The rapid yet uneven turnover of Earth's groundwater

Kevin M. Befus, Scott Jasechko, Elco Luijendijk, Tom Gleeson, and M. Bayani Cardenas

May 2017

This article was originally published at:

http://dx.doi.org/10.1002/2017GL073322

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL073322

Key Points:
- One third of present-day groundwater storage could have recharged prior to the Last Glacial Maximum
- Groundwater beneath most catchments could be turned over at least 3 to 8 times since the Last Glacial Maximum
- Spatial heterogeneity in groundwater recharge and storage capacity led to longer turnover times than globally integrated analyses predict

Supporting Information:
- Supporting Information S1

Correspondence to:
K. M. Befus,
kbefus@uwyo.edu

Citation:
Befus, K. M., S. Jasechko, E. Luijendijk, T. Gleeson, and M. Bayani Cardenas (2017), The rapid yet uneven turnover of Earth's groundwater, *Geophys. Res. Lett.*, *44*, doi:10.1002/2017GL073322.

Received 2 MAR 2017
Accepted 13 MAY 2017
Accepted article online 18 MAY 2017

The rapid yet uneven turnover of Earth's groundwater

Kevin M. Befus[1], Scott Jasechko[2], Elco Luijendijk[3], Tom Gleeson[4], and M. Bayani Cardenas[5]

[1]Civil and Architectural Engineering, University of Wyoming, Laramie, Wyoming, USA, [2]Department of Geography, University of Calgary, Calgary, Alberta, Canada, [3]Geoscience Centre, Georg-August-Universität Göttingen, Göttingen, Germany, [4]Civil Engineering, University of Victoria, Victoria, British Columbia, Canada, [5]Department of Geological Sciences, The University of Texas at Austin, Austin, Texas, USA

Abstract The turnover of groundwater through recharge drives many processes throughout Earth's surface and subsurface. Yet groundwater turnover rates and their relationship to regional climate and geology remain largely unknown. We estimated that over 200×10^6 km^3 of groundwater has recharged since the Last Glacial Maximum (LGM), which is 10 times the volume of global groundwater storage. However, flushing is very unevenly distributed throughout Earth's one million watersheds, with some aquifers turned over thousands of times to others with <1% turnover. The median global groundwater turnover of 5 ± 3 times since the LGM highlights groundwater's active role in Earth system processes. Incomplete groundwater turnover since the LGM beneath a third of land areas reveals the imprint of relict climate conditions on modern-day groundwater resources. The bulk groundwater turnover calculated here enables better quantification of groundwater's impact in dynamic global water budgets and the transport of nutrients, contaminants, and geologic weathering products.

Plain Language Summary The duration groundwater spends in an aquifer sets how long it is sequestered from the rest of the hydrologic cycle, where it can interact with the surrounding matrix and transport dissolved chemicals to and from the land surface. Over geologic timescales, these interactions transform landscapes, affect global climate, and regulate water resource sustainability and quality. We present how much groundwater has recharged since the Last Glacial Maximum and where groundwater on Earth is associated with previous climate conditions.

1. Introduction

Modern groundwater systems contain unquantified amounts of water recharged over the changing deglacial climate, i.e., since the Last Glacial Maximum (LGM). Water stored in the cryosphere during the glacial climate was released over millennia, leading to extensive but not ubiquitous increases in precipitation [*Clark et al.*, 2012] at the end of the Pleistocene (~21–11.7 thousand years ago) and throughout the early and middle Holocene (~11.7–5 thousand years ago). Regional climates were wetter than present day during the deglacial in some areas [*Clark et al.*, 2012] and potentially drove high groundwater recharge rates in certain regions [*Klump et al.*, 2008; *Lemieux et al.*, 2008], creating immense freshwater stores in regions where little groundwater recharge occurs in modern times [e.g., *Beyerle et al.*, 2003]. Most investigations of the effects of global climate change on groundwater systems have either focused on regions directly impacted by ice sheet and periglacial processes [*Beyerle*, 1998; *Person et al.*, 2012], where present-day groundwater storage is a relic of wetter interglacial climate [*Beyerle et al.*, 2003], or address future climate change [*Döll*, 2009; *Taylor et al.*, 2013b]. Despite the potential for global deglacial climate changes to influence present-day groundwater systems, little is known about how deglacial climate changes continue to be manifest in modern groundwater systems at the global scale.

Global estimates of groundwater turnover timescales predict that all of groundwater storage could be replaced or turned over in 1000 to 10,000 years (Table 1). While long compared to human timescales, these turnover times suggest that the majority of groundwater storage could have been turned over by recharge since the mid-Holocene and only contain water recharged under similar climate to present day (i.e., interglacial conditions). However, such turnover times were calculated using an integrated volume of groundwater and recharge rate for the entire Earth that does not resolve spatial differences related to geologic and climatic variabilities. Further, numerous discoveries of paleo-groundwater have been identified using geochemical tracers [*Jasechko*, 2016], implying that many modern aquifers contain groundwater recharged long before the onset of the Holocene [*Rozanski*, 1985; *Aggarwal et al.*, 2004].

Table 1. Summary of Continental Scale Analyses of Groundwater Storage (V_{gw}), Recharge (R), and Turnover Times ($T_{turnover}$)[a]

	V_{gw}	R	$T_{turnover}$
	10^6 km^3	10^3 km^3/yr	kyr
Nace [1969]	1–7	1.5	0.7–4.7
Nace [1971]	4–60	6.0	0.7–10.0
Garmonov et al. [1974]	23.4	13.3	1.2–2.2
L'vovich [1974]	60	12.0	1.3-5.0
Döll et al. [2002]	–	13.8	1.1–2.1
Döll and Fiedler [2008]	–	12.7	1.2-2.3
Wada et al. [2010]	–	15.2	1.0–1.9
GLDAS CLM annual[b]	–	17.7	0.9–1.7
GLDAS MOS annual mean[b]	–	15.3	0.6–1.2
GLDAS NOAH annual mean[b]	–	24.8	0.6–1.2
Bodnar et al. [2013]	10.5[c]	15.3[c]	0.69
Gleeson et al. [2015]	22.6 (15.8–29.5)	5.9 (2.7–11.0)	3.8 (2.7–5.0)

[a]V_{gw} from *Gleeson et al.* [2015] was used to calculate $T_{turnover}$ for studies without V_{gw} information. R estimates for the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004] are calculated to be the excess precipitation after removing surface runoff and evapotranspiration as calculated previously by *Fan et al.* [2013].
[b]As calculated by *Fan et al.* [2013]
[c]Assuming water density of 1000 kg/m^3.

A variety of groundwater timescales have been used to quantify multiple and diverse groundwater processes and responses. Hydraulic groundwater turnover time is perhaps the most basic, generally requiring only a volume of groundwater storage, V_{gw}, and a volumetric rate of flushing that can be approximated by groundwater recharge, R, giving $T_{turnover} = V_{gw}/R$ [*McGuire and McDonnell*, 2006]. Turnover time is not the same as groundwater age, which measures the time that a water molecule takes to travel from the water table to a point along a flow path; this is also the residence time or transit time when considered at the terminus of a flow path at an outlet [*Bethke and Johnson*, 2008]. In groundwater systems with piston-flow conditions and equal length flow paths, half the $T_{turnover}$ provides an estimate of the mean groundwater age [*McGuire and McDonnell*, 2006], but most natural groundwater flow systems follow a more complex power law residence time distribution arising from variable flow path lengths and contributions to discharge [*Kirchner et al.*, 2000; *Cardenas*, 2007; *Harman*, 2015]. Conservatively, groundwater turnover time represents the bulk timescale to completely replace or flush a given volume: it is a characteristic groundwater transit time for a whole domain that ignores groundwater flow dynamics and kinematics.

The conservation of mass and/or momentum underlies quantitative groundwater models and controls how groundwater systems respond to changing hydrologic conditions. Simulating how flow paths, pressure gradients, and transport phenomena change in transient groundwater systems requires either parameterization or simplifying assumptions that reduce real-world hydrogeologic complexity into computationally manageable forms [*Sanford*, 2011]. Lumped-parameter models reduce such complexity by focusing on the gross hydrologic behavior of a system with significantly fewer variables than numerical solutions, describing the conservation of mass but generally not momentum. Lumped-parameter models often provide the hydraulic framework for interpreting environmental tracer analyses and have varying complexity depending on the hydrologic system studied [*Małoszewski and Zuber*, 1982; *Glynn and Plummer*, 2005; *McGuire and McDonnell*, 2006]. Similarly, many streamflow-generation and land surface models treat groundwater within a catchment or cell as a linear reservoir that only supplies water to that area [*Schaller and Fan*, 2009]. Lumped-parameter models of groundwater systems are well-established tools for quantifying the timing and magnitude of responses to hydrologic signals and provide our catchment-scale framework for investigating how historic climate conditions have flushed or only partially replenished Earth's groundwater systems.

Here we calculate global hydraulic groundwater turnover times since the LGM to constrain when present-day groundwater storage recharged. Groundwater turnover was calculated for more than one million hydrologic catchments globally by flushing their groundwater storage with transient recharge fluxes defined by precipitation from a global paleoclimate model. We modeled the spatially distributed turnover of groundwater using a simple lumped-parameter water budget, in which groundwater flow is simplified as piston flow. The calculated turnover times were then used to quantify the regional potential for current groundwater

storage to have recharged under historic climate conditions in the Holocene epoch, deglacial conditions, or associated with climate prior to the LGM.

2. Methods

2.1. Transient Groundwater Recharge

Variability in groundwater recharge for the HydroSHEDS catchments [*Lehner et al.*, 2008] was calculated using decadal precipitation results from the full Simulation of Transient Climate Evolution of the last 21,000 years (TraCE-21 ka) global climate model [*He*, 2011]. TraCE-21 ka is an adapted form of the Community Climate System Model 3.0 that includes fully coupled and nonaccelerated atmosphere, ocean, sea ice, and land surface components in addition to modeling transient forcings from greenhouse gases, orbital insolation variations, ice sheet effects, and meltwater fluxes [*He*, 2011]. A global precipitation variability ratio, $P(x,y,t)/P_{\text{current}}$, was calculated by dividing the time series of total precipitation from TraCE-21 ka, $P(x,y,t)$, by P_{current}, the arithmetic mean of the total precipitation for the final millennium of the simulation prior to 1900 C.E. (i.e., 990–1890 C.E., CE = Common Era). This arithmetic mean defines a long-term average precipitation that attempted to reduce the effect of forced model convergence to measured data and spanned interdecadal variability. We did not account for the uncertainty of the simulated precipitation products as benchmarking modeled and reconstructed paleoclimate remains difficult [*Harrison et al.*, 2016], but similar climate models in the LGM and mid-Holocene successfully describe trends in precipitation changes while generally failing to match paleoproxy reconstructions regionally [*Braconnot et al.*, 2012; *Harrison et al.*, 2013]. Thus, we drive groundwater recharge with $P(x,y,t)/P_{\text{current}}$ to reduce uncertainty relative to assigning groundwater recharge directly from $P(x,y,t)$.

The variability in groundwater recharge, $R(x,y,t)/R_{\text{current}}$, was set equal to $P(x,y,t)/P_{\text{current}}$, implying that the proportion of precipitation that becomes recharge remains constant with changes in precipitation and generally describes the relationship across climates in modern times [*Sophocleous*, 1992; *Scanlon et al.*, 2006; *Izuka et al.*, 2010]. However, we acknowledge that average modern precipitation may not fully describe the precipitation regimes that recharge groundwater systems, where larger precipitation events may cause disproportionately more recharge [*Dripps and Bradbury*, 2009; *Taylor et al.*, 2013a; *Jasechko et al.*, 2014]. Additionally, it is important to note that precipitation is not the only driver of groundwater recharge [*de Vries and Simmers*, 2002], and multiple, coupled hydrologic processes determine the timing and magnitude of recharge with changing climate (see the supporting information for additional discussion). $R(x,y,t)/R_{\text{current}}$ values after 1890 C.E. were set to unity. To calculate $R(x,y,t)$, R_{current} was then prescribed as present-day steady state global groundwater recharge estimates [*Döll and Fiedler*, 2008; *De Graaf et al.*, 2015], developed for the 1960–1990 C.E. [*Döll and Fiedler*, 2008] and 1957–2002 C.E. [*De Graaf et al.*, 2015] climate normals. Additional development and discussion of the groundwater recharge calculations are included in the supporting information.

2.2. Groundwater Turnover Times

Groundwater flushing and turnover times were calculated using the TraCE-21 ka decadal time steps for each HydroSHEDS level 12 catchment with data available, totaling 1,019,079 catchments. These catchment areas average 130.8 km^2 and have a median of 135.4 km^2, an interquartile range of 103.1–166.6 km^2, and a 10th–90th percentile range of 35.0–202.1 km^2. The groundwater storage beneath each catchment, V_{gw}, was calculated from global porosity geospatial data [*Gleeson et al.*, 2014] and characteristic lithologic porosity-depth profiles [*Gleeson et al.*, 2015] from the water table to a depth of 2 km below the water table (see supporting information for more information on the calculation of V_{gw}). The transient water budget for each catchment calculated the groundwater storage recharged over each 10 year time step and the distribution of recharge times in storage (Figures S3 and S4 in the supporting information). At each time step, the volume of groundwater recharged replaced an equal volume of older groundwater, with the oldest groundwater in storage removed in chronological order (i.e., piston flow). V_{gw} remained constant for each catchment. Thus, the entire pore space in the upper 2 km of the crust participated equally in groundwater flow, and the oldest groundwater in storage was discharged first. In reality, groundwater discharge consists of a mixture of old and young groundwater with the most rapid turnover in shallow and permeable strata [*Bethke and Johnson*, 2008]. Therefore, our analysis is a first order and conservative estimate of groundwater turnover.

Both the groundwater turnover time, $T_{turnover}$, and flushing since the LGM were calculated from the transient water budget model. $T_{turnover}$ was the difference between the oldest and youngest groundwater in storage for a time step, representing the time required to recharge all of the groundwater in storage during that time step. To track groundwater flushing, we calculated the number of times groundwater storage beneath individual catchments could be entirely flushed or "turned over" by recharge since the LGM ($N_{turnover}$). Groundwater recharged prior to LGM made up the remainder of storage for catchments with $N_{turnover}$ less than one and a $T_{turnover}$ longer than 22,000 years.

3. Results

Using the precipitation results from a global paleoclimate model [*He*, 2011], we estimated transient groundwater recharge rates, $R(x,y,t)$, relative to current groundwater recharge, $R_{current}$, for over one million hydrologic catchments by adjusting present-day recharge estimates [*Döll and Fiedler*, 2008; *De Graaf et al.*, 2015] proportionally with precipitation variability since the LGM (Figure 1). Prior to deglaciation, modeled groundwater recharge was lower than today (>15%) in over half of terrestrial areas (Figure 1); however, some regions instead received higher than modern groundwater recharge, such as northeastern Africa, southwest Asia, Central America, and Australia (Figures S2a–S2e). Groundwater recharge began to increase substantially after ~17,000 years ago, where the global median recharge rate approached current recharge rates ~10,000 years ago. Two extended periods of decreasing recharge rates began ~14 and ~12.9 thousand years ago and correspond to the globally cooler and dryer Older and Younger Dryas climate events [*Clark et al.*, 2012; *Liu et al.*, 2012]. By the onset of the Holocene (~11.7 thousand years ago), global median recharge rates were within 5% of current groundwater recharge rates with decelerating convergence to current recharge throughout the remainder of the Holocene (Figure 1). Despite this overall convergence to present-day recharge in the early Holocene, regional climate continued to vary with notably higher recharge rates (>400%) in Saharan Africa, the Arabian Peninsula, and southwestern Asia in the mid-Holocene (Figure S2c). Since the LGM, 210.5–837.6 $\times 10^6$ km^3 of water recharged Earth's groundwater with the range accounting for uncertainty arising from differences in present-day groundwater recharge estimates [*Döll and Fiedler*, 2008; *De Graaf et al.*, 2015].

Our model estimated that ~30% (27.0–36.3% with uncertainty introduced by the two recharge estimates and by the range in porosity-depth relationships leading to V_{gw} uncertainty; see supporting information for detailed explanation) of catchments have not been turned over since the LGM (Figure 2a). Thus, about a third of catchments today may overlie groundwater systems that contain some paleo-groundwater that recharged prior to the LGM. The model also predicted that ~20% (13.4–28.8%) of global groundwater storage could be turned over since 1000 years ago and ~45% (45.0–71.0%) since 5000 years ago. These results suggest the majority of Earth's groundwater systems continue to store water recharged across the deglacial climate transition to mid-Holocene interglacial conditions.

Globally, groundwater stored beneath many catchments was turned over thousands of times, where in other catchments, 21,000 years of cumulative recharge flushed less than 1% of groundwater storage (Figure 2b). The median $N_{turnover}$ for catchments ranges from 3.0 to 8.1 with the recharge and V_{gw} uncertainties. Determined by the variability of recharge and geology, the spatial patterns of $N_{turnover}$ follow regional climate closely (Figure 2b), with less turnover in arid and semiarid regions (e.g., Saharan and southern Africa, Australia, the southwestern United States, and the Middle East) and more flushing in more humid regions (e.g., Amazonia, central Africa, eastern North America, and southeast Asia). At the global scale, $N_{turnover}$ increased with decreasing aridity (Figure S9), and almost all catchments in humid regions turned over at least once since the LGM.

The time-incremental $N_{turnover}$ starting from LGM was also calculated and reveals the variation in the timing of groundwater flushing for catchments globally (Figure 3a). A majority (>50%) of the catchments have had the potential to be flushed at least once by about 18,000 years ago. Treating groundwater systems as a single, global resource similar to previous analyses, the first integrated global groundwater storage turnover occurred around 19 (18.1–20.8) thousand years ago. Importantly, the globally integrated groundwater turnover always exceeded the median turnover behavior of individual catchments by allowing rapidly flushed catchments to supply recharge disproportionately to turn over the global V_{gw} (Figure 3a). Thus, the global perspective of groundwater turnover predicts shorter $T_{turnover}$ than our distributed analysis. If groundwater

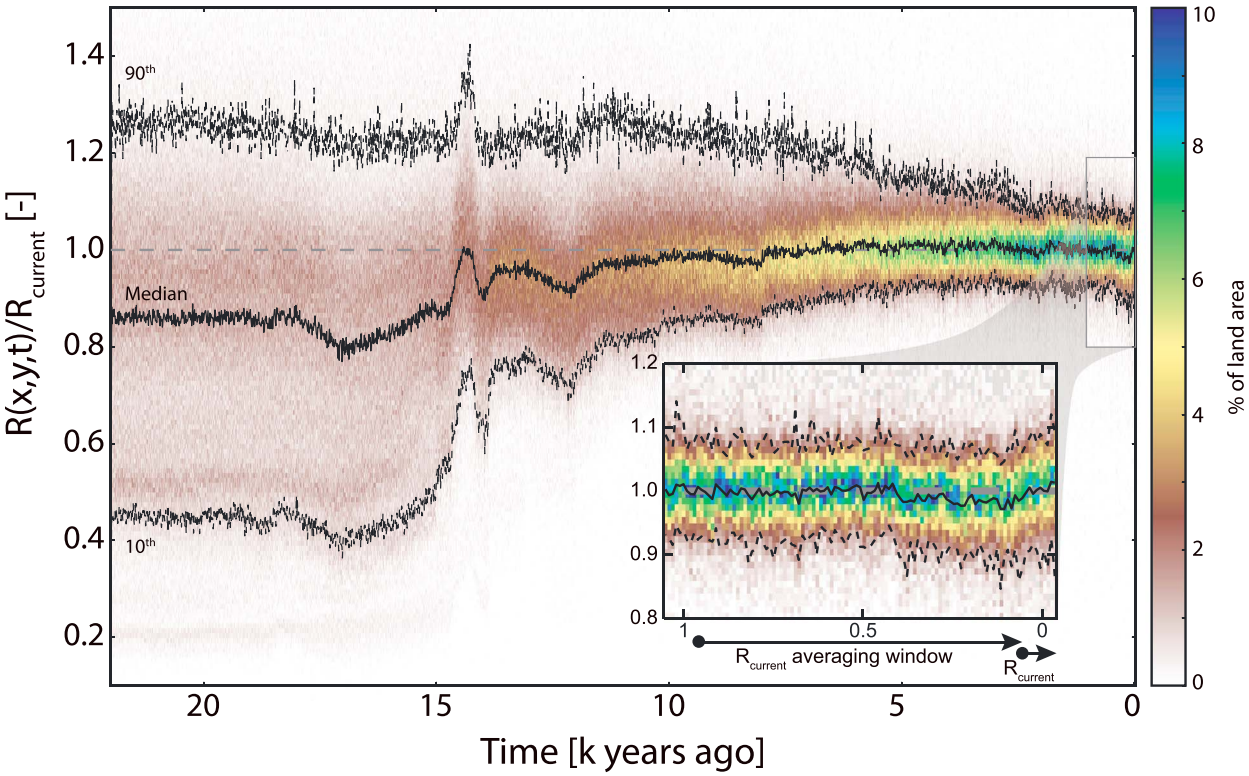

Figure 1. Global groundwater recharge time series. The calculated variability of groundwater recharge relative to current groundwater recharge rates ($R(x,y,t)/R_{current}$) shows the convergence of global climate to present-day conditions. The cumulative global $R(x,y,t)/R_{current}$ percentiles (10th, 50th, and 90th) are indicated by thick black lines.

recharge was equally apportioned globally, which previous global analyses assumed, the global volume of groundwater storage could have turned 9.9 (6.2–18.3) times since the LGM. This is, of course, not the case. Global integration fails to distinguish the spatial distributions of groundwater recharge and storage volumes, similar to previous global estimates of groundwater turnover times (Table 1). With the smaller spatial discretization of catchments, our model used climatic and geologic variability to calculate how groundwater turnover has been disproportionately distributed to groundwater beneath humid catchments, leading to longer estimates of $T_{turnover}$ than globally integrated analyses suggest. In summary, our geospatial analysis reveals that many regions likely contain groundwater recharged many thousands of years ago in the uppermost 2 km of the crust resulting from long-term, low recharge rates over the past 21,000 years.

But how much of present-day groundwater storage was recharged at some time after the LGM? Global estimates of groundwater storage and recharge have been used to estimate turnover at the continental scale (Table 1). However, these estimates use time-invariant recharge, implying that groundwater storage is composed of equal amounts of water recharged at all times in the past. Thus, previous analyses would predict a uniform distribution of recharge times, $T_{recharge}$, for groundwater in storage today (Figure 3b and Table 1). By modeling transient groundwater flushing, the amount of groundwater recharged at time $T_{recharge}$ for each catchment at the end of the simulation was integrated to yield the global distribution of $T_{recharge}$ by volume. The distribution of present-day groundwater storage recharged at time $T_{recharge}$ increases exponentially from the LGM to the present (Figure 3b), but a substantial amount of pre-LGM storage contributes to modern groundwater resources (Figure 2a). Even so, catchments with rapid turnover cycled vast quantities of water with nearly 80% (75.0–79.1%) of groundwater recharged since the LGM was consequentially flushed since 5000 years ago as higher groundwater recharge rates became the norm during the late Holocene (Figure 1). Thus, the most uncertainty in the timing of groundwater recharge currently in storage was manifest in the last few millennia determined by the integrated V_{gw} uncertainty of individual catchments that established the flushing responses to recharge (Figure 2b). Globally, much less groundwater that recharged

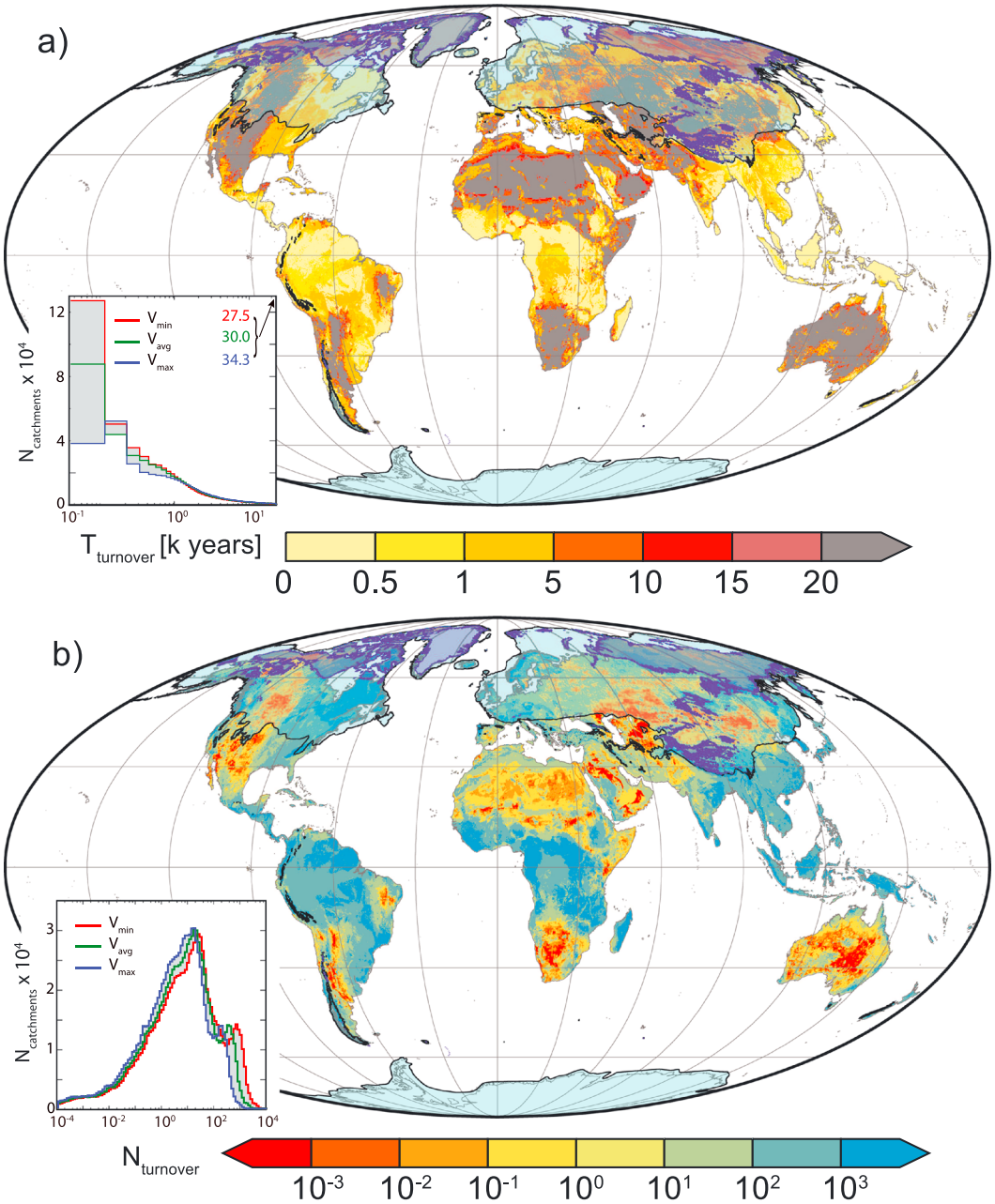

Figure 2. Global groundwater turnover since the LGM. Flushing was calculated by (a) the time required to turnover groundwater storage ($T_{turnover}$) at the present-day flushed by transient groundwater recharge (R) and (b) the number of times groundwater storage was turned over since LGM ($N_{turnover}$). The areas covered by ice sheets and continuous permafrost at LGM (light blue) and continuous permafrost at present (purple) indicate where periglacial processes would lead to changes in R not considered in the current model.

prior to 2000 years ago remained in storage at present and was less influenced by V_{gw} uncertainty than the more actively flushed catchments. By integrating the spatial differences in groundwater storage and recharge, the previous analyses roughly capture the median global $T_{turnover}$ of our transient analysis but fail to describe the regional variability in groundwater turnover. These previous analyses suggest that plenty of time has elapsed since the LGM to flush all groundwater storage. Instead, our globally integrated transient recharge results estimated that 30% (27.0–36.3%) of catchments have not been turned over since the LGM and contain some pre-LGM groundwater. Thus, our analysis highlights the ongoing significance of glacial and deglacial climates on groundwater storage.

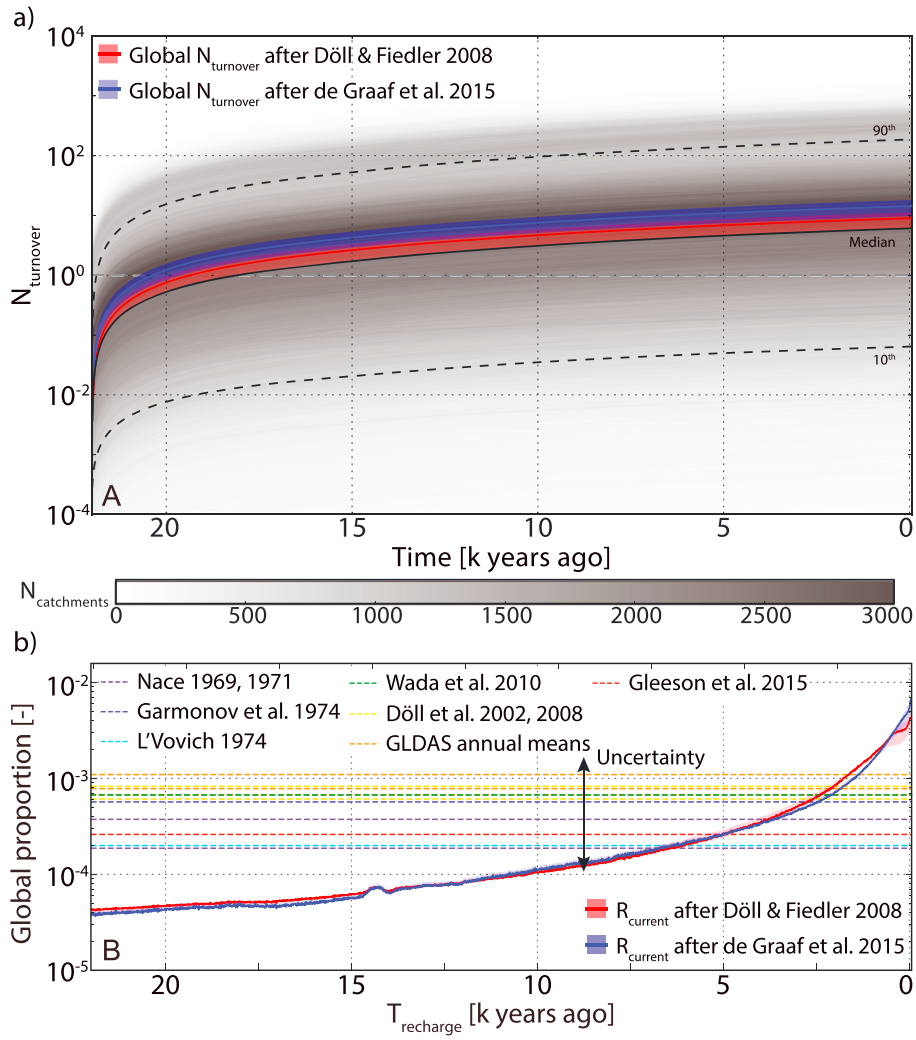

Figure 3. Timing of groundwater turnovers and recharge timing of present-day storage. (a) The transient distribution of $N_{turnover}$ for individual catchments globally showing the evolution of groundwater flushing since the LGM with percentiles shown. The global $N_{turnover}$ estimate curves demonstrate the flushing capacity for a single, integrated global groundwater reservoir, and their uncertainty. (b) The predicted globally integrated distribution of present-day groundwater storage recharged at a given time in the past ($T_{recharge}$) for the current analysis with shaded uncertainty from V_{gw} and for the minimum and maximum estimates from previous global analyses as dashed lines (see Table 1).

Our model-based results suggest that many catchments contain some "fossil groundwater," defined as groundwater recharged more than 11,700 years ago (i.e., prior to the onset of the Holocene). Our findings support recent radiocarbon-measurement-based results that show that most groundwater deeper than 250 m is fossil in age [*Jasechko et al.*, 2017]. The radiocarbon data suggest that fossil groundwater likely constitutes more than half of all groundwater in the uppermost 1 km of the crust. Our model results suggest that about 35% (32–39%) of global groundwater storage within 2 km of the land surface recharged prior to 11,700 years ago. Several differences in the two approaches may explain the disagreement between our model versus the measurement-based results, including (i) the simplifying assumptions made in our lumped-parameter model (e.g., piston flow, the precipitation to recharge relationship, and constraining the model domain to watershed boundaries); (ii) our model's underestimation of aquifer heterogeneity arising from the lack of global, 3-D geologic data; and (iii) sampling biases in the groundwater radiocarbon data set (e.g., toward more permeable sedimentary basins with productive aquifers; see discussion in *Jasechko et al.* [2017]). Nevertheless, both our model-based and their measurement-based [*Jasechko et al.*, 2017] findings highlight that many regions have not been flushed over the course of the current Holocene epoch, implying that relict waters are not an anomaly and instead likely to be widespread around the globe.

4. Implications for Groundwater Cycling in Earth Systems

Global climate changes over decadal to millennial timescales related to changes in solar activity [*Helama et al.*, 2010], Earth's orbit [*Yin and Berger*, 2012], and human activities [*Myhre et al.*, 2013]. Natural changes in the past led to glacial-interglacial cycles that typically lasted about 100,000 years [*Kawamura et al.*, 2007]. Our study shows that the entire volume of Earth's groundwater can be flushed through the upper 2 km of terrestrial crust over timescales that are a fraction of glacial-interglacial periods, but not all groundwater is flushed so quickly. Earth's groundwater is thus a very active component of the hydroclimate system over geologic time in regions with rapid turnover, while more arid areas may retain the effects of climate change for much longer.

While our simple water budget analysis approached the question of how groundwater systems store and flush water recharged over millennia from a theoretical perspective, time varying groundwater dynamics and kinematics will determine the actual amount of groundwater recharged and consequently flushed since the LGM. Since shallow and short groundwater flow paths are generally more active than deeper, longer flow paths [*Bethke and Johnson*, 2008], a large amount of the recharge supporting flushing in our analysis would discharge more quickly in reality, resulting in more flushing of the shallow subsurface while not flushing the deeper flow paths. Thus, our analysis likely underestimated N_{turnover} for shallow flow paths and overestimated N_{turnover} for longer, deeper flow paths, meaning our estimate of pre-LGM recharge remaining in groundwater storage today is likely to be an underestimate. Similarly, geologic heterogeneity and the presence of brines in the subsurface would make the portion of the crust that contains active groundwater flow paths thinner and create larger potential for a divergence of groundwater storage turnover times between more and less active flow systems than modeled under our assumption of fluid and geologic homogeneity [*Gassiat et al.*, 2013]. Evidence for the importance of heterogeneity in isolating some, usually deep, fluids include geochemical-based evidence for million- or even billion-year-old fluids in deep fracture zones [*Holland et al.*, 2013], globally widespread fossil groundwater identified by low radiocarbon, and anomalous stable oxygen and hydrogen isotope compositions [*Phillips*, 1995].

From the recharge areas, flowing groundwater interacts with the surrounding sediment and rocks. These time-sensitive geochemical reactions alter both the rock matrix and the groundwater, which then delivers the products of these processes to rivers [*Gomez-Velez et al.*, 2015], lakes [*Marcé et al.*, 2015], and oceans [*Slomp and Van Cappellen*, 2004]. Our results show that groundwater turnover times range from decades to timespans exceeding 21,000 years and reveal regional patterns of high and low groundwater turnover rates. These spatial patterns of groundwater turnover can be useful for quantifying the contribution of groundwater on the geochemical evolution of both surface and subsurface environments and to identify groundwater systems that may host paleowaters containing chemical compositions that provide useful archives of Quaternary and older hydroclimates [*Phillips*, 1995; *Weyhenmeyer et al.*, 2000; *Klump et al.*, 2008].

We calculated the worldwide potential of groundwater systems to flush and store significant volumes of groundwater that are relics of past climate. In many aquifers, groundwater is consumed more quickly than even present-day high recharge rates and environmental flows [*Gleeson et al.*, 2012], compared to the recharge rates that emplaced much of the groundwater in storage today. As groundwater systems are tapped to sustain human water needs [*Aeschbach-Hertig and Gleeson*, 2012], groundwater turnover times will shorten and groundwater storage may deplete, further shortening turnover times in some areas. The long groundwater turnover times for over one third of the world's catchments demonstrate that much of the future quality and availability of groundwater resources on Earth depend on climate and recharge histories spanning multiple millennia.

Acknowledgments
The study was supported by the National Science Foundation (EPS-1208909). The geomatic inputs and results are available at http://doi.org/10.15786/M26P4R.

References

Aeschbach-Hertig, W., and T. Gleeson (2012), Regional strategies for the accelerating global problem of groundwater depletion, *Nat. Geosci.*, *5*(12), 853–861, doi:10.1038/ngeo1617.

Aggarwal, P. K., K. Fröhlich, K. M. Kulkarni, and L. L. Gourcy (2004), Stable isotope evidence for moisture sources in the Asian summer monsoon under present and past climate regimes, *Geophys. Res. Lett.*, *31*, L08203, doi:10.1029/2004GL019911.

Bethke, C. M., and T. M. Johnson (2008), Groundwater age and groundwater age dating, *Annu. Rev. Earth Planet. Sci.*, *36*(1), 121–152, doi:10.1146/annurev.earth.36.031207.124210.

Beyerle, U. (1998), Climate and groundwater recharge during the last glaciation in an ice-covered region, *Science*, *282*(5389), 731–734, doi:10.1126/science.282.5389.731.

Beyerle, U., J. Rueedi, Leuenberger, Markus, W. Aeschbach-Hertig, F. Peeters, R. Kipfer, and A. Dodo (2003), Evidence for periods of wetter and cooler climate in the Sahel between 6 and 40 kyr BP derived from groundwater, *Geophys. Res. Lett.*, *30*(4), 1173, doi:10.1029/2002GL016310.

Bodnar, R. J., T. Azbej, S. P. Becker, C. Cannatelli, A. Fall, and M. J. Severs (2013), Whole Earth geohydrologic cycle, from the clouds to the core: The distribution of water in the dynamic Earth system, *Geol. Soc. Am. Spec. Pap.*, *500*, 431–461, doi:10.1130/2013.2500(13).

Braconnot, P., S. P. Harrison, M. Kageyama, P. J. Bartlein, V. Masson-Delmotte, A. Abe-Ouchi, B. Otto-Bliesner, and Y. Zhao (2012), Evaluation of climate models using palaeoclimatic data, *Nat. Clim. Change*, *2*(6), 417–424, doi:10.1038/nclimate1456.

Cardenas, M. B. (2007), Potential contribution of topography-driven regional groundwater flow to fractal stream chemistry: Residence time distribution analysis of Tóth flow, *Geophys. Res. Lett.*, *34*, L05403, doi:10.1029/2006GL029126.

Clark, P. U., et al. (2012), Global climate evolution during the last deglaciation, *Proc. Natl. Acad. Sci. U.S.A.*, *109*(19), 1134–1142, doi:10.1073/pnas.1116619109/-/DCSupplemental.www.pnas.org/cgi/doi/10.1073/pnas.1116619109.

De Graaf, I. E. M., E. H. Sutanudjaja, L. P. H. Van Beek, and M. F. P. Bierkens (2015), A high-resolution global-scale groundwater model, *Hydrol. Earth Syst. Sci.*, *19*(2), 823–837, doi:10.5194/hess-19-823-2015.

de Vries, J. J., and I. Simmers (2002), Groundwater recharge: An overview of process and challenges, *Hydrogeol. J.*, *10*(1), 5–17, doi:10.1007/s10040-001-0171-7.

Döll, P. (2009), Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment, *Environ. Res. Lett.*, *4*(3), 35006), doi:10.1088/1748-9326/4/3/035006.

Döll, P., and K. Fiedler (2008), Global-scale modeling of groundwater recharge, *Hydrol. Earth Syst. Sci.*, *12*(3), 863–885, doi:10.5194/hess-12-863-2008.

Döll, P., B. Lehner, and F. Kaspar (2002), Global modeling of groundwater recharge, in *Third International Conference on Water Resources and the Environment Research*, edited by G. H. Schmitz, pp. 27–31, Technical Univ. of Dresden, Germany.

Dripps, W. R., and K. R. Bradbury (2009), The spatial and temporal variability of groundwater recharge in a forested basin in northern Wisconsin, *Hydrol. Processes*, *24*, 383–392, doi:10.1002/hyp.7497.

Fan, Y., H. Li, and G. Miguez-Macho (2013), Global patterns of groundwater table depth, *Science*, *339*(6122), 940–943, doi:10.1126/science.1229881.

Garmonov, I. V., A. A. Konoplyantsev, N. P. Lushnikova, and S. and C. O. United Nations Educational 1978 (1974), Water storage in the upper part of the Earth's crust, in *The World Water Balance and Water Resources of the Earth*, edited by K. I. Korzun, pp. 48–50, Hydrometeoizdat, Leningrad.

Gassiat, C., T. Gleeson, and E. Luijendijk (2013), The location of old groundwater in hydrogeologic basins and layered aquifer systems, *Geophys. Res. Lett.*, *40*, 3042–3047, doi:10.1002/grl.50599.

Gleeson, T., Y. Wada, M. F. P. Bierkens, and L. P. H. van Beek (2012), Water balance of global aquifers revealed by groundwater footprint, *Nature*, *488*(7410), 197–200, doi:10.1038/nature11295.

Gleeson, T., N. Moosdorf, J. Hartmann, and L. P. H. van Beek (2014), A glimpse beneath Earth's surface: GLobal HYdrogeology MaPS (GLHYMPS) of permeability and porosity, *Geophys. Res. Lett.*, *41*, 3891–3898, doi:10.1002/2014GL059856.

Gleeson, T., K. M. Befus, S. Jasechko, E. Luijendijk, and M. B. Cardenas (2015), The global volume and distribution of modern groundwater, *Nat. Geosci.*, *9*(2), 161–167, doi:10.1038/ngeo2590.

Glynn, P. D., and L. N. Plummer (2005), Geochemistry and the understanding of ground-water systems, *Hydrogeol. J.*, *13*(1), 263–287, doi:10.1007/s10040-004-0429-y.

Gomez-Velez, J. D., J. W. Harvey, M. B. Cardenas, and B. Kiel (2015), Denitrification in the Mississippi River network controlled by flow through river bedforms, *Nat. Geosci.*, *8*(12), 941–945, doi:10.1038/ngeo2567.

Harrison, S. P., P. J. Bartlein, S. Brewer, I. C. Prentice, M. Boyd, I. Hessler, K. Holmgren, K. Izumi, and K. Willis (2013), Climate model benchmarking with glacial and mid-Holocene climates, *Clim. Dyn.*, *1–18*, doi:10.1007/s00382-013-1922-6.

Harrison, S. P., P. J. Bartlein, and I. C. Prentice (2016), What have we learnt from palaeoclimate simulations?, *J. Quat. Sci.*, *31*(4), 363–385, doi:10.1002/jqs.2842.

Harman, C. J. (2015), Time-variable transit time distributions and transport: Theory and application to storage-dependent transport of chloride in a watershed, *Water Resour. Res.*, *51*, 1–30, doi:10.1002/2014WR015707.

He, F. (2011), *Simulating Transient Climate Evolution of the Last Deglaciation with CCSM3*, 171 pp., Univ. of Wis., Madison.

Helama, S., M. M. Fauria, K. Mielikäinen, M. Timonen, and M. Eronen (2010), Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives, *Bull. Geol. Soc. Am.*, *122*(11–12), 1981–1988, doi:10.1130/B30088.1.

Holland, G., B. S. Lollar, L. Li, G. Lacrampe-Couloume, G. F. Slater, and C. J. Ballentine (2013), Deep fracture fluids isolated in the crust since the Precambrian era, *Nature*, *497*(7449), 357–360, doi:10.1038/nature12127.

Izuka, S. K., D. S. Oki, and J. A. Engott (2010), Simple method for estimating groundwater recharge on tropical islands, *J. Hydrol.*, *387*(1–2), 81–89, doi:10.1016/j.jhydrol.2010.03.034.

Jasechko, S. (2016), Late-Pleistocene precipitation δ18O interpolated across the global landmass, *Geochem. Geophys. Geosyst.*, *17*, 3274–3288, doi:10.1002/2016GC006400.

Jasechko, S., S. J. Birks, T. Gleeson, Y. Wada, P. J. Fawcett, Z. D. Sharp, J. J. McDonnell, and J. M. Welker (2014), The pronounced seasonality of global groundwater recharge, *Water Resour. Res.*, *50*, 8845–8867, doi:10.1002/2014WR015809.

Jasechko, S., et al. (2017), Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination, *Nat. Geosci.*, doi:10.1038/ngeo2943.

Kawamura, K., et al. (2007), Northern Hemisphere forcing of climatic cycles in Antarctica over the past 360,000 years, *Nature*, *448*(7156), 912–916, doi:10.1038/nature06015.

Kirchner, J. W., X. Feng, and C. Neal (2000), Fractal stream chemistry and its implications for contaminant transport in catchments, *Nature*, *403*(6769), 524–527, doi:10.1038/35000537.

Klump, S., T. Grundl, R. Purtschert, and R. Kipfer (2008), Groundwater and climate dynamics derived from noble gas, ^{14}C, and stable isotope data, *Geology*, *36*(5), 395, doi:10.1130/G24604A.1.

L'vovich, M. I. (1974), *World Water Resources and Their Future*, edited by R. L. Nace, 415 pp., AGU, Washington, D. C.

Lehner, B., K. Verdin, and A. Jarvis (2008), New global hydrography derived from spaceborne elevation data, *Eos Trans. AGU*, *89*(10), 93, doi:10.1029/2008EO100001.

Lemieux, J., E. A. Sudicky, W. R. Peltier, and L. Tarasov (2008), Dynamics of groundwater recharge and seepage over the Canadian landscape during the Wisconsinian glaciation, *J. Geophys. Res.*, *113*, F01011, doi:10.1029/2007JF000838.

Liu, Z., et al. (2012), Younger Dryas cooling and the Greenland climate response to CO_2, *Proc. Natl. Acad. Sci. U.S.A.*, *109*(28), 11,101–11,104, doi:10.1073/pnas.1202183109.

Małoszewski, P., and A. Zuber (1982), Determining the turnover time of groundwater systems with the aid of environmental tracers: 1. Models and their applicability, *J. Hydrol.*, *57*(3–4), 207–231, doi:10.1016/0022-1694(82)90147-0.

Marcé, R., B. Obrador, J.-A. Morguí, J. Lluís Riera, P. López, and J. Armengol (2015), Carbonate weathering as a driver of CO_2 supersaturation in lakes, *Nat. Geosci.*, *8*(2), 107–111, doi:10.1038/ngeo2341.

McGuire, K. J., and J. J. McDonnell (2006), A review and evaluation of catchment transit time modeling, *J. Hydrol.*, *330*(3–4), 543–563, doi:10.1016/j.jhydrol.2006.04.020.

Myhre, G., et al. (2013), Anthropogenic and natural radiative forcing, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., pp. 659–740, Cambridge Univ. Press, Cambridge, U. K., and New York..

Nace, R. L. (1969), World water inventory and control, in *Water, Earth, and Man: A Synthesis of Hydrology, Geomorphology, and Socio-Economic Geography*, edited by R. J. Chorley, pp. 31–42 , Methuen and Co. Ltd., London.

Nace, R. L. (1971), *Scientific Framework of World Water Balance*, UNESCO, 27 pp., Paris.

Person, M., V. Bense, D. Cohen, and A. Banerjee (2012), Models of ice-sheet hydrogeologic interactions: A review, *Geofluids*, *12*(1), 58–78, doi:10.1111/j.1468-8123.2011.00360.x.

Phillips, F. M. (1995), The use of isotopes and environmental tracers in subsurface hydrology, *Rev. Geophys.*, *33*(2S), 1029–1033, doi:10.1029/95RG00247.

Rodell, M., et al. (2004), The Global Land Data Assimilation System, *Bull. Am. Meteorol. Soc.*, *85*(3), 381–394, doi:10.1175/BAMS-85-3-381.

Rozanski, K. (1985), Deuterium and oxygen-18 in European groundwaters—Links to atmospheric circulation in the past, *Chem. Geol. Isot. Geosci. Sect.*, *52*(3–4), 349–363, doi:10.1016/0168-9622(85)90045-4.

Sanford, W. (2011), Calibration of models using groundwater age, *Hydrogeol. J.*, *19*(1), 13–16, doi:10.1007/s10040-010-0637-6.

Scanlon, B. R., K. E. Keese, A. L. Flint, L. E. Flint, C. B. Gaye, W. M. Edmunds, and I. Simmers (2006), Global synthesis of groundwater recharge in semiarid and arid regions, *Hydrol. Processes*, *20*(15), 3335–3370, doi:10.1002/hyp.6335.

Schaller, M. F., and Y. Fan (2009), River basins as groundwater exporters and importers: Implications for water cycle and climate modeling, *J. Geophys. Res.*, *114*, D04103, doi:10.1029/2008JD010636.

Slomp, C. P., and P. Van Cappellen (2004), Nutrient inputs to the coastal ocean through submarine groundwater discharge: Controls and potential impact, *J. Hydrol.*, *295*(1–4), 64–86, doi:10.1016/j.jhydrol.2004.02.018.

Sophocleous, M. (1992), Groundwater recharge estimation and regionalization: The Great Bend Prairie of central Kansas and its recharge statistics, *J. Hydrol.*, *137*(1–4), 113–140, doi:10.1016/0022-1694(92)90051-V.

Taylor, R. G., M. C. Todd, L. Kongola, L. Maurice, E. Nahozya, H. Sanga, and A. M. MacDonald (2013a), Evidence of the dependence of groundwater resources on extreme rainfall in East Africa, *Nat. Clim. Change*, *3*(4), 374–378, doi:10.1038/nclimate1731.

Taylor, R. G., et al. (2013b), Ground water and climate change, *Nat. Clim. Change*, *3*(4), 322–329, doi:10.1038/nclimate1744.

Wada, Y., L. P. H. van Beek, C. M. van Kempen, J. W. T. M. Reckman, S. Vasak, and M. F. P. Bierkens (2010), Global depletion of groundwater resources, *Geophys. Res. Lett.*, *37*, L20402, doi:10.1029/2010GL044571.

Weyhenmeyer, C. E., S. J. Burns, H. N. Waber, W. Aeschbach-Hertig, R. Kipfer, H. H. Loosli, and A. Matter (2000), Cool glacial temperatures and changes in moisture source recorded in Oman Groundwaters, *Science*, *287*(5454), 842–845, doi:10.1126/science.287.5454.842.

Yin, Q. Z., and A. Berger (2012), Individual contribution of insolation and CO_2 to the interglacial climates of the past 800,000 years, *Clim. Dyn.*, *38*(3–4), 709–724, doi:10.1007/s00382-011-1013-5.