions **(a, b)** and vertical water leakage under semi-confined conditions **(c, d)**. The leaky aquitard has $K' = 5 \times 10^{-5}$ m/s and $b' = 2$ m. The plots are calculated for a hypothetical well with radius of 25 mm and screen length of 1 m and realistic ranges of hydraulic conductivity and specific storage.

a hypothetical groundwater observation point with radius of 25 mm and screen length of 1 m. For the leaky aquifer solution, we assumed an aquitard with $K' = 5 \times 10^{-5}$ m/s and vertical thickness of 2 m. We used this value as a worst-case higher limit for an aquitard as the resulting amplitudes and phases provide a contrast to the confined case that is significant enough to visualise. The solutions illustrate that there is a frequency-dependent damping and phase shift in the well water level response to the aquifer pore pressure. Importantly, Fig. 1 highlights the following:

- The strongest modification of the harmonic response occurs for fully confined and not for leaky conditions (Fig. 1).
- both amplitude damping and phase shifts are mainly controlled by the subsurface hydraulic conductivity. For the confined case, $A^r_{S_2} > 0.99$, which means that the relative error is smaller than 1 % for $K > 1 \times 10^{-5}$ m/s and is therefore negligible. However, TS3 A dramatically decreases under lower hydraulic conductivity conditions and must therefore be considered for $\mathrm{BE}^{\mathrm{AT}}$ estimations.
- S_s does not significantly affect the well water level response, especially for $K > 1 \times 10^{-5}$ m/s. However, the amplitude response to the Earth tide strain is proportional to S_s (Eq. 7).

Using Eqs. (4)–(7), a generalised method for objective $\mathrm{BE}^{\mathrm{AT}}$ quantification, using the groundwater response to atmospheric tides, for example at S_2, can be formulated as follows:

$$\mathrm{BE}^{\mathrm{AT}}_{S_2} = \frac{1}{A^r_{S_2}} \mathrm{abs}\left[\frac{\hat{z}^{\mathrm{GW.AT}}_{S_2}}{\hat{z}^{\mathrm{AT}}_{S_2}}\right]. \tag{9}$$

Here, $A^r_{S_2}$ accounts for the damping introduced by the subsurface well system under conditions of low hydraulic conductivity. Due to the closeness of the S_2 and the M_2 frequencies, we can assume that $A^r_{S_2} \approx A^r_{M_2}$.

The tidal disentanglement further enables estimation of the subsurface hydraulic conductivity (K) and specific storage (S_s), using the water level response to Earth tides. A negative phase shift between M_2 and its groundwater response (well water level lags the Earth tide strain) requires horizontal flow in and out of the well and is therefore indicative of confined conditions (Roeloffs et al., 1989; Allègre et al., 2016; Xue et al., 2016). In this case, the amplitude and phase response of the well water level to an ET strain component is related