

# Typhoons reseal mountain groundwater systems after earthquake damage

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## Abstract

Bedrock groundwater supplies drinking water to half the global population, and earthquakes can disrupt this resource for years by changing subsurface permeability. Previous studies proposed several mechanisms to explain coseismic permeability changes but lacked an observational tool to distinguish them; moreover, all assumed an immediate onset. Here, we analyse groundwater and seismic data from eastern Taiwan capturing the responses of the groundwater system and

the rock substrate to the 2024 M7.2 Hualien earthquake. Tracking substrate and groundwater responses separately enables us to distinguish permeability changes driven by mechanisms confined to the groundwater network from those affecting the entire subsurface. Earthquakes modify permeability in two distinct ways: coseismic shaking produces immediate permeability increases that co-evolve with substrate changes. Months later, two consecutive typhoons triggered abrupt permeability decreases, unlike typhoons before the earthquake. As the substrate remains unaffected by these typhoons, we attribute this response to the combined effect of the earthquake, which increased sediment availability and enhanced infiltration capacity, and typhoon-induced overland flow, delivering the sediment into the fracture network, sealing fractures and causing potential discharge deficits of up to 24 %. Our results demonstrate that large earthquakes can prime landscapes for delayed hydrological disruption, with long-lasting consequences for mountain groundwater resources.

**Keywords:** earthquake hydrology, postseismic recovery, permeability changes, groundwater recovery

## 1 Introduction

Bedrock groundwater is the largest terrestrial freshwater reservoir [1], providing drinking water to ~50 % of the global population [2]. Perturbations to this system can have dramatic socioeconomic and ecological consequences [3] and may alter landscape dynamics, for example by impacting landslide distributions [4]. Among these, earthquake-driven perturbations have been observed for thousands of years [5]. They manifest, for example, as sudden changes in river discharge [6], the appearance or disappearance of springs [7], or abrupt changes in water composition [8]. At depth, groundwater disturbances occur as abrupt recharge or discharge events that can cause excess discharge on the order of cubic kilometres [9] or in the form of longer-lasting changes in recharge and drainage dynamics [10] with potentially important consequences for fresh water resources. Such perturbations have been attributed to changes in aquifer permeability [11].

Previous studies have invoked a variety of mechanisms for coseismic permeability changes, such as static strain changes [12], the sudden contraction of material leading to increased pore pressure [13], comparable to liquefaction, modifications in aquifer confinement [14, 15], or the clearing and clogging of pore spaces and fractures [16]. However, field observations of the mechanisms are lacking. While tidal transmissivity monitoring [17] has been useful in identifying coseismic permeability changes, it is unable to distinguish between the mechanisms triggering the change. For example, the commonly invoked clearing and clogging cannot be distinguished from changes in the mechanical state of the rock matrix itself, including the geometry of the fracture network. Moreover, it is not clear whether and when sediment infilling can affect open fracture networks. Various studies have independently observed coseismic disturbances followed by multi-annual recovery in the elastic properties of the rock substrate

[18–20] and in the groundwater system [11, 21, 22]. Yet we do not know whether substrate and permeability changes respond to earthquakes independently or in a coupled fashion. This gap makes groundwater recovery times difficult to predict and leaves open whether subsequent events can compound the disturbance. It can be addressed through a joint study of the two components.

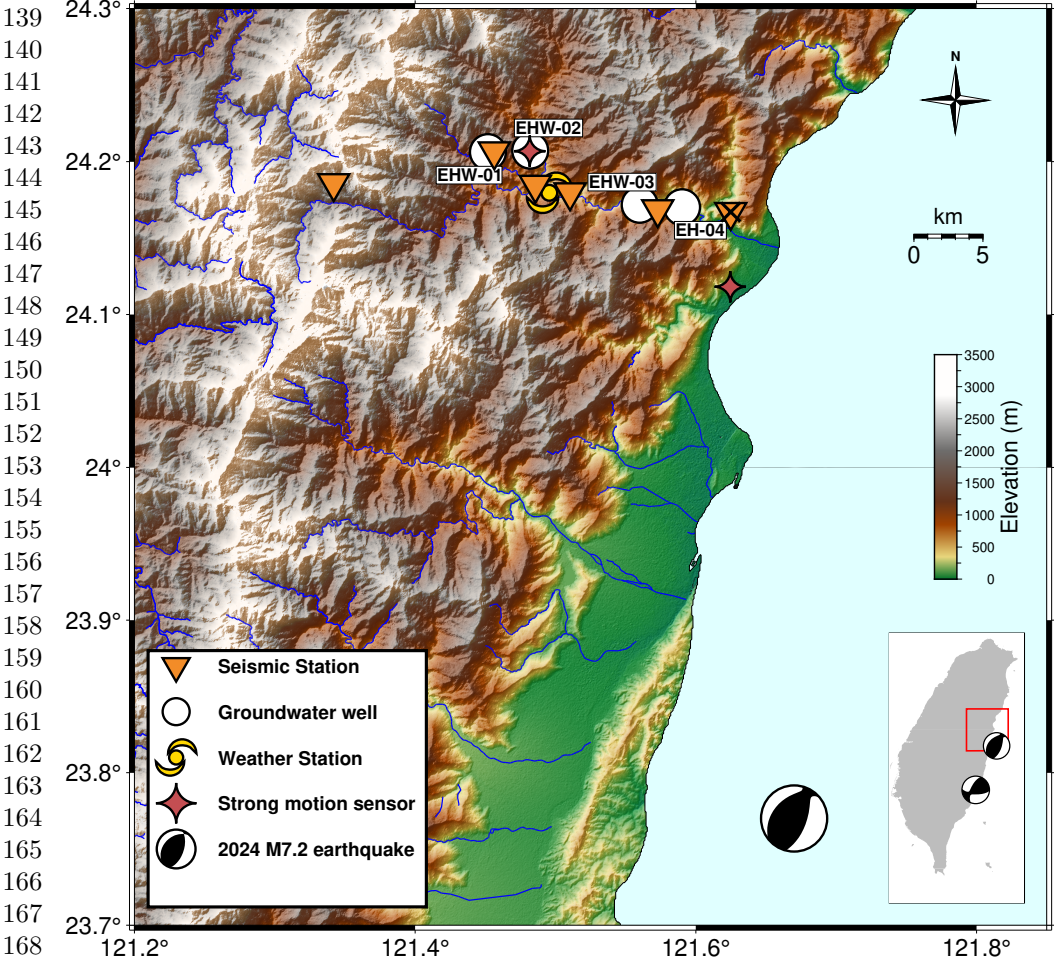
Here, we investigate the co-evolution of the permeability of mountain groundwater systems and substrate properties in response to two large earthquakes to evaluate their coupling. Specifically, we compare the time-dependent transmissivity [23], which is proportional to the permeability of the groundwater network, with changes in the seismic wavespeed [24] that depend on rock stiffness. Independent observables enable us to distinguish mechanisms associated with substrate changes, such as spatially homogeneous fracture opening, which would manifest in both records simultaneously, from mechanisms confined to the groundwater system, such as fracture clearing or clogging.

We pursue this comparison with seismological and hydrometric data from the Liwu River catchment in the east flank of the Taiwan Central Range (see Fig. 1). Taiwan is located above a system of subduction zones that cause regular large earthquakes and produce steep mountain topography with fast sediment generation. Furthermore, Taiwan experiences regular typhoons, causing intense rainfall and flooding that can quickly transfer large amounts of sediment. Regional aquifers are hosted by a body of bedrock with a deeply penetrating network of fractures. Locally, the degree of fracturing varies substantially — low transmissivity portions constitute aquitards. This bedrock is overlain by an irregular high-transmissivity layer of regolith and colluvium. In April 2024, an M7.2 megathrust earthquake occurred just off the coast of Hualien at a depth of  $\sim 35$  km and about 40 km south of the Liwu catchment. The Hualien earthquake is the largest seismic event recorded around Taiwan in the last quarter century, causing thousands of coseismic landslides [25] and perturbing the fractured bedrock aquifers of the eastern Central Range along with its surface hydrological system. Four and seven months later, the typhoons Gaemi and Kong-Rey impacted the earthquake’s epicentral area. The latter was one of Taiwan’s most intense typhoons in recent history [26] with more than 1000 mm of precipitation at our field site. We probe the effects of this extraordinary combination of events on the groundwater system and the bulk substrate by leveraging recordings from a dense network of groundwater wells and seismic stations. From our analysis, we infer two opposing effects on the permeability of the groundwater network: first, coseismic permeability increases associated with bulk substrate changes and, second, typhoon-induced but earthquake-primed sealing causing sudden permeability decreases.

## 2 Results

### 2.1 The impact of earthquakes on the raw water level

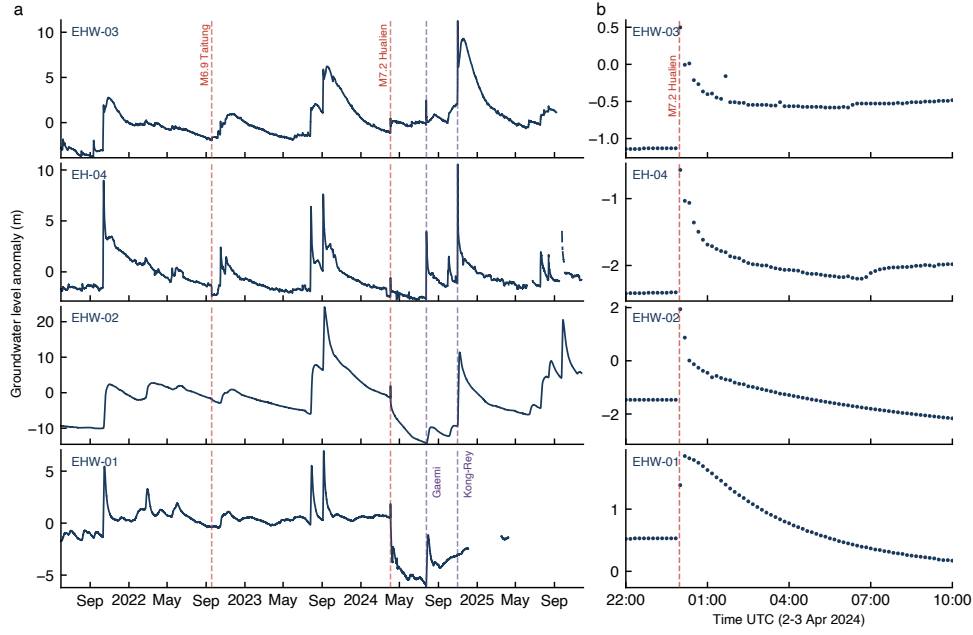
Groundwater data from four boreholes show coseismic changes (see Fig. 2), illustrating the range of drainage dynamics and coseismic responses. Prior to the M7.2 Hualien earthquake, the water levels in all four wells were gradually decreasing. All wells recorded a sudden step rise of 1–3.5 m coincident with the earthquake, followed by



**Fig. 1** Locations of sensors, from which data were used. Data from the seismic station marked with a cross (TQ01) have been used to produce Fig. 3. We used data from well EHW-02 co-located with the strong motion sensor F072 to perform the tidal analysis. The remaining three wells were used only for the groundwater compensation of  $\delta v/v$ . The map inset contains the moment tensor solutions for the M7.2 2024 Hualien and M6.9 2022 Taitung (outside the map limits) earthquakes.

a decay on the order of 6 hours in all wells except in EHW-03. In the following months, two wells — EHW-03 and EH-04 — returned to their pre-earthquake declining trend, whereas the trend steepened for EHW-01 and EHW-02 compared to before the earthquake. More subtle groundwater changes occurred in these four wells after the 2022 M6.5 and M6.9 Taitung sequence, which struck ~100 km south of the Liwu catchment at a shallow depth of around 10 km.



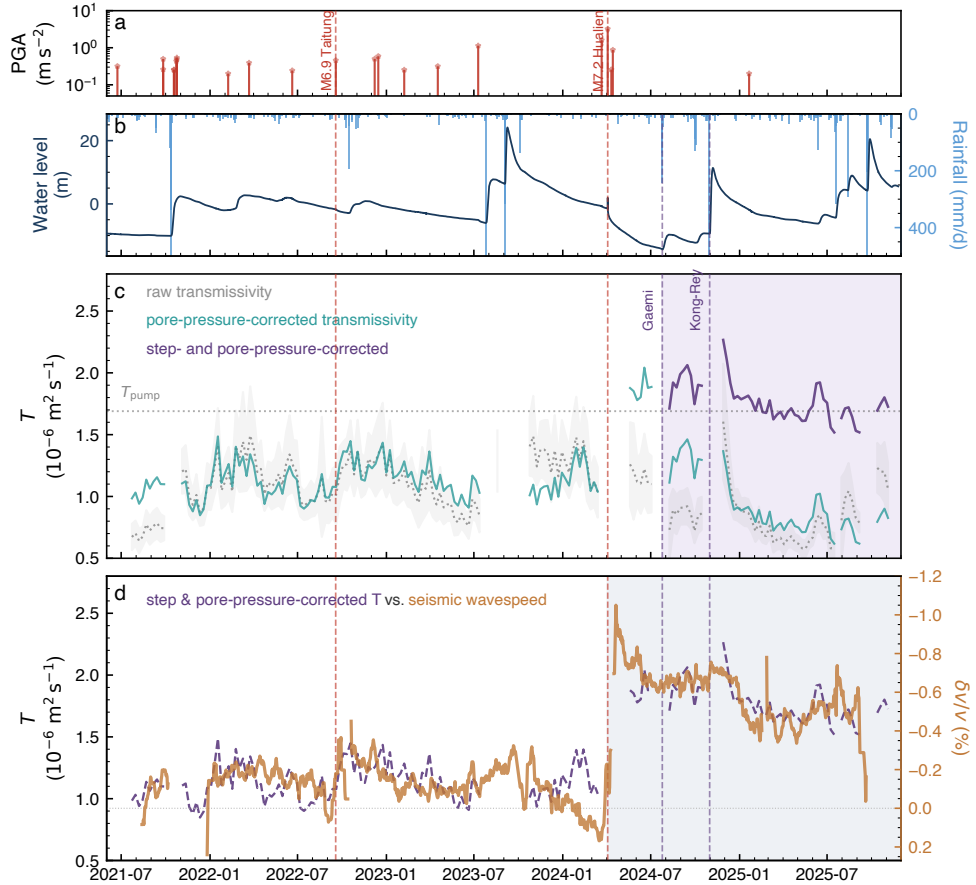


**Fig. 2** Piezometric groundwater level records from Taroko National Park. Panel **a** shows water level records for the study period from four wells. The water level exhibits step-like changes and alterations in drainage dynamics at the marked M6.9 Taitung and M7.2 Hualien earthquake sequences. Panel **b** shows a zoom-in on panel **a** of the hours following the 2024 M7.2 Hualien earthquake. For the tidal analysis, we use data from EHW-02.

## 2.2 Time-dependent transmissivity

We obtain the time-dependent transmissivity from July 2021 to November 2025 by fitting the 10-minute-sampled semidiurnal tidal response in the piezometric head to the solid Earth tides and barometric fluctuations. This analysis yields time-dependent transfer functions that we invert for the transmissivity, assuming a leaky-aquifer model (see 4.2 for details). Independent pump tests, performed in 2013 for depth ranges within the wells (see supplementary Table S1), provide a reference order of magnitude for the transmissivity. Of the four wells, EHW-02 yields robust tidal-derived transmissivity estimates (see supplementary discussion) and, therefore, we centre the following analysis around results obtained from EHW-02.

Until April 2024, the transmissivity deviates less than 20 % from its median value of  $\sim 1.1 \times 10^{-6} \text{ m}^2/\text{s}$ . Pump tests indicate a somewhat higher value of  $\sim 1.7 \times 10^{-6} \text{ m}^2/\text{s}$  (see Fig. 3) but validate the order of magnitude of the values retrieved from our tidal analysis. As we analyse relative transmissivity changes, the accuracy of its absolute value is of lesser importance. Small variability in the transmissivity can often be explained by rising (falling) groundwater, which leads to lower (higher) effective stresses and thereby causes fracture apertures to increase (decrease) [27]. To isolate co- and postseismic changes, we correct for this pore pressure effect (see 4.2.1).



**Fig. 3 Co-evolution of the transmissivity and the seismic wavespeed ( $\delta v/v$ ).** **a** Peak ground accelerations (PGAs) measured for regional earthquakes  $M \geq 4.5$ . **b** Piezometric water level records measured at EHW-02 and daily rainfall at the automatic weather station COT820. **c** From tidal inversion, we retrieve the raw transmissivity (dotted grey curve) and its  $\pm\sigma$  error envelopes. For comparison, we show the transmissivity estimated from hydraulic pump tests  $T_{pump}$ . We apply a pore pressure correction (teal curve) and remove steps introduced by the typhoons Gaemi and Kong-Rey (purple curve). **d** The low-frequency seismic wavespeed co-evolves with the fully corrected transmissivity. The shading in panel c emphasises the typhoon-induced, lasting transmissivity decrease, while panel d is shaded for times following the Hualien earthquake. We computed  $\delta v/v$  from data in the frequency band 0.5-1 Hz from station TQ01. We exclude  $\delta v/v$  values with a correlation coefficient of  $R_{av} < 0.25$  and transmissivity values with standard deviations  $> 5 \times 10^{-7} \text{ m}^2/\text{s}$ . Note that the  $\delta v/v$  axis is inverted.

The pore pressure-corrected transmissivity exhibits several abrupt excursions. Two of these changes are transmissivity increases that coincided with large regional earthquakes — the 2024 M7.2 Hualien earthquake and the 2022 M6.9 Taitung earthquake sequence. Most prominently, following the Hualien earthquake, which caused ground-shaking of 0.5 g, the pore pressure-corrected transmissivity in EHW-02 increased by

about 80 %. For about two weeks after the earthquake, our transmissivity estimate exhibits large uncertainties (see supplementary Fig. S3), which may be due to high-frequency noise in the water level record. Therefore, we choose not to interpret the immediate transmissivity response to the M7.2 earthquake. Over the rest of the study period, the pore pressure-corrected transmissivity gradually decreased, superimposed with two step decreases. A more subtle transmissivity increase of  $\sim 30\%$  occurred with the September 2022 Taitung earthquake sequence that induced a moderate peak ground acceleration (PGA) of  $<0.1\text{ g}$ . After those events, the transmissivity recovered over about 10 months to pre-earthquake levels.

Two further, distinct transmissivity decreases occurred well separated from any earthquakes within the time series. Specifically, four months after the Hualien earthquake, the transmissivity dropped by  $\sim 55\%$  coincident with the landfall of typhoon Gaemi. The raw transmissivity even reached values below its pre-earthquake baseline. Another  $\sim 25\%$  decrease coincided with typhoon Kong-Rey, three months later. Notably, we find no imprint on the transmissivity from typhoons before the 2024 Hualien earthquake, although some delivered more than twice Gaemi's rainfall (see Fig. 4). After the two typhoons in 2024, transmissivity values have not recovered to background values within the study period.

### 2.3 Seismic wavespeed changes

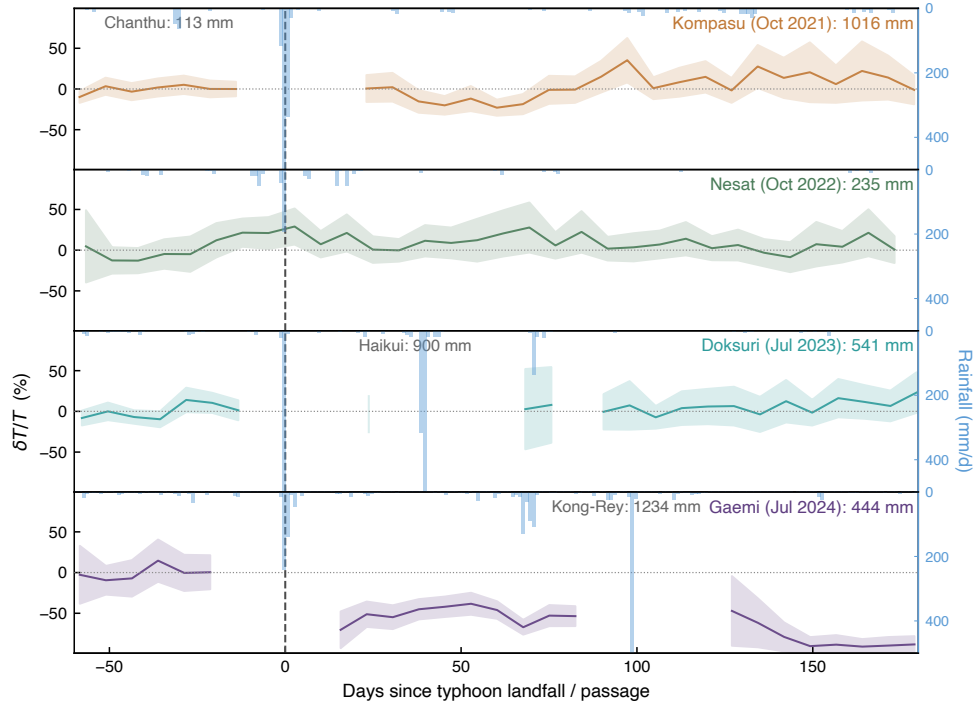
As a measure of the solid substrate's rock mechanical state, we consider seismic wavespeed changes ( $\delta v/v$ ). To obtain  $\delta v/v$  estimates for several depth ranges, we compute  $\delta v/v$  from several frequency bands, where higher frequencies result in  $\delta v/v$  estimates for shallower depths [28]. High-frequency  $\delta v/v$  is anticorrelated with water level, which is expected from the pressure-dependency of the elastic properties [e.g., 29–31]. Here, we aim to analyse properties of the substrate independently from ground-water level variations in the aquifer. Therefore, we focus the analysis on low-frequency (0.5–1 Hz)  $\delta v/v$  (representative example from station TQ01 in Fig. 3d) that shows only minimal impacts of water level fluctuations (see supporting Figs. S4–5).

Within these low-frequency  $\delta v/v$  time series, we find two significant drops. Both of these drops occurred coseismically with the 2022 Taitung earthquakes and the 2024 Hualien earthquake and with amplitudes of 0.25 % and 0.8 %, respectively. The drops are followed by periods of postseismic recovery: the seismic wavespeed drop induced by the Taitung earthquakes recovered after about 10 months, while the postseismic recovery transient following the Hualien earthquake continued throughout the remainder of the time series.

## 3 Discussion

### 3.1 Earthquakes and typhoons induced two kinds of transmissivity changes

The two most striking features in the comparison of evolution of the seismic wavespeed and the pore pressure-corrected transmissivity are their co-evolution in the co- and



**Fig. 4 Transmissivity response to major typhoons.** The relative pore pressure-corrected transmissivity ( $\delta T/T$ ) only shows a statistically significant change in response to the Gaemi and Kong-Rey typhoons, which occur  $\sim$ four and seven months after the 2024 M7.2 Hualien earthquake. For all other typhoons, including Nesat that follows the significantly smaller Taitung earthquakes, no change is detectable. For  $\delta T/T$ , we show the  $\pm\sigma$  error envelopes. We exclude  $\delta T/T$  values with  $\sigma > 50\%$ . For each typhoon, we indicate the total rainfall  $\pm 3$  days from its occurrence. Data gaps result from increased noise level in the tidal inversion due to barometric fluctuations and strong water level changes.

postseismic periods and their divergence in response to the 2024 typhoons. Importantly, the only coseismic transmissivity changes in the four-year time window covered by this study coincide with the only coseismic wavespeed changes. Furthermore, coseismic transmissivity increases are not only accompanied by decreases in  $\delta v/v$ , but the ensuing postseismic recovery to a base value follows similar trajectories. This co-evolution holds across all stations and for depth ranges  $> \sim 200$  m (see supplementary Figs. S6 & S7). Shallower depths show residuals of groundwater signals — even after correction. Unlike the local transmissivity, the seismic wavespeed does not show any changes unrelated to pore pressure changes following the 2024 Gaemi and Kong-Rey typhoons.

The sequence of an earthquake followed by two typhoons provides two independent diagnostics for the mechanisms behind each transmissivity change. As a first diagnostic, mechanisms that modify the substrate as a whole, such as pervasive changes in pore space geometry, should affect both the transmissivity and the seismic wavespeed. By

contrast, mechanisms confined to the groundwater system, such as fracture clearing or clogging, should affect only the transmissivity. Second, the typhoons struck while the groundwater system was still recovering from the earthquake perturbation; had both perturbations acted through the same mechanism, the typhoons should have altered the postseismic recovery trajectory. Both diagnostics separate the two kinds of change: the wavespeed responds only to the earthquakes, and the postseismic transmissivity recovery continues unbroken through the typhoon season. Below, we use these diagnostics to test candidate mechanisms, starting with the typhoon-induced decreases, because the mechanism we identify for them is needed to constrain the cause of the coseismic increases.

### *The 2024 typhoon season*

There is a sharp contrast in the response of the groundwater system to typhoons before and after the 2024 Hualien earthquake: typhoons typically do not impact the transmissivity beyond their direct effect on the water level, but, in the months after the earthquake, typhoons produced lasting transmissivity decreases (Fig. 4). We do not find a change in the groundwater system's response to rainfall following any other earthquake, including the 2022 Taitung sequence, raising the question how the Hualien event differed from preceding earthquakes. Compared to the larger Hualien earthquake, all other earthquakes produced substantially less coseismic landsliding [32, 33] and presumably also loosened less sediment that could have been mobilised during subsequent typhoons [34, 35]. Such sediment can drive local transmissivity changes in two ways: increased effective stress from sediments redeposited by typhoon-induced flooding, or fracture clogging by sediment particles [16]. Two observations are inconsistent with increased effective stress by redeposited sediment as the driving mechanism. First, we estimate that the added sediment thickness needed to produce the first typhoon-induced transmissivity drop alone is at least  $\sim 5$  m (see 4.2.2). Such deposition may have occurred at select locations, but overall, in mountain landscapes, typhoons cause erosion rather than deposition [36], reducing effective stress at landscape scale. Second, effective stress modifications impact the seismic wavespeed. However, for the 2024 typhoons, we do not observe wavespeed changes unrelated to pore pressure changes. We can thus rule out effective stress modifications as the mechanism for the 2024 typhoon-induced transmissivity changes.

Fracture clogging by sediment particles [16], capable of decreasing transmissivity, may have been enabled by the combination of surface fracturing due to strong ground motion, increased sediment availability through coseismic mass wasting, and typhoon-induced overland flow and infiltration capable of delivering sediments deeper into the fracture network. Because the resulting clogging affects only a small part of the volume that the seismic waves are sensitive to and the effect of clogging on the elastic properties of the bulk substrate is likely negligible in general, it does not noticeably impact the seismic wavespeed. Our transmissivity observations suggest that typhoons do not only deliver sediments to rivers [37] but also flush them into groundwater systems, likely facilitated by the large pressure gradients created by rapid flooding of open fissures, enabling injection within hours to days [38, 39]. Large earthquakes prime this mechanism in two complementary ways: they generate sediment across



steep mountain terrain [35, 40], and they open and widen macrofractures that increase the infiltration capacity of the landscape and allow sediment particles to reach deeper parts of the groundwater system [41, 42]. Smaller earthquakes before the Hualien earthquake likely were insufficient to change crack opening at the surface pervasively and generated insufficient sediment in our study area to facilitate fracture clogging. This delayed earthquake-primed but typhoon-triggered fracture clogging has not been previously identified.

#### ***Co- and postseismic transmissivity changes***

Unlike the typhoon-induced drops, the coseismic transmissivity increases that we observe for the 2022 Taitung and 2024 Hualien earthquakes were accompanied by wavespeed decreases and they recovered over time. Such transmissivity increases could be linked to coseismic static stress changes [12], unclogging or clearing of fractures by seismic wave passage [11, 16, 44], or changes in fracture geometry that enhance connectivity [27], but no single mechanism has been universally agreed on.

Coseismic static stress changes have generally been discarded as a major cause of seismic wavespeed changes, as they cannot explain their spatial pervasiveness, their sign consistency (almost invariably negative), or their logarithmic recovery [19, 20]. Moreover, the Taitung earthquake would not have caused significant static stress changes at our site due to its relatively large epicentral distance.

Clearing of fractures by seismic shaking, opposite to the mechanism we invoked for the typhoon-induced transmissivity drop, could cause transmissivity to increase [44], but we dismiss this mechanism as the main driver of the coseismic transmissivity increase for two reasons. First, if clearing of fractures was the dominant driver of the coseismic transmissivity increase, its gradual postseismic recovery would correspond to progressive refilling of fractures. Within this hypothetical framework, typhoon-induced fracture clogging would accelerate such refilling and disrupt or even reset the postseismic recovery trajectory. Instead, we observe an unbroken postseismic transmissivity recovery, which indicates that coseismic and typhoon-triggered transmissivity changes stem from two unrelated processes that do not directly interact on a microscopic level. Second, as clearing or clogging of pore spaces does not impact the seismic wavespeed, the parallel postseismic recovery of the seismic wavespeed and the transmissivity would have to be coincidental.

Instead, we consider that seismically induced changes of rock fracture geometry likely simultaneously affected the seismic wavespeed and the permeability. The seismic wavespeed is controlled by the contact area within micro- and macrofractures [45]. The permeability, on the other hand, depends mostly on the aperture of these fractures [46]. Some processes, such as clearing and clogging of fractures, alter the effective hydraulic aperture [46] but do not affect the contact area. However, in some cases, for example, when changes in effective stress open or close fractures, these properties may covary. Because permeability scales with the cube of fracture aperture [46] while seismic wavespeed changes are proportional to grain contact area [45], a geometric change that widens fractures while reducing contact area produces permeability changes that far exceed wavespeed changes — consistent with relative transmissivity changes two orders of magnitude larger than relative wavespeed changes (Fig. 3). Following the

coseismic change, contact area and aperture of the fracture network recover on the same trajectory. Seismic wavespeed decreases and their recovery are an expression of the so-called nonclassical nonlinear response of materials to stress changes, in which grain contacts are disrupted and recover logarithmically [47–49]. The co-evolution of transmissivity and seismic wavespeed, and their parallel postseismic recovery, indicate that coseismic changes in fracture aperture and grain contact area are coupled, and that both recover on the timescale predicted by nonclassical nonlinear elasticity. These earthquake-induced changes of the fracture geometry likely later allowed typhoon-mobilised sediment to percolate deeply into the groundwater network, where clogging narrowed the fractures without interrupting the geometric recovery of their contacts. This interpretation remains a hypothesis, but it is the only single-mechanism explanation consistent with all our observations.

### 3.2 The seismic wavespeed as a diagnostic tool for permeability changes

Earthquakes with similar intensity do not necessarily affect the groundwater system equally. In contrast to findings by [11], peak ground acceleration (PGA) is not a reliable measure for the amplitude or even the occurrence of a transmissivity change. In particular, we find earthquakes producing higher PGAs than the 2022 Taitung earthquake that are not associated with discernible transmissivity changes (see Fig. 3), consistent with observations by [22, 23]. For our data, we find that coseismic changes in seismic wavespeed are a good indicator for coseismic transmissivity modifications: every coseismic transmissivity change is accompanied by a coseismic variation in wavespeed and vice versa (see Fig. 3). This likely reflects differences in spatial sensitivities: the PGA is a point measure that is heavily influenced by local topography, near-surface geology, and source directionality [50–52], whereas the seismic wavespeed integrates changes over larger volumes [28]. When the underlying transmissivity change is rock-mechanical, the seismic wavespeed may serve as a proxy for postseismic permeability recovery. However, when clogging or clearing dominates, as for the 2024 typhoons, the seismic wavespeed does not respond. Where continuous groundwater observations are available, the seismic wavespeed can become a discriminator of the underlying causes of transmissivity change.

### 3.3 Implications for postseismic water availability

Because the postseismic transmissivity transient follows a similar trajectory to that of the seismic wavespeed, we can use observations of seismic wavespeed recovery to infer expected recovery times of rock-mechanical transmissivity changes in the absence of sealing effects. Postseismic wavespeed recovery has been observed to take several months to over a decade [e.g., 18, 20, 53–55]. This implies that groundwater volumes and flow rates will take similarly long to return to pre-earthquake baselines [as independently estimated by 11, 56].

While previous studies have invoked fracture clogging as a coseismic mechanism [10, 16, 21], we demonstrate that it can manifest postseismically as an abrupt transmissivity drop, months after the earthquake, when sediments made available by coseismic

landsliding are flushed into the fracture network opened up by earthquake damage. For the following year, there is no sign of recovery from these transmissivity decreases in our data, indicating that the clogging of the millimetric-to-centimetric fractures that control permeability [43] may persist for years. This can cause significant discharge deficits in seismically perturbed catchments. In the case of the Liwu catchment, the observed typhoon-induced transmissivity decrease of about 50 % relative to pre-earthquake values caused discharge deficits estimated at 8–24 % (see 4.6). Long-lasting groundwater perturbations are consistent with observed impacts on vegetation health in the years following large earthquakes [57–59]. When, whether, and how clogged fractures are cleared, and transmissivity is restored to pre-earthquake values, remain important open questions, although earthquake-induced shaking [11, 16] or flushing by steep pressure gradients during intense rainfall on a landscape without open surface fissures could potentially clear fractures.

In steep landscapes like the Taiwan Central Range, transmissivity changes are unlikely to be spatially uniform. Topographic amplification focuses earthquake damage on mountain ridges [50–52], inducing stronger transmissivity changes and enhancing the known effect of postseismic redistribution of water from higher to lower elevations [60]. Storm-driven clogging, on the other hand, will preferentially take place in valleys, where topography concentrates overland flow and sediment-laden flooding [37], further amplifying the difference between valley and ridge transmissivities. Such effects are most consequential at convergent plate boundaries, where steep landscapes and megathrust earthquakes combine, altering permeability distributions within the mountain catchments that provide essential water services for years. Knowing the dynamic nature of the mountain groundwater systems and their response to sequenced seismic and meteorological perturbations will help to anticipate trends and changes in resource availability.

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## 534 4 Data and Methods

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### 536 4.1 Groundwater records

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We obtain water level records from four wells: EH-04, EHW-03, EHW-01, and EHW-02. Based on the lithological information, transfer function characteristics, pump test results and the drainage and recharge behaviour, we classify EHW-03 and EH-04 as unconfined wells. Their barometric transfer functions exhibit near-zero barometric efficiency, and tidal transfer functions derived from their piezometric records have broad optima leading to large uncertainties (i.e.,  $> 20^\circ$  for the tidal phase), precluding reliable tidal inversion. EHW-01 samples a confined but very low-permeability formation ( $T \approx 1 \times 10^{-8} \text{ m}^2/\text{s}$ ), for which semidiurnal tidal forcing is insufficient to drive measurable flow from the aquifer into the borehole within a half-tidal period. For these three wells, we only use their piezometric records to correct  $\delta v/v$  for water-level-induced fluctuations (see 4.4.2). EHW-02, which samples a semi-confined fractured aquifer, delivers robust tidal transfer functions.

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Geologically, eastern Taiwan is dominated by intense tectonic deformation resulting in an extraordinarily steep topography and a lithology dominated by metamorphic rocks. In particular, schists, marbles, and quartzites are prevalent. EHW-02 was drilled

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through a sequence of fractured schists overlain by  $\sim 17$  m of colluvium. The resulting borehole was cased and closed to isolate it from atmospheric influences. The well is screened between 97 and 100 m depth at a 10 min sampling interval and logged as groundwater level above sea level in metres. To obtain the groundwater level anomaly time series shown in the manuscript, we demean the data.

## 4.2 Computing transmissivity time series from well records, solid Earth tides, and barometric records

To obtain the transmissivity time series, we closely follow the procedure proposed by [23], who extended earlier work by [17] and [61] to compute such time series from tidal areal strain time series, barometric records, and groundwater level records for semi-confined aquifers. The algorithm consists of a two-step procedure: First, the tidal and barometric transfer functions of the groundwater level are computed for narrow frequency bands. Thereafter, one can invert for the aquifer's transmissivities  $T(t)$  and shear moduli  $G(t)$  that minimise the misfit to the observed transfer functions. This inversion requires knowledge of some well specifications and hydraulic parameters that can be derived from pump tests. Aside from assuming a constant vertical diffusivity  $D'$  for the leaky aquitard, we follow the procedure described in [23].

Like previous authors, we focus our analysis on tidal modes around the semi-diurnal tidal bands, including the M2, N2, and S2 modes, which separate more cleanly from harmonic noise than diurnal tides [11, 17, 23, 61]. To avoid introducing high-frequency noise into our analysis, we detrend and taper the data before applying a simple spike and step removal that removes water level changes above 2.5 cm per 10 min. Then, we bandpass filter the piezometric time series between 1.6 and 2.4 cycles per day using a 4th-order zero-phase Butterworth filter, effectively removing harmonic noise outside our band of analysis. To decrease the computational cost of the remaining steps, we decimate the water level and tidal data to a 60 min sampling interval.

To obtain the tidal and barometric transfer functions (i.e., time-dependent functions for barometric and tidal gain and phase lag), we apply a harmonic least-squares fit to the areal solid Earth tide strain, the barometric pressure, and the bandpass-filtered water level; thereby, we obtain complex functions containing amplitude and phase for each of the three frequencies. As in [22], we assume each frequency component  $k$  of the piezometric record to be the linear sum of the barometric and the tidal forcing:

$$\forall k \in [1, n], \tilde{h}_k = \frac{1}{\rho g} (Z_{a,k} \tilde{P}_k + Z_{\epsilon,k} \tilde{\epsilon}_k), \quad (1)$$

where  $\tilde{h}$ ,  $\tilde{P}$ , and  $\tilde{\epsilon}$  are the complex amplitudes of the piezometric water level, the atmospheric pressure, and the tidal strain, respectively. We set  $\rho = 1000 \frac{\text{kg}}{\text{m}^3}$  and  $g = 9.81 \frac{\text{m}}{\text{s}^2}$ . To solve for the barometric and tidal transfer functions  $Z_a$  and  $Z_\epsilon$ , we need to extract the values for at least two frequencies. It further requires us to assume that the frequency dependency between those frequencies is negligible [62]. Here, we solve for three quasi-semidiurnal frequencies (M2, N2, and S2), allowing us to create an overconstrained system of linear equations, to which we apply a complex least-squares

599 solve, thereby obtaining additional uncertainty estimates:

$$\begin{aligned}
 600 \quad & \rho g \tilde{h}_1 = Z_a \tilde{P}_1 + Z_\epsilon \tilde{\epsilon}_1 \\
 601 \quad & \rho g \tilde{h}_2 = Z_a \tilde{P}_2 + Z_\epsilon \tilde{\epsilon}_2 \\
 602 \quad & \rho g \tilde{h}_3 = Z_a \tilde{P}_3 + Z_\epsilon \tilde{\epsilon}_3
 \end{aligned} \tag{2}$$

603  
604  
605 We solve this equation for time steps of 29.5 days (i.e., one lunar month) and in  
606 increments of 7.5 days. To refine our uncertainty estimates, we bootstrap the result  
607 2000 times. We show the resulting transfer functions  $Z_a(t)$  and  $Z_\epsilon(t)$  in supplementary  
608 Fig. S2.

609 Finally, to obtain  $T(t)$  from the estimated transfer functions, we use the solution for  
610 a two-layered model by [23] that requires us to solve two partial differential equations  
611 for the atmospheric pressure and the tidal response:

$$612 \quad T \nabla^2 h + q = S \left( \frac{\partial h}{\partial t} - \frac{\gamma}{\rho g} \frac{\partial P}{\partial t} \right), \tag{3}$$

$$613 \quad T \nabla^2 h + q = S \left( \frac{\partial h}{\partial t} - \frac{2\gamma G}{\rho g} \frac{\partial \epsilon}{\partial t} \right), \tag{4}$$

614 where  $q$  is the vertical leakage flow,  $G$  the aquifer's shear modulus,  $\gamma$  its uniaxial  
615 Skempton coefficient or loading efficiency,  $T$  the transmissivity, and  $S$  the storativity.  
616 The full solution is provided in [23]. In contrast to them, we solve the equation for a  
617 time-invariant vertical diffusivity  $\frac{dD'}{dt} = 0$ , which reduces the number of unknowns and  
618 thereby decreases the noise level in the inversion procedure. We characterise the upper  
619 layer as a leaky aquitard with a thickness of 20 m and a storativity of  $S' = 8 \times 10^{-4}$ ,  
620 and the lower layer as an aquifer with a storativity of  $S = 7.2 \times 10^{-5}$  (see 4.3).  
621 Furthermore, the algorithm requires us to define the well's screen and casing radii,  
622 which are  $r_w = r_c = 0.0254$  m.

623 As we do not have any direct measurements of the uniaxial Skempton coefficients  
624  $\gamma$  and  $\gamma'$  and the hydraulic diffusivity  $D'$ , we calibrate them directly from the transfer  
625 functions. To this end, we exploit the dependency of the loading efficiency ratio  $R =$   
626  $\frac{1-\gamma'}{1-\gamma}$ , required to calibrate our model, on the median phase difference between tidal and  
627 barometric transfer functions  $\tilde{\Delta}\phi \approx 19^\circ$  and the vertical diffusivity  $D'$  (as described in  
628 appendix B2 of [23]). For a given  $D'$ , we find the  $R$  that produces this phase difference  
629 analytically. We independently assess numerical stability by checking the fraction of  
630 time steps at which the inversion pins at its search bounds across a range of  $D'$ - $R$   
631 pairs, preferring pairs that minimise this fraction. This procedure yields  $R \approx 0.23$  and  
632  $D' \approx 2.1 \times 10^{-3} \frac{m^2}{s}$ , agreeing to first order with independent pump test results (see  
633 4.3). Finally, we invert for  $T(t)$  from the tidal phase response. The tidal amplitude  
634 gain and  $T(t)$  constrain the shear modulus  $G(t)$ , which we do not interpret for reasons  
635 laid out in 4.2.1.

#### 4.2.1 Postprocessing the transmissivity

##### *Removing the water level dependency in $T(t)$*

We find a subtle water level dependency for  $T(t)$ . Higher pore pressures lead to an extension of existing pores and cracks, increasing their permeability. This dependency can be corrected as demonstrated by [23]. We do so by fitting our observations of transmissivity and effective stress changes to a model relating the two [27]:

$$\left(\frac{T}{T_0}\right)^{1/3} = 1 - \alpha \ln \frac{\sigma^*}{\sigma_0^*}, \quad (5)$$

where  $\sigma^*$  is the effective stress,  $T_0$  and  $\sigma_0^*$  are the mean transmissivity and mean effective stress, respectively.  $\alpha$  is the proportionality coefficient that we find through a least-squares misfit optimisation in a simple gridsearch process. To avoid noise introduced by co- and postseismic transmissivity changes, we only consider observations before the Hualien earthquake. The resulting correction and fit are shown in supplementary Fig. S3.

##### *Step removal in $T(t)$*

Coinciding with the Gaemi typhoon, we find a step decrease in  $T$  (see 2.2) of  $-6 \times 10^{-7} \text{m}^2/\text{s}$ . For Kong-Rey, the corresponding step is  $-3 \times 10^{-7} \text{m}^2/\text{s}$ . To facilitate the comparison of the postseismic transient behaviours in  $\delta v/v$  and  $T$ , we remove these steps simply by subtracting them from the time series following each typhoon's landfall.

##### *Water level dependency in $G(t)$*

We find a strong positive correlation between the tidal transfer function's gain and the piezometric water level, which carries through into the inferred  $G(t)$  (see supplementary Figs. S2 and S3). As structural shear modulus changes and pore pressure-induced gain changes are in practice indistinguishable, we chose not to interpret  $G(t)$ .  $T(t)$  is unaffected as it is derived solely from the tidal phase response.

#### 4.2.2 Estimating sediment load changes

After finding  $\alpha$  for Eq. 5, we can simply infer the amount of effective stress required to produce the observed typhoon-triggered transmissivity changes from the fitted model. As a lower-bound estimate, we assume drained conditions, i.e. we set the Skempton coefficient to 0. The thickness of newly deposited sediment required to produce the step change introduced only by typhoon Gaemi ( $-6 \times 10^{-7} \text{m}^2/\text{s}$ ) is 4.8 m, assuming a mass density of  $1800 \text{kg}/\text{m}^3$ .

#### 4.3 Aquifer and aquitard properties inferred from pump tests

The Geological Survey and Mining Management Agency performed hydraulic pump tests at our borehole site (see supplementary Table S1). These tests yielded values for the specific storativity  $S_s$  and the hydraulic conductivity  $K$  at various depth ranges.



691 We infer storativity values for aquifer and aquitard and transmissivity values for the  
 692 aquifer from these values. Specifically, we obtain  $T_{PT}^{87-100\text{ m}} = K\Delta h = 1.3 \times 10^{-7} \text{ m/s} \times$   
 693  $13 \text{ m} = 1.69 \times 10^{-6} \text{ m}^2/\text{s}$  assuming an isotropic hydraulic conductivity. We plot this  
 694 value as reference in Fig. 3. We directly take  $S = 7.2 \times 10^{-5}$  from the depth range of  
 695 28 to 100 m. For the aquitard, we choose the geometric mean,  $S' = 8 \times 10^{-4}$ , computed  
 696 from the  $S$  values derived from the intervals 30-31.5 m with  $S_s = 1.1 \times 10^{-5} \text{ m}^{-1}$  and  
 697 39-40.5 m depth with  $S_s = 1.4 \times 10^{-4} \text{ m}^{-1}$ , yielding  $S' = S'_s \times h' = 2.2 \times 10^{-4}$  and  
 698  $S' = 2.8 \times 10^{-3}$ , respectively, assuming an aquitard thickness of  $h' = 20 \text{ m}$ . We can  
 699 also use these values to validate our choice for  $D'$  as  $D' = K'/S'_s$  [63], again assuming  
 700 an isotropic hydraulic conductivity. Using this relation, we obtain values spanning  
 701 between  $7.86 \times 10^{-5} \text{ m}^2/\text{s}$  and  $2.45 \times 10^{-3} \text{ m}^2/\text{s}$ , depending on the chosen depth range  
 702 - placing our chosen  $D' \approx 2.1 \times 10^{-3} \text{ m}^2/\text{s}$  at the upper end of the range. Generally,  
 703 pump test values vary by around one order of magnitude, depending on the depths  
 704 from which they were derived, leaving substantial room for data uncertainty.

#### 706 4.4 Obtaining seismic wavespeed changes from ambient 707 seismic noise

709 To obtain the  $\delta v/v$  time series, we follow the stretching method as proposed by [24] and  
 710 implemented in the SeisMIC software package [64]. During preprocessing, we taper,  
 711 detrend, anti-alias filter, and decimate the data to 5, 10, 12.5, 25, or 50 Hz, depending  
 712 on the octave frequency band in which we subsequently bandpass filter. Our chosen  
 713 frequency bands, 0.5-1 Hz, 1-2 Hz, 2-4 Hz, 4-8 Hz, and 8-16 Hz, provide us with depth  
 714 sensitivities of tens of metres (16 Hz) down to 1-2 km (0.5 Hz) [28]. Finally, we impose  
 715 one-bit-normalisation and whiten their amplitude spectra [65].

716 The actual algorithm to retrieve relative seismic wavespeed changes consists of  
 717 a two-step procedure: First, one correlates continuous seismic data from time  $t_n$  to  
 718 remove the source-side effect, extracting empirical Green's functions (EGFs). There-  
 719 after, the EGF from  $t_n$  is stretched against a reference to obtain a homogeneous  
 720 velocity change at  $t_n$  (see [64] for a detailed description of the algorithm). In practice,  
 721 we cross-correlate hourly seismic data recorded on the three directional components  
 722 (vertical, north, east), thereby obtaining three cross-component correlations or EGFs  
 723 per station (E-N, E-Z, and N-Z). To estimate  $\delta v/v(t)$ , we compare 2-week-long aver-  
 724 ages of those EGFs with stretched versions of the temporal average of all EGFs, which  
 725 acts as our reference, corresponding to 0 % velocity change. Specifically, we compare  
 726 the early coda of the EGFs between lag times of  $\tau_s = 5/T_0$  and  $\tau_e = 10/T_0$ , where  $T_0$   
 727 is the low-corner period of the applied bandpass filter. This early coda is dominated  
 728 by surface waves, for which our depth estimates are valid [28]. We find the wavespeed  
 729 change for each day by stretching the reference by up to 5 % and identifying the stretch-  
 730 ing factor producing the highest correlation for each daily smoothed EGF. We then  
 731 apply a weighted average to the three  $\delta v/v$  estimates from each station [66], obtain-  
 732 ing one  $\delta v/v$  curve per station with a one-day sampling interval. For representation  
 733 purposes, we roll the results so that the 1st February 2024 has 0 % wavespeed change.

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#### 4.4.1 Quality controlling $\delta v/v$

In eastern Taiwan, extreme weather events lead to flooding, sliding, and slumping that affect the sensors. As a result, stations may fail, or their ground coupling may deteriorate. Generally, we disregard stations without available data around the M7.2 Hualien earthquake or whose data quality does not satisfy the threshold described below. As a result, we discard six stations from our analysis: TQ00, TQ03, TQ04, TQ05, TQ07, and TQ11 (none of which is plotted in Fig. 1).

The quality of a  $\delta v/v$  estimate can be assessed using the correlation coefficient between the stretched reference and the daily correlation function. After averaging the three components, we obtain an average correlation coefficient that is inherently lower than the individual values but still represents a reliable measure for the stability of each  $\delta v/v(t_n)$  [66]. After inspection, we opt to discard  $\delta v/v$  time series that exhibit significant portions of data points with  $R_{av} < 0.4$ . As a result, we consider only some frequency bands for some stations.

#### 4.4.2 Water level compensation

To remove the influence of groundwater fluctuations on  $\delta v/v$ , we compute linear fitting coefficients for a simple least-squares fit between each  $\delta v/v$  and the water level curve with a soft L1 loss criterion, where the loss function is defined as  $\rho(z) = 2(\sqrt{1+z} - 1)$  and  $z$  corresponds to the least-squares loss [67]. We estimate the linear fitting coefficients for all  $\delta v/v$  points with  $R_{av} > 0.25$  and the period before the Hualien earthquake to avoid the influence of the coseismic wavespeed drop and postseismic recovery. Finally, the water-level-corrected version of  $\delta v/v$  is then:

$$(\delta v/v)_{corr}(t) = (\delta v/v)(t) - (\delta v/v)_{lqm}(t), \quad (6)$$

where  $(\delta v/v)_{lqm}$  is the modelled pore pressure-induced seismic wavespeed change.

#### 4.5 Peak ground acceleration

To compute the PGA, we download data from stations F072 and F026 from the Taiwan Strong Motion Instrumentation Program Network (TSMIP), a network of force-balance accelerometers. Data are downloaded for the five minutes following the origin time of each seismic event with  $M \geq 4.5$ , hypocentral depth  $z \leq 40$  km, longitude  $120^\circ \leq \lambda \leq 121.5^\circ$ , and a latitude of  $22.5^\circ \leq \phi \leq 25.5^\circ$ . From the resulting traces, we remove the instrumental response and determine the envelope's maximum for each of the instrument's three components. We define the maximum value for each event as the event's PGA. For events after 07 April 2022, we consider the PGA from F072, which is co-located with well EHW-02 but has no available data before this date. We do not plot PGAs below a threshold of  $0.2 \text{ m/s}^2$ .

#### 4.6 Translating transmissivity perturbations to discharge deficits

To estimate the potential catchment-scale consequence of the typhoon-induced transmissivity decrease, we use a deliberately simple first-order calculation. Its purpose is

not to reproduce the transient groundwater response of the Liwu catchment but to bracket how a spatially distributed transmissivity reduction could affect cumulative discharge at the catchment outlet.

We consider the period from typhoon Kong-Rey (31 October 2024) to the latest available precipitation record (31 May 2026;  $\Delta t \approx 1.58$  yr). Over this period, station C0T820 recorded a cumulative precipitation of  $P = 4183.5$  mm. We approximate actual evapotranspiration as 700 mm/yr, i.e.,  $ET \approx 1106$  mm. Neglecting changes in long-term storage and deep groundwater losses, the reference volume available for discharge from the catchment area  $A = 616.3$  km<sup>2</sup> is

$$V_0 = (P - ET) A \approx 1.90 \text{ km}^3, \quad (7)$$

which corresponds to a mean discharge of  $Q_0 = V_0/\Delta t \approx 38$  m<sup>3</sup>/s.

We assume that a fraction  $f$  of the catchment experiences a fractional transmissivity decrease  $r$ , and that outlet discharge scales linearly with the spatially averaged transmissivity. The relative discharge deficit and the cumulative volume deficit are then

$$\frac{\Delta Q}{Q_0} = fr, \quad \Delta V_Q = V_0 fr, \quad (8)$$

independent of the absolute background transmissivity. For  $f = 20$ –40 % and  $r = 40$ –60 % (bracketing the  $\sim 50$  % decrease observed at EHW-02), we obtain relative deficits of 8–24 %, or  $\Delta V_Q \approx 0.15$ –0.46 km<sup>3</sup>. The calculated volume should not be interpreted as water that physically disappears from the catchment. It is more appropriately described as a potential cumulative outlet-flow deficit relative to a hypothetical catchment in which the transmissivity perturbation had not occurred. In other words, the calculated volume represents water that, according to the simple transmissivity scaling adopted here, would have reached the outlet during the considered period in the absence of fracture clogging but may not yet have done so in the perturbed system.

**Supplementary information.** This article is accompanied by a supplementary file in PDF format, containing additional figures and a discussion about Taroko’s aquifers.

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## Declarations

### 4.7 Data availability

The seismic data from the TQ network [68] used to compute the seismic velocity change time series can be downloaded from the Geofon FDSN service [69]. Piezometric water levels for the wells are openly available with a one-day-sample interval from the Taiwan hydrogeological information system at <https://hydro.geologycloud.tw/>.

The 10-minute-sampled piezometric data is provided as electronic supplement to this manuscript (see Code availability for details). The barometric and precipitation data for weather station C0T820 were obtained from Taiwan’s Central Weather Administration (CWA) at <https://codis.cwa.gov.tw>. To compute the PGA, we obtained data from stations F072 and F026 from the Taiwan Strong Motion Instrumentation Program (TSMIP) network, provided by the CWA at <https://gdms.cwa.gov.tw>. The digital elevation model used in the map plots was obtained from the Shuttle Radar Topography Mission [70]. Locations of rivers and streams shown in Fig. 1 are copyrighted by OpenStreetMap contributors and available from <https://www.openstreetmap.org>, while we obtained the moment tensors from the global CMT project [71] at [www.globalcmt.org](http://www.globalcmt.org).

## 4.8 Code availability

During peer-review: The research codes and raw data required to reproduce this work are included in the submission. Upon acceptance, these will be made available to the public via a DOI-minted archive (Zenodo). We computed the solid Earth tide predictions using the PyGTide software [72]. Seismic velocity changes were estimated using the SeisMIC software suite [64]. We plotted maps with PyGMT [73]. Moreover, we heavily relied on the Python community packages NumPy [74], SciPy [67], and Matplotlib [75].

## 4.9 Author contribution

**Conceptualization:** PM, NB, LI, NH

**Data Curation:** PM, WAC, JMC

**Formal Analysis:** PM, LI

**Investigation:** JMT, WSC, JMC, WAC, WYC

**Methodology:** PM, NB, LI

**Software:** PM

**Supervision:** NH, JMT

**Visualization:** PM

**Writing — Original Draft:** PM

**Writing — Review & Editing:** PM, JMT, NB, NH, LI

## 4.10 Competing interests

The authors declare no competing interests.

## References

- [1] Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E. & Cardenas, M. B. The global volume and distribution of modern groundwater. *Nature Geoscience* **9**, 161–167 (2016).
- [2] Richard Connor & Michela Miletto. The United Nations World Water Development Report 2022: Groundwater: Making the invisible visible; executive summary.

- 875 Tech. Rep. 0000380726, UNESCO World Water Assessment Programme, France  
876 (2022).  
877  
878 [3] Foster, S. S. D. & Chilton, P. J. Groundwater: The processes and global signifi-  
879 cance of aquifer degradation. *Philosophical Transactions of the Royal Society B:*  
880 *Biological Sciences* **358**, 1957–1972 (2003).  
881  
882 [4] Pelascini, L., Steer, P., Mouyen, M. & Longuevergne, L. Modelling the control  
883 of groundwater on landslides triggering: The respective role of atmosphere and  
884 rainfall during typhoons. *Natural Hazards and Earth System Science* (2022).  
885  
886 [5] Shi, Z., Wang, G., Manga, M. & Wang, C.-Y. Continental-scale water-level  
887 response to a large earthquake. *Geofluids* **15**, 310–320 (2015).  
888  
889 [6] Mohr, C. H., Manga, M., Wang, C.-Y. & Korup, O. Regional changes in stream-  
890 flow after a megathrust earthquake. *Earth and Planetary Science Letters* **458**,  
891 418–428 (2017).  
892  
893 [7] Wang, C.-Y. & Manga, M. New streams and springs after the 2014 Mw6.0 South  
894 Napa earthquake. *Nature Communications* **6**, 7597 (2015).  
895  
896 [8] Jin, Z. *et al.* Seismically enhanced solute fluxes in the Yangtze River headwaters  
897 following the A.D. 2008 Wenchuan earthquake. *Geology* **44**, 47–50 (2016).  
898  
899 [9] Biais, Z., Andermann, C., Steer, P. & Longuevergne, L. Substantial Excess  
900 Groundwater Release following the 2015 Gorkha Earthquake in Nepal. *ESS Open*  
901 *Archive* **2026**.  
902  
903 [10] Manga, M. *et al.* Changes in permeability caused by transient stresses: Field  
904 observations, experiments, and mechanisms. *Reviews of Geophysics* **50** (2012).  
905  
906 [11] Elkhoury, J. E., Brodsky, E. E. & Agnew, D. C. Seismic waves increase  
907 permeability. *Nature* **441**, 1135–1138 (2006).  
908  
909 [12] Muir-Wood, R. & King, G. C. P. Hydrological signatures of earthquake strain.  
910 *Journal of Geophysical Research: Solid Earth* **98**, 22035–22068 (1993).  
911  
912 [13] Mohr, C. H., Manga, M., Wang, C.-y., Kirchner, J. W. & Bronstert, A. Shaking  
913 water out of soil. *Geology* **43**, 207–210 (2015).  
914  
915 [14] Shi, Z. & Wang, G. Aquifers switched from confined to semiconfined by  
916 earthquakes. *Geophysical Research Letters* **43**, 11,166–11,172 (2016).  
917  
918 [15] Wang, C.-Y., Liao, X., Wang, L.-P., Wang, C.-H. & Manga, M. Large earthquakes  
919 create vertical permeability by breaching aquitards. *Water Resources Research*  
920 **52**, 5923–5937 (2016).

- [16] Brodsky, E. E., Roeloffs, E., Woodcock, D., Gall, I. & Manga, M. A mechanism for sustained groundwater pressure changes induced by distant earthquakes. *Journal of Geophysical Research: Solid Earth* **108** (2003). 921  
922  
923  
924
- [17] Hsieh, P. A., Bredehoeft, J. D. & Farr, J. M. Determination of aquifer transmissivity from Earth tide analysis. *Water Resources Research* **23**, 1824–1832 (1987). 925  
926  
927  
928
- [18] Brenguier, F. *et al.* Postseismic Relaxation Along the San Andreas Fault at Parkfield from Continuous Seismological Observations. *Science* **321**, 1478–1481 (2008). 929  
930  
931  
932
- [19] Gassenmeier, M. *et al.* Field observations of seismic velocity changes caused by shaking-induced damage and healing due to mesoscopic nonlinearity. *Geophysical Journal International* **204**, 1490–1502 (2016). 933  
934  
935  
936
- [20] Illien, L., Turowski, J. M., Sens-Schönfelder, C., Berenfeld, C. & Hovius, N. Predictable recovery rates in near-surface materials after earthquake damage. *Nature Communications* **16**, 1790 (2025). 937  
938  
939  
940
- [21] Vittecoq, B., Fortin, J., Maury, J. & Violette, S. Earthquakes and extreme rainfall induce long term permeability enhancement of volcanic island hydrogeological systems. *Scientific Reports* **10**, 20231 (2020). 941  
942  
943  
944
- [22] Thomas, A., Fortin, J., Vittecoq, B. & Violette, S. Earthquakes and Heavy Rainfall Influence on Aquifer Properties: A New Coupled Earth and Barometric Tidal Response Model in a Confined Bi-Layer Aquifer. *Water Resources Research* **59**, e2022WR033367 (2023). 945  
946  
947  
948
- [23] Thomas, A. *et al.* Hydro-Mechanical Characterization of a Fractured Aquifer Using Groundwater Level Tidal Analysis: Effect of Pore Pressure and Seismic Dynamic Shear Stresses on Permeability Variations. *Journal of Geophysical Research: Solid Earth* **129**, e2024JB028847 (2024). 949  
950  
951  
952  
953
- [24] Sens-Schönfelder, C. & Wegler, U. Passive image interferometry and seasonal variations of seismic velocities at Merapi Volcano, Indonesia. *Geophysical Research Letters* **33**, 1–5 (2006). 954  
955  
956  
957
- [25] Chang, J.-M., Chao, W.-A., Yang, C.-M. & Huang, M.-W. Coseismic and subsequent landslides of the 2024 Hualien earthquake (M7.2) on April 3 in Taiwan. *Landslides* **21**, 2591–2595 (2024). 958  
959  
960  
961
- [26] Huang, X., Chan, J. C. L., Bai, L., Yu, Z. & Sun, T. Tropical Cyclone Activities in the Western North Pacific in 2024. *Tropical Cyclone Research and Review* **15**, 29–42 (2026). 962  
963  
964  
965  
966



- 967 [27] Walsh, J. B. Effect of pore pressure and confining pressure on fracture per-  
968 meability. *International Journal of Rock Mechanics and Mining Sciences &*  
969 *Geomechanics Abstracts* **18**, 429–435 (1981).  
970
- 971 [28] Obermann, A., Planès, T., Larose, E., Sens-Schönfelder, C. & Campillo, M.  
972 Depth sensitivity of seismic coda waves to velocity perturbations in an elastic  
973 heterogeneous medium. *Geophysical Journal International* **194**, 372–382 (2013).  
974
- 975 [29] Clements, T. & Denolle, M. A. Tracking Groundwater Levels Using the Ambient  
976 Seismic Field. *Geophysical Research Letters* **45**, 6459–6465 (2018).  
977
- 978 [30] Lecocq, T., Longuevergne, L., Pedersen, H. A., Brenguier, F. & Stammer, K.  
979 Monitoring ground water storage at mesoscale using seismic noise: 30 years of  
980 continuous observation and thermo-elastic and hydrological modeling. *Scientific*  
981 *Reports* **7** (2017).  
982
- 983 [31] Mao, S., Lecointre, A., van der Hilst, R. D. & Campillo, M. Space-time mon-  
984 itoring of groundwater fluctuations with passive seismic interferometry. *Nature*  
985 *Communications* **13**, 4643 (2022).  
986
- 987 [32] Chen, C.-W., Wei, L.-W., Yamada, R. & Iida, T. Spatial distribution of land-  
988 slides triggered by the 2022 Taitung Earthquakes in relation to active fault  
989 systems, topographic effects, and geological conditions. *Geomorphology* **473**,  
990 109615 (2025).  
991
- 992 [33] Marc, O., Hovius, N., Meunier, P., Gorum, T. & Uchida, T. A seismologi-  
993 cally consistent expression for the total area and volume of earthquake-triggered  
994 landsliding. *Journal of Geophysical Research: Earth Surface* **121**, 640–663 (2016).  
995
- 996 [34] Lin, G.-W. *et al.* Effects of earthquake and cyclone sequencing on landsliding and  
997 fluvial sediment transfer in a mountain catchment. *Earth Surface Processes and*  
998 *Landforms* **33**, 1354–1373 (2008).  
999
- 1000 [35] Marc, O., Hovius, N., Meunier, P., Uchida, T. & Hayashi, S. Transient changes  
1001 of landslide rates after earthquakes. *Geology* **43**, 883–886 (2015).  
1002
- 1003 [36] Steer, P. *et al.* Earthquake statistics changed by typhoon-driven erosion. *Scientific*  
1004 *Reports* **10**, 10899 (2020).  
1005
- 1006 [37] Dadson, S. J. *et al.* Earthquake-triggered increase in sediment delivery from an  
1007 active mountain belt. *Geology* **32**, 733–736 (2004).  
1008
- 1009 [38] Mahler, B. J. & Lynch, F. L. Muddy waters: Temporal variation in sediment  
1010 discharging from a karst spring. *Journal of Hydrology* **214**, 165–178 (1999).  
1011
- 1012 [39] Pronk, M., Goldscheider, N., Zopfi, J. & Zwahlen, F. Percolation and Particle  
Transport in the Unsaturated Zone of a Karst Aquifer. *Groundwater* **47**, 361–369

- (2009). 1013
- [40] Zhou, Y. *et al.* Suspended Sediment Pulses and Sediment-Discharge Relations in Earthquake-Affected Rivers Along the Tibetan Plateau Margins. *Water Resources Research* **62**, e2025WR042351 (2026). 1014
- [41] Montgomery, D. R. & Manga, M. Streamflow and Water Well Responses to Earthquakes. *Science* **300**, 2047–2049 (2003). 1015
- [42] Wang, W. L. *et al.* Assessment of damage in mountain tunnels due to the Taiwan Chi-Chi Earthquake. *Tunnelling and Underground Space Technology* **16**, 133–150 (2001). 1016
- [43] Jeanpert, J. *et al.* Fracture controlled permeability of ultramafic basement aquifers. Inferences from the Koniambo massif, New Caledonia. *Engineering Geology* **256**, 67–83 (2019). 1017
- [44] Candela, T., Brodsky, E. E., Marone, C. & Elsworth, D. Laboratory evidence for particle mobilization as a mechanism for permeability enhancement via dynamic stressing. *Earth and Planetary Science Letters* **392**, 279–291 (2014). 1018
- [45] Trofimov, A., Drach, B., Kachanov, M. & Sevostianov, I. Effect of a partial contact between the crack faces on its contribution to overall material compliance and resistivity. *International Journal of Solids and Structures* **108**, 289–297 (2017). 1019
- [46] Witherspoon, P. A., Wang, J. S. Y., Iwai, K. & Gale, J. E. Validity of Cubic Law for fluid flow in a deformable rock fracture. *Water Resources Research* **16**, 1016–1024 (1980). 1020
- [47] Meyer, G. G., Brantut, N., Mitchell, T. M., Meredith, P. G. & Plümper, O. Time Dependent Mechanical Crack Closure as a Potential Rapid Source of Post-Seismic Wave Speed Recovery: Insights From Experiments in Carrara Marble. *Journal of Geophysical Research: Solid Earth* **126**, e2020JB021301 (2021). 1021
- [48] Sens-Schönfelder, C., Snieder, R. & Li, X. A model for nonlinear elasticity in rocks based on friction of internal interfaces and contact aging. *Geophysical Journal International* **216**, 319–331 (2019). 1022
- [49] Asnar, M. *et al.* Anisotropy reveals contact sliding and aging as a cause of post-seismic velocity changes. *Nature Communications* **16**, 7587 (2025). 1023
- [50] Bouchon, M., Schultz, C. A. & Toksöz, M. N. Effect of three-dimensional topography on seismic motion. *Journal of Geophysical Research: Solid Earth* **101**, 5835–5846 (1996). 1024
- [51] Hough, S. E. *et al.* Localized damage caused by topographic amplification during the 2010 M 7.0 Haiti earthquake. *Nature Geoscience* **3**, 778–782 (2010). 1025

- 1059 [52] Lee, S.-J., Chan, Y.-C., Komatitsch, D., Huang, B.-S. & Tromp, J. Effects of  
1060 Realistic Surface Topography on Seismic Ground Motion in the Yangminshan  
1061 Region of Taiwan Based Upon the Spectral-Element Method and LiDAR DTM.  
1062 *Bulletin of the Seismological Society of America* **99**, 681–693 (2009).  
1063
- 1064 [53] Illien, L. *et al.* Seismic Velocity Recovery in the Subsurface: Transient Dam-  
1065 age and Groundwater Drainage Following the 2015 Gorkha Earthquake, Nepal.  
1066 *Journal of Geophysical Research: Solid Earth* **127**, e2021JB023402 (2022).  
1067
- 1068 [54] Clements, T. & Denolle, M. A. The Seismic Signature of California’s Earth-  
1069 quakes, Droughts, and Floods. *Journal of Geophysical Research: Solid Earth* **128**,  
1070 e2022JB025553 (2023).
- 1071 [55] Makus, P., Denolle, M. A., Sens-Schönfelder, C., Köpfl, M. & Tilmann, F. Ana-  
1072 lyzing Volcanic, Tectonic, and Environmental Influences on the Seismic Velocity  
1073 from 25 Years of Data at Mount St. Helens. *Seismological Research Letters* **95**,  
1074 2674–2688 (2024).  
1075
- 1076 [56] Kagabu, M., Ide, K., Hosono, T., Nakagawa, K. & Shimada, J. Describing coseis-  
1077 mic groundwater level rise using tank model in volcanic aquifers, Kumamoto,  
1078 southern Japan. *Journal of Hydrology* **582**, 124464 (2020).  
1079
- 1080 [57] Rodriguez, J., Ustin, S., Sandoval-Solis, S. & O’Geen, A. T. Food, water, and  
1081 fault lines: Remote sensing opportunities for earthquake-response management of  
1082 agricultural water. *Science of The Total Environment* **565**, 1020–1027 (2016).  
1083
- 1084 [58] Gao, S. *et al.* Shifts of forest resilience after seismic disturbances in tectonically  
1085 active regions. *Nature Geoscience* **17**, 189–196 (2024).  
1086
- 1087 [59] Zhang, J. *et al.* Eco-hydrological recovery following large vegetation disturbances  
1088 from a mega earthquake on the eastern Tibetan plateau. *Journal of Hydrology*  
1089 **651**, 132595 (2025).
- 1090 [60] Hosono, T., Yamada, C., Manga, M., Wang, C.-Y. & Tanimizu, M. Stable isotopes  
1091 show that earthquakes enhance permeability and release water from mountains.  
1092 *Nature Communications* **11**, 2776 (2020).  
1093
- 1094 [61] Wang, C.-Y., Doan, M.-L., Xue, L. & Barbour, A. J. Tidal Response of Ground-  
1095 water in a Leaky Aquifer—Application to Oklahoma. *Water Resources Research*  
1096 **54**, 8019–8033 (2018).  
1097
- 1098 [62] Acworth, R. I., Halloran, L. J. S., Rau, G. C., Cuthbert, M. O. & Bernardi,  
1099 T. L. An objective frequency domain method for quantifying confined aquifer  
1100 compressible storage using Earth and atmospheric tides. *Geophysical Research*  
1101 *Letters* **43**, 11,671–11,678 (2016).  
1102  
1103  
1104

- [63] Neuman, S. P. & Witherspoon, P. A. Theory of Flow in a Confined Two Aquifer System. *Water Resources Research* **5**, 803–816 (1969).  
[64] Makus, P. & Sens-Schönfelder, C. SeisMIC - an Open Source Python Toolset to Compute Velocity Changes from Ambient Seismic Noise. *Seismica* **3** (2024).  
[65] Bensen, G. D. *et al.* Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements. *Geophysical Journal International* **169**, 1239–1260 (2007).  
[66] Makus, P. *et al.* Deciphering the Whisper of Volcanoes: Monitoring Velocity Changes at Kamchatka’s Klyuchevskoy Group With Fluctuating Noise Fields. *Journal of Geophysical Research: Solid Earth* **128**, e2022JB025738 (2023).  
[67] Virtanen, P. *et al.* SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods* **17**, 261–272 (2020).  
[68] Turowski, J. M. *et al.* Taiwan multi-parametric environmental seismic network (2022).  
[69] Quinteros, J. *et al.* The GEOFON Program in 2020. *Seismological Research Letters* **92**, 1610–1622 (2021).  
[70] Rabus, B., Eineder, M., Roth, A. & Bamler, R. The shuttle radar topography mission—a new class of digital elevation models acquired by spaceborne radar. *ISPRS Journal of Photogrammetry and Remote Sensing* **57**, 241–262 (2003).  
[71] Ekström, G., Nettles, M. & Dziewoński, A. M. The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors* **200–201**, 1–9 (2012).  
[72] Rau, G. C., Eulenfeld, T. & Miller, C. Hydrogeoscience/pygtide: PyGTide v0.9.1 (2026).  
[73] Uieda, L. *et al.* PyGMT: A Python interface for the Generic Mapping Tools (2021).  
[74] Harris, C. R. *et al.* Array programming with NumPy. *Nature* **585**, 357–362 (2020).  
[75] Hunter, J. D. Matplotlib: A 2D Graphics Environment. *Computing in Science & Engineering* **9**, 90–95 (2007).

# Supplementary material for: Typhoons reseal mountain groundwater systems after earthquake damage

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## 1 Supplementary discussion: Taroko's aquifers

All four boreholes, from which we obtain data, are drilled into fractured metamorphic bedrock typical of eastern Taiwan. However, their hydraulic properties vary substantially, impacting their water level dynamics and suitability for tidal analysis. EHW-03 and EH-04 are drilled through unconfined aquifers hosted in marble and gneiss, respectively, with high transmissivities that lead to rapid recharge, apparent in their raw water level records (see Fig. 2 in the main text). Their tidal transfer functions yield poorly constrained phase estimates, precluding a tidal inversion. EH-04 is located adjacent to the Liwu River and, due to its high hydraulic conductivity, its piezometric water level closely tracks river stage, explaining the absence of persistent postseismic water level anomalies at this well. EHW-01 is confined within a low-permeability schist ( $T \approx 1 \times 10^{-8} \text{ m}^2/\text{s}$ ). Its transmissivity is so low that diffusion within the aquifer is slower than a half-period of the semi-diurnal tide, yielding no exploitable tidal signal. EHW-02 samples a semi-confined fractured aquifer isolated from the surface by  $\sim 17 \text{ m}$  of colluvium. Its intermediate transmissivity,  $\sim 1 \times 10^{-6} \text{ m}^2/\text{s}$ , allows pore pressure diffusion within the tidal period while confinement suppresses atmospheric noise, making it the only well suited for our tidal inversion.

## 2 Supplementary figures

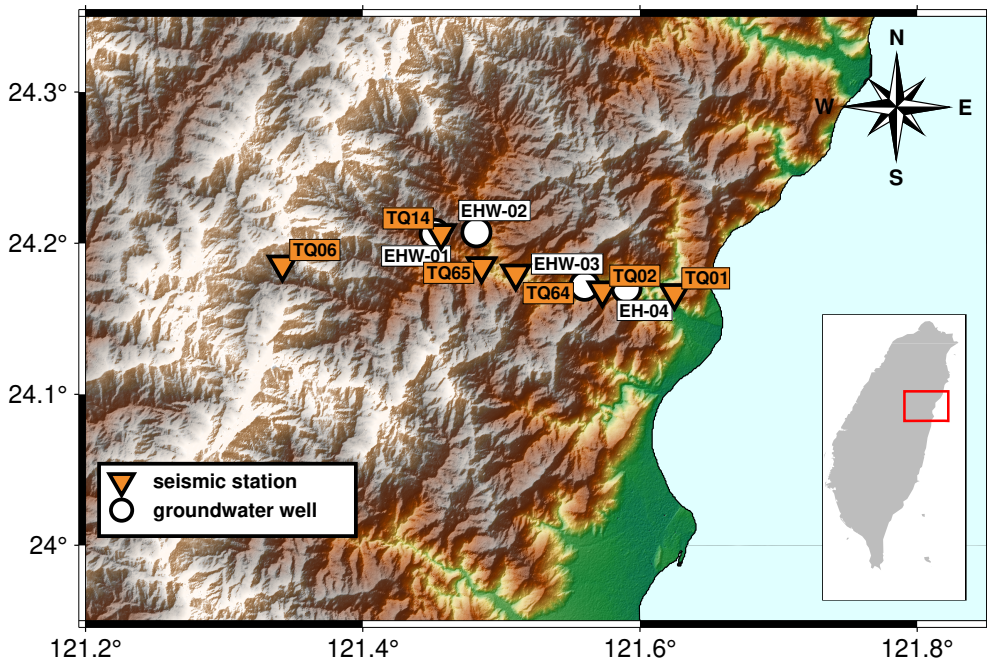
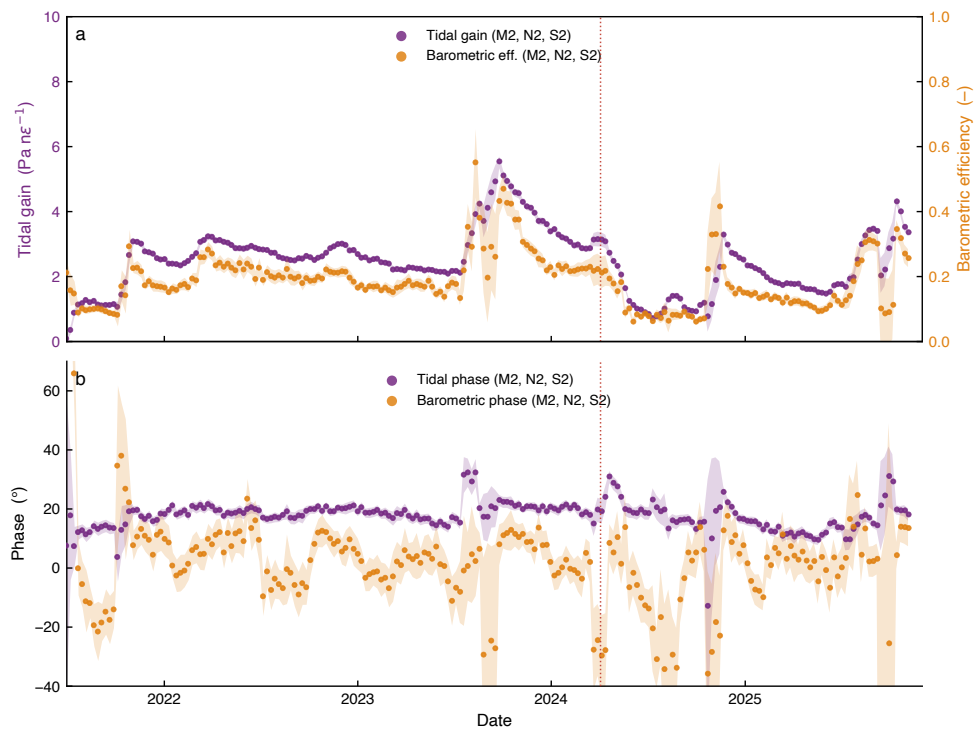
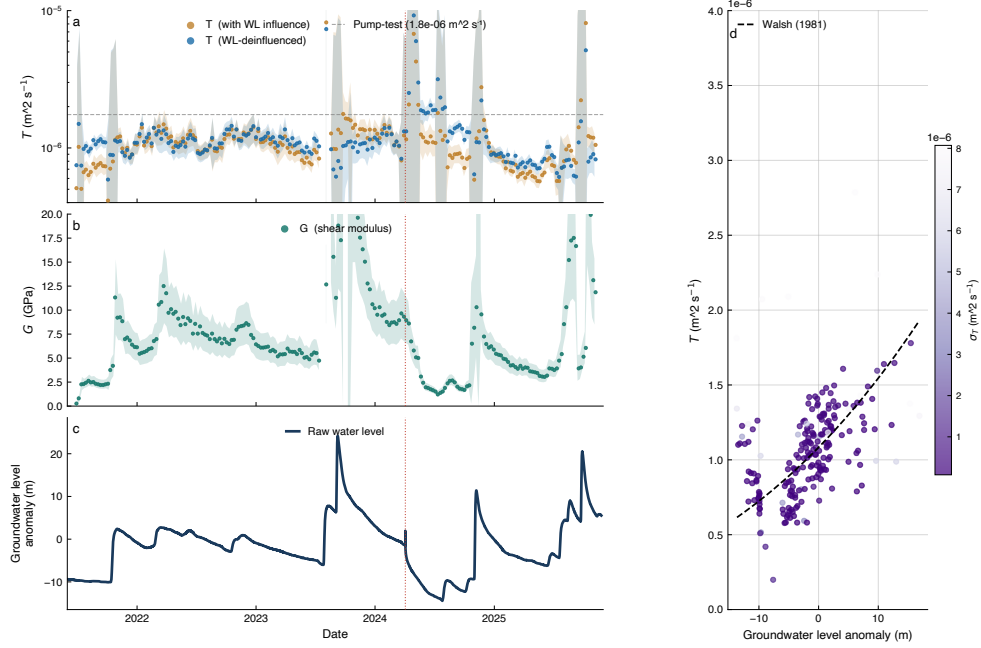


Fig. S1 Location and code of seismic stations and groundwater wells used in this work.

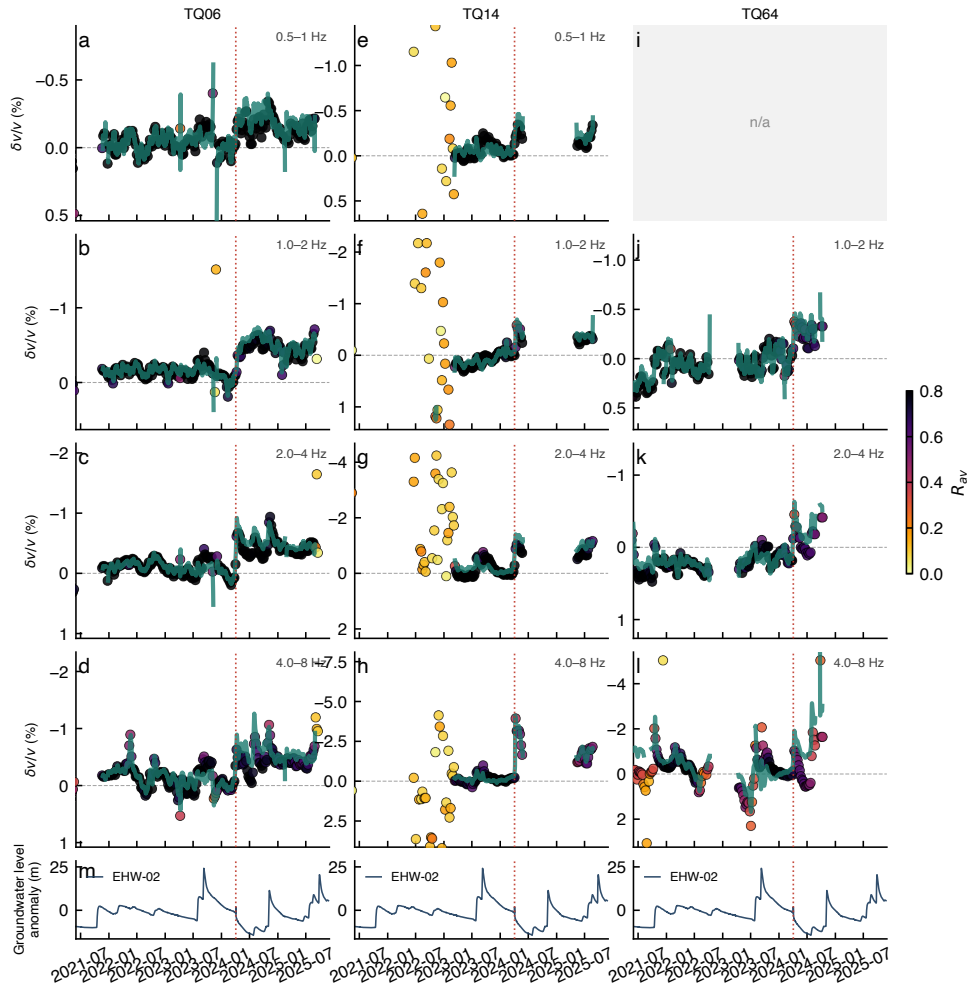


**Fig. S2 Tidal and barometric transfer functions.** The first part of the transmissivity inversion yields tidal and barometric gain (a) and phase (b) as a function of time. Both show a dependency on the groundwater level; this dependency is particularly apparent for the gain. The dashed red vertical line demarcates the M7.2 2024 Hualien earthquake.

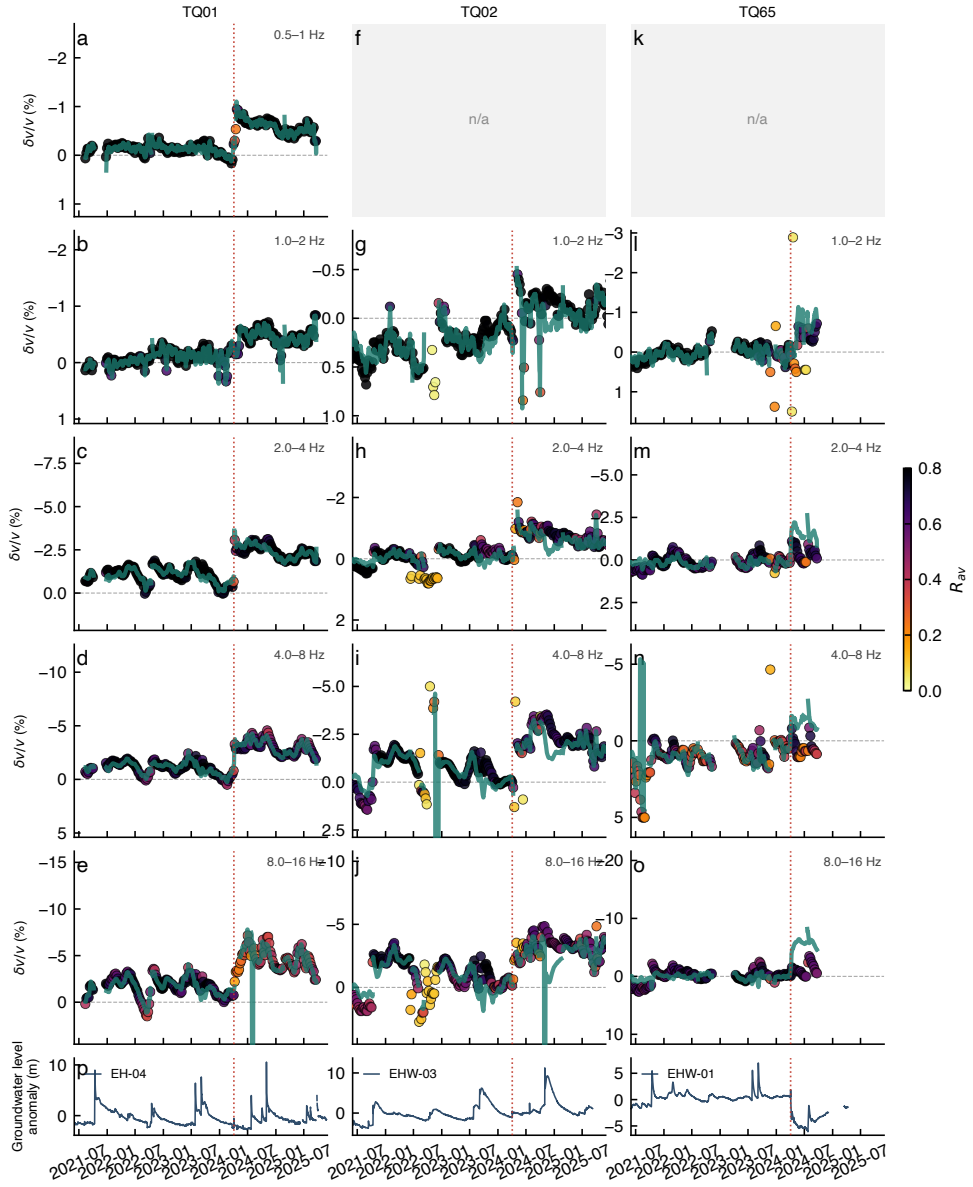




**Fig. S3 Time-dependent transmissivity and shear modulus.** The second part of the transmissivity inversion yields the aquifer's transmissivity  $T(t)$  (a) and shear modulus  $G(t)$  (b). Due to its strong water level dependency (shown in c), we do not interpret  $G(t)$ . In panel a, we compare  $T$  retrieved from hydraulic pump tests with the pore-pressure-corrected transmissivity. The dashed red vertical line demarcates the M7.2 2024 Hualien earthquake. Panel c shows the transmissivity as a function of the groundwater level anomaly up to the Hualien earthquake, with the best-fit curve for main text Eq. 5 derived from [1] superimposed as a yellow dashed line. The points are shaded according to their standard deviation.



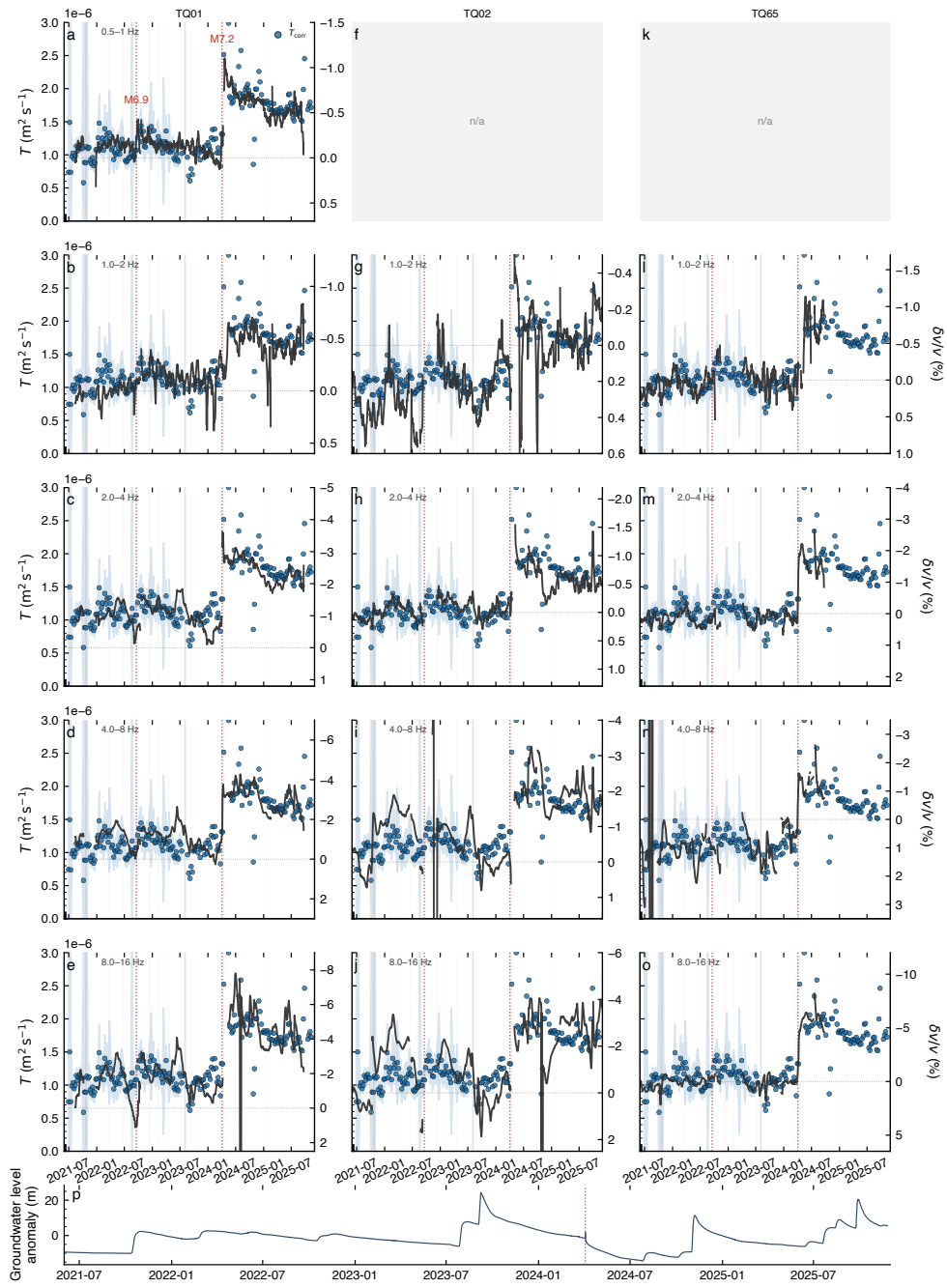
**Fig. S4 Pore pressure correction of  $\delta v/v$ .** We show  $\delta v/v$  computed from the frequency bands and stations indicated in each panel. The pore-pressure-corrected  $(\delta v/v)_{corr}$  is plotted in green, whereas the raw  $\delta v/v$  is shown as a scatter plot with its colour depending on the average cross-correlation  $R_{av}$  as a quality metric. Note that lower frequency bands show lower pore pressure dependency. The performance of the pore-pressure correction varies from station to station. Panels marked with “n/a” are  $\delta v/v$  time series that did not pass the quality control criteria.



**Fig. S5 Pore pressure correction of  $\delta v/v$ . Refer to Fig. S4's caption.**



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**Fig. S7 Co-evolution of the transmissivity and the seismic wavespeed change ( $\delta v/v$ ).**  
Refer to Fig. S6's caption.

### 3 Supplementary tables

**Table S1 Hydraulic pump test results for borehole EHW-02.**

We use the storativity values to parametrise the transmissivity inversion, whereas the hydraulic conductivity  $K$  serves purely as a validation metric.

| $z_{\min}$ (m) | $z_{\max}$ (m) | $K$ (m s <sup>-1</sup> ) | $S$                   | $S_s$ (m <sup>-1</sup> ) |
|----------------|----------------|--------------------------|-----------------------|--------------------------|
| 5.00           | 10.00          | $4.50 \times 10^{-6}$    | —                     | —                        |
| 11.00          | 16.00          | $2.80 \times 10^{-5}$    | —                     | —                        |
| 30.00          | 31.50          | $2.70 \times 10^{-8}$    | $1.70 \times 10^{-5}$ | $1.10 \times 10^{-5}$    |
| 39.00          | 40.50          | $2.90 \times 10^{-8}$    | $2.20 \times 10^{-4}$ | $1.40 \times 10^{-4}$    |
| 52.50          | 54.00          | $2.20 \times 10^{-8}$    | $4.20 \times 10^{-4}$ | $2.80 \times 10^{-4}$    |
| 54.00          | 100.00         | $4.00 \times 10^{-7}$    | $4.60 \times 10^{-5}$ | $1.00 \times 10^{-6}$    |
| 60.00          | 100.00         | $6.10 \times 10^{-8}$    | $4.00 \times 10^{-5}$ | $1.00 \times 10^{-6}$    |
| 64.40          | 65.90          | $2.80 \times 10^{-8}$    | $1.10 \times 10^{-3}$ | $7.40 \times 10^{-4}$    |
| 71.80          | 73.30          | $6.70 \times 10^{-8}$    | $2.00 \times 10^{-4}$ | $1.40 \times 10^{-4}$    |
| 87.00          | 100.00         | $1.30 \times 10^{-7}$    | $1.30 \times 10^{-5}$ | $1.00 \times 10^{-6}$    |
| 87.00          | 88.50          | $4.40 \times 10^{-7}$    | $1.90 \times 10^{-6}$ | $1.30 \times 10^{-6}$    |
| 28.00          | 100.00         | $3.10 \times 10^{-6}$    | $7.20 \times 10^{-5}$ | $1.00 \times 10^{-6}$    |

### References

- [1] Walsh, J. B. Effect of pore pressure and confining pressure on fracture permeability. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* **18**, 429–435 (1981).