Rethinking Groundwater Age

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It is commonly thought that old groundwater cannot be pumped sustainably, and that recently recharged groundwater is inherently sustainable. We argue that both old and young groundwaters can be used in physically sustainable or unsustainable ways.

The idea that old or "fossil" groundwater with long residence times is a non-renewable resource is found in scientific literature about groundwater sustainability[1–4] and in media coverage of groundwater issues on a regional to global scale. However, we argue that groundwater residence times and ages are not metrics that can directly define groundwater sustainability. Instead, quantifying the distribution of groundwater ages in an aquifer can improve our understanding of aquifer systems and in turn indirectly inform sustainable groundwater use. Dispelling the myth that groundwater sustainability depends on its age is important for tackling groundwater depletion problems around the world[5]. Here we discuss what groundwater age and residence time can and cannot tell us about the functioning of past and present groundwater systems, and their sustainability.

Infiltration of a myth

Groundwater age and residence time - as defined in Box 1 - are a function of groundwater recharge, and this has contributed to the notion that they are key considerations in the sustainable development of groundwater. Groundwater recharge rate prior to pumping has been assumed to represent the amount of renewable groundwater[6]. However, defining groundwater renewability as the simple balance between pumping and pre-development recharge has been called the "Water Budget Myth"[7]. Pumped groundwater actually has several sources: groundwater storage, and groundwater capture, which reflects changes in both recharge and discharge. The timescales associated with capture will dictate whether groundwater is renewable rather than pre-development recharge rates.

Similarly, we caution that groundwater sustainability should not be directly defined by groundwater age and residence time. The residence time of groundwater in an aquifer is a function of its recharge rate and the storage volume of the aquifer. Larger aquifers have longer residence times for a given recharge rate. Using residence time as a measure of renewability therefore leads to the incorrect conclusion that groundwater use from a smaller aquifer is necessarily more sustainable than from a larger aquifer, even if they both have the same rate of replenishment.

Groundwater age is a function of distance from the recharge area (Figure 1). If pumping old groundwater is less sustainable than pumping young groundwater, then shallower wells or wells nearer to a recharge area should be preferred. However, this is not necessarily the case because declines in hydraulic heads from pumping are independent of the age of the water (Figure 1). In some instances, pumping a mixture of older groundwater near a discharge area may result in less groundwater depletion than pumping young groundwater if recharge is induced by lowering water levels. In any groundwater pumping scenario, tradeoffs between reduced drawdown of groundwater and increased capture of streamflow need to be evaluated to determine the locations that allow for the sustainable development of the system.

Large-scale depletion of groundwater has been documented globally by NASA's GRACE satellite mission[8]. Some of these cases of groundwater depletion, such as those in North Africa, do occur in aquifers that contain old groundwater [9], but this is not the case everywhere. Depletion is widespread across California's Central Valley despite the presence of modern water in most production wells[4]. Conversely, groundwater pumping in the northern USA and Canada, where fossil waters are common[10], has not resulted in widespread depletion. There is no predictive relationship between the age of groundwater and groundwater depletion.

A variety of studies have documented the presence of very old groundwater in aquifer systems, including groundwater that was recharged under past climates more humid than today[9]. It has been suggested that use of such ancient groundwater is unsustainable because these systems are currently recharged at much lower rates than they were in the past[2]. Reductions in groundwater recharge over time do affect the amount of water available for capture and could lead to increased groundwater depletion, but the temporal change in groundwater recharge rates and associated decreases in groundwater levels need to be quantified to determine the sustainability of groundwater use.

Studies that have compiled groundwater age data for regional groundwater systems, such as the Nubian aquifer[9] and Great Artesian Basin[11], have found a continuum of ages, indicating continuous groundwater recharge over long time periods rather than episodic replenishment of these aquifers. Further complicating this issue is that hydraulic heads may re-equilibrate to shifts in climate faster than groundwater transport times[12], so observed distributions of groundwater ages can be disconnected from current groundwater flow patterns. Rigorous integration of age data with groundwater flow modelling is therefore needed to improve our understanding of the past and future functioning of groundwater systems[13].

Rethinking groundwater age, residence times and sustainability

Groundwater age does not provide a direct measure of whether groundwater resources can be sustainably developed. Pumping young groundwater does not guarantee sustainability and pumping old groundwater does not guarantee non-sustainability. Avoiding 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 is overly simplistic.

We are not advocating indiscriminate or wanton use of old or young groundwater. Rather, we argue for adopting a more nuanced definition of groundwater sustainability [5] that uses field observations of water levels and flows and water quality as the metric of groundwater sustainability (Box 1).

We are not suggesting researchers cease collecting data on groundwater ages; detailed groundwater age data can provide valuable insights into how groundwater systems function. Groundwater ages, or the tracer concentrations used to derive those ages, can provide calibration targets for numerical models of groundwater flow that can support sustainability assessments[14]. Characterizing the distribution of groundwater ages will also improve our understanding of the origin and distribution of natural and anthropogenic contaminants [4,13,15].

Groundwater age distributions additionally offer an opportunity to measure how groundwater systems are changing. Age distributions of groundwater in aquifers in The Anthropocene have changed due to altered directions of groundwater flow and increased velocities associated with pumping[13] and altered groundwater recharge patterns associated with irrigation[4] (Fig 1). Managed aquifer recharge projects using either surface water or wastewater are becoming increasingly common in India, the United States, Israel and Australia[16], increasing the amount of young groundwater in these regions. Measurements of ages using multiple isotopes can provide a record of the fate of this managed recharge and the degree to which these waters mix with *in situ* waters.

Groundwater age measurements are capable of providing valuable insights into how groundwater systems function under natural and perturbed conditions. However, groundwater ages and mean residence times should not be used as simple measures of groundwater sustainability. Instead, we need more constructive metrics of groundwater sustainability that are based on maintaining water levels, water quality, and environmental flows, as well as effective governance and management of these systems.

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Box 1. Defining groundwater age, residence time, and sustainability

Groundwater age is the interval of time that has elapsed since the water entered the groundwater system[1] whereas mean **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[14]. **Fossil groundwater** is groundwater that was recharged by precipitation more than approximately 12,000 years ago, prior to the beginning of the Holocene Epoch, whereas **modern groundwater** is often defined as being less than about 50 years old[15]. Ages are typically derived from interpretation of various isotope tracers, and may differ from the actual age of the water due to mixing and transport processes that occur within groundwater systems, as well as the different flowpaths over the screened interval of wells used for sampling[13,14].

Groundwater sustainability is the maintenance of long-term, dynamically-stable flows and accessible storage of high-quality groundwater using inclusive, equitable, and long-term governance and management[5]. This requires avoiding drops in water levels that cause wells to go dry and maintaining flows of sufficient quantity, rate, and quality to sustain ecosystems.

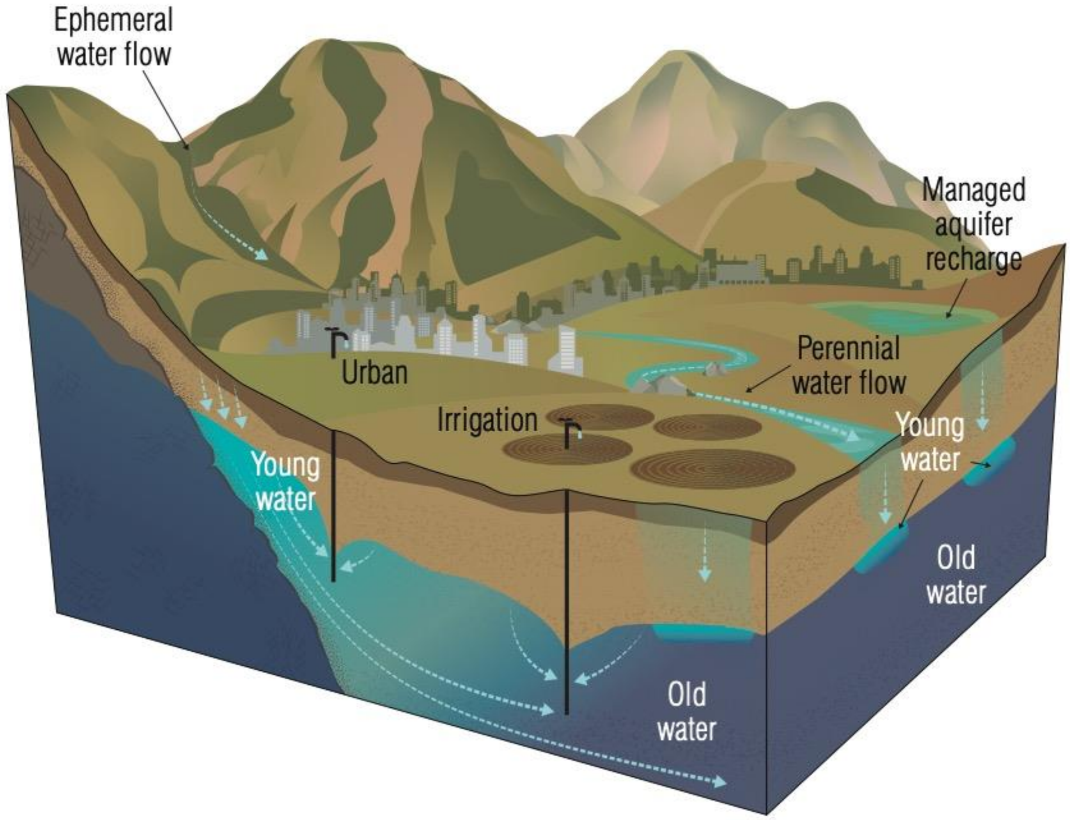

Figure 1. Flow of water and distribution of ages in a groundwater system in an arid region. Human activities interface with natural hydrologic processes to set the distribution of groundwater ages, which therefore do not necessarily reflect the renewability or sustainability of the groundwater. Similar declines in the water table will develop from wells with identical pumping rates located in positions with different mixes of groundwater ages.