GROUNDWATER

Climate-induced pumping

Groundwater resources are directly affected by climate variability via precipitation, evapotranspiration and recharge. Analyses of US and India trends reveal that climate-induced pumping indirectly influences groundwater depletion as well.

Jason J. Gurdak

Groundwater depletion is recognized as an increasingly serious problem in aquifers around the world: it threatens the sustainability of water resources[1] and dependent ecosystems[2], as well as hydrologic system services[3]. The most alarming instances of depletion can be found in arid and semi-arid climates, and beneath some of the most productive agricultural regions of the world. This so-called global groundwater crisis is attributed to several socioeconomic and political factors[4] — none more important than groundwater pumping rates that support irrigated agriculture and commonly exceed natural recharge rates. Writing in *Nature Geoscience*, Russo and Lall[5] report widespread declines in groundwater levels across the US, including in some regions that are not climatically water stressed; instead, these declines can be attributed indirectly to climate in the form of climate-induced pumping.

Groundwater is a fundamental component of the hydrologic cycle and a vital natural resource that not only supports irrigated agriculture and food security, but is also the primary source of drinking water for over two billion people. Groundwater sustains many rivers, lakes, wetlands, ecosystems, energy extraction methods and economies[6]. Many of the United Nation's sustainable development goals (https://sustainabledevelopment.un.org/sdgs) such as zero hunger, and clean water and sanitation will be realized through increased development of local groundwater resources in developing countries. Given the growing global population — and the corresponding increase in demand for water, food and energy resources — the need to access groundwater is likely to increase in many regions.

Climate change and the associated modifications to the global hydrologic cycle are compounding the concerns about global water scarcity. The direct impacts of climate variability and change on groundwater through natural processes that influence precipitation, evapotranspiration, recharge rates and groundwater quality are now better understood[6,7]. However, knowledge gaps remain in our grasp of the indirect influence of climate variability and change on groundwater.

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Figure 1 | Groundwater-supported irrigated agriculture on the northern High Plains aquifer, Nebraska, USA. Russo and Lall[5] show that increased groundwater pumping during times of low precipitation significantly contributes to groundwater depletion in the US as an indirect consequence of climate variability, even in regions that are not water stressed.

Untangling the direct and indirect influence of climate on groundwater is more complex than with surface water, as residence times range from days to tens of thousands of years or more, and so a detectable response to climatic change can be delayed, especially in deep aquifers. It is also difficult to distinguish between human and climatic stresses on groundwater: shifting climate conditions can affect not only drought and recharge, but also the human demand[6].

Russo and Lall[5] analysed water levels since 1940 from over 15,000 wells across the continental US. They found statistically significant declines in water level in most large aquifers, especially in irrigated agricultural areas, confirming well-known declines in systems such as the High Plains aquifer[1] (Fig. 1). They also identified significant declines in the Mississippi Embayment and North Atlantic coast aquifer systems, which have both experienced dramatic growth in irrigated agriculture. Notable rising water tables are observed in the northern part of the Central Valley aquifer of California, southern Nevada and the northern High Plains aquifer of Nebraska[5].

Water levels in shallow aquifers are expected to readily respond to sub-annual and annual climate variability due to the physical constraints on recharge. In contrast, water levels in deep aquifers are more sensitive to interannual and longer-term climate variability[8]. However, in addition to the direct climate responses, human pumping can locally influence groundwater levels.

Frequency analysis from Russo and Lall indicates that water levels from shallow (less than 30 m deep) and intermediate (30–150 m deep) wells both show significant coherence to interannual and decadal climate variability. They also find evidence for a strong link between groundwater and climate connections in deep aquifers. This is counter-intuitive given the expectation of long lag times between climate and recharge signals that also dampen with depth[8,9].

The climate response in deep aquifers could reflect a rapid transmission of the recharge through well-connected aquifer systems. But Russo and Lall attribute the near-synchronous signal of precipitation and groundwater in deep aquifers to human pumping responses to persistent drought and wet periods that are associated with natural climate variability. Russo and Lall report the strongest response in deep groundwater to annual precipitation variability in the irrigated agricultural areas of the western US, including parts of the High Plains aquifer and Mississippi Embayment.

Tackling a similar problem in India, Asoka *et al.*[10] used satellite and local well data to characterize the regional patterns in groundwater storage change and the relative contribution of groundwater pumping and monsoon precipitation. They report that groundwater storage variability in north-central and southern India is largely explained by precipitation and recharge variability, whereas groundwater storage variability in northwestern India is largely explained by variability in pumping for irrigated agriculture due to changes in monsoon precipitation. Asoka *et al.* suggest that climate-induced pumping is influenced by precipitation variability that is coupled to warming patterns in sea surface temperatures over the Indian Ocean.

The evidence from the US and India suggests groundwater resources are vulnerable to climate variability and are in need of informed management. However, records of groundwater pumping and storage are lacking in many regions[4], a deficiency that has received increasing attention in places like California. The Sustainable Groundwater Management Act has been introduced to empower local agencies across California to adopt management plans that meet local needs for groundwater and help provide a buffer against drought and climate change. This legislation will enable local agencies to measure and report groundwater pumping. Such data are vital for long-term management of sustainable groundwater resources.

The findings of Russo and Lall[5] and Asoka *et al.*[10] reveal a link between atmosphere–ocean circulation systems and groundwater storage — both directly via climate-induced changes in recharge and evapotranspiration, and indirectly via climate-induced changes in anthropogenic pumping. The indirect effects of interannual climate variability on groundwater via changes in water demand and pumping need to be considered in future estimates of long-term groundwater-storage trends, especially in irrigated agricultural regions. ❐

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MOON FORMATION

Punch combo or knock-out blow?

The twin isotopic signatures of the Moon and Earth are difficult to explain by a single giant impact. Impact simulations suggest that making the Moon by a combination of multiple, smaller moonlet-forming impacts may work better.

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Among the wide diversity of isotopic signatures found in our samples of planetary bodies and meteorite families, those of the Moon and Earth are nearly identical[1–3]. This unique shared identity is difficult to reconcile with the hypothesis of Moon formation by a single giant impact. In most numerical giant-impact simulations the Moon is derived primarily from the impacting planetesimal, not Earth, and it is likely that the moon-forming impactor and proto-Earth were isotopically distinct. In this issue, Rufu *et al.*[4] offer a resolution to this isotopic identity crisis: they show how a Moon that is formed largely out of Earth-derived material may be a more natural consequence of building the Moon from a number of moonlets, formed by a series of large impacts, rather than in one go (Fig. 1).

Since it was proposed in the mid-1970s, the giant-impact hypothesis[5] has become the favoured explanation for how the Moon was born. Numerical simulations showed how a grazing, low-speed collision of a Mars-sized planetary embryo with the proto-Earth would produce a hot, massive, rapidly rotating disk around the Earth from which the Moon could have condensed and accreted. The model was simple and elegant: simple, because it formed a Moon that matched almost all of the available observational constraints — such as high angular momentum, low iron content, large mass and a lack of volatiles — in a single process[6]; elegant, because a giant impact is perfectly plausible given Earth's violent adolescence.

According to the favoured giant-impact scenario[6], the material ejected by the impact to form the Moon was comprised of about four parts impactor mantle to one part Earth mantle. If the impactor and proto-Earth were isotopically distinct,