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Renewability of fossil groundwaters affected by present-day climate conditions

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Aquifer residence times are commonly used to make inferences about groundwater renewability. However, the link between aquifer residence times and hydraulic response times, which control groundwater storage changes, remains unclear. Here we show that water levels in many aquifers containing fossil groundwater are controlled by modern climates. Evaluation of the renewability of fossil groundwaters should include hydraulic analysis that consider their responses to abstraction and shifts in climate.

A large portion of the world's groundwater was recharged thousands to millions of years ago, often in climates that were cooler and wetter than that of today[1–3]. These fossil groundwaters are being increasingly used to address water security, especially in arid and semi-arid regions[4,5]. Whether these waters will be replenished under current climate conditions is unclear[6–8]. Testing whether renewal of fossil groundwater will occur requires precise definition of hydraulic response time and aquifer residence time (or aquifer renewal time).

An aquifer's hydraulic response time describes how quickly its groundwater levels adjust across the entire aquifer to a shift in boundary conditions such as a climate-induced change in recharge. Residence time refers to the time for water to flow through an aquifer system[9], which is also referred to as the aquifer renewal time[6,7]. This is defined as the ratio of storage volume to recharge rate, which for simple one-dimensional systems is equivalent to the transit time from the recharge area to the discharge area. This approach assumes steady-state conditions, which are unlikely in large aquifer systems[10]. Although both hydraulic response time and aquifer residence time are affected by flow system size and hydraulic conductivity, these two metrics are controlled by fundamentally different properties and processes[11–13]. How these two metrics relate to each other is key to understanding what groundwater ages can or cannot tell us about the effect of past recharge conditions on current groundwater storage volumes.

Here we compare hydraulic response times and aquifer residence times for 31 major aquifer systems distributed across all continents except Antarctica and spanning seven orders of magnitude for both timescales. Of the 31 aquifer systems examined, hydraulic response times were less than the aquifer residence times in 21 systems (Fig. 1a). Aquifer residence times ranged from 0.7 years to 10 Ma, and aquifer response times (t_{ne}) varied from 1.6 years to 6.9 Ma. These values should be viewed as approximations, given the complexities of interpreting representative residence times from tracers[2,3,14] and effective hydraulic parameters at the scale of aquifer systems[10].

Theory (as outlined in the Methods and equations (1) and (2) therein) shows that aquifer residence time will increase linearly with the length of the flow system (L) and that hydraulic response time will increase as a function of L^2. However, neither aquifer residence time nor hydraulic response time is significantly correlated with either L or L^2 at a significance level of $P = 0.1$. This lack of a coherent relationship between flow system length and both aquifer residence time and hydraulic response times may be attributed to the variability in hydraulic gradients (3×10^{-5} to 9×10^{-2}) and storage coefficients (10^{-6} to 0.39) in the cases examined here. Hydraulic gradients are related to fluid fluxes

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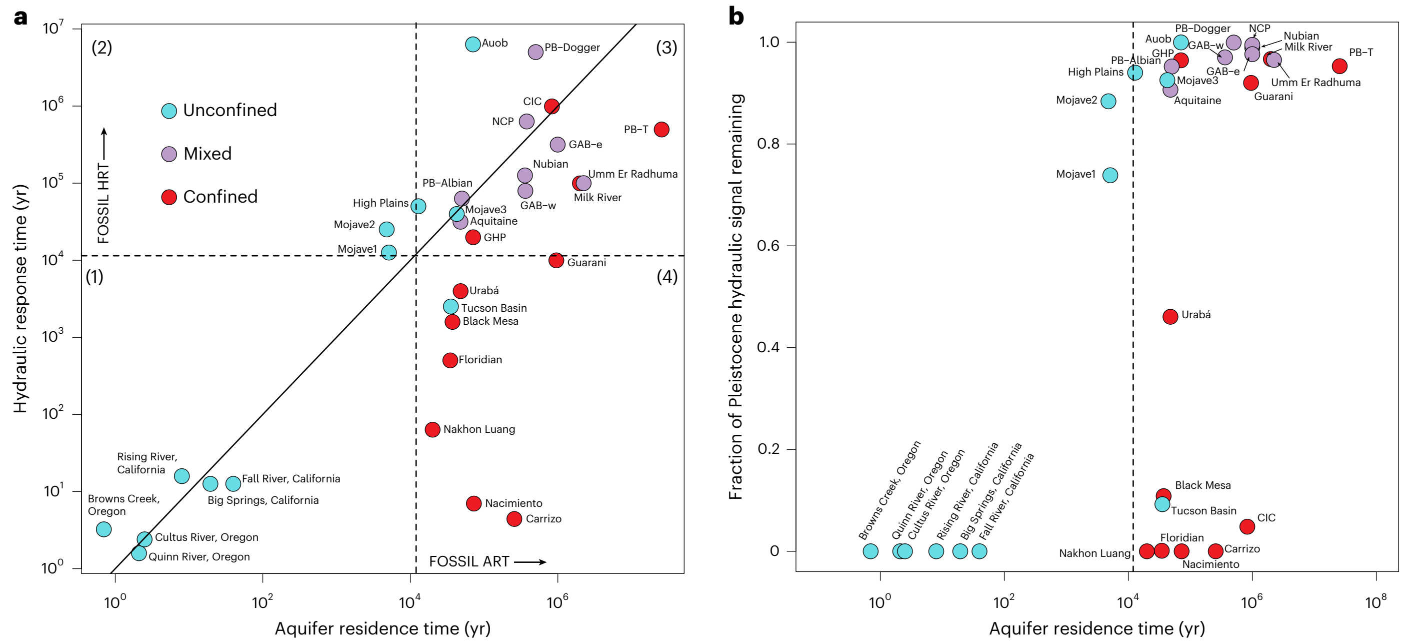

Fig. 1 | Aquifer systems with similar residence times exhibit a range of hydraulic response times. **a**, Hydraulic response times[10,28–39] tend to be shorter than aquifer residence times[26,29,40–58] for confined aquifers than mixed aquifers and unconfined aquifers. The solid line is 1:1. Quadrant (1) is hydraulic response times and aquifer residence times <12,000 years, quadrant (2) is hydraulic response times >12,000 years and aquifer residence times <12,000 years, quadrant (3) is both hydraulic response times and aquifer residence times >12,000 years and quadrant (4) is hydraulic response times <12,000 years and aquifer residence times >12,000 years. **b**, Preservation of the hydraulic signal from the Pleistocene is highly variable for aquifers with similar aquifer residence times. Abbreviated aquifers include: Continental Intercalaire (CIC); Paris Basin–Albian (PB–Albian); Paris Basin–Dogger (PB–Dogger); Paris Basin–Triassic (PB–T); Great Hungarian Plain (GHP); Great Artesian Basin–east (GAB–e); Great Artesian Basin–west (GAB–w) and North China Plain (NCP).

and hydraulic conductivity (that is, Darcy's law; equation (1)) whereas variability in storage coefficients, which affects hydraulic diffusivity (equation (2)), is controlled by the compressibility and porosity of the aquifer (equation (3)). The variability in both hydraulic gradients and storage coefficients may account for the presence of hydraulic response times that range over six orders of magnitude for similar aquifer residence times (Fig. 1). Hydraulic gradients and storage coefficients are not related to each other in such a manner that would facilitate the prediction of hydraulic response times from aquifer residence times.

So how does our analysis deal with the pressing groundwater management question of whether use of 'fossil' groundwater may or may not be renewable?[6] We address this by considering cases from the quadrants delineated using combinations of HRT and ART in Fig. 1a and referencing conceptually the relationships that are possible between the three key timescales (HRT, ART and time of climate shift) in Fig. 2.

(1) Aquifers in this quadrant have ART and HRT within the Holocene (about 12 thousand years ago (ka)) but can have HRTs that are either less than or greater than the ART (Fig. 2). A cluster of six aquifers studied here have HRT and ART values that are all less than 100 years. Because the re-equilibration of hydraulic heads is possible on human timescales, these aquifers will probably facilitate renewable groundwater use if pumping is also within flux-renewable limits determined by the hydraulic capture of the system. None of the aquifers studied here have HRT greater than human timescales but less than 12 ka.

(2) High HRT and low ART systems in this quadrant, which by definition always have HRT > ART (Fig. 2), are not well represented in our dataset aside for parts of the Mojave aquifer. The inherently long timescales for aquifer-wide hydraulic re-equilibration in this quadrant implies that storage-renewable use is unlikely for many pumping scenarios although flux-renewable use may still be possible.

(3) Aquifers in this quadrant have ART and HRT both greater than the Holocene timescale (about 12 ka) but can have HRTs that are either less than or greater than the ART. Importantly, ART may also be greater or less than the last substantial palaeo-climatic shift (that is, any of the curves in Fig. 2). Hence the hydrogeological controls on the relationships between residence times and heads in such systems may be hard to disentangle. Ten of the 31 systems examined here are not expected to have their water levels affected by climate shifts on timescales equal to their aquifer residence times but are expected to preserve at least 60% of a hydraulic signal from the Pleistocene Epoch (that is, the timescale associated with fossil groundwater[2]). For example, stable isotopes of H and O associated with ^{81}Kr dates of ~360 ka in the Nubian aquifer have been used to infer higher recharge rates associated with atmospheric circulation that differed from today[15]. The hydraulic response time for the Nubian aquifer indicates that current conditions should be ~94% readjusted from a climate shift at 360 ka. Anomalous storage and discharge from the Nubian[16] and other aquifers in the region are probably associated with more recent wet conditions between ~130 ka and the early Holocene[17]. Estimates of past water table depths in the Nubian aquifer from noble gas concentrations have documented decreases in the water table of up to ~30 m (ref. 18). It is unclear how much additional change is required to bring hydraulic heads into equilibrium with modern recharge rates, which, although lower, are non-zero[19,20]. These changes, which are expected to occur at low rates, will be superposed on any changes in hydraulic head from groundwater abstraction[21] and should be considered in an outcome-based assessment of sustainable groundwater use (that is, based on maintaining fluxes and water levels)[22]. Under long management time frames, hydraulic adjustment to past climate conditions is therefore crucial to understand[23].

(4) Low HRT and high ART combination systems in this quadrant by definition also always have HRT < ART (Fig. 2), allowing for retention of fossil water where groundwater levels are close to equilibrium with current recharge conditions. Our analysis shows that seven such aquifer systems examined are expected to have reached 80% or more equilibration with Holocene climate conditions (that is, <12 ka), despite having aquifer residence times of 20 ka or greater. Numerical models

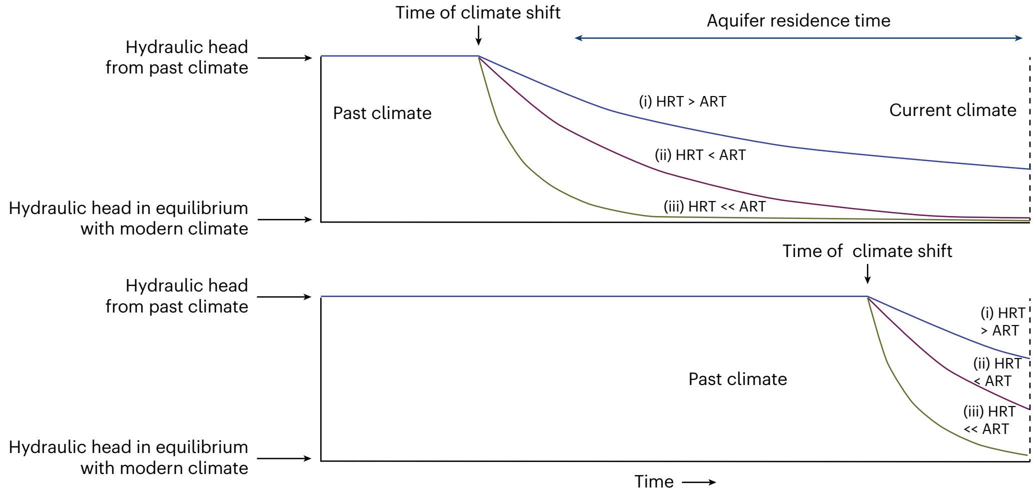

Fig. 2 | Hydraulic anomalies may correspond to different climate events than those associated with recharge of fossil groundwater. Hydraulic head anomalies from past climates occurring at times earlier than aquifer residence times can persist where (i) hydraulic response times exceed aquifer residence times. When climate shifts have occurred more recently than aquifer residence time, hydraulic anomalies can persist for hydraulic response times that are sufficiently long that can be either (i) greater than (for example, Mojave) or (ii) less than (for example, Nubian) aquifer residence times. Where hydraulic response times are much smaller than aquifer residence times (iii), water levels can be close to equilibrium with current conditions even if they contain fossil groundwater (for example, Nakhon Luang, Lower Floridian aquifers, Black Mesa Basin and Tucson Basin).

of Nakhon Luang aquifer[24], Lower Floridian aquifer[25], Black Mesa Basin[26] and Tucson Basin[27] have successfully reproduced observed hydraulic heads without considering past climates. In these aquifers, the presence of fossil groundwater appears to have little bearing on groundwater management in terms of controlling water levels and fluxes. These systems have hydraulic response times on the order of centuries to a few millennia, suggesting that if pumped at sufficiently low rates, they may be renewable on human timescales[11].

In conclusion, our compilation shows that a wide range of hydraulic response times are possible for similar aquifer residence times. Uncertainty is present in both parameters due to the coarse characterization of many of the aquifer systems and challenges associated with upscaling field measurements to the aquifer scale. Improved estimates of aquifer residence times and hydraulic response times along with examination of additional aquifer systems may result in additional insights into the relationship between these two metrics.

The presence of fossil groundwater does not necessarily indicate that groundwater levels are affected by past climates, and hence hydraulic response times should be estimated to further explore this possibility. Hydraulic response times in many aquifers that contain fossil groundwater are sufficiently short that modern climate conditions are probably a dominant control on groundwater levels. In other instances, aquifers containing fossil groundwater will have hydraulic conditions that are affected by past climates. Detailed considerations of the relationship between HRT, ART and the timescale of known palaeo-climatic shifts are recommended for any system before the presence of fossil aged water is given any particular meaning relevant to groundwater renewability.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-026-01923-4.

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Methods

Theory

Groundwater age is a function of various groundwater flow and transport processes, which can result in complex mixtures of waters recharged at different times[2,3,59,60]. Common models include exponential and piston flow that date back to the 1950s[61,62] and are still widely used[14,63]. Although many aquifer flow systems can be approximated by a piston-exponential model, where recharge only occurs over part of the flow systems, the distribution of age is similar to that described with a piston flow model where the recharge area is less than 20% of the area of the aquifer receiving negligible recharge[14]. For the case of piston flow in an aquifer with negligible dispersion[59], residence time (t_{age}) is a function of flow system length (L) and average linear groundwater velocity (v), which can further be described in terms hydraulic conductivity (K), hydraulic gradient (∇h) and porosity (η):

$$t_{age} = \frac{L}{v} = \frac{L\eta}{K\nabla h} \tag{1}$$

Bulk ages will also be influenced to various degrees by flow paths containing younger recharge at intermediate flow system positions (also affected by parameters in equation (1)) and contributions of older water from adjacent confining units, with an overall bias in calculated bulk ages towards younger ages due to aggregation errors[59]. Ages will also be affected by choice of tracer, as individual tracers may not capture the entire age distribution of a given sample[2,3,64].

Hydraulic response time (t_{NE})—the time required to reach near-equilibrium (NE) hydraulic conditions (95% readjustment) after an aquifer system is perturbed—for a confined aquifer is defined as[65]:

$$t_{NE} = \frac{12}{\pi^2}\frac{L^2}{D} = \frac{12}{\pi^2}\frac{SL^2}{T} = \frac{12}{\pi^2}\frac{S_sL^2}{\mathrm{K}} \tag{2}$$

where D is hydraulic diffusivity, S is storativity, T is transmissivity and S_s is specific storage. Specific storage is a function of fluid density (ρ), acceleration due to gravity (g), porosity (η) and the compressibility of the fluid (α) and aquifer skeleton (β) defined as:

$$S_s = \rho g(\alpha + \eta\beta) \tag{3}$$

The time required for an unconfined aquifer to reach 95% of re-equilibration following a change in hydraulic conditions is:

$$t_{NE} = \frac{S_yL^2}{T} \tag{4}$$

where a is a correction factor between 0.7 and 3.6 and S_y is specific yield. The value of the correction factor depends on how transmissivity is defined and computed. The few case studies available do not make it clear whether use of geometric, harmonic or arithmetic means or maximum or minimum values is the correct approach[66].

For aquifers containing both confined and unconfined conditions, the hydraulic response time can be estimated as:

$$t_{NE} \sim \frac{3S_uL_u}{T}\left(L_c + \frac{L_u}{2}\right) \tag{5}$$

where S_u is the storage coefficient for an unconfined aquifer ($S_u \sim S_yB$), L_c is the length of the confined portion of the aquifer and L_u is the length of the unconfined portion of the aquifer.

Equations (2), (4) and (5) provide the time for 95% adjustment of hydraulic heads (that is, water levels) to a change in a hydraulic boundary condition or three times the e-folding value, which would give 63% (=1 − 1/e) adjustment to the new boundary conditions. More generally, the fraction of hydraulic head anomaly (h/h_o) remaining after a period t has elapsed since a change in boundary conditions is given by:

$$\frac{h}{h_o} = \exp\left(-\frac{3t}{t_{NE}}\right) \tag{6}$$

where h/h_o is the fraction of the hydraulic head from the previous steady-state condition remaining following a change in hydraulic boundary conditions.

Hydraulic gradient data

Hydraulic gradients for regional aquifers were determined using regional potentiometric surface maps. Hydraulic gradients for systems in western Quaternary volcanic aquifers in the Oregon (OR) and California (CA) Cascades, USA, use a recharge elevation determined from O and H isotopes[40,67].

Compiling groundwater age data

Groundwater ages, transmissivity, storativity and hydraulic gradients were compiled for 31 regional aquifer systems from around the globe from published values. Hydraulic response times were taken from existing estimates[28,65,66] for these same aquifers or estimated from hydraulic properties and aquifer lengths (equation (2)). Data scarcity limits the ability to rigorously characterize the uncertainty in hydraulic response times, but using minimum and maximum reported material properties typically results in ranges that differ from the geometric mean by less than an order of magnitude. Groundwater age determinations using ^{14}C, ^{36}Cl, ^{81}Kr and/or ^{4}He from compiled from wells near the discharge zones in aquifers were used as proxies for aquifer residence times (t_{age}). Uncertainty in aquifer residence times used a range of approaches in the various studies examined here, including analytical error, uncertainty in parameters used for correcting ages and uncertainty in numerical models, with a maximum reported uncertainty of 60% (ref. 15). We note that additional uncertainty in residence times will occur due to the use of single tracers that may not capture the entire distribution of groundwater ages.

Limitations

Our analysis is based on best available data from peer-reviewed studies. Nevertheless, there are limitations that may affect our analysis and interpretation of the results. These include:

- Reliance of wells as proxies for aquifer conditions and known limitations linked to disturbance of flow systems linked to presence of wells. Wells have screens with finite lengths that intersect multiple flow paths, which may not be representative of the full distribution of groundwater ages, resulting in bias of the estimates of groundwater residence times. Installation of wells may also connect strata that were relatively hydraulically isolated under background conditions.
- Reliance on a limited number of wells in discharge areas. Groundwater systems are heterogeneous, and a large number of wells may be necessary to adequately characterize the spatial distribution of groundwater ages.
- Limitations linked to use of a single value of groundwater age derived from an individual tracer. Different tracers are likely to provide ages that do not agree with each other because they are affected by different processes and applicable to different ranges of ages. Samples containing groundwater of mixed ages are particularly sensitive to aggregation errors.
- Limitations related to characterization of hydraulic properties. Hydraulic properties used here are from past studies that have estimated these properties through field testing and numerical modelling. Their use as effective parameters at the aquifer scale is an approximation and is likely to result in errors in estimating changes in hydraulic head at specific locations in these heterogeneous systems.

- Limitations related to characterizing changes in climate as step functions. Changes in climate may be better described using cyclical or more complex functions. Treating shifts in climate as step functions should only be viewed as a first approximation.

Data availability

Compiled aquifer residence time and hydraulic response time necessary to recreate Fig. 1 is available via the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) Hydroshare repository at https://www.hydroshare.org/resource/39d42f15f720431e8114d79cc6baeb9b/.

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Author contributions

This research was conceived by G.F., M.O.C. and J.C.M. Data were compiled and analysed by G.F., C.E.N. and M.M. Writing and drafting of figures was led by G.F. with editing by all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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