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ESSAY

Groundwater quality: global challenges, emerging threats and novel approaches

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Abstract
Improving our understanding of groundwater quality threats to human health and the environment is essential to protect and manage groundwater resources effectively. This essay highlights some global groundwater quality challenges, describes key contaminant groups and threats of emerging concern, including antimicrobial resistance, and discusses novel approaches to assessing groundwater quality. Groundwater quality monitoring needs to improve significantly in order to effectively identify and mitigate threats to groundwater from historical, current and future pollution.

Keywords Contaminants · Health · Emerging threats · Monitoring · Water-resources management

Introduction

Assessing and protecting groundwater quality is vital to our understanding of water resources and subsequently managing groundwater effectively. Threats to groundwater quality derive from both naturally occurring contaminants and those introduced or mobilised due to human activities (Misstear et al. 2022). Groundwater provides a wide range of functions, is often a critical drinking-water source—e.g. nearly 50% of urban populations rely on it; (UN 2022)—and supports environmental flows in surface waters; as such, understanding its potential impacts to human and ecosystem health are essential. Historically, many aspects of groundwater quality (e.g. arsenic and microbiological contamination) were overlooked during resource assessments, resulting in present-day human health impacts and natural groundwater quality degradation. While the paradigm that ‘groundwater quality is generally good’ may hold true in many locations, this assumption requires careful assessment, and in some cases (e.g. shallow accessible aquifers—critical for drinking water/ecosystems) is not a stationary condition. Different groundwater quality threats can manifest over a range of spatial and temporal scales and need suitable monitoring strategies.

Awareness of threats to global groundwater quality has grown rapidly in recent years, particularly in the light of rapid development of analytical techniques, computational power and rising societal awareness of environmental

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threats. Concurrently, global groundwater resources are under unprecedented and increasing pressure from a wide range of competing anthropogenic factors including population growth, food production, urbanisation and sea level rises, all of which have potential consequences for groundwater quality. Groundwater is the focus of the 2022 United Nations (UN) World Water Day, thus representing an important opportunity to reflect on challenges to groundwater quality if the sustainable development goals (SDGs) are to be met and human health and groundwater-dependent ecosystems are to be safeguarded.

Global groundwater contaminant challenges

There are a number of documented global groundwater contaminant challenges. Some of these were summarised in the recent UN World Water Development Report (UN 2022). Key challenges include firstly, the intensification of food production globally and associated use of large quantities of agrochemicals which pollute groundwater, this trend set to continue to meet ever- increasing demand. Secondly, pumping in coastal setting and associated seawater intrusion represents a threat to fresh coastal groundwater resources. Thirdly, extensive irrigation, particularly in more arid settings or areas with shallow water tables, is a major threat to groundwater quality through the build-up of soil and groundwater salinity. Forthly, urbanisation and the multiple threats from both legacy and current sources of contamination, including microbes, to urban groundwater within the context of a growing demand for self-supply from groundwater sources to sustain access to water. Finally, threats due to impacts of climate change, specifically impacts from intensification of rainfall on the ingress of surface contaminants, impacts of sea level rise on coastal aquifers and contaminant threats which emerge due to changes in land use and pests controls. Some hydrogeological settings, such as karst landscapes which are widely used for water supply, are more intrinsically susceptible to surface contamination. Other global challenges arise due to geogenic sources of contamination.

Faecal waste in the form of treated sludge from wastewater systems continues to be used globally to improve the nutrient status of soils for food production. In addition to nutrients, sludge contains co-contaminants, including pathogens, heavy metals, pharmaceuticals and plastics, which are concentrated during the treatment process, and may subsequently contaminate soil and aquifers (WWQA 2021). Increasingly intensive production of livestock, including cattle and poultry, can also threaten the subsurface environment due to the concentration of waste storage facilities, field applications of manures and leaching of contaminants (Lapworth et al. 2012).

Several other issues pose potential new threats to groundwater quality, including energy transition from fossil fuels to low/zero carbon economies and desalination, but are not considered further in this essay.

Emerging threats to groundwater quality and human health

A diverse array of manufactured chemicals are used by humans for health and personal care, manufacturing and food production. Thousands of registered chemicals are in commonly used daily products, many of which pose a direct threat to groundwater quality and human health (Lapworth et al. 2012). There are several broad groups of contaminants of emerging concern (CEC) now receiving more attention, many of which remain unregulated by water quality legislation. These include some pharmaceuticals and personal care products, veterinary products, plasticisers, biocides and per- and polyfluoroalkyl substances (PFAS), some with known toxicity, but many for which toxicity data are unavailable (Lapworth et al. 2019). While microplastic pollution has been extensively researched in oceans and surface waters, this is still very much an emerging research area in groundwater (Viaroli et al. 2022; WWQA 2021). Only a handful of groundwater studies have assessed microplastic pollution and these have typically been focussed on vulnerable hydrogeological settings. Further work in this area is needed to understand the extent of microplastic contamination, sources and pathways in groundwater systems and potential impacts on human and ecosystem health.

Recent studies using molecular and ‘omics’ approaches (i.e., technologies assessing biological function at gene, protein and metabolic levels) have widened general understanding of the threat from microbiological contamination in groundwater from a range of potentially pathogenic bacteria, protozoa and viruses (WWQA 2021). However, a relatively limited understanding of the global extent of microbiological groundwater contamination remains. The use of faecal indicator bacteria (e.g. *Escherichia coli*) does not provide any information regarding the magnitude, types, strains, virulence or sources of other pathogens, a notable limitation of the current global legislative framework.

Anti-microbial resistance (AMR) is an important emerging global health challenge and is not restricted to wastewaters and surface waters. Understanding the sources and pathways for antimicrobial-resistant bacteria (ARB) is critical for safeguarding human health. Andrade et al. (2020) recently reported that where bacteria were present, ARB were identified in 76.9±33.7% of wells and springs, leaving little doubt that groundwater represents an important reservoir for AMR. Multiple stress factors and drivers enhancing AMR exist in the subsurface. Many of these processes are inherently linked to anthropogenic groundwater contamination via the facilitation of microbial activity (i.e., nutrients) and microbial stress (e.g. pharmaceuticals, pesticides, heavy metals), leading to conditions increasingly conducive to the development of AMR in polluted groundwater systems. A new microbial groundwater quality group has started in association with the International Association of Hydrogeologists (IAH) Groundwater Quality Commission, to address this and related aspects of microbiological pollution in groundwater.

Novel approaches for assessing groundwater pollution

Important themes including geoinformatics, remote sensing and the use of 'big' data science will be key areas of change in further developing the understanding of groundwater quality challenges. These are covered partly by WWQA (2021) and Misstear et al. (2022). Other novel approaches regarding groundwater quality monitoring are covered in the following section.

Perhaps the most significant advancement in the understanding of microbiological groundwater contamination has been the rapid recent development of molecular and "omics" approaches to isolating and sequencing key microbial targets in environmental samples. These approaches include (multiplex) polymerase chain reaction (PCR), Clermont phylotyping, whole genome sequencing and bioinformatics (in parallel with the improved computational processing power needed to analyse genomic data). In addition to increasingly accurate identification and enumeration of (pathogenic/nonpathogenic) microbes, scientists now have the capacity to pinpoint likely contaminant sources (via microbial source tracking of nonpathogenic *Bacteriodes* spp.), use whole genome sequencing to concurrently identify AMR, virulence and biofilm formation genes, and apply fingerprinting techniques (e.g., phylotyping) to elucidate microbial genetic substructure (i.e., the microbial genetic tree). For example, a recent study in Ontario, Canada, employed multilocus sequencing of *E. coli* DNA isolated from contaminated private wells, and reported that 30.3% of wells were characterised by an entirely adapted *E. coli* community (i.e., capable of reproducing in the subsurface). This has major repercussions for future groundwater monitoring and modelling, insofar as currently used faecal indicators may not actually be indicative of recent faecal contamination.

Gas and liquid chromatography mass spectroscopy (GC/LC-MS) has been used for the analysis of organic compounds in samples for several decades. However, some relatively recent advances have significantly enhanced their application(s) for surveillance purposes. New time-of-flight semiquantitative approaches are now being more widely employed for broad screening of large numbers of organic contaminants, with methods now able to screen for >1,000 compounds in a single sample, which opens the possibility for improved surveillance of a large range of organic contaminants in groundwater (e.g. Moreau et al. 2019; Lapworth et al. 2019). While this does not replace the need for accurate quantification, it does enable more extensive screening for new CECs to inform ongoing groundwater monitoring protocols.

In-situ sensors have been used for decades for key parameters such as electrical conductivity and pH, and are a rapidly developing field and have been used to assess a range of groundwater contaminants, including in disaster zones. Notable recent examples include fluorescence-based methods which can be used as proxies for faecal indicator bacteria (Sorensen et al. 2018) and dissolved organic carbon, microbial fuel cell (MFC) biosensors for assessing in-situ faecal contamination (Velasquez-Orta et al. 2017) and two-dimensional nanocomposite sensors for metals and selected organics (e.g. Nigam et al. 2021; Khanam et al. 2022). When employed in a network, sensor techniques can be particularly powerful for tracking water quality changes, understanding pollution dynamics and quantifying groundwater/surface-water interactions (Rose et al. 2021).

Micro-toxicity assays/probes are now being developed for a wide range of water quality applications, potentially including groundwater studies (e.g. Johnson 2018). This is a field that brings together two important elements: water quality and environmental health. These approaches typically use an MFC biosensor or bacterial bioluminescence panel as proxies for chemical or biological oxygen demand or to assess water toxicity (e.g. Do et al. 2020). The probes can be used to assess the toxicity of samples with contaminant mixtures or to explore the toxicity effects of specific chemicals (e.g. Harpaz et al. 2018). To date, there has been limited use of these approaches to understand changes in microtoxicity of groundwaters or evaluate their application for complex contaminant mixtures at concentrations typically found in groundwater. In general, indirect assays could be used more widely for assessing and managing groundwater resources.

Conclusions

Improved understanding and characterisation of groundwater quality threats from both widely regulated/monitored contaminants (e.g. nitrate, arsenic, salinity) and less widely monitored CECs are essential for managing groundwater resources. While it is important to further develop an understanding of established threats to groundwater quality, it is also essential to prioritise threats which are currently poorly understood but could pose significant human/

ecosystem health impacts now and in the future. Prominent groups of CECs that currently warrant further investigation in groundwater include PFAS compounds, pharmaceutical compounds (including anti-microbial agents), microplastics, viruses and protozoa.

In recent years there has been huge progress in the methods and techniques that can be employed to assess groundwater threats across both space and time, and for prioritising measures for monitoring and protecting groundwater resources and human health. Groundwater has huge potential for improving adaptation to a range of global challenges, but this can only be realised if there is significant progress towards assessing groundwater quality threats and protecting groundwater resources and human health.

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