

Earthquake drainage and drought timing

Cemil Yavas

cy024700@georgiasouthern.edu

Georgia Southern University <https://orcid.org/0009-0006-9552-1731>

Christopher Kadlec

Department of Information Technology, Georgia Southern University

Nancy Mead

Software and Societal Systems Department, Carnegie Mellon University

Article

Keywords: earthquake hydrology, catchment memory, groundwater, drought, streamflow recession

Posted Date: October 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11148707/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Earthquake drainage and drought timing

Cemil Emre Yavas^{1*}, Christopher Kadlec¹ and Nancy R. Mead²

¹Department of Information Technology, Georgia Southern University,
Statesboro, GA, USA.

²Software and Societal Systems Department, Carnegie Mellon University,
Pittsburgh, PA, USA.

*Corresponding author(s). E-mail(s): cy02470@georgiasouthern.edu;
Contributing authors: CKadlec@georgiasouthern.edu;
nm00@andrew.cmu.edu;

Abstract

Earthquakes can increase river discharge while changing the subsurface stores that sustain subsequent low flows. Whether faster postseismic drainage necessarily increases drought vulnerability remains unresolved at catchment scale. We combine a transient storage–drainage model with 1,128 usable catchment–earthquake-sequence comparisons from 335 catchments in New Zealand and Chile. The model yields an exact condition for an initial flow increase to become a later deficit during uninterrupted recession: integrated drainage enhancement must exceed the logarithmic gain in accessible storage. Rapid recovery of drainage pathways can instead accelerate recession without producing a late deficit. An ensemble of 480,766 recharge and drought scenarios extends this distinction to delayed drought onset. Observations do not establish a general persistent loss of catchment memory. For Kaikōura, the best-supported exposure comparison, the strong-minus-light shaking contrast in log recession-rate change is -0.009 , with a 95% spatial-block interval of -0.157 to 0.100 . Most other sequences lack adequate exposure overlap or spatial replication. These results distinguish an observable recession change from the storage depletion required for earthquake-amplified drought and identify the measurements needed to connect them.

Keywords: earthquake hydrology, catchment memory, groundwater, drought, streamflow recession

Earthquakes perturb the groundwater systems that sustain rivers between rainfall events. Discharge can rise after shaking, springs can appear, and groundwater levels can change far from a rupture[1–3]. Such responses have been attributed to poroelastic pressure changes, enhanced permeability and the connection of previously isolated stores[4–7]. These mechanisms have different consequences for later water availability. An increased outlet flux may represent additional accessible water, more rapid drainage of existing water, or both. Its sign therefore does not determine the sign of the subsequent low-flow response.

This distinction matters because drought develops through the interaction of meteorological deficits with antecedent storage. Long hydrological memory can buffer a short dry spell yet prolong the consequences of repeated dry years[8–11]. Recent analyses demonstrate the importance of antecedent drying, vertically distributed soil-water deficits, heat and the timing of precipitation for water availability[12–15]. Groundwater storage can sustain flow while being depleted, and human withdrawals further alter this balance[16–18]. Earthquake-related changes must be distinguished from these concurrent processes before assigning a persistent drought legacy to shaking.

The possibility of earthquake-enhanced drought sensitivity is already supported by site-specific research. Recession changes following the 2016 central Italian earthquakes were interpreted as faster aquifer emptying[19]; subsequent work documented sustained redistribution and the interaction of groundwater depletion with drought[20, 21]. Conversely, increased streamflow can occur without a changed recession constant[22, 23]. Isotope evidence from Kumamoto and South Napa shows that new water sources can be mobilized[24, 25]. At regional scale, Maule studies established substantial immediate discharge responses and showed that their detection depends on the observation window and the statistical model[26, 27]. The outstanding issue is therefore a quantitative one: which combination of added drainage, recovery and accessible storage makes a later deficit possible, and how much of that combination can be inferred from discharge alone?

Here we address this question with a reduced physical model and a comparative analysis of daily observations. We use *recession memory* to mean the reciprocal rate at which discharge declines under selected dry conditions. It is an operational flow-persistence measure, distinct from water age, total groundwater storage and the persistence of climate anomalies[28–30]. The model isolates the conditions for a reversal from excess to deficient flow. The observational analysis tests whether persistent recession changes distinguish strongly shaken from lightly shaken catchments, retaining sequences with weak comparison support in the coverage assessment. We do not infer unobserved storage or permeability changes from a recession coefficient.

Drainage enhancement is not a drought diagnosis

Let S denote mobile water storage feeding the monitored outlet, R net recharge and $Q = kS$ discharge, where k is an effective drainage coefficient. For an earthquake at $t = 0$, consider

$$\frac{dS}{dt} = R(t) - k(t)S, \quad k(t) = k_0 \left(1 + ae^{-t/h}\right), \quad S_e(0) = (1 + s)S_0(0). \quad (1)$$

The subscript e denotes the perturbed catchment, $a \geq 0$ the fractional initial drainage enhancement, $h > 0$ its recovery time, $s \geq 0$ the fractional increase in accessible storage and $\tau_0 = 1/k_0$ the undisturbed drainage time. Accessible storage can increase through connection to another reservoir without creating water. This representation abstracts the documented diversity of earthquake-related pathways rather than resolving a fault or aquifer geometry (Fig. 1)[31–33].

For an uninterrupted recession with $R = 0$, direct integration gives

$$\log \frac{Q_e(t)}{Q_0(t)} = \log(1 + s) + \log \left(1 + ae^{-t/h} \right) - \frac{ah}{\tau_0} \left(1 - e^{-t/h} \right). \quad (2)$$

The first two terms increase discharge through accessible water and drainage; the third records accumulated depletion relative to the unperturbed store. For $a > 0$, this log ratio decreases strictly with time. Consequently, an initially enhanced flow crosses below its unperturbed counterpart at one finite time if and only if

$$\mathcal{I} \equiv \frac{ah}{\tau_0} > \log(1 + s). \quad (3)$$

Equality gives convergence to the same flow ratio without a finite crossing. This criterion concerns relative discharge; both absolute discharges approach zero in a sufficiently long recession. It does not establish a practically consequential drought deficit by itself.

The discharge recession rate is also not identical to the drainage coefficient when pathways recover:

$$r_e(t) \equiv -\frac{d \log Q_e}{dt} = k(t) - \frac{\dot{k}(t)}{k(t)} = k_0 \left(1 + ae^{-t/h} \right) + \frac{ae^{-t/h}}{h \left(1 + ae^{-t/h} \right)}. \quad (4)$$

Thus a rapid decline of the drainage coefficient can steepen the hydrograph while generating little integrated depletion. For $a = 1$, $s = 0.2$ and $h/\tau_0 = 0.1$, initial discharge is 2.4 times baseline and the initial recession rate is seven times baseline, yet the asymptotic flow ratio is 1.086: there is no later deficit. Increasing h/τ_0 to 1 reduces the initial recession-rate ratio to 2.5 but produces a crossing at $0.804\tau_0$ and an asymptotic flow ratio of 0.441 (Table 2). Ranking these two cases by initial recession steepness would reverse their ranking by eventual relative depletion.

Observational support is concentrated in one sequence

We screened 1,621 catchment–sequence pairs using daily discharge, precipitation and potential evapotranspiration, obtaining 1,128 recession estimates from 335 distinct catchments. Eighteen New Zealand earthquakes with available shaking products were grouped into 13 sequences; Maule and Illapel added two Chilean sequences (Fig. 2; Table 1). The data come from CAMELS-NZ and CAMELS-CL, whose common attributes permit a consistent initial screen[34, 35]. A usable estimate required sufficient positive-flow observations and enough dry recession days in five years before and two

years after each sequence. The resulting population emphasizes persistently flowing, non-snow-dominated catchments and does not represent rivers that cease flowing.

The primary shaking contrast compared peak ground velocity (PGV) of at least 10 cm s^{-1} with PGV of at most 2 cm s^{-1} . Only Kaikōura and Darfield supplied at least five usable catchments in both categories. Darfield’s eight strongly shaken catchments occupied a single 100-km spatial block, preventing a replicated regional contrast at that block scale. Maule supplied 33 strongly shaken catchments but only one lightly shaken comparator; Illapel supplied only one strongly shaken catchment. These are limits of the selected records and exposure definitions, not evidence that the earthquakes had no hydrological effects. In particular, independently documented immediate responses at Maule, Darfield and Kaikōura remain compatible with our coverage assessment[26, 36, 37].

Kaikōura provided 230 recession estimates, including 32 strongly and 97 lightly shaken catchments, with eight and 21 occupied spatial blocks, respectively. Median changes in log recession rate were -0.115 and -0.107 . Their difference was -0.009 (95% spatial-block interval -0.157 to 0.100), equivalent to a recession-rate ratio of 0.991 with an interval of 0.854 – 1.105 (Fig. 3). The shared slowing was much larger than the difference between exposure categories. These data neither establish a persistent regional acceleration nor demonstrate equivalence of the categories: effects within the interval remain compatible with the sampling uncertainty, and localized effects may be obscured by aggregation.

The Kaikōura contrast remained close to zero when shaking was averaged over catchment area (-0.033), overlapping catchments were removed (-0.031), or only catchments classified as natural were retained (0.014). Across the eight alternative recession definitions, point estimates ranged from -0.131 to 0.069 , and every spatial-block interval included zero (Extended Data Fig. 1). Six historical dates on the same calendar anniversary produced contrasts from -0.098 to 0.065 . These overlapping temporal comparisons are diagnostics of background variability rather than independent null experiments.

A separate weather-conditioned analysis also failed to establish a uniform drought penalty. For Kaikōura, the strong-minus-light contrast in mean dry-weather log-flow residual was -0.173 , with a spatial-block interval of -0.252 to 0.076 , based on 31 and 96 catchments. These residuals describe departures from a pre-earthquake weather–flow relationship, not causal earthquake effects. They can contain unmodelled changes in water use, vegetation, rainfall measurement and hydrological state. Their incomplete alignment with recession changes (Fig. 3d) reinforces the need to assess flow persistence and available water separately. The long drought beginning around Maule further illustrates the difficulty of separating concurrent forcing without suitable comparisons[9, 38, 39].

Drought onset changes the relevant water balance

To examine timing beyond uninterrupted recession, we initialized the undisturbed store at recharge equilibrium, maintained identical constant recharge in both systems until a drought delay d , and then set recharge to zero for $3\tau_0$. We calculated the ratio of

integrated discharge during that interval. This experiment spans 480,766 combinations of drainage enhancement, recovery time, accessible storage gain and drought delay; none of these parameters was fitted to the catchment estimates.

For the illustrated slice with $a = 0.96$, $h/\tau_0 = 1.05$ and $s = 0.2$, an immediate drought yields 23.9% more integrated flow, whereas onset at $1.2\tau_0$ yields 23.6% less. The intermediate delay allows the accessible-storage gain to dissipate while enhanced drainage persists. Thus the most adverse timing need not be a drought beginning immediately after the earthquake. The ensemble shows why equation (3) cannot be applied to a later drought without tracking intervening recharge (Fig. 4). Before drought onset, recharge can replace part of the water released by enhanced drainage. During drought, the relevant flux depends on both the remaining storage anomaly and the drainage coefficient at that time. The sign boundary for drought-integrated discharge therefore changes with onset delay. Even within this linear model, an observed postseismic recession rate is insufficient to locate a catchment relative to that boundary. A water-volume comparison also differs from a comparison of late instantaneous flows: excess discharge early in a dry interval can compensate for a late flow deficit in the integrated water balance.

Implications for earthquake hydrology

The distinction between drainage, accessible storage and pathway recovery reconciles otherwise contrasting observations. New mountain water at Kumamoto and South Napa can sustain additional flow[24, 25, 40], whereas opening a route across a groundwater divide can benefit one outlet while depleting another[20, 21]. Spring-discharge changes in central Italy and Kobe demonstrate that the response can persist and differ among neighboring outlets[41–43]. Chi-Chi observations and San Simeon hydrothermal release likewise caution against assigning a single reservoir origin to excess flow[44–46]. Our model expresses a common water-balance constraint across such mechanisms; its single recovering coefficient is not a universal description of their dynamics.

The field result places a narrower constraint on the proposed earthquake–drought connection. Persistent regional memory loss is not established in the available comparison, while the scarcity and spatial concentration of strongly shaken gauges limit replication. A general claim that earthquakes shorten catchment memory would exceed this evidence. Conversely, failure to detect a regional contrast does not exclude changes at individual aquifers, effects during the first month, or changes in seasonally dry and snow-dominated systems that our screen excludes. New Zealand well observations distinguish water-level responses from changes in aquifer properties[47], and recent evidence of lasting hydraulic changes after distant shaking shows why an exponential recovery assumption must remain conditional[48].

Linking this framework to a specific drought requires measurements that constrain both sides of equation (3). Repeated recession observations constrain an outlet response but require information about recovery to separate k from $-\dot{k}/k$. Water-level and deformation measurements can identify pressure transients[49–51]; groundwater chemistry, isotopes and temperature profiles constrain source mixing and redistribution[52–55]. Integrated flow and groundwater models can then test whether

connected storage increases or water is merely transferred between outlets[56–58]. This combination is particularly important where structural permeability controls hydraulic connections[59, 60].

Ecosystem responses provide another reason to avoid equating an outlet hydrograph with catchment water security. Earthquakes can mobilize soil water[61, 62], alter riparian groundwater uptake[63–65], and change forest growth and resilience[66, 67]. Vegetation disturbance and landslides can also change runoff thresholds and recovery over longer periods[68–70]. Bedrock-mediated storage and plant demand help determine whether additional water buffers drought or supports a demand that later becomes unsustainable[71]. These mechanisms lie outside the reduced reservoir, but each modifies recharge, accessible storage or losses and can therefore alter its timing boundary.

Earthquake-related water availability should consequently be evaluated over the intended dry period and for the monitored outlet. The relevant question is whether drainage and other losses exceed accessible storage gains and intervening recharge before that period ends. This formulation is consistent with the broader role of groundwater in short-term hazard buffering[72] and water-cycle resilience[73], while identifying a specific limitation: neither an initial discharge increase nor a shorter observed recession time is sufficient evidence of a later drought deficit.

Methods

Data, versions and hydrological screening

CAMELS-NZ version 5 provides catchment attributes and daily hydroclimatic records[34, 74]. We obtained the daily discharge, precipitation, temperature and potential evapotranspiration archives, catchment attributes and boundaries from the versioned repository. Fourteen stations explicitly restricted in the provider’s readme were excluded. Discharge at station 91103 was censored after 1 July 2016; other stated time restrictions were applied before analysis. New Zealand discharge was converted from $\text{m}^3 \text{s}^{-1}$ to mm d^{-1} using published upstream areas; temperature was converted from kelvin to degrees Celsius. Date strings were parsed individually because source files use more than one date representation. We retained the common 1980–2022 processing interval without filling missing flow values.

The Chilean collection contains 516 catchments[35, 75]. We acquired the 2022 update distributed by the camelsCL service for the 391 gauges between 27° and 45° S, using its catchment metadata and daily `Qobs_mm`, `P_mm`, `Tavg_degC` and `PET_mm` fields. These are the service’s basin-aggregated products; alternative precipitation columns were retained as input provenance but not used in the reported estimates. Attributes followed the large-sample comparison approach developed for CAMELS[76]. All downloads were recorded with file hashes and source identifiers.

The static screen required catchment area of $10\text{--}10,000 \text{ km}^2$, no dam flag, and no snow-influence flag in New Zealand or a climatological snow fraction above 0.1 in Chile. New Zealand gauges also required the provider’s acceptable-rating flag. An equivalent Chilean rating-quality flag was unavailable and was not inferred from the data. This screen retained 283 New Zealand and 199 Chilean catchments; 481 had at least one relevant finite shaking estimate. Abstraction and ephemeral-flow flags were

retained for sensitivity tests rather than treated as proof of unmodified or perennial conditions. The natural-only sensitivity used the provider’s New Zealand classification. Chilean natural status required zero dam index and an intervention index based on allocated rights relative to flow of at most 0.1. These static descriptors cannot rule out unrecorded changes during an event window.

Earthquake selection and shaking exposure

The initial candidate set comprised the 2010 Maule and 2015 Illapel earthquakes and the 2016 Kaikōura earthquake. The exposure audit found insufficient lightly shaken Chilean gauges for a well-supported Maule contrast. Additional New Zealand events were therefore sought by an outcome-independent USGS catalog query: magnitude at least 6.5, depth at most 50 km, dates 1985–2018, and coordinates 33–48° S and 165–180° E. Of 20 catalog events, 18 had available ShakeMap grids. Events separated by at most 90 days and 200 km were grouped into sequences, yielding 13 New Zealand sequences. Maule and Illapel remained separate. This grouping prevents large aftershocks from being counted as independent replications; it does not make all sequences or observation windows independent. Smaller earthquakes outside the magnitude threshold can also affect these windows, including the 2011 Christchurch earthquake within the Darfield post-event interval.

We used archived USGS ShakeMap Atlas grids[77], selecting products by preferred weight and then update time and retaining their exact source URLs. Magnitudes in Table 1 follow the selected USGS records; the Darfield value is 7.0 in these records, although the New Zealand literature commonly reports 7.1[36]. PGV was bilinearly interpolated at gauge coordinates. Out-of-grid values remained missing. For grouped events, exposure was the maximum of available member-event PGV estimates at each location. PGV is a shaking proxy, not a measurement of catchment permeability or a claim that effects cannot occur below the thresholds. Responses to several earthquakes at a single site and the Nisqually and Alum Rock cases demonstrate that local conditions affect hydrological sensitivity[23, 78, 79].

The primary contrast used $\text{PGV} \geq 10$ versus $\leq 2 \text{ cm s}^{-1}$. We also evaluated a 5 cm s^{-1} upper threshold. For the New Zealand area-exposure sensitivity, 1,024 uniformly sampled points per catchment were generated in NZTM2000 coordinates with a fixed seed equal to the station identifier, transformed to geographic coordinates and interpolated against the same grids. A catchment required at least 95% finite samples. We averaged the pointwise maximum shaking across sequence members. The non-nested sensitivity selected catchments in increasing area order, excluding any whose intersection with a retained catchment exceeded 10% of the smaller polygon’s area. The static New Zealand subset yielded 226 retained polygons. Geographic outlines in Fig. 2 use public-domain Natural Earth boundaries.

State-conditioned recession estimates

Recession analysis has a long history as a means of characterizing groundwater-supported flow[80, 81]. Its interpretation depends on recharge, flow state and the extraction rule[28, 29]. We estimated persistent changes using a five-year pre-sequence

interval ending 30 days before the first event and a two-year post-sequence interval beginning 30 days after the final grouped event. The final-event exclusion was represented as a sequence-specific washout from the first event. Integer windows used 1,826 pre-event and 730 post-event days.

At least 90% of days in both intervals had to contain finite precipitation, potential evapotranspiration and positive discharge. This condition explicitly removes many intermittently flowing records. For a daily step $\Delta t = 1$ d, we calculated

$$r_t = -\frac{\log Q_t - \log Q_{t-1}}{\Delta t}, \quad z_t = \log \left(\frac{\sqrt{Q_t Q_{t-1}}}{Q_{\text{ref}}} \right), \quad (5)$$

where Q_{ref} is median positive pre-event discharge. Eligible days had precipitation below 1 mm d^{-1} on the current and previous three days, three consecutive positive recession rates, current discharge between the pre-event 10th and 70th percentiles, and $10^{-5} < r_t < 1 \text{ d}^{-1}$. The last condition removes effectively flat or extremely abrupt declines that give unstable log rates. At least 60 eligible pre-event and 25 post-event days were required. Missing rainfall interrupts the dry-day test.

We fitted, separately for each catchment–sequence pair,

$$\log r_t = \beta_0 + \beta_1 z_t + \beta_2 z_t^2 + \beta_3 E_t + \beta_4 \sin \theta_t + \beta_5 \cos \theta_t + \delta \mathbf{1}_{\text{post}} + \epsilon_t, \quad (6)$$

where E_t is potential evapotranspiration, $\theta_t = 2\pi \text{ dayofyear}/365.25$, and δ is the reported change in log recession rate. Conditioning on flow state avoids equating a shift in the sampled discharge distribution with a change in drainage behavior. Seasonal and evaporative terms reduce, but cannot eliminate, differences in recharge and losses. In particular, rain-free conditions do not imply zero deep recharge. The response is not a permeability estimate. Reference recession times were evaluated at $z = 0$, median pre-event potential evapotranspiration and zero mean seasonal harmonics. Daily ordinary-least-squares errors were not used to construct the reported regional intervals.

Eight alternative definitions changed one choice at a time: rainfall thresholds of 0.5 or 2 mm d^{-1} ; six dry days; three or seven pre-event years; one or three post-event years; and a 90-day initial exclusion. The longer-window variants can overlap other earthquakes and are interpreted as robustness diagnostics, not isolated treatment effects. Additional screens excluded gauges with abstraction or ephemeral flags or retained only natural catchments. The primary choices were recorded before the corresponding hydrological outcome inspection; the catalog expansion followed the exposure audit. Further diagnostics developed during analysis are not presented as preregistered tests.

Exposure contrasts and uncertainty

For each sequence we computed the descriptive difference of category medians,

$$D = \text{median}_{\text{PGV} \geq 10}(\delta_i) - \text{median}_{\text{PGV} \leq 2}(\delta_i). \quad (7)$$

A 100-km square grid in NZTM2000 for New Zealand and UTM zone 19S for Chile defined spatial blocks. We drew blocks with replacement and retained all catchments within each selected block, including repeated selections. The 2.5th and 97.5th percentiles of 2,000 bootstrap contrasts define primary intervals[82]. Sensitivity intervals use 500 resamples. Resamples missing either exposure category are undefined and omitted. We report intervals only when both categories include at least five catchments and occupy at least five blocks. This prevents a single cluster of strongly shaken gauges, as at Darfield, from being presented as spatial replication. It is a pragmatic reporting rule, not a proof of independence among blocks.

These intervals describe variation across sampled spatial blocks conditional on the event, fitted catchment responses and grid origin. They do not propagate all daily regression, shaking-model, rating-curve or measurement uncertainty. They are not causal confidence intervals. Serial and spatial dependence, emphasized in work on comparisons before and after interventions[83], also makes pooled catchment counts an inappropriate count of independent earthquakes. No cross-sequence pooled significance test was used.

Historical calendar-placebo dates were shifted three to eight years before each of the five named candidate events. We repeated the recession analysis using the actual event’s exposure categories. A catchment was removed from a placebo if another catalogued sequence with local $PGV \geq 5 \text{ cm s}^{-1}$ occurred between 30 days before and 730 days after that date. Overlapping placebo windows remain dependent. An exploratory matched comparison selected the nearest lightly shaken catchment with replacement using standardized log area, elevation, aridity, log mean precipitation and log pre-event median discharge. A Euclidean covariate distance of at most 2.5 and geographic distance of at most 500 km were required. All 32 Kaikōura strong-exposure catchments could be matched; the median paired difference was -0.017 . Because matching does not establish exchangeability, it was used as a diagnostic rather than as an identified causal estimate.

Weather-conditioned low-flow analysis

We used gradient-boosted regression trees[84, 85] to characterize departures from the pre-event weather–flow relationship. Machine learning has also been applied to earthquake prediction[86]; our use is confined to retrospective hydrological adjustment. To avoid temporal leakage, validation withheld the final pre-event year instead of randomly splitting daily observations[87]. Predictors were log-transformed precipitation sums over 1, 3, 7, 14, 30, 90, 180 and 365 days; mean temperature and potential evapotranspiration over 7, 30 and 90 days; and annual and semiannual sine and cosine terms. No post-event discharge or lagged discharge predictor entered the model.

The target was $\log[Q/(1 \text{ mm d}^{-1}) + 0.01]$, which permits zero observations in this separate analysis. At least 1,500 complete pre-event and 620 complete post-event days were required, with at least 300 days in the withheld validation year. The fixed estimator used 150 iterations, ten maximum leaf nodes, 30 minimum samples per leaf, learning rate 0.05 and L2 regularization 5. After validation it was refitted to all pre-event observations. The post-event window ended at day 730 inclusive. Of 1,136 pairs with an evaluable weather model, 1,093 achieved withheld-year $R^2 \geq 0.3$; median

R^2 across the evaluable set was 0.768 (Extended Data Fig. 2). The 0.3 threshold was applied for the reported secondary contrasts and does not certify causal adjustment or extrapolation skill.

Dry-weather days had a preceding 90-day precipitation sum below the pre-event 20th percentile for the same calendar month. We averaged observed minus predicted log flow on at least 30 such post-event days, then compared exposure-category medians using the same spatial blocks. The metric is a conditional flow anomaly, not a standardized drought index or a direct measure of water-supply failure. Soil-water persistence and groundwater–surface exchange make antecedent meteorology informative but incomplete proxies for hydrological state[88, 89]. Model bias can change under climate nonstationarity or altered human use. No correction was inferred from post-event flow itself.

Analytical and numerical experiments

Equation (2) follows by integrating $d \log S/dt = -k(t)$. Its time derivative is negative for $a > 0$, giving the unique-crossing result in equation (3). The derivation assumes one linear, well-mixed mobile store, no recharge or other losses during recession, an exponentially recovering drainage enhancement, and a non-negative instantaneous accessible-storage gain. It omits altered evapotranspiration, nonlinear or multiple reservoirs, delayed recharge and intercatchment transfers after the initial gain. Permanent enhancement, drainage reduction and inaccessible storage loss require different parameterizations; the criterion should not be extrapolated to them without re-derivation.

For delayed drought, time was normalized by τ_0 , and baseline storage and equilibrium recharge were set to one. The perturbed initial storage was $1 + s$. Recharge was one until delay d and zero for the subsequent duration $T = 3\tau_0$. The outcome was

$$V_e/V_0 = \frac{\int_d^{d+T} Q_e(t) dt}{\int_d^{d+T} Q_0(t) dt}. \quad (8)$$

The parameter grid contained 41 logarithmically spaced a values from 0.05 to 4; 41 logarithmically spaced h/τ_0 values from 0.05 to 10; 11 linearly spaced s values from zero to one; and 26 delays from zero to $5\tau_0$. These ranges probe dimensionless behavior and are not an empirical parameter distribution. Scenario fractions therefore must not be interpreted as earthquake-drought probabilities.

We advanced storage with a positive exponential update, holding recharge constant within each step and evaluating k at its midpoint:

$$S_{n+1} = S_n e^{-k_{n+1/2} \Delta t} + \frac{R_n}{k_{n+1/2}} (1 - e^{-k_{n+1/2} \Delta t}). \quad (9)$$

The within-step discharge volume was obtained from mass balance, $S_n - S_{n+1} + R_n \Delta t$. A time step of $0.02\tau_0$ placed every drought onset and end on a step boundary. The complete sweep ran in single precision on an Apple M3 Pro GPU. At 512 deterministic parameter-grid locations, CPU double-precision recomputation differed in volume

ratio by at most 1.56×10^{-6} ; halving the step changed it by at most 4.82×10^{-4} . Independent adaptive integration of four uninterrupted-recession cases agreed with the analytical flow ratio to within 4.47×10^{-10} . The zero-perturbation identity was also checked. These are numerical consistency tests rather than field validation.

Independent catchment calculations used ten CPU processes with one numerical-library thread per process. Array calculations, numerical integration and plotting used established scientific Python libraries[90–92]. All random calculations used seed 1729 except station-specific area sampling. Processor acceleration changes runtime, not the interpretation or evidential status of the simulations.

Data and code availability

The analysis inputs, experiment code and numerical results for v1.2.1 are available on Zenodo [93] (<https://doi.org/10.5281/zenodo.22930703>) and on GitHub at <https://github.com/cemildocuments/earthquake-memory>.

Acknowledgements

We thank the monitoring agencies and the CAMELS-NZ, CAMELS-CL and USGS data providers for making the observations accessible. This research received no funding.

Competing interests

The authors declare no competing interests.

Author identifiers

Cemil Emre Yavas: [0009-0006-9552-1731](https://orcid.org/0009-0006-9552-1731); Christopher Kadlec: [0009-0008-2377-9113](https://orcid.org/0009-0008-2377-9113); Nancy R. Mead: [0000-0002-2919-086X](https://orcid.org/0000-0002-2919-086X).

References

- [1] Montgomery, D. R. & Manga, M. Streamflow and Water Well Responses to Earthquakes. *Science* **300**, 2047–2049 (2003).
- [2] Ingebritsen, S. E. & Manga, M. Earthquake Hydrogeology. *Water Resources Research* **55**, 5212–5216 (2019).
- [3] Wang, C.-Y. & Manga, M. *Water and Earthquakes* (Springer International Publishing, 2021).
- [4] Muir-Wood, R. & King, G. C. P. Hydrological signatures of earthquake strain. *Journal of Geophysical Research: Solid Earth* **98**, 22035–22068 (1993).

- [5] Rojstaczer, S., Wolf, S. & Michel, R. Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes. *Nature* **373**, 237–239 (1995).
- [6] Elkhoury, J. E., Brodsky, E. E. & Agnew, D. C. Seismic waves increase permeability. *Nature* **441**, 1135–1138 (2006).
- [7] Manga, M. *et al.* Changes in permeability caused by transient stresses: Field observations, experiments, and mechanisms. *Reviews of Geophysics* **50**, RG2004 (2012).
- [8] Van Loon, A. F. Hydrological drought explained. *WIREs Water* **2**, 359–392 (2015).
- [9] Alvarez-Garreton, C., Boisier, J. P., Garreaud, R., Seibert, J. & Vis, M. Progressive water deficits during multiyear droughts in basins with long hydrological memory in Chile. *Hydrology and Earth System Sciences* **25**, 429–446 (2021).
- [10] Berghuijs, W. R., Woods, R. A., Anderson, B. J., Hemshorn de Sánchez, A. L. & Hrachowitz, M. Annual memory in the terrestrial water cycle. *Hydrology and Earth System Sciences* **29**, 1319–1333 (2025).
- [11] Van Loon, A. F. *et al.* Review article: Drought as a continuum – memory effects in interlinked hydrological, ecological, and social systems. *Natural Hazards and Earth System Sciences* **24**, 3173–3205 (2024).
- [12] Bevacqua, E. *et al.* Direct and lagged climate change effects intensified the 2022 European drought. *Nature Geoscience* **17**, 1100–1107 (2024).
- [13] Gu, X. *et al.* Multilayer soil moisture depletion intensifies drought impacts on global ecosystems. *Nature Geoscience* (2026). URL <https://doi.org/10.1038/s41561-026-02083-1>. Published online 1 September 2026.
- [14] Gu, L. *et al.* Flash drought impacts on global ecosystems amplified by extreme heat. *Nature Geoscience* **18**, 709–715 (2025).
- [15] Lesk, C. S. & Mankin, J. S. More concentrated precipitation decreases terrestrial water storage. *Nature* **653**, 425–432 (2026).
- [16] Siirila-Woodburn, E. R. *et al.* Warming and snow loss increase reliance on old groundwater in a Colorado River headwater. *Nature Geoscience* **19**, 549–555 (2026).
- [17] Pokhrel, Y. *et al.* Global terrestrial water storage and drought severity under climate change. *Nature Climate Change* **11**, 226–233 (2021).
- [18] Van Loon, A. F. *et al.* Drought in the Anthropocene. *Nature Geoscience* **9**, 89–91 (2016).

- [19] Di Matteo, L. *et al.* Effects of earthquakes on the discharge of groundwater systems: The case of the 2016 seismic sequence in the Central Apennines, Italy. *Journal of Hydrology* **583**, 124509 (2020).
- [20] Mastrorillo, L. *et al.* Sustained post-seismic effects on groundwater flow in fractured carbonate aquifers in Central Italy. *Hydrological Processes* **34**, 1167–1181 (2020).
- [21] Mastrorillo, L., Viaroli, S. & Petitta, M. Co-Occurrence of Earthquake and Climatic Events on Groundwater Budget Alteration in a Fractured Carbonate Aquifer (Sibillini Mts.—Central Italy). *Water* **15**, 2355 (2023).
- [22] Manga, M. Origin of postseismic streamflow changes inferred from baseflow recession and magnitude-distance relations. *Geophysical Research Letters* **28**, 2133–2136 (2001).
- [23] Manga, M., Brodsky, E. E. & Boone, M. Response of streamflow to multiple earthquakes. *Geophysical Research Letters* **30**, 1214 (2003).
- [24] Hosono, T., Yamada, C., Manga, M., Wang, C.-Y. & Tanimizu, M. Stable isotopes show that earthquakes enhance permeability and release water from mountains. *Nature Communications* **11**, 2776 (2020).
- [25] Wang, C.-Y. & Manga, M. New streams and springs after the 2014 Mw6.0 South Napa earthquake. *Nature Communications* **6**, 7597 (2015).
- [26] Mohr, C. H., Manga, M., Wang, C.-Y. & Korup, O. Regional changes in streamflow after a megathrust earthquake. *Earth and Planetary Science Letters* **458**, 418–428 (2017).
- [27] Korup, O., Mohr, C. H. & Manga, M. M. Bayesian Detection of Streamflow Response to Earthquakes. *Water Resources Research* **57**, e2020WR028874 (2021).
- [28] Kirchner, J. W. Catchments as simple dynamical systems: Catchment characterization, rainfall-runoff modeling, and doing hydrology backward. *Water Resources Research* **45**, W02429 (2009).
- [29] Stoelzle, M., Stahl, K. & Weiler, M. Are streamflow recession characteristics really characteristic? *Hydrology and Earth System Sciences* **17**, 817–828 (2013).
- [30] Sutanto, S. J. & Van Lanen, H. A. J. Catchment memory explains hydrological drought forecast performance. *Scientific Reports* **12**, 2689 (2022).
- [31] 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**, 2390 (2003).
- [32] Wang, C.-Y., Liao, X., Wang, L.-P., Wang, C.-H. & Manga, M. Large earthquakes create vertical permeability by breaching aquitards. *Water Resources Research*

52, 5923–5937 (2016).

- [33] Hosono, T., Saltalippi, C. & Jean, J.-S. Coseismic hydro-environmental changes: Insights from recent earthquakes. *Journal of Hydrology* **585**, 124799 (2020).
- [34] Bushra, S., Shakya, J., Cattoën, C., Fischer, S. & Pahlow, M. CAMELS-NZ: hydrometeorological time series and landscape attributes for New Zealand. *Earth System Science Data* **17**, 5745–5760 (2025).
- [35] Alvarez-Garreton, C. *et al.* The CAMELS-CL dataset: catchment attributes and meteorology for large sample studies – Chile dataset. *Hydrology and Earth System Sciences* **22**, 5817–5846 (2018).
- [36] Cox, S. *et al.* Hydrological effects of the M W 7.1 Darfield (Canterbury) earthquake, 4 September 2010, New Zealand. *New Zealand Journal of Geology and Geophysics* **55**, 231–247 (2012).
- [37] Weaver, K. C. *et al.* Seismological and Hydrogeological Controls on New Zealand-Wide Groundwater Level Changes Induced by the 2016 Mw7.8 Kaikōura Earthquake. *Geofluids* **2019**, 9809458 (2019).
- [38] Garreaud, R. D. *et al.* The 2010–2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation. *Hydrology and Earth System Sciences* **21**, 6307–6327 (2017).
- [39] Tolorza, V. *et al.* Suspended Sediments in Chilean Rivers Reveal Low Postseismic Erosion After the Maule Earthquake (Mw 8.8) During a Severe Drought. *Journal of Geophysical Research: Earth Surface* **124**, 1378–1397 (2019).
- [40] Ide, K. *et al.* Changes of groundwater flow systems after the 2016 Mw 7.0 Kumamoto earthquake deduced by stable isotopic and CFC-12 compositions of natural springs. *Journal of Hydrology* **583**, 124551 (2020).
- [41] Valigi, D. *et al.* Earthquake-Induced Spring Discharge Modifications: The Pescara di Arquata Spring Reaction to the August–October 2016 Central Italy Earthquakes. *Water* **12**, 767 (2020).
- [42] Sato, T., Sakai, R., Furuya, K. & Kodama, T. Coseismic spring flow changes associated with the 1995 Kobe Earthquake. *Geophysical Research Letters* **27**, 1219–1222 (2000).
- [43] Tokunaga, T. Modeling of earthquake-induced hydrological changes and possible permeability enhancement due to the 17 January 1995 Kobe Earthquake, Japan. *Journal of Hydrology* **223**, 221–229 (1999).
- [44] Wang, C.-y., Wang, C.-H. & Manga, M. Coseismic release of water from mountains: Evidence from the 1999 (Mw = 7.5) Chi-Chi, Taiwan, earthquake. *Geology* **32**,

769–772 (2004).

- [45] Wang, C.-y., Cheng, L.-H., Chin, C.-V. & Yu, S.-B. Coseismic hydrologic response of an alluvial fan to the 1999 Chi-Chi earthquake, Taiwan. *Geology* **29**, 831–834 (2001).
- [46] Wang, C.-Y., Manga, M., Dreger, D. & Wong, A. Streamflow increase due to rupturing of hydrothermal reservoirs: Evidence from the 2003 San Simeon, California, Earthquake. *Geophysical Research Letters* **31**, L10502 (2004).
- [47] Weaver, K. C., Doan, M.-L., Cox, S. C., Townend, J. & Holden, C. Tidal Behavior and Water-Level Changes in Gravel Aquifers in Response to Multiple Earthquakes: A Case Study From New Zealand. *Water Resources Research* **55**, 1263–1278 (2019).
- [48] He, G. *et al.* Permanent Hydraulic and Poroelastic Property Changes in a Deep Aquifer Triggered by the Distant Tohoku Earthquake. *Geophysical Research Letters* **53**, e2026GL122462 (2026).
- [49] Roeloffs, E. Poroelastic Techniques in the Study of Earthquake-Related Hydrologic Phenomena. *Advances in Geophysics* **37**, 135–195 (1996).
- [50] Jónsson, S., Segall, P., Pedersen, R. & Björnsson, G. Post-earthquake ground movements correlated to pore-pressure transients. *Nature* **424**, 179–183 (2003).
- [51] Hosono, T. *et al.* Coseismic Groundwater Drawdown Along Crustal Ruptures During the 2016 Mw 7.0 Kumamoto Earthquake. *Water Resources Research* **55**, 5891–5903 (2019).
- [52] Rosen, M. R. *et al.* Mechanisms of Earthquake-Induced Chemical and Fluid Transport to Carbonate Groundwater Springs After Earthquakes. *Water Resources Research* **54**, 5225–5244 (2018).
- [53] Hosono, T. & Masaki, Y. Post-seismic hydrochemical changes in regional groundwater flow systems in response to the 2016 Mw 7.0 Kumamoto earthquake. *Journal of Hydrology* **580**, 124340 (2020).
- [54] Barberio, M. D., Barbieri, M., Billi, A., Doglioni, C. & Petitta, M. Hydrogeochemical changes before and during the 2016 Amatrice-Norcia seismic sequence (central Italy). *Scientific Reports* **7**, 11735 (2017).
- [55] Miyakoshi, A. *et al.* Identification of changes in subsurface temperature and groundwater flow after the 2016 Kumamoto earthquake using long-term well temperature–depth profiles. *Journal of Hydrology* **582**, 124530 (2020).
- [56] Kagabu, M., Ide, K., Hosono, T., Nakagawa, K. & Shimada, J. Describing coseismic groundwater level rise using tank model in volcanic aquifers, Kumamoto,

- southern Japan. *Journal of Hydrology* **582**, 124464 (2020).
- [57] Tawara, Y., Hosono, T., Fukuoka, Y., Yoshida, T. & Shimada, J. Quantitative assessment of the changes in regional water flow systems caused by the 2016 Kumamoto Earthquake using numerical modeling. *Journal of Hydrology* **583**, 124559 (2020).
 - [58] Wang, C.-Y., Wang, L.-P., Manga, M., Wang, C.-H. & Chen, C.-H. Basin-scale transport of heat and fluid induced by earthquakes. *Geophysical Research Letters* **40**, 3893–3897 (2013).
 - [59] Sibson, R. H. & Rowland, J. V. Stress, fluid pressure and structural permeability in seismogenic crust, North Island, New Zealand. *Geophysical Journal International* **154**, 584–594 (2003).
 - [60] Charmoille, A., Fabbri, O., Mudry, J., Guglielmi, Y. & Bertrand, C. Post-seismic permeability change in a shallow fractured aquifer following a ML 5.1 earthquake (Fourbanne karst aquifer, Jura outermost thrust unit, eastern France). *Geophysical Research Letters* **32**, L18406 (2005).
 - [61] Mohr, C. H., Manga, M., Wang, C.-y., Kirchner, J. W. & Bronstert, A. Shaking water out of soil. *Geology* **43**, 207–210 (2015).
 - [62] Breen, S. J., Zhang, Z. & Wang, C.-Y. Shaking Water Out of Sands: An Experimental Study. *Water Resources Research* **56**, e2020WR028153 (2020).
 - [63] Wang, C.-Y., Wang, L.-P., Manga, M. & Liang, X. Groundwater-surface interaction amplified post-seismic streamflow fluctuation. *Communications Earth & Environment* **5**, 612 (2024).
 - [64] Loheide, S. P., II & Gorelick, S. M. Riparian hydroecology: A coupled model of the observed interactions between groundwater flow and meadow vegetation patterning. *Water Resources Research* **43**, W07414 (2007).
 - [65] Szilágyi, J., Gribovszki, Z., Kalicz, P. & Kucsara, M. On diurnal riparian zone groundwater-level and streamflow fluctuations. *Journal of Hydrology* **349**, 1–5 (2008).
 - [66] Gao, S. *et al.* Shifts of forest resilience after seismic disturbances in tectonically active regions. *Nature Geoscience* **17**, 189–196 (2024).
 - [67] Mohr, C. H. *et al.* Trees Talk Tremor—Wood Anatomy and $\delta^{13}\text{C}$ Content Reveal Contrasting Tree-Growth Responses to Earthquakes. *Journal of Geophysical Research: Biogeosciences* **126**, e2021JG006385 (2021).
 - [68] Zhang, G. *et al.* Increased nonstationarity of stormflow threshold behaviors in a forested watershed due to abrupt earthquake disturbance. *Hydrology and Earth*

System Sciences **27**, 3005–3020 (2023).

- [69] Zhang, J. *et al.* Eco-hydrological recovery following large vegetation disturbances from a mega earthquake on the eastern Tibetan plateau. *Journal of Hydrology* **651**, 132595 (2025).
- [70] Frith, N. V. *et al.* Carbon export from mountain forests enhanced by earthquake-triggered landslides over millennia. *Nature Geoscience* **11**, 772–776 (2018).
- [71] Callahan, R. P. *et al.* Forest vulnerability to drought controlled by bedrock composition. *Nature Geoscience* **15**, 714–719 (2022).
- [72] Gleeson, T., Endo, T., Taniguchi, M. & Di Baldassarre, G. Natural hazard susceptibilities and inequities reduced by short-term groundwater use. *Nature Geoscience* **19**, 12–18 (2026).
- [73] Gleeson, T. *et al.* Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resources Research* **56**, e2019WR024957 (2020).
- [74] Bushra, S., Shakya, J., Cattoën, C., Fischer, S. & Pahlow, M. CAMELS-NZ: Hydrometeorological time series and landscape attributes for New Zealand (2026). URL <https://doi.org/10.26021/canterburynz.28827644.v5>. Dataset, version 5.
- [75] Alvarez-Garreton, C. *et al.* The CAMELS-CL dataset - links to files (2018). URL <https://doi.org/10.1594/pangaea.894885>. Dataset.
- [76] Addor, N., Newman, A. J., Mizukami, N. & Clark, M. P. The CAMELS data set: catchment attributes and meteorology for large-sample studies. *Hydrology and Earth System Sciences* **21**, 5293–5313 (2017).
- [77] Marano, K. *et al.* ShakeMap Atlas V4 and AtlasCat (2023). URL <https://doi.org/10.5066/p98atogz>. Dataset.
- [78] Montgomery, D. R., Greenberg, H. M. & Smith, D. T. Streamflow response to the Nisqually earthquake. *Earth and Planetary Science Letters* **209**, 19–28 (2003).
- [79] Manga, M. & Rowland, J. C. Response of Alum Rock springs to the October 30, 2007 Alum Rock earthquake and implications for the origin of increased discharge after earthquakes. *Geofluids* **9**, 237–250 (2009).
- [80] Brutsaert, W. & Nieber, J. L. Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resources Research* **13**, 637–643 (1977).
- [81] Tallaksen, L. A review of baseflow recession analysis. *Journal of Hydrology* **165**, 349–370 (1995).

- [82] Efron, B. Bootstrap Methods: Another Look at the Jackknife. *The Annals of Statistics* **7**, 1–26 (1979).
- [83] Bertrand, M., Duflo, E. & Mullainathan, S. How Much Should We Trust Differences-In-Differences Estimates? *The Quarterly Journal of Economics* **119**, 249–275 (2004).
- [84] Friedman, J. H. Greedy function approximation: A gradient boosting machine. *The Annals of Statistics* **29**, 1189–1232 (2001).
- [85] Pedregosa, F. *et al.* Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research* **12**, 2825–2830 (2011). URL <https://www.jmlr.org/papers/v12/pedregosa11a.html>.
- [86] Yavas, C. E., Chen, L., Kadlec, C. & Ji, Y. Predictive Modeling of Earthquakes in Los Angeles With Machine Learning and Neural Networks. *IEEE Access* **12**, 108673–108702 (2024).
- [87] Roberts, D. R. *et al.* Cross-validation strategies for data with temporal, spatial, hierarchical, or phylogenetic structure. *Ecography* **40**, 913–929 (2017).
- [88] McColl, K. A. *et al.* The global distribution and dynamics of surface soil moisture. *Nature Geoscience* **10**, 100–104 (2017).
- [89] Illien, L. *et al.* Subsurface Moisture Regulates Himalayan Groundwater Storage and Discharge. *AGU Advances* **2**, e2021AV000398 (2021).
- [90] Harris, C. R. *et al.* Array programming with NumPy. *Nature* **585**, 357–362 (2020).
- [91] Virtanen, P. *et al.* SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature Methods* **17**, 261–272 (2020).
- [92] Hunter, J. D. Matplotlib: A 2D Graphics Environment. *Computing in Science & Engineering* **9**, 90–95 (2007).
- [93] Yavas, C. E., Kadlec, C. & Mead, N. R. earthquake-memory: Earthquake drainage and drought timing (2026). URL <https://doi.org/10.5281/zenodo.22930703>.

Table 1 Observation and exposure support by earthquake sequence.

Sequence	M	Screened	Usable	$PGV \geq 10$	$PGV \leq 2$
1987-03-02	6.5	148	71	1	55
1993-08-10	7.0	44	30	0	18
1994-06-18	6.8	111	71	1	46
1994-12-15	7.1	62	45	1	28
2003-08-22	7.2	56	47	1	23
2007-10-16	6.8	42	36	0	20
2007-12-20	6.6	33	26	0	15
Dusky Sound 2009	7.8	68	61	3	21
Darfield 2010	7.0	157	143	8	100
2013-07-21	6.5	88	73	1	33
2014-11-17	6.7	132	112	0	111
2016-09-02	7.0	128	112	0	109
Kaikōura 2016	7.8	264	230	32	97
Maule 2010	8.8	198	56	33	1
Illapel 2015	8.3	90	15	1	7

Screened pairs satisfy the static catchment conditions and have finite point-sampled shaking. Usable pairs additionally pass the temporal-completeness and recession-day requirements. PGV is in cm s^{-1} . For grouped events, the magnitude is the largest catalog value and the label identifies the first event date unless a common sequence name is given. Repeated catchments and overlapping time windows are not independent replications. Only Kaikōura has at least five occupied spatial blocks in both primary exposure categories.

Table 2 Illustrative uninterrupted-recession scenarios.

a	h/τ_0	s	$Q_e(0)/Q_0(0)$	$r_e(0)/k_0$	$\lim Q_e/Q_0$	t_*/τ_0
1.00	0.10	0.20	2.40	7.00	1.086	None
1.00	1.00	0.20	2.40	2.50	0.441	0.804
1.00	3.00	0.20	2.40	2.17	0.060	0.854
0.25	1.00	0.20	1.50	1.45	0.935	1.991
2.00	0.10	0.20	3.60	9.67	0.982	0.482

These are specified model scenarios, not fitted catchment parameters. The limit is as $t \rightarrow \infty$; t_* is the unique time at which perturbed and undisturbed discharge become equal. “None” denotes no finite crossing. Initial flow enhancement and initial recession steepness alone do not determine the existence or magnitude of the later relative deficit.

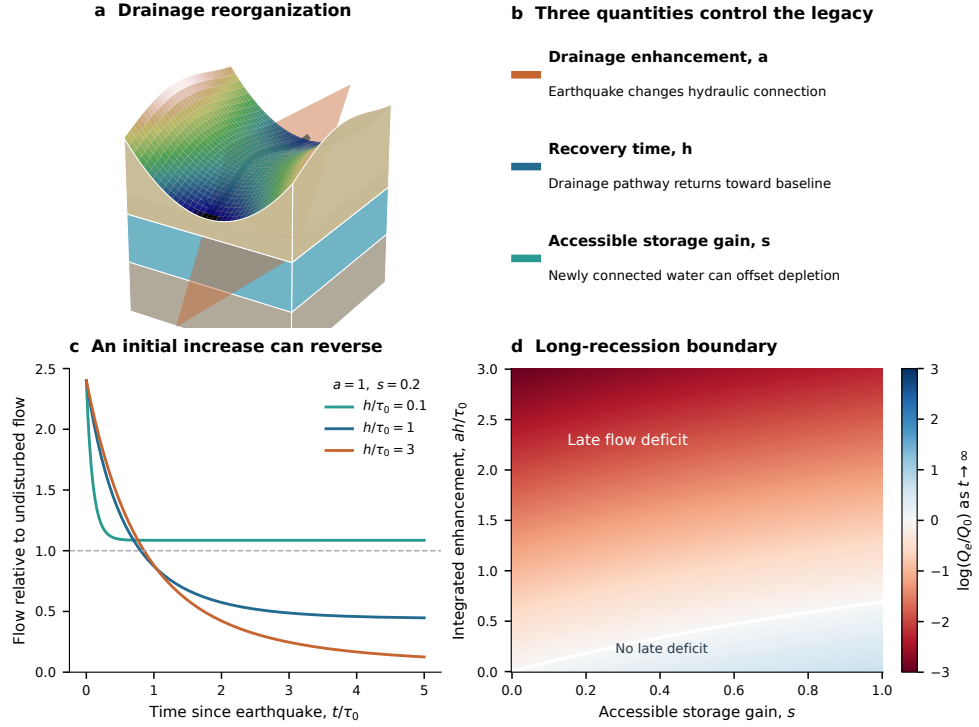


Fig. 1 Drainage recovery separates recession steepness from later depletion. **a**, Conceptual catchment cutaway showing a mobile water-bearing layer (blue) and a changed hydraulic connection associated with a fault or fracture zone (orange). The geometry is schematic. **b**, Three quantities in the reduced model. **c**, Exact discharge ratios during uninterrupted recession for $a = 1$ and $s = 0.2$, with different recovery times. A common initial increase can lead to either a persistent relative surplus or a later deficit. **d**, Asymptotic log discharge ratio; the white line is the boundary $ah/\tau_0 = \log(1 + s)$. Absolute flow approaches zero on both sides of this long-recession limit. All panels describe the conceptual model rather than field reconstructions.

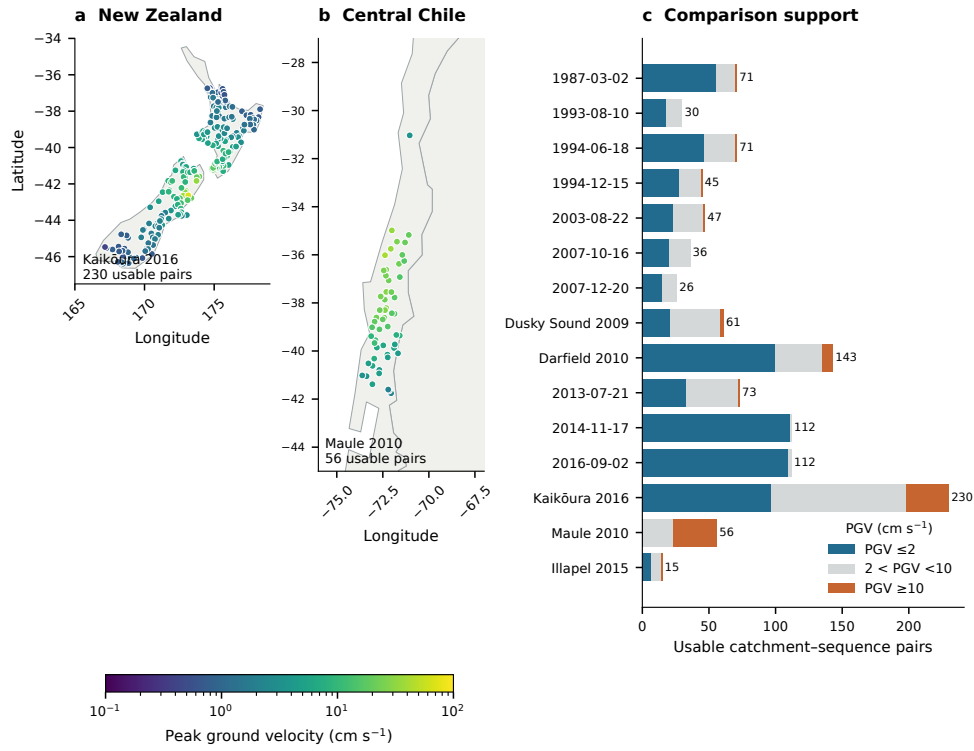


Fig. 2 Available records do not guarantee replicated earthquake contrasts. **a,b,** Locations and point-sampled peak ground velocity for usable catchments following Kaikōura and Maule. **c,** Usable catchment–sequence pairs by exposure category for all 15 sequences. The intermediate category contributes to the observational description but not to the primary strong-minus-light contrast. Counts are pairs, not independent earthquakes or distinct catchments. The archive includes 1,128 usable pairs from 335 distinct catchments. Exposure overlap and spatial replication concentrate the principal comparison at Kaikōura.

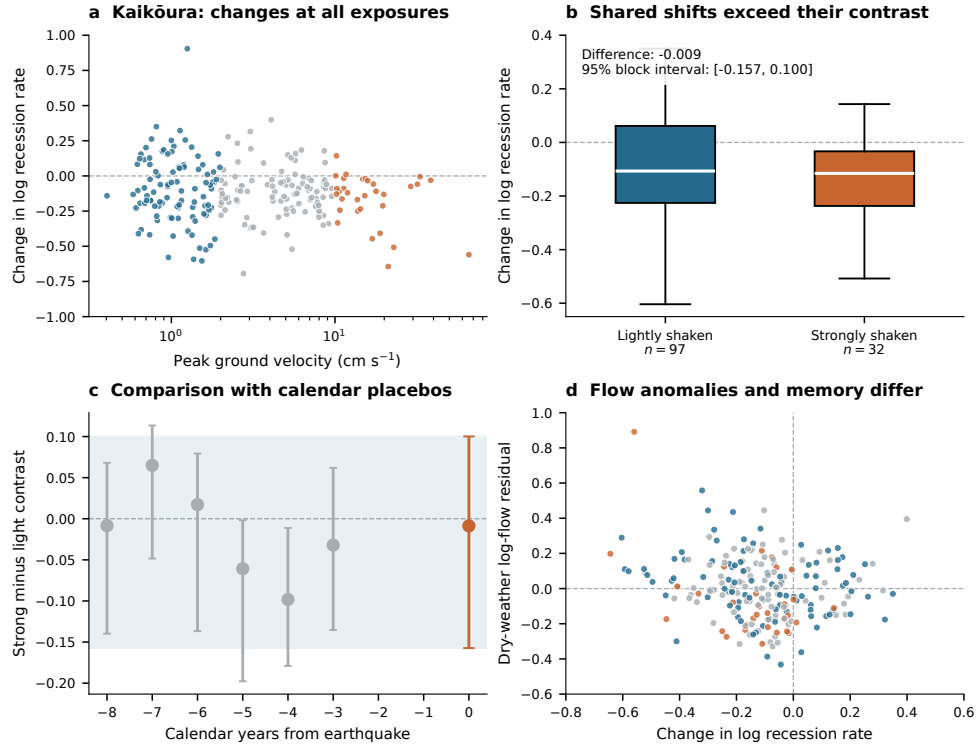


Fig. 3 Kaikōura observations do not establish persistent regional memory loss. **a**, State-conditioned recession-rate changes for 230 catchments; blue and orange denote the primary light and strong exposure categories, with intermediate exposure in grey. **b**, Boxplots for the primary categories show medians and interquartile ranges, with whiskers at 1.5 interquartile ranges; outliers are omitted from this panel but retained in calculations. **c**, Same-calendar-date placebo contrasts three to eight years earlier (grey) and the earthquake-date contrast (orange). Intervals are 95% spatial-block bootstrap intervals; the shaded band marks the earthquake-date interval. Placebo windows overlap. **d**, Recession changes and mean dry-weather log-flow residuals for catchments passing the weather-model criteria. Negative residuals indicate less flow than the pre-event weather relationship predicts; they are not uniquely attributable to the earthquake.

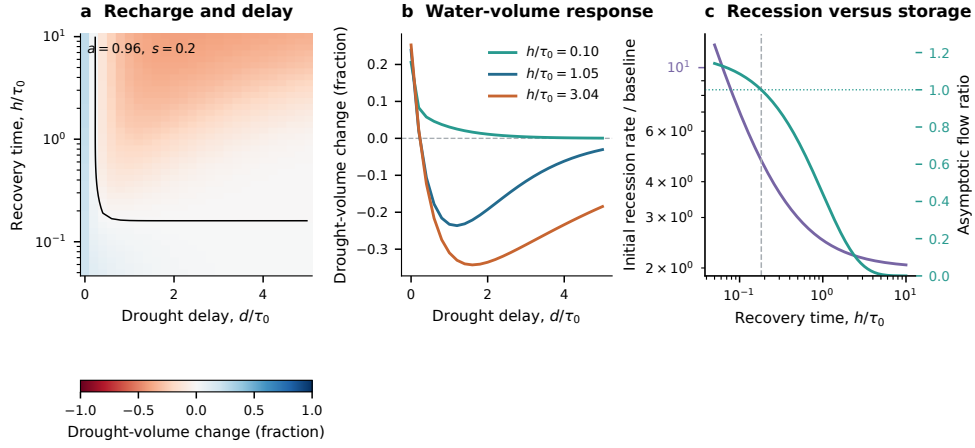
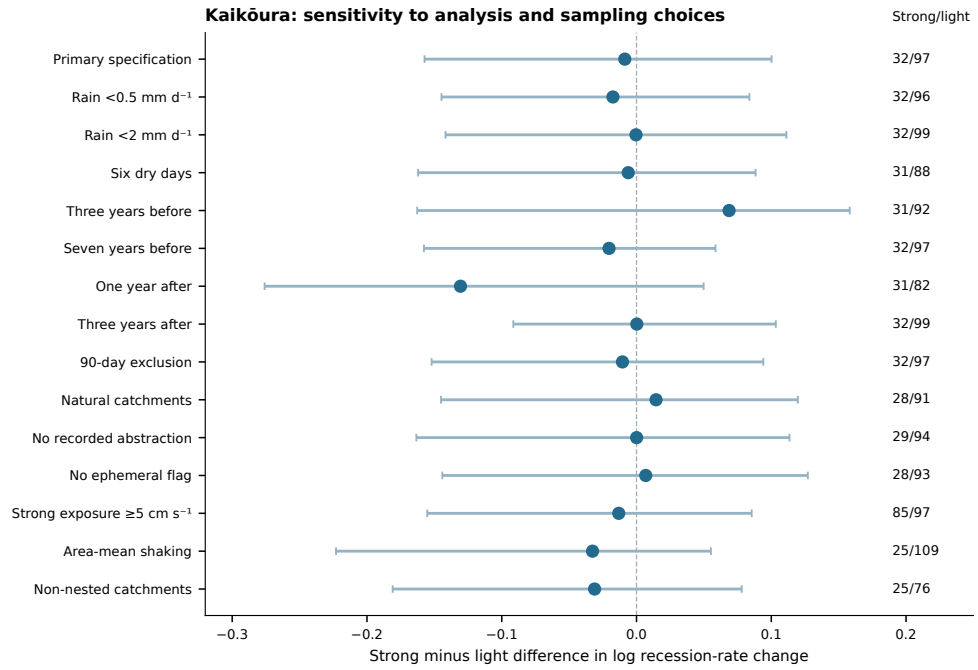
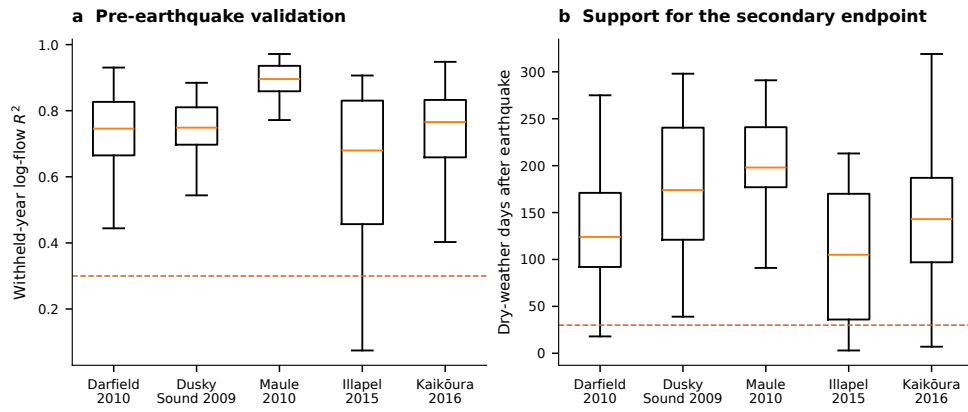


Fig. 4 Drought timing and pathway recovery change the water-volume response. **a**, Simulated fractional change in discharge integrated over a drought of duration $3\tau_0$, following a period of identical equilibrium recharge. The plotted slice has $s = 0.2$ and the grid value of a closest to one (shown in the panel); the black contour marks zero change. **b**, Slices through the ensemble for three recovery times; these are numerical scenario results. **c**, Exact initial recession-rate ratio (purple, left axis) and asymptotic uninterrupted-recession flow ratio (teal, right axis) for $a = 1$ and $s = 0.2$. The vertical dashed line marks $h/\tau_0 = \log(1.2)$; shorter recovery can produce steeper initial recession without a late flow deficit. No scenario parameters are estimated from the observed catchments.



Extended Data Fig. 1 Sensitivity of the Kaikōura exposure contrast. Points are differences in median log recession-rate change between strongly and lightly shaken catchments. Horizontal bars show 95% spatial-block intervals, based on 2,000 resamples for the primary specification and 500 for alternatives. Counts on the right give the strong and light sample sizes. Each alternative changes one primary choice except for the indicated sampling restrictions. The area-shaking definition averages shaking over catchment polygons; the non-nested subset limits catchment overlap. These intervals are conditional on the observed event and do not include every source of measurement or exposure uncertainty.



Extended Data Fig. 2 Predictive support for the secondary dry-weather endpoint. a, Withheld pre-event year R^2 in log flow for the five named earthquakes. The dashed line marks the minimum retained value of 0.3. **b,** Post-event dry-weather-day counts among models passing that threshold; the dashed line marks the required 30 days. Boxes show medians and interquartile ranges, whiskers extend to 1.5 interquartile ranges and outliers are omitted from the display. Daily temporal dependence means these day counts do not represent independent droughts. Successful validation before an event does not establish unbiased prediction under later nonstationary conditions.