Groundwater exposed

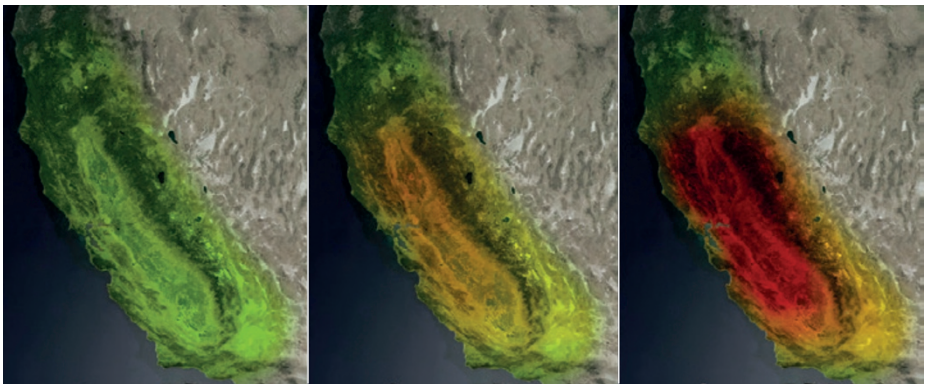
Groundwater flow meddles with hydrological, environmental and geological processes. As water scarcity issues mount for people living above ground, the vast stores of freshwater in the subsurface require research attention.

From California's severe multiyear drought to El Niño-induced rainfall to retreating glaciers, the spotlight has been on the hydrological cycle. As the Year of Water, as proclaimed by the Geological Society of London (https://www.geolsoc.org.uk/water16), kicks off in 2016, *Nature Geoscience* is shining a light on the Earth's darkest water resources: those below ground. As discussed in a web focus published with this issue (http://www.nature.com/ngeo/focus/groundwater/index.html), groundwater — Earth's vast store of freshwater that is hidden beneath the continents — is not only an important component of the hydrological cycle, but its flow influences the workings of the other components of the Earth System.

Entire communities rely on groundwater as a freshwater resource. Yet, as Ying Fan explains in a News & Views piece on page 93 we know very little about how much groundwater there is and what journey it takes beneath our feet. Models of the Earth's global groundwater budget have relied on volume estimates from 40 years ago. In a much needed update, Gleeson *et al.* (page 161) map groundwater reservoirs on a global scale and estimate that there are 22.6 km^3 of groundwater in the uppermost 2 km of the continental crust — a volume equivalent to a lake of 180 metres depth, if spread across the entire global land surface. The volume of groundwater thereby far exceeds all other freshwater stores on Earth.

Unlike water that enters a flowing river and is swiftly discharged, water that reaches the subsurface can take a range of flow paths. As a result, an aquifer contains a mixture of groundwater of various ages. Young groundwater derives from recent, local precipitation and is sensitive to local climate conditions, whereas old groundwater was recharged long ago, is often from elsewhere and may reflect larger scale (both spatially and temporally) climatic conditions. The most accessible and easily recharged groundwater is a finite resource: Gleeson *et al.* find that less than 6% of the total global groundwater store was recharged less than 50 years ago.

The youngest groundwater is not only the most renewable groundwater resource but it is also the most sensitive to climate variations and land use changes, and is vulnerable to contamination. Streams are fed by groundwater and the youngest groundwater and the contaminant species it carries have a disproportionate influence on stream water quality. Specifically, Jasechko *et al.* (page 126) report that a third of global river discharge derives from groundwater that was recharged by precipitation less than a few months earlier — representing less than 0.1% of the global groundwater store. This highlights the influence that a tiny fraction of the world's groundwater has on the above-ground hydrological cycle and environment, and the need to better understand the biogeochemical processes affecting young groundwater.



NASA/JPL-CALTECH/UNIV. OF CALIFORNIA, IRVINE

NASA's Gravity Recovery and Climate Experiment (GRACE) satellites are remotely monitoring changes in groundwater storage across the globe, including in drought-stricken California, USA (from left to right: June 2002, 2008 and 2014).

Although drought may begin as a lack of precipitation, meteorological drought propagates to hydrological drought, which can include below-normal groundwater levels. As Van Loon *et al.* argue in a commentary on page 89, both natural climatic changes and human activities influence drought and the feedbacks are complex. Anthropogenic groundwater abstraction acts to further exacerbate drought. For example, increased groundwater withdrawal to offset soil moisture deficit in agricultural regions during meteorologically dry years has led to severe groundwater depletions in India over the past decade (page 98). Particularly troubling, although not surprising, is Gleeson and co-workers' assertion that there is little young groundwater in arid regions where water is in high demand. Instead, people are unsustainably withdrawing older groundwater, only a fraction of which is being replenished.

The Earth's groundwater reserves not only feed rivers and sate the thirst and agricultural needs of society, but influence the solid Earth in which they circulate. For example, the flow of groundwater — cool in recharge areas and warm in discharge areas — redistributes heat in the surrounding rocks and can induce cooling of the lithosphere beneath groundwater basins by up to tens of degrees Celsius (H. Kooi, *Nature Geosci.* http://dx.doi.org/10.1038/ngeo2642; 2016) and potentially affect temperature-dependent metamorphic and tectonic processes at these depths too.

Despite these advances, what we know about the available reservoirs of groundwater and their interactions with other components of the Earth system is outweighed by what we do not know. Much research attention has been focused on the water visible above ground — just the tip of the Earth's hydrological iceberg, as it were. It is time we more fully explored the millions of cubic kilometres of water that circulate beneath the Earth's surface upon which our planet and its inhabitants rely. ❐