# Disentangling the groundwater response to Earth and atmospheric tides reveals subsurface processes and properties

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# What is Tidal Subsurface Analysis (TSA)?

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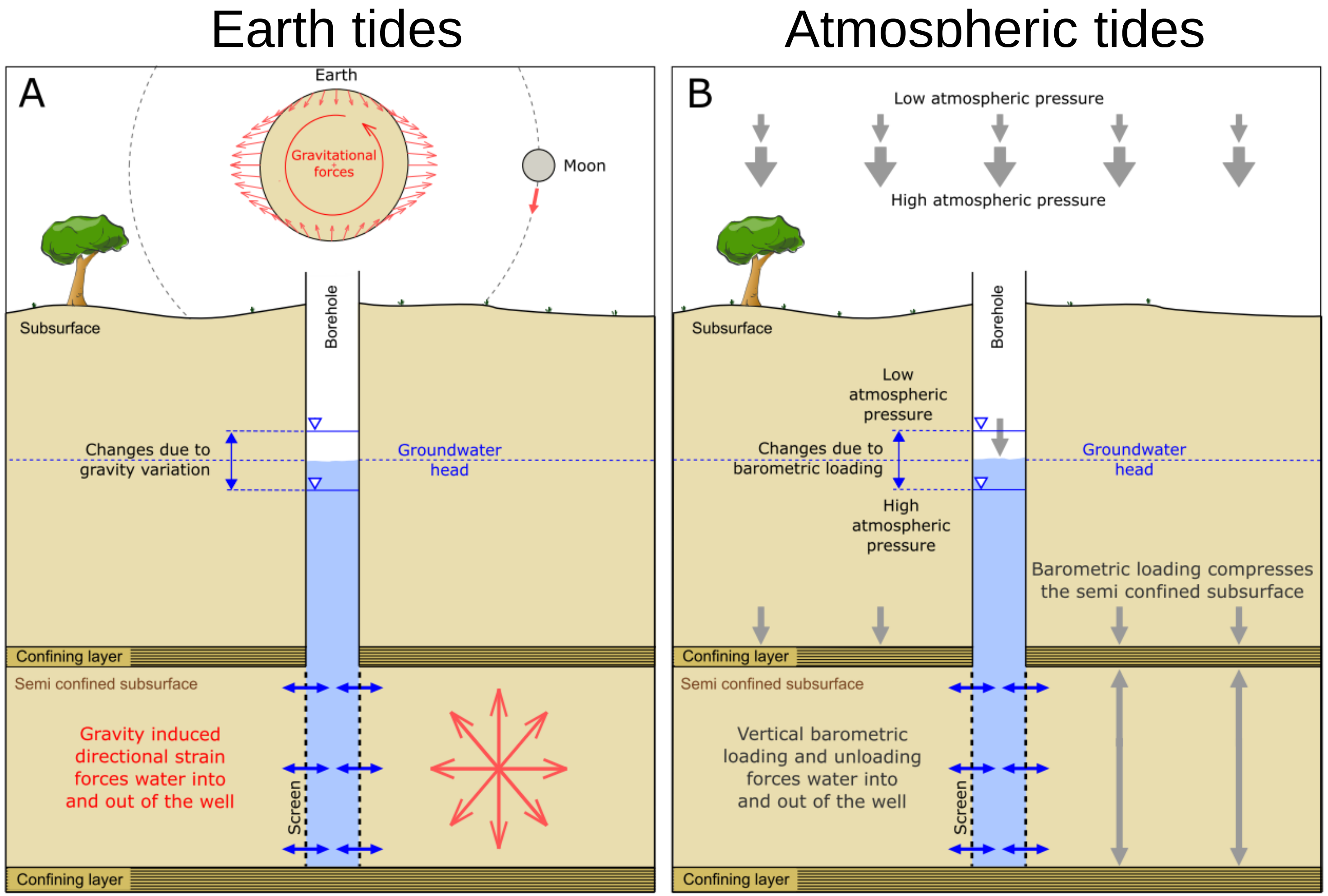
- Earth and atmospheric tides cause subsurface compression and expansion at well-known cycles (i.e. tides)

- By knowing these drivers (tides), the groundwater response can be inverted to quantify **in-situ subsurface hydro-geomechanical properties**
  - Hydraulic conductivity
  - Specific storage
  - Porosity
  - Bulk modulus




McMillan et al. (2019) *Reviews of Geophysics*

# Subsurface compressible properties

- The impact of Earth and atmospheric tides (EAT) can be used to understand and quantify groundwater processes and properties
- Advantage: Passive approach - no active testing required
  [McMillan et al., 2019]
- Earth tides have been used to quantify hydraulic conductivity and specific storage
- Atmospheric tides have been used to quantify barometric efficiency (BE) [Acworth et al., 2016]
- Given a porosity estimate, formation specific storage and compressibility
- Calculating BE using the impact of EAT was compared to Barometric Response Functions (BRF) [Turnadge et al., 2019]

# Dominant EAT frequency components

| Darwin name | Frequency [cpd] | Tidal Potential $[m^2/s^2]$ | Tidal Gravity Variation $[m/s^2]$ | Tidal Dilation [–] | Description | Attribution |
|---|---|---|---|---|---|---|
| **Diurnal** | | | | | | |
| $O_1$ | 0.929536 | 5.363385 | 8.26E-06 | 3.347E-08 | Principal Lunar diurnal | Earth |
| $M_1$ | 0.966446 | 10.286769 | 1.58E-05 | 6.419E-08 | Lunar Diurnal | Earth |
| $P_1$ | 0.997262 | 7.407625 | 1.14E-05 | 4.622E-08 | Diurnal Lunar perigee | Earth |
| $\boxed{S_1}$ | 1.000000 | | | | Principal Solar Atmospheric Pressure (thermal) | Atmosphere |
| $K_1$ | 1.002738 | 22.924982 | 3.53E-05 | 1.431E-07 | Lunar Solar Diurnal | Earth |
| **Semidiurnal** | | | | | | |
| $N_2$ | 1.895982 | 12.963403 | 1.996E-05 | 8.089E-08 | Lunar elliptic Semidiurnal (variation in moon distance) | Earth |
| $\boxed{M_2}$ | 1.932274 | 42.060943 | 6.477E-05 | 2.625E-07 | Principal Lunar Semidiurnal | Earth |
| $\boxed{S_2}$ | 2.000000 | 19.309855 | 2.973E-05 | 1.205E-07 | Principal Solar Semidiurnal | Atmosphere/Earth |
| $K_2$ | 2.005476 | 11.791770 | 1.816E-05 | 7.358E-08 | Lunar Solar Semidiurnal | Earth |

Table 1: Frequency components found in borehole water level records [McMillan et al.,2019]

# Confinement, Barometric Efficiency and $S_s$

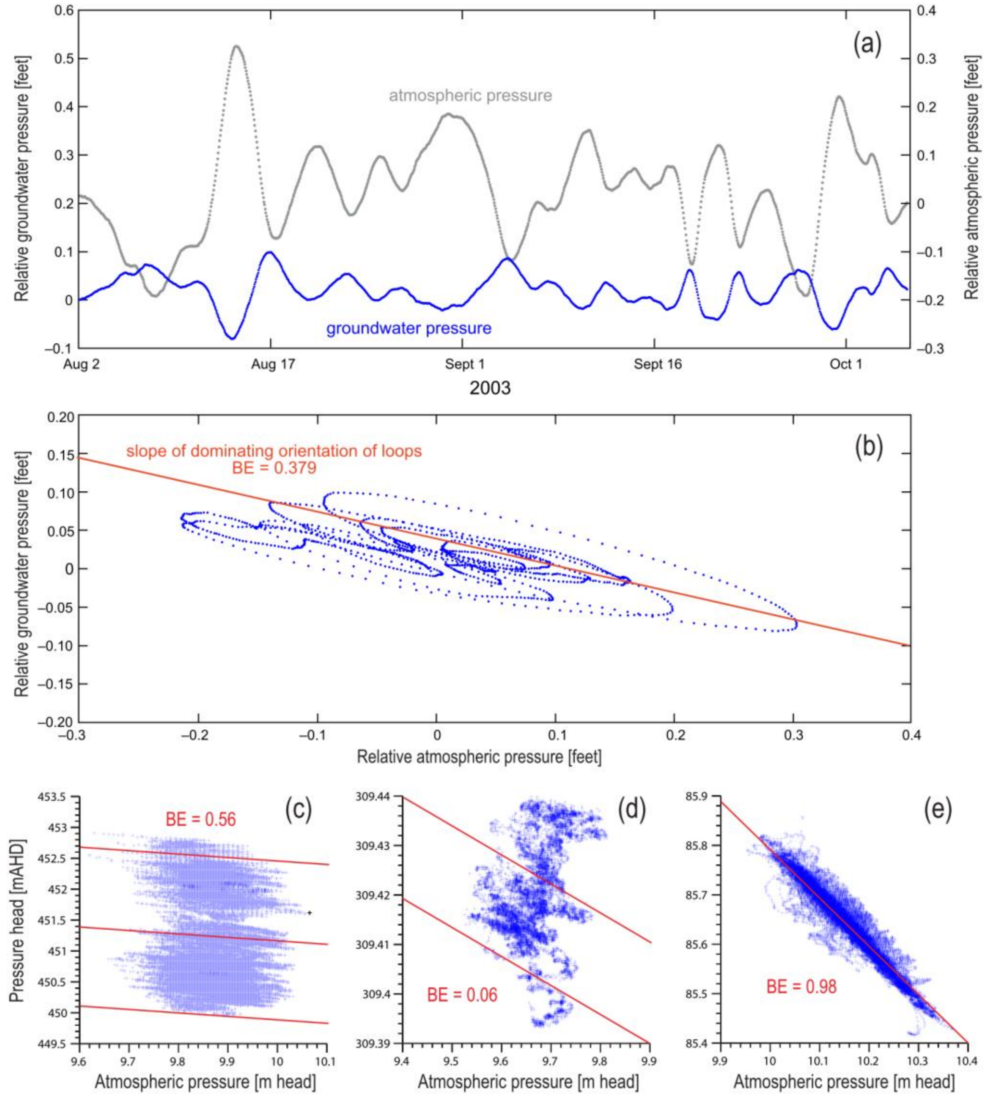
- Definition of BE [Jacob, 1940]

$$BE = \frac{\Delta h}{\Delta p} = 1 - \frac{\alpha}{\phi\beta + \alpha}$$

- Need to remove ET influences from S2 component [Acworth et al., 2016]

$$BE = \frac{S_2^{GW} + S_2^{GW}\cos(\Delta\phi)\frac{M_2^{GW}}{M_2^{ET}}}{S_2^{AT}}$$

- Water compressibility $\beta$ is known
- Given a porosity estimate, we obtain:
  - formation compressibility $\alpha$
  - specific storage $S_s = \rho g(\phi\beta + \alpha)$



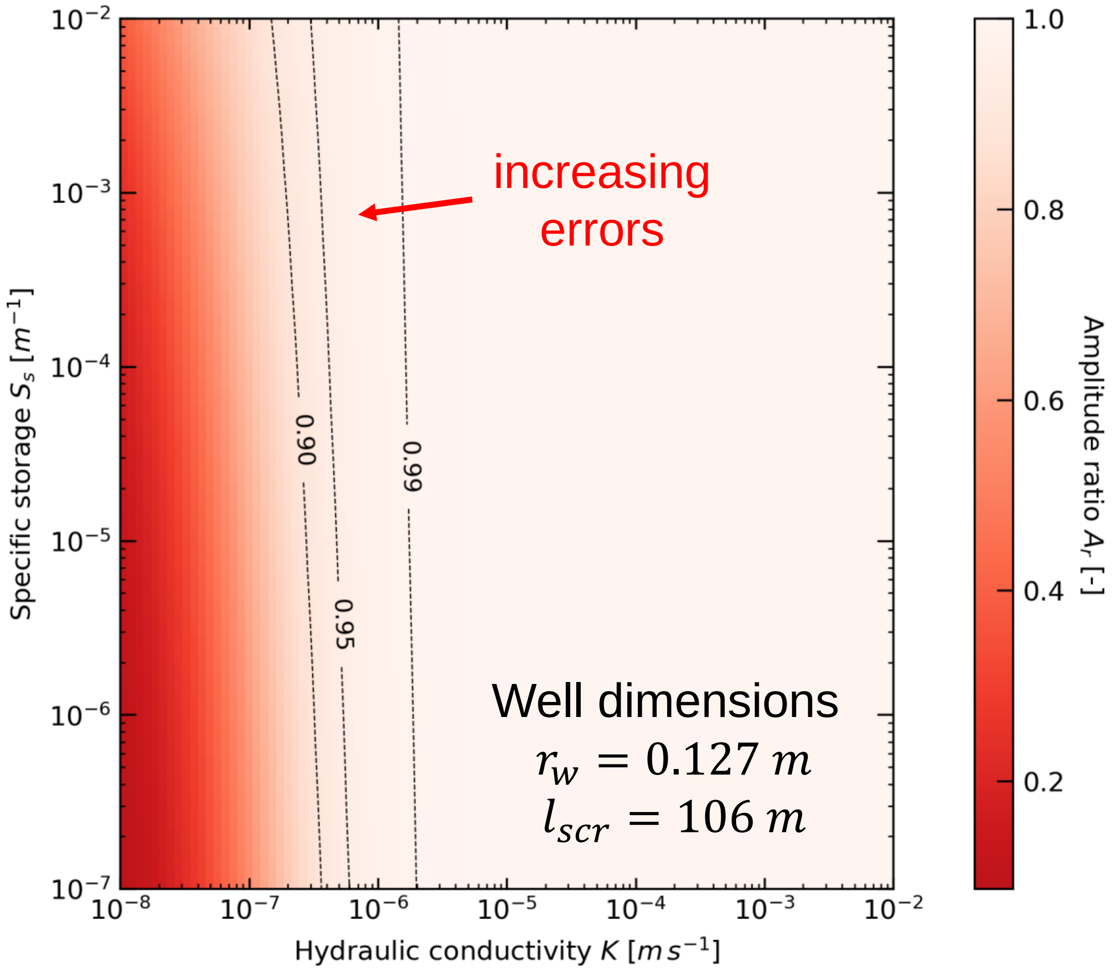
# Limitations when using AT



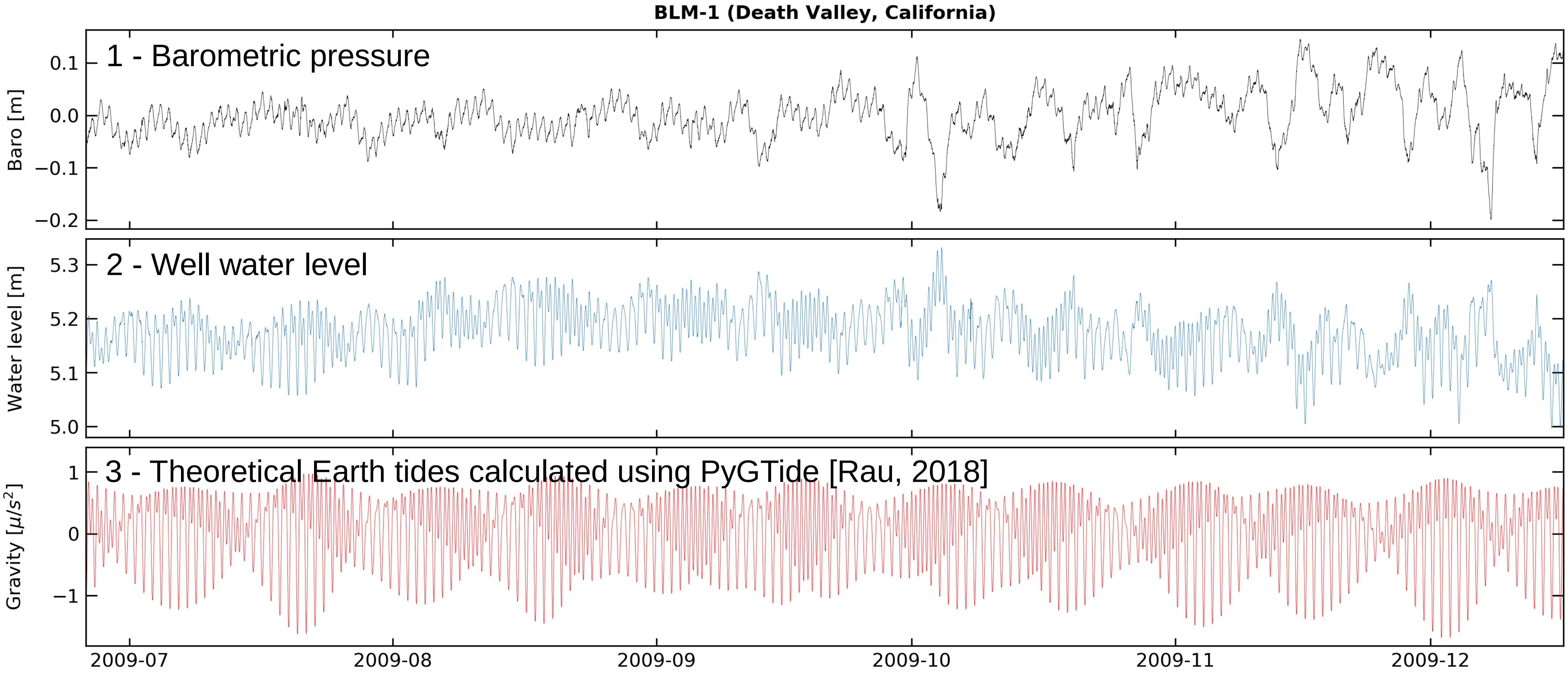
- Inherent assumptions are instantaneous response between
  1. EAT strain and pore pressure
  2. Pore pressure and well
- Assumption (1) requires more research
- Assumption (2) can be assessed assuming confined conditions and horizontal harmonic flow [Hsieh et al., 1988]

$$A_r = \frac{A_{wl}}{A_p}$$

- Well response depends on the well dimensions and formation permeability
- BE method by Acworth et al. [2016] is limited to higher formation permeabilities

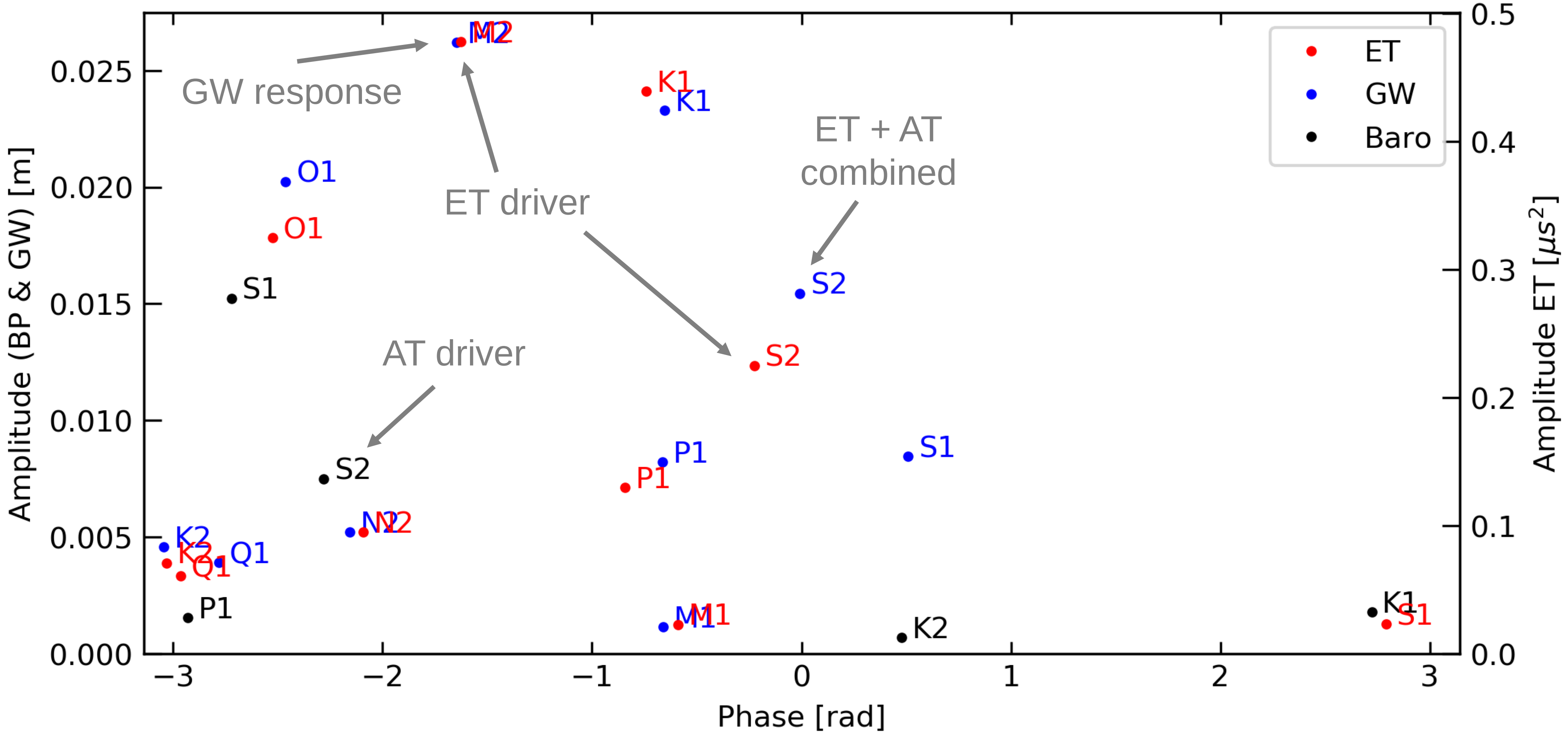


# A case study testbed

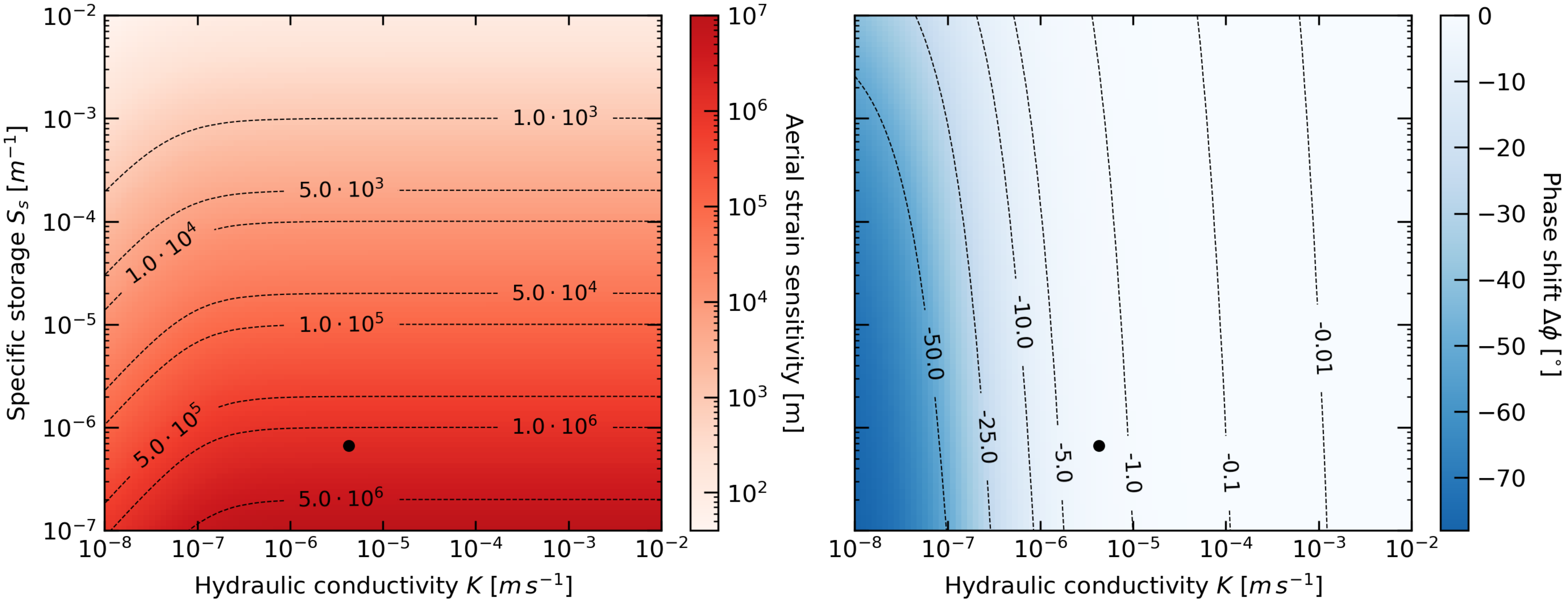



*Data courtesy of National Park Service (NPS), California, USA – Details about hydrogeology and borehole see Cutillo and Bredehoeft [2011]*

# Main harmonic components in testbed data



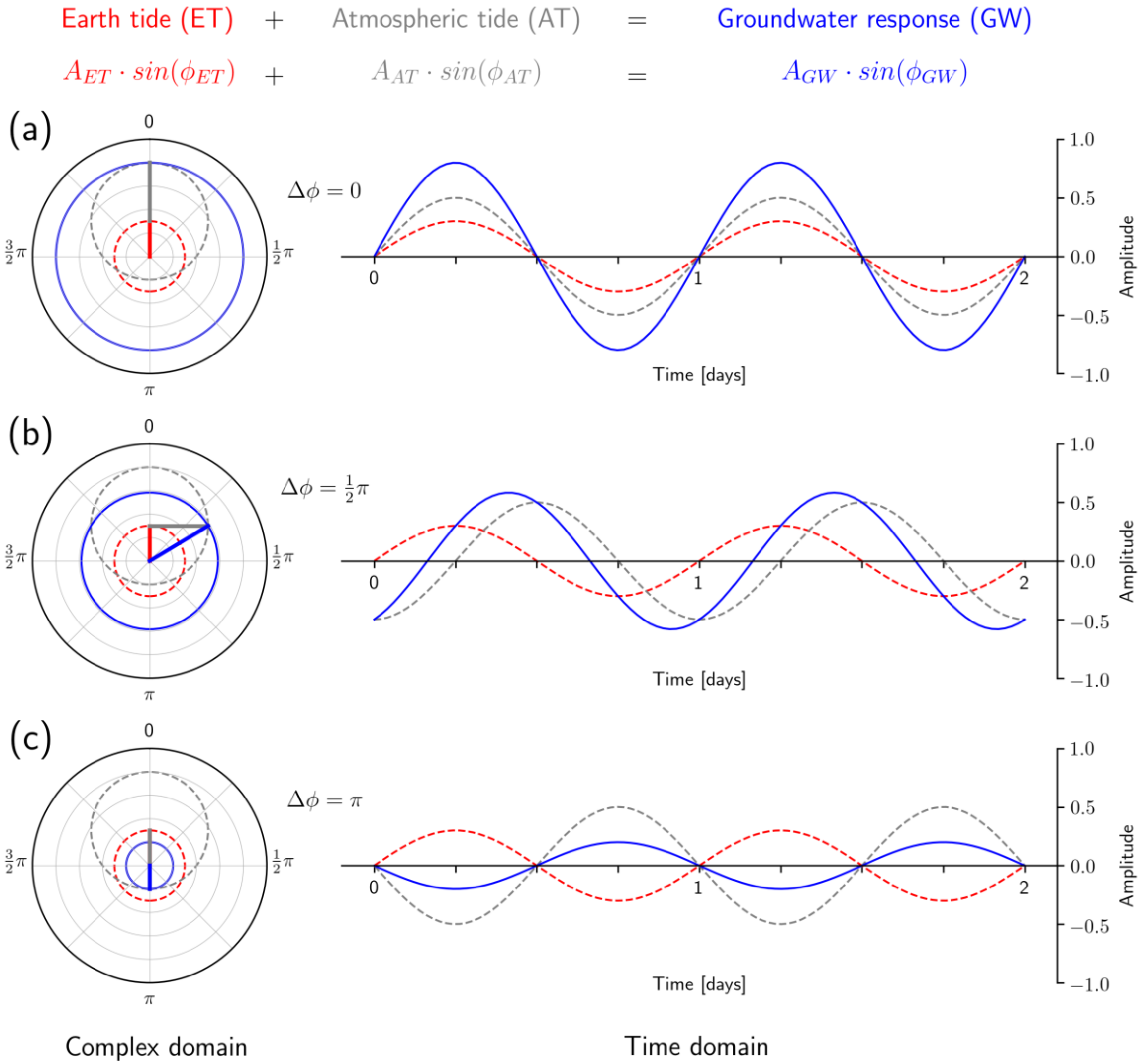
# Earth tide response in testbed data




- Areal strain sensitivity (1,481,280) and phase shift between ET and GW ($-1.08°$)
- Solving equations [Hsieh et al., 1988]: $S_s$ ~ 6.7 x $10^{-7}$ /m and K ~ 4.3 x $10^{-6}$ m/s
- The amplitude ratio between well water level and pore pressure: $A_r = 0.998$ (~0.2% error!)

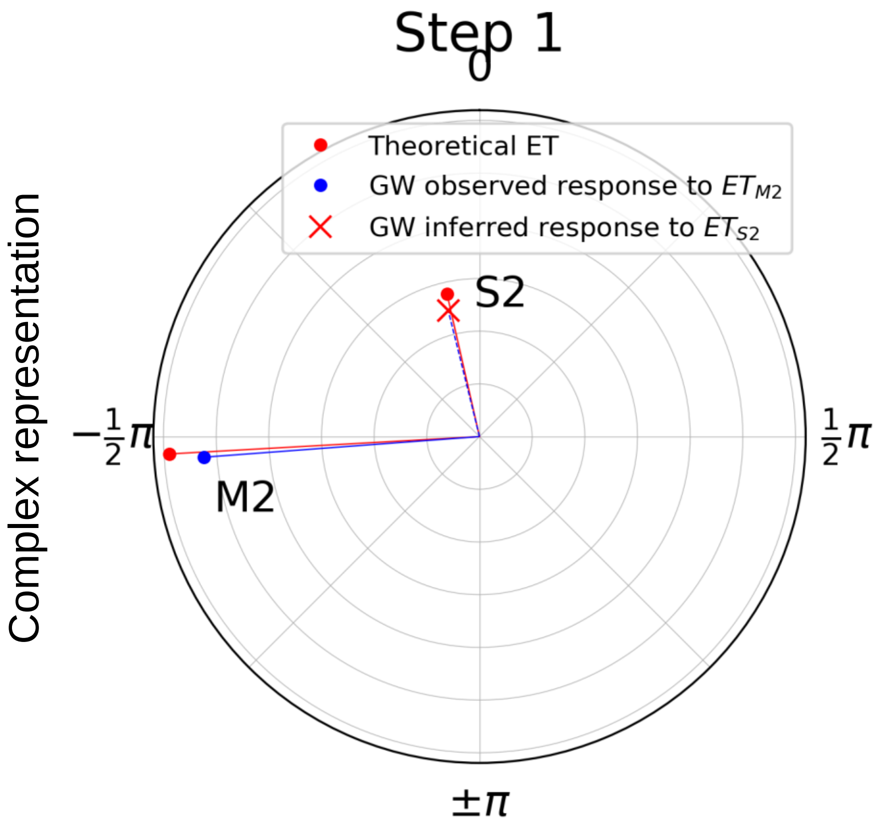
# ET and AT influences can be disentangled

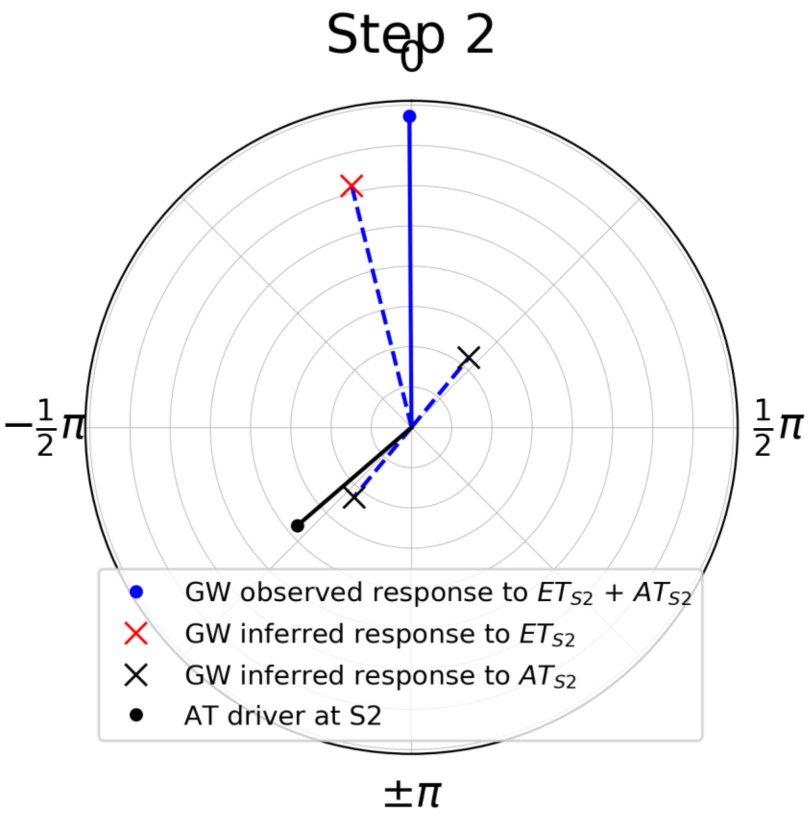
- The groundwater response to ET and AT at the same frequency is superimposed
- Influences from ET and AT can be disentangled using the harmonic addition theorem [McMillan et al., 2016]
- The results can be used to characterise the individual strain responses




McMillan et al. [2019]

# Disentangling the S2 component …




- We use M2 of the theoretical ET record to reference the GW response
- This allows us to determine the GW response to S2 – amplitude and phase!
- We can use the inferred GW response to S2 to unravel the response to AT (amplitude is magnified)
- <u>This results in complete disentanglement and a universally applicable BE estimate</u>

# Results

- Barometric efficiency
  - BE ~ 1.29 using Acworth et al. [2016] is obviously impossible!
  - BE ~ 0.60 using standard ration is confirmed by calculating the *Barometric Response Function* (*BRF): BE~0.585*) [Rasmussen and Crawford, 1997]
- For complete confinement (at 2 cpd), the phase difference between GW and AT should be the same as between GW and ET
  - $\Delta\phi_{M2}^{GW-ET} \sim -1.1°$ and $\Delta\phi_{M2}^{GW-AT} \sim -9.8°$
  - The phase discrepancy points to vertical proximity to drainable pore space in the pressure response between surface and depth – not completely confined at that frequency
- ET strain response is high, but BE << 1 which points to a vertical contrast in formation compressibility

# Conclusions

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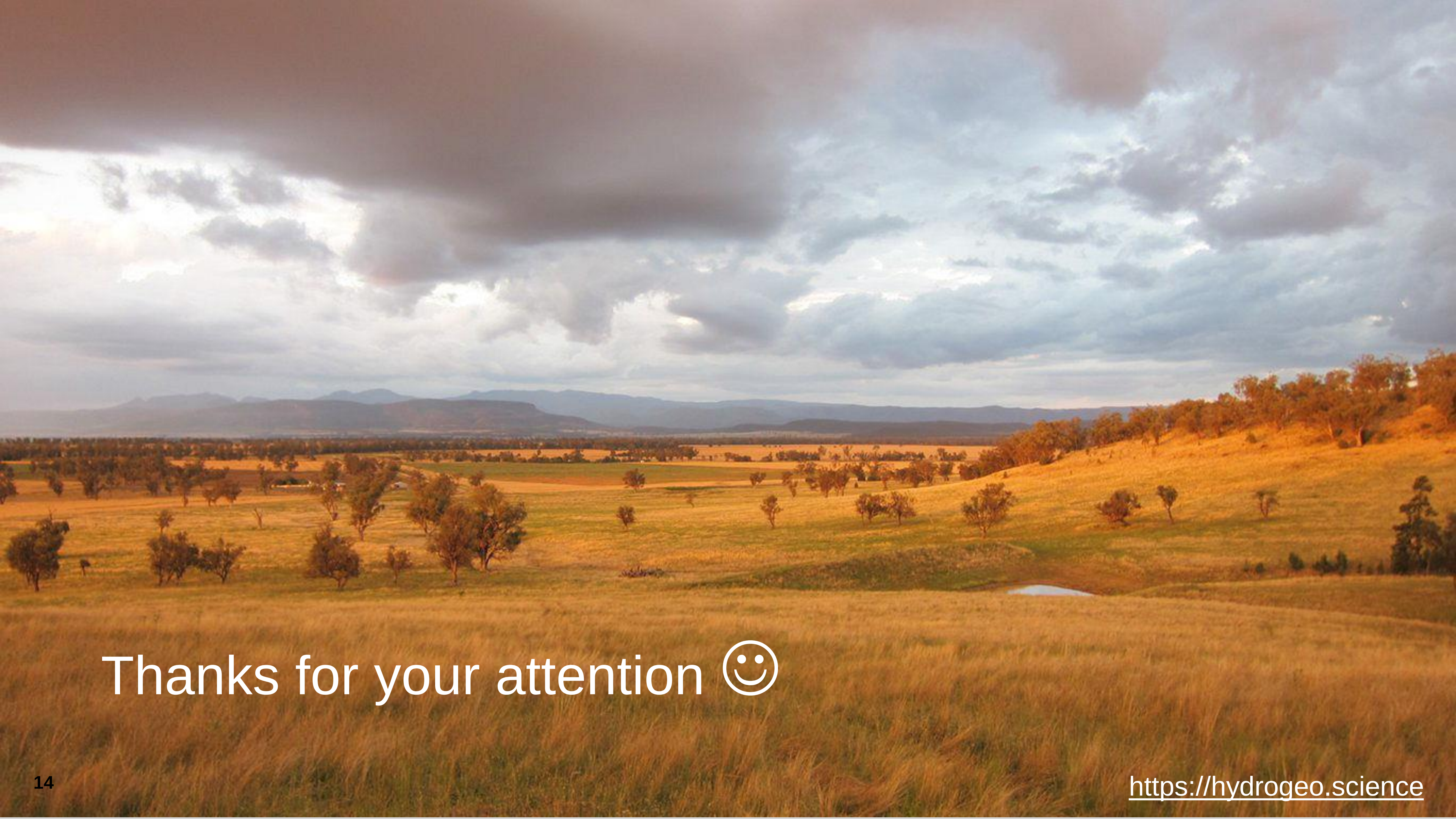
- The testbed dataset provides a textbook example for impacts of Earth and atmospheric tides on groundwater systems
  - Compared to Acworth et al. (2016), we assess a case with ET > AT impact
  - Large ET impact is usually associated with deeper, more consolidated systems (e.g., fractured rock with low compressibility)
- We illustrate a new, more complete approach to disentangle GW response to ET and AT
- Individual groundwater response to ET and AT can be used to calculate properties and understand subsurface processes
  - Hydraulic conductivity, specific storage, BE, compressibility
  - Strain anisotropy: Small AT strain response (BE) relative to large ET strain response reveals vertical geomechanical heterogeneity of the formation



Thanks for your attention ☺