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Groundwater and climate change: threats and opportunities

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Abstract

The important role of groundwater in adaptation to climate change is explored, and the competing threats and opportunities that climate change pose to groundwater systems are evaluated. This has been achieved through a review of current thinking on the complex interactions between human activities, climate and the hydrological cycle affecting groundwater quantity and quality, across different regions and time scales.

Keywords Climate change · Groundwater recharge · Groundwater discharge · Groundwater quality · Adaptation

Introduction

Human activities, whether directly through pumping and overuse or indirectly through changes in terrestrial hydrology caused by climate change, are fundamentally affecting groundwater systems globally. However, the continued lack of public awareness and limited understanding of the existence, function and capacity of groundwater systems, means that these impacts have remained largely invisible in the public consciousness. This is in direct contrast to the strong visual impact of climate change on surface-water systems, particularly in response to extreme events such as floods and drought. When rivers stop flowing, or when flooding occurs, the reality of climate change is viscerally apparent. When groundwater declines and the quality deteriorates, one sees nothing until it is too late. In 2022, the UN-Water theme is "*Groundwater: Making the invisible visible*", with the intention of improving public understanding of the impact of human activities and climate change on groundwater, but also the role that groundwater can play in adaptation to climate change impacts.

To evaluate the impacts of climate change specifically on groundwater, it is helpful to acknowledge three points: (1) the dominant role of human activities; (2) the complex interactions between natural and anthropogenic processes; and (3) the direct and indirect connections between "visible" surface water and "invisible" groundwater, operating on very different timescales. While addressing these aspects of climate change impacts, this essay explores the important role of groundwater and the opportunities provided in adaptation, in some cases incidental, in other cases more structural, optimizing the benefits that groundwater provides to ecosystems and the societies that reside within them.

Recharge and storage: the foundations of a water-secure future

Aquifers are the world's vital stores of freshwater; maintaining and enhancing aquifer recharge and storage is hence central to climate adaptation. How climate change affects natural groundwater recharge is still subject to discussion, simply because recharge responses cannot be generalised across different environmental settings and contexts. Continued uncertainty in precipitation projections combined with localised soil and geology, relief and land cover prevent a "one-size" fits all approach. This is further compounded by the complexity of atmospheric processes and limitations in the coverage and detail of the current observational networks that are needed to improve modelled projections of rainfall and recharge. Models tend to agree on the long-term decline in precipitation in certain hotspot regions (e.g. Stigter et al. 2014; IPCC 2021), as well as the occurrence of longer droughts, which will increase irrigation demand and thus groundwater abstraction (Wu et al. 2020). The latter illustrates the interactions between natural and anthropogenic processes. After all, the immediate human response to drought typically involves, where possible, increased groundwater abstraction. Whether evapotranspiration increases due to global warming remains unclear (IPCC 2021), but more frequent and longer droughts do call for enhanced capture and

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storage of the fewer but heavier precipitation events. Higher-intensity rainfall has been observed to exceed soil infiltration capacities, generating runoff rather than recharge (e.g. Wang et al. 2015), and this may be further aggravated by heavy rains falling on dried (encrusted) soils or other surfaces that have become impermeable. What is interesting is that studies in tropical drylands (e.g. Taylor et al. 2013; Cuthbert et al. 2019) show that overland flow can also generate focused recharge. Moreover, episodic extreme rainfall events are likely to become an increasingly significant mechanism of groundwater recharge across a range of environments (Jasechko and Taylor 2015; Boas and Mallants 2022), either by exceeding field capacity (pore-matrix flow) or due to bypass flow through macropores. In this context, episodic extreme rainfall could be regarded as an incidental but fortunate side-effect of climate change in many regions. Protection of the main infiltration and recharge areas could further amplify this beneficial effect, for instance by avoiding or minimizing their impermeabilization (e.g. increased greening of urban areas, and other forms of urban water uptake and slow release), optimizing their land use (e.g. Owuor et al. 2016) or (where possible, e.g. agricultural areas) increasing antecedent soil-moisture conditions prior to forecasted heavy rains.

A more structured approach towards augmenting groundwater storage is managed aquifer recharge (MAR), which shows enormous potential in many parts of the world, not only from a theoretical perspective, but also with success stories of implementation (e.g. Dillon et al. 2019). Major challenges that still need to be tackled are: ensuring a satisfactory quality of recharge water, the uptake of MAR into policies and the upscaling in terms of volume, which requires land, infrastructure and resources.

Managing discharge

Groundwater discharge is directly linked to groundwater recharge, but there are important time lags between the two that range from years to millennia. This in part reflects the different time scales over which surface-water systems (years to decades) and groundwater systems (decades to millennia) operate (e.g. Sprenger et al. 2019). The true impact of a reduction in recharge may therefore not be immediately noticeable. However, localised dramatic changes in anthropogenic-driven discharge (i.e. groundwater pumping) are rapidly escalating and reinforcing subtle and not-so-subtle changes in terrestrial hydrological systems as the balance between recharge and discharge volumes evolves. One of the clearest signs of reduced groundwater discharge is reduced baseflow to support rivers, lakes and reservoirs (e.g. Costa et al. 2021a; Mukherjee et al. 2018), visual monitors of the impact of climate change and indicators of drought. The 2015–2018 “Day Zero” drought in Cape Town, South Africa, was monitored by how low the level of the municipal dams dropped (LaVanchy et al. 2019) and drought in the Colorado River Basin (USA) is being monitored in the public news by the declining levels of Lake Mead (and the interesting things that declining water levels have brought to light). Both of these situations and the many more around the world currently happening, are a reflection of groundwater systems under stress and struggling to support the surface-water systems they are linked to. Whilst some of this stress is related to poor water management decisions (e.g. LaVanchy et al. 2019), climate change is exacerbating the effects and leading to widespread groundwater depletion (Bierkens and Wada 2019), posing direct threats to the world’s population, as depletion is most readily observed in the large productive food-growing regions worldwide. More and more wells are abstracting groundwater from increasing depths with little regard for the timescales of groundwater recharge and flow through aquifer systems. The consequences of these actions are also affecting energy production systems, particularly dams that provide hydro-electric power (e.g. Abdelhalim et al. 2020), and civil and agricultural infrastructure through land subsidence (Herrera-García et al. 2021). The recovery of such groundwater-dependent systems (ecosystems, food production, energy, infrastructure) is closely tied to the recharge dynamics discussed in the previous section, but will also depend on the configuration and age of the flow system (see the electronic supplementary material (ESM), which discusses “*How old is too old? Using fossil groundwater”).*

Protecting water quality

Irrespective of the age of groundwater, protecting groundwater quality is critical for ensuring future reserves and enhancing our resilience in adaptation (see also Lapworth et al. 2022). Thus, it is necessary to also address the enhanced risk of leaching of salts and (traditional and emerging) contaminants by high-intensity rainfall generating recharge linked to climate change, possibly amplified by changes in land use (e.g. Amdan et al. 2013). A nice overview is provided in chapter 7 of the *World Water Development Report 2022* (United Nations 2022), particularly for urbanised environments with inadequate sanitation. For instance, leaching from surface waste has already increased groundwater concentrations of nitrate, and this is influenced by climate (e.g. Graham et al. 2015). At the same time, denitrifying bacteria also tend to be more active in the rainy season (Zhu et al. 2019), especially under warm climate conditions. Contaminant levels will thus vary as a function of contaminant load, redox conditions and abundance/activity of bacteria, controlled by groundwater depth and linked to seasonal and long-term climate change in a way that is nonlinear and complex. Important changes in the interaction between surface and groundwater will also be relevant, particularly in riparian zones that are essential for improving and maintaining water quality and protecting the riverine ecosystem (Zhu et al. 2020).

In areas suffering from reduced recharge, an additional threat from climate change could be a diminished dilution and increased evapoconcentration potential of shallow aquifers, particularly relevant for conservative contaminants (e.g. Mas-Pla and Menció 2019; Costa et al. 2021b). Their concentrations could be further affected by enhanced groundwater pumping and irrigation return flow, dramatically increasing salinisation and shortening the available time over which natural attenuation processes (e.g. denitrification) can ameliorate contamination. Climate change here is seen to provide threats in multiple ways, but is strongly amplified by the intensified food production systems of modern society. Future changes in agricultural practices provoked by a changing climate could provide an additional complexity, further increasing nitrate loadings on groundwater (e.g. Paradis et al. 2016). In coastal areas, particularly those of urbanised deltas and islands, sea-level rise increases the risk of groundwater salinization, further amplified by groundwater abstractions that, in many of these areas, are generating land subsidence rates exceeding those of sea-level rise (e.g. Herrera-García et al. 2021).

Thus, it can be concluded that groundwater quality–climate relationships are variable and a function of hydroclimatic conditions, geographic setting, land use and contaminant characteristics. Notwithstanding, there are opportunities for water quality improvement and subsequent strengthening of the groundwater potential. In areas where a long-term decrease in recharge rates is expected, the longer residence times can stimulate the passive remediation or natural in situ treatment of reactive contaminants, explained by John Cherry to be highly effective for contaminant removal, in his keynote lecture at the 2020 IWRA-UNESCO-IAH Conference. Increasing recharge in other aquifers can lead to a higher dilution potential and lower contaminant levels. MAR itself, if well applied, does not only lead to an increase in groundwater recharge and storage, but also facilitates improved water quality (Dillon et al. 2019), thanks to the overall higher capacity of subsurface (soil and aquifer) systems to remove contaminants as compared to surface systems.

Demand management and socially inclusive adaptation

Increased dependence on groundwater, as a natural interannual store of freshwater, is in many places inevitable; indeed, improved climate resilience of water supplies is often associated with a shift to increased groundwater dependence in conjunction with surface water. As groundwater represents a natural interseasonal and interannual storage, its exploitation becomes a logical adaptive strategy for more variable freshwater in the soil and at the surface under climate change. Recent high-profile droughts have all pointed to the need to tap into the groundwater system to support municipal supply networks when traditional surface-water systems are under pressure (e.g. Olivier and Xu 2019). However, drought also puts pressure on groundwater systems, demonstrating the need to address both the demand and supply side of the story (e.g. Xiao et al. 2017). In particular, with a growing population and economic development, the increase in water demand seems inevitable (Boretti and Rosa 2019), and many groundwater systems are simply too limited or stressed (e.g. Herbert and Döll 2019) to cope with this. Even if one manages to further optimize groundwater recharge and abstractions through significant financial, technical and capacity investments, equally serious efforts are needed to tackle water demand. Addressing the many socio-economic and political aspects around reducing water use for food production, water supply and energy falls outside the scope of this essay, but possible gains could be made regarding reducing the virtual water trade, improving water efficiency, reducing food waste, decreasing energy consumption and improving water management. Such measures to reduce water demand can be complex and conflicting, and thus require a careful assessment of the many socio-economic and cultural aspects involved, considering the legitimacy, feasibility and social justice of proposed solutions, thereby promoting equal access (e.g. Hoekstra 2018). Despite the many examples worldwide of groundwater improving peoples' livelihoods (e.g. Re et al. 2022), related impacts of climate change represent a serious threat to human health (e.g. possible increase of waterborne infections, reduced access to safe drinking water and sanitation, reduced food security), and can become a driver for social instability. Civil unrest and migration are global-scale issues that most severely affect impoverished and marginalised communities in areas where freshwater is scarce, with women and girls disproportionately affected (Miletto et al. 2017). These aspects are seldom considered and gaps remain between research and gender-blind policies, especially when groundwater is at stake. Understanding the social and gendered dimension requires a deeper analysis and systematic collection of gender-disaggregated water data (e.g. Miletto et al. 2019), that would allow researchers and practitioners to promote adaptation and mitigation strategies based on scientific evidence and the intersectionality among groundwater, climate change and livelihood.

Looking forward

Climate change, and global change as a whole, underscores the urgency of looking forward and anticipating the role and importance of groundwater in climate adaptation. This essay shows that despite the many threats that need to be addressed, there are also clear opportunities to promote, by increasing aquifer recharge and storage, preserving groundwater quality, and the planned and informed use of fossil reserves. Such groundwater opportunities can be reinforced by technological innovations (e.g. for MAR, water treatment), but should primarily be supported by improved water resources and land use management (e.g. to allow the protection of recharge zones and the upscaling of MAR), and a more inclusive and sustainable development of groundwater resources. The latter inevitably links to reducing the freshwater demand at a global scale, while at the same time improving access to groundwater at a local scale, to reduce social instability and improve livelihoods. Finally, consistent and participatory monitoring is necessary to build ownership, support research and inform policies on groundwater and climate change impacts.

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Conflict of interest statement On behalf of all authors, the corresponding author states that there is no conflict of interest.

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