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Citation for final published version:

Ferguson, Grant, Cuthbert, Mark O. , Jasechko, Scott, Manga, Michael, J.McDonnell, Jeffrey, McIntosh, Jennifer C., Noyes, Chander E., Lollar, Barbara Sherwood and Taylor, Richard G. 2026. Renewability of fossil groundwaters affected by present-day climate conditions. *Nature Geoscience* 10.1038/s41561-026-01923-4

Publishers page: <https://doi.org/10.1038/s41561-026-01923-4>

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1 **Link Between Residence Times and Groundwater Renewability Obscured by**
2 **Hydraulics**

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27 **Abstract**

28 **Aquifer residence times are commonly used to make inferences about groundwater**
29 **system behaviour. However, the link between average aquifer residence times and**
30 **hydraulic response times which control groundwater storage changes relevant to**
31 **sustainable pumping, remains unclear. Here, we show that water levels in some aquifers**
32 **containing fossil groundwater are controlled by modern climates while many others are**
33 **affected by past climates over periods shorter than their aquifer residence times.**

34

35 **Main**

36 Many aquifer systems worldwide contain “fossil” groundwater that is thousands to
37 millions of years old¹⁻³, the use of which is an increasingly important water security strategy,
38 particularly in arid and semi-arid regions^{4,5}. Using groundwater age as a metric of
39 groundwater renewability, which requires dynamically stable re-equilibrium of groundwater
40 levels on human timescales (i.e. 100 years)⁶, has recently been questioned due to the
41 confounding effects of aquifer geometry and well hydraulics⁷. The effect of past climates was
42 noted as a possible exception. Groundwater has previously been assumed to be non-
43 renewable if groundwater ages corresponding to past recharge rates were higher due to wetter
44 and cooler climates⁸⁻¹⁰. Testing this assumption requires precise definition of hydraulic
45 response time (HRT) and aquifer residence time (ART) (or aquifer renewal time).

46 An aquifer’s hydraulic response time describes how quickly its groundwater levels
47 and flows adjust across the entire aquifer to a shift in boundary conditions such as a climate
48 induced changes in recharge. Residence time refers to the time for water to flow through an
49 aquifer system¹¹, which is also referred to as the aquifer renewal time^{8,9}. This is defined as the
50 ratio of storage volume to recharge rate, which for simple one-dimensional systems is

AQUIFER RESIDENCE TIMES VERSUS HYDRAULIC RESPONSE TIMES

51 equivalent to the transit time from the recharge area to the discharge area. This approach
52 assumes steady-state conditions, which are unlikely in most large aquifer systems¹². Although
53 both hydraulic response time and aquifer residence time are affected by flow system size and
54 hydraulic conductivity, these two metrics are controlled by fundamentally different properties
55 and processes^{6,7,13}. How these two metrics relate to each other is key to understanding what
56 groundwater ages can or cannot tell us about the effect of past recharge conditions on current
57 groundwater storage volumes.

58 Here, we compare hydraulic response times and aquifer residence times for 31 major
59 aquifer systems distributed across all continents except Antarctica, and spanning seven orders
60 of magnitude for both timescales. Of the 31 aquifer systems examined, hydraulic response
61 times were less than the aquifer residence times in 21 systems (Figure 1a). Aquifer residence
62 times ranged from 0.7 years to 10 Ma, and aquifer response times (t_{ne}) varied from 1.6 years
63 to 6.9 Ma. These values should be viewed as approximations, given the complexities of
64 interpreting representative residence times from tracers^{2,3,14} and effective hydraulic
65 parameters at the scale of aquifer systems¹².

66 Theory (as outlined in the Methods and equations S1 and S2 therein) shows that
67 aquifer residence time will increase linearly with the length of the flow system (L) and that
68 hydraulic response time will increase as a function of L^2 . However, neither aquifer residence
69 time nor hydraulic response time is significantly correlated with either L or L^2 at a
70 significance level of $p = 0.1$. This lack of a coherent relationship between flow system length
71 and both aquifer residence time and hydraulic response times may be attributed to the
72 variability in hydraulic gradients (3×10^{-5} to 9×10^{-2}) and storage coefficients (10^{-6} to 0.39)
73 in the cases examined here. Hydraulic gradients are related to fluid fluxes and hydraulic
74 conductivity (i.e., Darcy's law; equation S1) whereas variability in storage coefficients,
75 which affects hydraulic diffusivity (equation S2), is controlled by the compressibility and

AQUIFER RESIDENCE TIMES VERSUS HYDRAULIC RESPONSE TIMES

76 porosity of the aquifer (equation S3). The variability in both hydraulic gradients and storage
77 coefficients may account for the presence of hydraulic response times that range over six
78 orders of magnitude for similar aquifer residence times (Figure 1). Hydraulic gradients and
79 storage coefficients are not related to each other in such a manner that would facilitate the
80 prediction of hydraulic response times from aquifer residence times.

81 So how does our analysis deal with the pressing groundwater management question of
82 whether use of “fossil” groundwater may or may not be renewable⁶? We address this by
83 considering cases from the quadrants delineated using combinations of HRT and ART in
84 Figure 1a and referencing conceptually the possible relationships that are possible between
85 the three key timescales (HRT, ART and time of climate shift) in Figure 2.

86 **(1).** Aquifers in this quadrant have ART and HRT within the Holocene (c. 12 ka) but
87 can have HRTs that are either less than or greater than the ART (Figure 2 i, ii or iii). A cluster
88 of 6 aquifers studied here have HRT and ART values that are all less than 100 years. Since
89 the re-equilibration of hydraulic heads is possible on human timescales (assumed to be the
90 order of 100 years here) will likely facilitate renewable groundwater use if pumping is also
91 within flux-renewable limits determined by the hydraulic capture of the system. None of the
92 aquifers studied here have HRT greater than human timescales but less than 12 ka.

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

98 **(3)** Aquifers in this quadrant have ART and HRT both greater than the Holocene
99 timescale (c. 12 ka) but can have HRTs that are either less than or greater than the ART.
100 Importantly ART may also be greater or less than the last substantial paleo-climatic shift (i.e.

AQUIFER RESIDENCE TIMES VERSUS HYDRAULIC RESPONSE TIMES

101 any of the curves in Figure 2 i-vi). Hence the hydrogeological controls on the relationships
102 between residence times and heads in such systems may be hard to disentangle. Ten of the 31
103 systems examined here are not expected to have their water levels affected by climate shifts
104 on timescales equal to their aquifer residence times but are expected to preserve at least 60%
105 of a hydraulic signal from the Pleistocene Epoch (i.e. the timescale associated with fossil
106 groundwater²). For example, stable isotopes of H and O associated with ⁸¹Kr dates of ~360 ka
107 in the Nubian aquifer have been used to infer higher recharge rates associated with
108 atmospheric circulation that differed from today¹⁵. The hydraulic response time for the
109 Nubian aquifer indicates that current conditions should be ~94% readjusted from a climate
110 shift at 360 ka. Anomalous storage and discharge from the Nubian¹⁶ and other aquifers²⁶ in
111 the region are likely associated with more recent wet conditions between ~130 ka and the
112 early Holocene¹⁷. Estimates of past water table depths in the Nubian aquifer from noble gas
113 concentrations have documented decreases in the water table of up to ~30 m¹⁸. It is unclear
114 how much additional change is required to bring hydraulic heads into equilibrium with
115 modern recharge rates, which, although lower, are non-zero^{19,20}. These changes, which are
116 expected to occur at low rates, will be superposed on any changes in hydraulic head from
117 groundwater abstraction²¹ and should be considered in an outcome-based assessment of
118 sustainable groundwater use (i.e. based on maintaining fluxes and water levels)²². Under long
119 management timeframes, hydraulic adjustment to past climate conditions is therefore crucial
120 to understand²³.

121 **(4)** Low HRT and high ART combination systems in this quadrant by definition also
122 always have HRT < ART (Figure 2), allowing for retention of fossil water where
123 groundwater levels are close to equilibrium with current recharge conditions. Our analysis
124 shows that such seven aquifer systems examined are expected to have reached 80% or more
125 equilibration with Holocene climate conditions (i.e. < 12 ka), despite having aquifer

AQUIFER RESIDENCE TIMES VERSUS HYDRAULIC RESPONSE TIMES

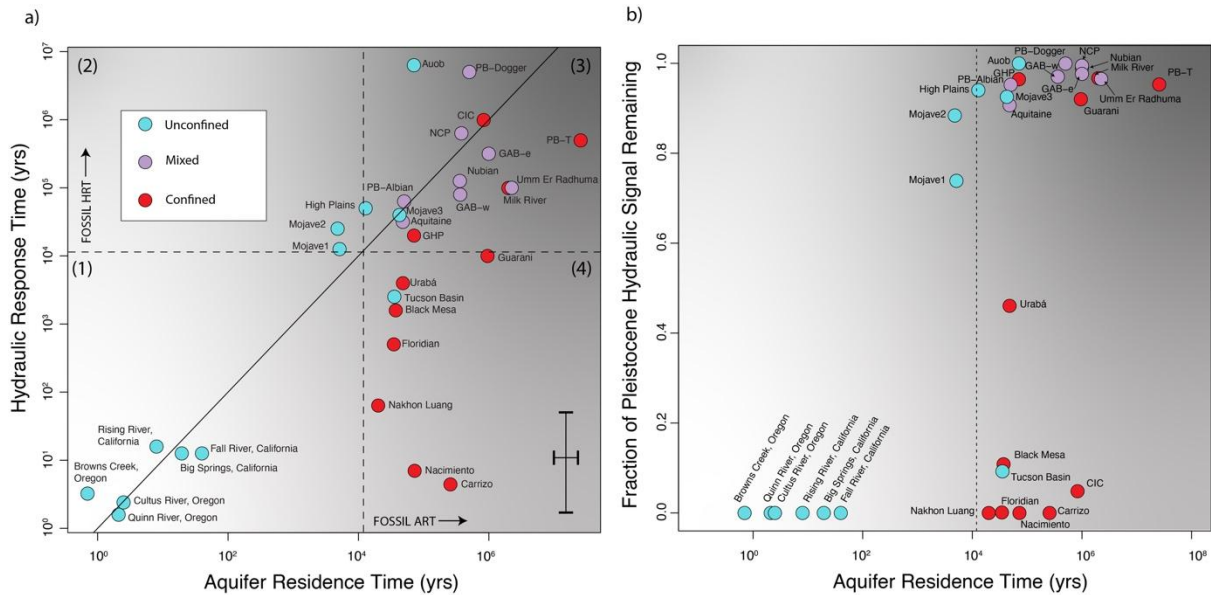
126 residence times of 20 ka or greater. Numerical models of Nakhon Luang²⁴, Lower Floridian
127 aquifers²⁵, Black Mesa Basin²⁶ and Tucson Basin²⁷ have successfully reproduced observed
128 hydraulic heads without considering past climates. In these aquifers, the presence of fossil
129 groundwater appears to have little bearing on groundwater management in terms of
130 controlling water levels and fluxes. These systems have hydraulic response times on the order
131 of centuries to a few millennia, suggesting that if pumped at sufficiently low rates they may
132 be renewable on human timescales⁶.

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

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

149

AQUIFER RESIDENCE TIMES VERSUS HYDRAULIC RESPONSE TIMES



150

151

Figure 1a) Hydraulic response times (HRTs) tend to be shorter than aquifer residence

152

times (ARTs) for confined aquifers than mixed aquifers and unconfined aquifers. The

153

solid line is 1:1. Abbreviated aquifers include: Continental Intercalaire (CIC); Paris

154

Basin-Albian (PB-Albian); Paris Basin-Dogger (PB-Dogger); Paris Basin-Triassic (PB-

155

T); Great Hungarian Plain (GHP); Great Artesian Basin-East (GAB-e); Great Artesian

156

Basin-West (GAB-w) and North China Plain (NCP). For hydraulic response times from

157

Rousseau-Gueutin et al. (2013), the values presented are the geometric mean of the low

158

and high values. Quadrant (1) is HRT and ART < 12,000 years, quadrant (2) is HRT >

159

12,000 years and ART < 12,000 years, quadrant (3) is both HRT and GRT > 12,000

160

years and quadrant (4) is HRT < 12,000 years and ART > 12,000 years. Error bars in

161

the lower right corner correspond to maximum reported uncertainty from residence

162

times used here²⁸ and average range between low and high log groundwater response

163

times. b) Preservation of the hydraulic signal from the Pleistocene is highly variable for

164

aquifers with similar aquifer residence times. Abbreviated aquifers include:

165

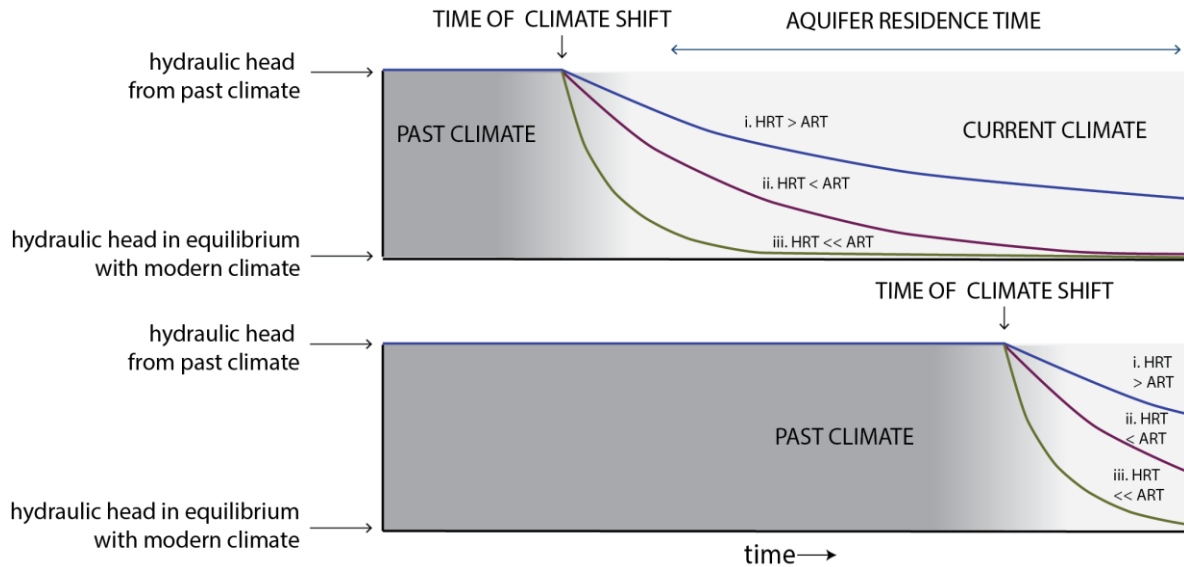
Continental Intercalaire (CIC); Paris Basin-Albian (PB-Albian); Paris Basin-Dogger

166

(PB-Dogger); Paris Basin-Triassic (PB-T); Great Hungarian Plain (GHP); Great

167 **Artesian Basin-East (GAB-e); Great Artesian Basin-West (GAB-w) and North China**
 168 **Plain (NCP).**

169



170

171 **Figure 2: Hydraulic head (h) anomalies from past climates occurring at times earlier**
 172 **than aquifer residence times can be persist where (i) hydraulic response times (HRTs)**
 173 **exceed aquifer residence times (ARTs). When climate shifts have occurred more**
 174 **recently than aquifer residence time, hydraulic anomalies can persist for hydraulic**
 175 **response times that are sufficiently long that can be either (i) greater than (e.g. Mojave)**
 176 **or (ii) less than (e.g. Nubian) aquifer residence times. Where hydraulic response times**
 177 **are much smaller than aquifer residence times (iii), water levels can be close to**
 178 **equilibrium with current conditions even if they contain fossil groundwater (e.g.**
 179 **Nakhon Luang, Lower Floridian aquifers, Black Mesa Basin and Tucson Basin).**

180

181

182 **Methods**

183 **Theory**

AQUIFER RESIDENCE TIMES VERSUS HYDRAULIC RESPONSE TIMES

184 Groundwater age is a function of various groundwater flow and transport processes,
185 which can result in complex mixtures of waters recharged at different times^{2,3,29,30}. Common
186 models include exponential and piston flow that date back to the 1950s^{31,32} and are still
187 widely used^{14,33}. Although many aquifer flow systems can be approximated by a piston-
188 exponential model, where recharge only occurs over part of the flow systems, the distribution
189 of age is similar to that described with a piston flow model where the recharge area is less
190 than 20% of the area of the aquifer receiving negligible recharge¹⁴. For the case of piston
191 flow in an aquifer with negligible dispersion²⁹, residence time (t_{age}) is a function of flow
192 system length (L) and average linear groundwater velocity (v), which can further be described
193 in terms hydraulic conductivity (K), hydraulic gradient (∇h), and porosity (η):

$$194 \quad t_{age} = \frac{L}{v} = \frac{L\eta}{K\nabla h} \quad [S1]$$

195 Bulk ages will also be influenced to various degrees by flowpaths containing younger
196 recharge at intermediate flow system positions (also affected by parameters in [S1]) and
197 contributions of older water from adjacent confining units, with an overall bias in calculated
198 bulk ages towards younger ages due to aggregation errors (Bethke and Johnson, 2008). Ages
199 will also be affected by choice of tracer, as individual tracers may not capture the entire age
200 distribution of a given sample^{2,3,34}.

201 Hydraulic response time (t_{NE})—the time required to reach near-equilibrium (NE)
202 hydraulic conditions (95% readjustment) after an aquifer system is perturbed—for a confined
203 aquifer is defined as¹³:

$$204 \quad t_{NE} = \frac{12 L^2}{\pi^2 D} = \frac{12 S L^2}{\pi^2 T} = \frac{12 S_s L^2}{\pi^2 K} \quad [S2]$$

205 where D is hydraulic diffusivity, τ_c is the time constant for a confined aquifer, S is
206 storativity, T is transmissivity, and S_s is specific storage. Specific storage is a function of

207 fluid density (ρ), acceleration due to gravity (g), porosity (η) and the compressibility of
 208 the fluid (α) and aquifer skeleton (β) defined as:

$$209 \quad S_s = \rho g(\alpha + \eta\beta) \quad [S3]$$

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

$$212 \quad t_{NE} = \frac{S_y L^2}{T} \quad [S4]$$

213 where a is a correction factor between 0.7 and 3.6 and S_y is specific yield. The value of the
 214 correction factor depends on how transmissivity is defined and computed. The few case
 215 studies available do not make it clear whether use of geometric, harmonic or arithmetic
 216 means or maximum or minimum values is the correct approach.¹²

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

$$219 \quad t_{NE} \sim \frac{3S_u L_u}{T} \left(L_c + \frac{L_u}{2} \right) \quad [S5]$$

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

222 Equations [S2, S4, S5] provide the time for 95% adjustment of hydraulic heads (i.e., water
 223 levels) to a change in a hydraulic boundary condition or three times the e-folding value,
 224 which would give 63% ($= 1 - 1/e$) adjustment to the new boundary conditions. More
 225 generally, the fraction of hydraulic head anomaly (h/h_o) remaining after a period t has elapsed
 226 since a change in boundary conditions is given by:

$$227 \quad \frac{h}{h_o} = \exp\left(-\frac{3t}{t_{NE}}\right) \quad [S4]$$

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

230

231 **Hydraulic gradient data**

232 Hydraulic gradients for regional aquifers were determined using regional
233 potentiometric surface maps (Supplementary Data 1). Hydraulic gradients for systems in
234 western Quaternary volcanic aquifers in the Oregon (OR) and California (CA) Cascades,
235 USA use a recharge elevation determined from O and H isotopes^{35,36}.

236

237 **Compiling groundwater age data**

238 Groundwater ages, transmissivity, storativity and hydraulic gradients were compiled
239 for 31 regional aquifer systems from around the globe from published values (Supplementary
240 Data 1 and 2). Hydraulic response times were taken from existing estimates^{12,37,38} for these
241 same aquifers or estimated from hydraulic properties and aquifer lengths (Supplementary
242 Data 1; equation 2). Data scarcity limits the ability to rigorously characterize the uncertainty
243 in hydraulic response times but using minimum and maximum reported material properties
244 typically results in ranges that differ from the geometric mean by less than an order of
245 magnitude (Supplementary Data 1). Groundwater age determinations using ¹⁴C, ³⁶Cl, ⁸¹Kr
246 and/or ⁴He from compiled from wells near the discharge zones in aquifers (Supplementary
247 Data 2) were used as proxies for aquifer residence times (t_{age}). Uncertainty in aquifer
248 residence times used a range of approaches in the various studies examined here, including
249 analytical error, uncertainty in parameters used for correcting ages, and uncertainty in
250 numerical models (Supplementary Data 2), with a maximum reported uncertainty of 60%¹⁵.
251 We note that additional uncertainty in residence times will occur due to the use of single
252 tracers that may not capture the entire distribution of groundwater ages.

253

254 **Limitations**

AQUIFER RESIDENCE TIMES VERSUS HYDRAULIC RESPONSE TIMES

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

258 • Reliance of wells as proxies for aquifer conditions and known limitations
259 linked to disturbance of flow systems linked to presence of wells. Wells have screens with
260 finite lengths that intersect multiple flowpaths, which may not be representative of the full
261 distribution of groundwater ages, resulting in bias of the estimates of groundwater residence
262 times. Installation of wells may also connect strata that were relatively hydraulically isolated
263 under background conditions.

264 • Reliance on a limited number of wells in discharge areas. Groundwater
265 systems are heterogeneous and a large number of wells may be necessary to adequately
266 characterize the spatial distribution of groundwater ages.

267 • Limitations linked to use of a single value of groundwater age derived from an
268 individual tracer. Different tracers are likely to provide ages that do not agree with each other
269 because they are affected by different processes and applicable to different ranges of ages.
270 Samples containing groundwater of mixed ages are particularly sensitive to aggregation
271 errors.

272 • Limitations related to characterization of hydraulic properties. Hydraulic
273 properties used here are from past studies that have estimated these properties through field
274 testing and numerical modeling. Their use as effective parameters at the aquifer scale is an
275 approximation and is likely to result in errors in estimating changes in hydraulic head at
276 specific locations in these heterogeneous systems.

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

280

281 **Acknowledgments**

282 This research was funded by an NSERC Discovery Grant to GF. MOC gratefully
283 acknowledges funding for an Independent Research Fellowship from the UK Natural
284 Environment Research Council (NE/P017819/1). Ideas were further developed at a CIFAR
285 Catalyst workshop organized by Manga and Taylor. Manga, McDonnell, McIntosh,
286 Sherwood Lollar and Taylor are fellows of the CIFAR Earth 4D: Subsurface Science and
287 Exploration program. CEN was supported by a scholarship from the ARCS Foundation.

288 **Contributions**

289 This research was conceived by GF, MOC and JCM. Data was compiled and analyzed by
290 GF, CEN and MM. Writing and drafting of figures was led by GF with editing by all co-
291 authors.

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293

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386 **Supplementary Information**

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388 **Supplementary Table 1. 31 globally distributed aquifer systems**