The groundwater age-sustainability myth

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Preface

The ideas that old or “fossil” groundwater cannot be pumped sustainably, or that recently recharged groundwater is inherently sustainable are both mistaken. Both old and young groundwaters can be used in physically sustainable or unsustainable ways.

The myth that old groundwater with long residence times is a non-renewable resource has infiltrated the scientific literature[1–3] and has been bolstered by media coverage of regional to global groundwater issues. The propagation of this myth is problematic because it creates confusion around what constitutes sustainable development of groundwater resources and their renewability (see box for definitions). **We show how groundwater residence times and ages are not metrics that can directly define groundwater sustainability. However, quantifying the distribution of groundwater ages in an aquifer can improve our understanding of aquifer systems, which can indirectly enable sustainable groundwater use.** Dispelling the groundwater age-sustainability myth is critical to enable clear thinking about groundwater depletion which continues to emerge as a global problem[4]. Our commentary focuses on what groundwater age and residence time can and cannot tell us about the functioning of past and present groundwater systems and their connections to other Earth system processes.

Box: defining groundwater age, residence time, sustainability and renewability

Groundwater age is the interval of time that has elapsed since the water entered the groundwater system whereas mean **residence time** (herein just called 'residence time') is the volume of water in a groundwater system divided by the volumetric recharge (or discharge) rate, which gives an average turnover time for the system[5]. **Fossil groundwater** is groundwater that was recharged by precipitation more than ~12,000 years ago, prior to the beginning of the Holocene Epoch, whereas **modern groundwater** is often defined as being less than ~50 years old[6]. Ages are typically derived from interpretation of various isotope tracers, which may differ from the actual age of the water due to various mixing and transport processes that occur within groundwater systems as well as capture of different flowpaths over the screened interval of wells used for sampling[5,7].

Groundwater sustainability is maintaining long-term, dynamically stable flows and accessible storage of high-quality groundwater using inclusive, equitable, and long-term governance and management[4]. Physical groundwater sustainability is groundwater use that can be dynamically captured during pumping that leads to a new dynamically stable equilibrium in groundwater levels while maintaining environmental flows. Groundwater is **renewable** if this new equilibrium occurs within human timescales (i.e. decades to a century)[4]. This differs from previous definitions of renewable groundwater, which have invoked recharge rates[8] or threshold residence times[2,3].

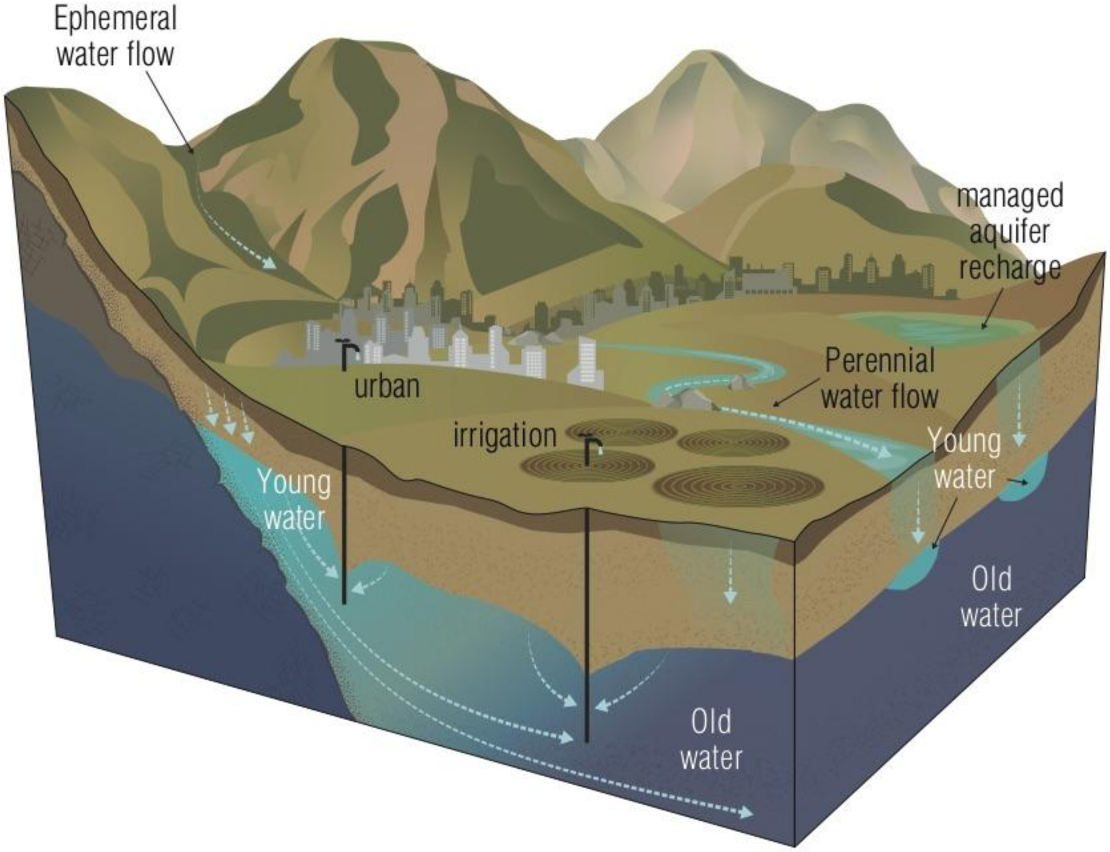

Figure 1: Human activities interface with natural hydrologic processes to set the distribution of groundwater ages, which are not a metric of groundwater sustainability or renewability. Similar drawdown cones will develop from wells with identical pumping rates located in positions with different mixes of groundwater age.

Infiltration of a myth

Groundwater age and residence time are a function of groundwater recharge rate, contributing to the notion that they are important considerations in the sustainable development of groundwater. This is based on the idea that pre-development groundwater recharge represents the amount of renewable groundwater[8]. Defining groundwater renewability by balancing pumping with pre-development recharge has been called the "Water Budget Myth"[9], as pumped groundwater actually has three sources: 1) groundwater storage, and ‘capture’ which is a combination of changes in 2) recharge and/or 3) discharge.

Our focus is another myth: the notion that sustainable development of groundwater resources can be defined on the basis of thresholds of groundwater residence times or age[1–3]. The residence time of groundwater in an aquifer is a function of its recharge rate and pore volume and larger aquifers will have longer residence times for a given recharge rate. Using residence times as a renewability benchmark therefore leads to the nonsensical conclusion that groundwater use from smaller aquifers may be more sustainable, despite having the same rates of replenishment. Instead, we argue that physical sustainability should only be defined relative to human use: whether water levels and flows stabilize to acceptable levels on reasonable timescales (Box).

Further, groundwater age is a function of distance from the recharge area (Figure 1). If pumping older groundwater is less sustainable than pumping young groundwater, in general terms this implies that pumping will be more sustainable if wells are either shallower, or situated nearer to a recharge area. However, situating pumping wells closer to a recharge area has no obvious connection to the renewability of groundwater resources. In contrast, pumping a mixture of older groundwaters near discharge areas may in some cases result in less groundwater depletion if induced recharge from surface water occurs, which may be more sustainable if the impacts on environmental flows are insignificant. In either situation, tradeoffs between reduced drawdown and increased capture of streamflow would need to be evaluated to determine which locations allow for the sustainable development of the system.

A variety of studies have documented the presence of very old groundwater, some of which were recharged under climates that were more humid than those present today[10]. It has often been suggested that use of such groundwater is unsustainable because these systems are being currently recharged at much lower rates than they were in the past[3]. While pre-development recharge is not an upper limit to the amount of water that can be sustainably withdrawn from an aquifer, reductions in groundwater recharge over time may affect the amount of water available for capture and could lead to increased groundwater depletion. However, in most cases where the presence of old groundwater has been invoked to determine the sustainability of groundwater use, there has been no attempt to quantify variation in groundwater recharge rates over time. Most studies that have compiled groundwater age data covering regional groundwater systems, such as the Nubian aquifer[10], Great Artesian Basin[11] and Black Mesa Basin,[12] have found a continuum of ages, indicating continuous groundwater recharge over long time periods. Further complicating this issue is the difference between the transport times that lead to the observed groundwater age distributions and the time required for hydraulic heads to re-equilibrate to shifts in climate[13], which may be shorter. There is an opportunity to improve our understanding of the past and future functioning of groundwater systems and the wider Earth system by more rigorously integrating age data with hydraulic analyses than has been typically done.

Rethinking groundwater age, residence times and sustainability

Groundwater age does not provide a direct measure of whether groundwater resources can be sustainably developed, and reducing groundwater sustainability decision making to such a simplistic dichotomy undermines fundamental concepts in groundwater sustainability science. Pumping young groundwater does not guarantee sustainability and pumping old groundwater does not guarantee non-sustainability. Prohibiting use of old groundwater could needlessly decrease water security in some instances. Similarly, the concept of renewable groundwater as defined by mean groundwater residence times should be abandoned. In dispelling the myth that groundwater age is linked to sustainable groundwater use, we are not advocating indiscriminate or wanton use of old or young groundwaters. Rather, we argue for adopting a new definition of groundwater sustainability that uses field observations of water levels and flows and water quality to directly be the metric of groundwater sustainability[4] (Box).

Despite the lack of a direct connection between groundwater age and sustainability, we are not suggesting to cease collecting isotopic and other geochemical data used to estimate groundwater ages. Detailed groundwater age data can be valuable in reducing uncertainty in models used to test groundwater resource development scenarios because of the sensitivity of age data to spatial variations in permeability[7]. However, mean residence times are unlikely to provide useful information because of the broad spectrum of residence times of various flowpaths present in groundwater systems. Characterizing the distribution of groundwater ages, using multiple age tracers that span the full age spectrum, can be more valuable in the protection of water quality, evaluating capture, and understanding the origin and distribution of natural or anthropogenic contaminants in the subsurface[6,7]. However, a substantial challenge exists in addressing dispersive processes in groundwater systems, which lead to the presence of mixed ages within individual water samples. Recent development of new intermediate age tracers (e.g., ^{39}Ar, ^{85}Kr) helps fill in the 'data gap' between modern and fossil recharge, providing new opportunities to disentangle mixed ages, understand the myriad of groundwater flowpaths, and constrain models used for water resource management.

An emerging use of groundwater age data is the documentation of the rearrangement and acceleration of groundwaters in the Anthropocene. In addition to changes in age distributions due to altered directions of groundwater flow and increased velocities associated with pumping[7], other impacts may occur due to variations in groundwater recharge patterns associated with land-use change and return flows from irrigation[14] (Fig 1). For example, managed aquifer recharge projects using either surface water or effluent are becoming increasingly common in India, the United States, Israel and Australia[15], increasing the amount of young groundwater in these regions. Measurement of ages using multiple isotopes can provide insights into mixing that has arisen in groundwater systems due to these and other human interventions. These changes in flow patterns and associated mixing are likely not important to physical groundwater sustainability, however, they may be important to groundwater quality[6], geochemical and carbon cycles[16], and geomicrobiology[17].

Groundwater age measurements are capable of providing valuable insights into the functioning of groundwater systems both under natural and perturbed conditions. However, the use of groundwater ages and mean residence times as metrics of sustainable development of groundwater is incorrect. This myth must be dispelled in favour of more constructive metrics of groundwater sustainability based on maintaining water levels, water quality, and environmental flows.

References

1. Bethke, C. M. & Johnson, T. M. Groundwater age and groundwater age dating. *Annu Rev Earth Planet Sci* **36**, 121–152 (2008).
2. Margat, J., Foster, S. & Droubi, A. Concept and importance of non-renewable resources. *Non-Renew. Groundw. Resour. Guideb. Socially-Sustain. Manag. Water-Policy Mak.* **10**, 13–24 (2006).
3. Bierkens, M. F. & Wada, Y. Non-renewable groundwater use and groundwater depletion: a

review. *Environ. Res. Lett.* **14**, 063002 (2019).

4. Gleeson, T., Cuthbert, M., Ferguson, G. & Perrone, D. Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. *Annu. Rev. Earth Planet. Sci.* (2020) doi:10.1146/annurev-earth-071719-055251.
5. Suckow, A. The age of groundwater–definitions, models and why we do not need this term. *Appl. Geochem.* **50**, 222–230 (2014).
6. Jasechko, S. *et al.* Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination. *Nat. Geosci.* **10**, 425–429 (2017).
7. Weissmann, G. S., Zhang, Y., LaBolle, E. M. & Fogg, G. E. Dispersion of groundwater age in an alluvial aquifer system. *Water Resour. Res.* **38**, 16–1 (2002).
8. Döll, P. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environ. Res. Lett.* **4**, 035006 (2009).
9. Bredehoeft, J. D. The water budget myth revisited: why hydrogeologists model. *Groundwater* **40**, 340–345 (2002).
10. Sturchio, N. *et al.* One million year old groundwater in the Sahara revealed by krypton-81 and chlorine-36. *Geophys. Res. Lett.* **31**, (2004).
11. Bethke, C. M., Zhao, X. & Torgersen, T. Groundwater flow and the 4He distribution in the Great Artesian Basin of Australia. *J. Geophys. Res. Solid Earth* **104**, 12999–13011 (1999).
12. Zhu, C., Waddell Jr, R. K., Star, I. & Ostrander, M. Responses of ground water in the Black Mesa basin, northeastern Arizona, to paleoclimatic changes during the late Pleistocene and Holocene. *Geology* **26**, 127–130 (1998).
13. Cuthbert, M. *et al.* Global patterns and dynamics of climate–groundwater interactions. *Nat. Clim. Change* **9**, 137–141 (2019).
14. Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E. & Dennehy, K. F. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Glob. Change Biol.* **11**, 1577–1593 (2005).
15. Dillon, P. *et al.* Sixty years of global progress in managed aquifer recharge. *Hydrogeol. J.* **27**, 1–30 (2019).
16. Maher, K. & Chamberlain, C. Hydrologic regulation of chemical weathering and the geologic

carbon cycle. *Science* **343**, 1502–1504 (2014).

17. Ben Maamar, S. *et al.* Groundwater isolation governs chemistry and microbial community structure along hydrologic flowpaths. *Front. Microbiol.* **6**, 1457 (2015).