Groundwater Quality: Global Threats, Opportunities and Realising the Potential of Groundwater

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Abstract

Groundwater is a critical resource enabling adaptation due to land use change, population growth, environmental degradation, and climate change. It can be a driver of change and adaptation, as well as effectively mitigate impacts brought about by a range of human activities. Groundwater quality is key to assessing groundwater resources and we need to improve our understanding and coverage of groundwater quality threats if we are to use groundwater sustainably to not further burden future generations by limiting resources and/or increasing treatment or abstraction costs. Good groundwater quality is key to progress on a range of Sustainable Development Goals, but achievement of those goals most affected by groundwater contamination is often hindered by of a lack of resources to enable adaptation. A range of threats to groundwater quality exist, both natural and anthropogenic, which may constrain groundwater use. However, groundwater often provides good quality water for a range of purposes and is the most important water resource in many settings. This special issue explores some of the key groundwater quality challenges we face today as well as the opportunities good groundwater quality and treatment solutions bring to enhance safe groundwater use. Legacy anthropogenic contaminants and geogenic contaminants may be well documented in certain places, such as N America, Europe and parts of Asia, however, there is a real issue of data accessibility in some regions, even for more common contaminants. This paucity of information can restrict our understanding and ability to manage and protect groundwater sources. Compared to surface water quality, large scale assessments for groundwater quality are still scarce and often rely on inadequate data sets. Better access to existing data sets and more research is needed on many groundwater quality threats. Identification and quantification of these threats will support the wise use and protection of this subsurface resource, allow society to adequately address future challenges, and help communities realise the full potential of groundwater.

Keywords: Groundwater Quality, Geogenic, Anthropogenic, Adaptation, Water Security, SDGs

1. Introduction

Groundwater is the largest freshwater store on earth, its use underpins a huge range of human activities as well as important ecosystems (Margat and Van der Gun, 2013; Rohde et al., 2017). Historically, groundwater quantity has often been the focus of groundwater resource assessments, and there is a real need to now focus more attention towards groundwater quality. There is a direct connection between stores of available freshwater provided by groundwater and their status and utility in terms of quality (Gleeson et al., 2020). The excellent quality provided by groundwater in many regions, often reflecting the degree of protection from surface contaminants that groundwater provides, is critical for sustaining agriculture, industry, drinking water services and is fundamental to reaching key Sustainable Development Goals (SDGs), e.g. SDGs 2, 6, 9, 11 (UN 2019). However, there are several natural and human-induced water quality threats to groundwater which may constrain its use and necessitate treatment prior to consumption (WWQA, 2021).

The recent World Bank report ‘Quality Unknown: The Invisible Water Crisis’ (Damania et al., 2019), made almost no mention of groundwater quality nor a clear distinction between the threats affecting surface water and groundwater. This is telling and perhaps exposes two important issues: the lack of visibility of groundwater quality as an important topic and the more limited compilation of groundwater-quality data at a global scale compared to surface-water data (WWQA, 2021). Working towards a global groundwater quality assessment is important because of the significant pressures placed upon quality by human activities and climate variability. Protection of groundwater resources is necessary for protecting human health, groundwater-dependent livelihoods and ecosystems. Many regions globally rely on naturally clean groundwater as advanced centralised water treatment is not feasible due to logistics and costs (Howard et al., 2006; Edokpayi et al., 2018; Khan et al., 2020). Knowing where to source clean groundwater, as well as understanding threats to this resource, and sustainable treatment solutions is therefore of paramount importance.

Recent studies assessing the availability of groundwater have begun to consider the quality dimension and factor in the potential constraints due to poor water quality (Gleeson et al., 2020). Indeed, in the Indo-Gangetic Basin, the world’s most heavily abstracted aquifer system, groundwater quality constraints have been shown to exceed those due to depletions in groundwater stores caused by over-pumping (MacDonald et al., 2016). Deterioration of groundwater quality is a global threat, impacting at a range of scales, from localised point sources of contamination e.g. from septic tanks or pit latrines (e.g. Graham and Polizzotto 2013), to diffuse pollution affecting large aquifer systems e.g. nitrate contamination (Ascott et al., 2017) or salinity induced by irrigation (Bouafar and Kuper 2012). Natural groundwater quality may also be compromised, for example geogenic arsenic, fluoride and natural sources of salinity impacts compromise drinking water quality use of groundwater for irrigation. Thus, natural groundwater quality needs to be understood and the risks of groundwater development in compromised environments mitigated before development and use (Smedley and Kinniburgh 2002; Edmunds and Smedley 2013; Hug et al., 2020). There are many groundwater quality threats that occur at a global level, underpinned by common geological controls and drivers in land use, land management and stewardship.

It is also important to recognize that surface water and groundwater are closely linked – pollution of one can pollute the other. Worldwide, a large volume of river and streamflow discharge is sourced from groundwater as baseflow, with many rivers deriving over half their flow from groundwater sources (Swanson et al 2020; Beck et al 2013). Particularly vulnerable are springs and wetlands where subsurface contamination can directly impact groundwater-dependent ecosystems (Springer et al. 2008; Kreamer et al. 2015).

This special issue provides a unique collection of papers which address some of the water quality challenges we face at a global scale. It covers opportunities that groundwater provides for a range of uses, and covers some treatment and management solutions for several key groundwater quality threats. Groundwater quality threats are varied, this Special Issue covers many of these (e.g. faecal contaminants, salinity, arsenic, fluoride, radionuclides, iron, manganese, pesticides and per- and polyfluoroalkyl substances) but clearly it was beyond the scope of this special issue to deal with all groundwater quality challenges. Indeed, many are covered in other recent publications (e.g. Horst et al., 2018; Stockdyk et al., 2020; Wang et al., 2020; Andrade et al., 2020; Podgorski and Berg 2020; Bunting et al., 2021; Birhanu et al., 2021). This collection provides evidence from large scale studies and some examples from data-scarce regions and emphasises the critical importance of groundwater quality when considering water availability and protection of water sources for future water use. This special issue comes at a time when our focus is drawn towards the importance of groundwater - the UN World Water Day 2022 is focussed on “Groundwater: Making the Invisible Visible”, and the threats from climate change (COP26). The special issue provides a timely reminder of the groundwater-quality challenges we continue to face as well as the opportunities it can bring to build resilient and sustainable water supplies today and in the future.

2. Capacity for aquifers to buffer water quality threats

One of the core attributes of groundwater is its ability to provide high-quality water which requires limited treatment for drinking water in many cases. This is due to the protective cover provided by the soil as well in cases with deeper unsaturated zones. This means that surficial contamination sources can be attenuated through a combination of physical, chemical and biological processes. While the protective properties of groundwater systems can be absent or by-passed in some instances, overall groundwater is much less susceptible to high levels of surface contamination compared to surface waters. This water-quality buffering capacity mirrors the water-quantity buffering capacity of groundwater compared to surface sources replenished directly by rainfall and runoff.

Shallow groundwater systems are evidently more susceptible to surficial contamination threats from anthropogenic sources compared to deeper groundwater systems with much longer residence times (Lapworth et al., 2015, 2013; Banks et al., 2021). In some cases, geogenic sources of contamination (e.g. As and U) are hosted in surficial and shallow sediments or deposits which limits the use of these more easily accessible aquifers for drinking-water supply and irrigation (Nickson et al., 1998; Smedley and Kinniburgh 2002; Van Geen et al., 2006). However, in many settings the water quality of shallow aquifers is highly suited for other uses such as industry. This raises the issues of development of deeper groundwater sources which are replenished over much longer timescales (Bethke et al., 1999; Edmunds et al., 2006; Hoque and Burgess 2012). At intermediate depths in many sedimentary basins fresh paleo waters that are present in some regions provide important sources of drinking water (e.g. Michael and Voss 2009; Burgess et al., 2010). At greater depths water quality can deteriorate and at the base of many sedimentary systems flow is often limited and saline groundwaters are found (Ferguson et al., 2018).

3. Global threats to groundwater quality

There are numerous global treats to groundwater quality, and these can be categorised broadly into two groups – those controlled by variations in geogenic contaminants such as arsenic and fluoride, and those introduced by human activities either at the surface or at depth which compromise groundwater quality. Examples include the deterioration of groundwater quality due to over pumping of coastal aquifers (Tam et al., 2014), the mobilisation of buried contaminants due to pumping and the influx of fresh sources of organic matter (Lawson et al., 2016) and the stimulation of denitrification due to flooding in alluvial aquifer systems or raised groundwater levels (Bernard-Jannin et al., 2017).

Threats to groundwater quality have been researched for many decades, necessitate treatment in some cases and limit water use globally. These include threats from contaminants derived from agricultural activities, e.g. nitrate, plant protection products and co-contaminants of fertilisers such as uranium (Kolpin et al., 1998; Squillace et al., 2002; Liesch et al., 2015; Padilla et al., 2018). Threats from industry and urban settlements, e.g. heavy metals, petroleum based contaminants, selected waste water organics and microbiological contaminants (Lapworth et al., 2012; 2017a; Hepburn et al., 2019; Diaw et al., 2020; Steelman et al., 2020). There are also threats from widely occurring geogenic contaminants, e.g. arsenic, fluoride, radionuclides, iron, manganese (Coyte et al., 2018; Johnson et al., 2018; Bhattacharya et al., 2020). High salinity is perhaps one of the most pervasive and challenging groundwater quality issues and can arise due to natural sources of salinity as well as anthropogenic sources and drivers of salinity (Micheal et al., 2013; Comte et al., 2016; Thorslund and van Vliet 2020). Many of these water quality threats are the focus of papers within this special issue due to their global footprint. While the groups of contaminants described above pose a global threat and are better characterised than other contaminants, there are still many regions for which basic information on water-quality parameters such as nitrate and salinity are inaccessible or have not yet been collected. This lack of data and knowledge is in itself a challenge for using and managing groundwater resources effectively.

There are also many new groups of contaminants, often referred to as ‘emerging contaminants’ or ‘contaminants of emerging concern’ such as per- or polyfluorinated organic compounds, pharmaceuticals, microplastics, nanomaterials and a whole range of organic breakdown products. These new types of threats to groundwater clearly have a global footprint, but there is still limited evidence globally with which to understand their occurrence, controls and wider impacts on groundwater quality (Re et al., 2019; Lapworth et al., 2019; Panno et al., 2019). This is due to both the costs of analysis for these groups of contaminants, in some cases still developing protocols for sampling and analysis (e.g. microplastics), and the lack of regulatory drivers for the collection of this type of water quality data in groundwater in many regions (Re et al., 2019; Lapworth et al 2019). To date, the focus of many of these emerging contaminants has been in surface-water bodies due to the dominant risk posed by many of these contaminants, but more work clearly needs to be undertaken to improve our understanding of pathways and threats to groundwater sources from these types of contaminants.

The field of microbial contamination in groundwater is arguably still a rapidly progressing research area, particularly for more challenging microbes such as viruses (Stokdyk et al., 2020; Sorensen et al., 2021). The issue of anti-microbial resistance (AMR) is a very active and developing field of research. However, there are still only limited studies focussing on groundwater systems as hosts for conditions which enhance AMR including drivers due to complex mixtures of organic contaminants and other stress factors (Andrade et al., 2020). Much like the field of 'emerging organic contaminants', recent advances in analytical and data processing capabilities are rapidly advancing our ability to understand biological threats and the complexity of groundwater biomes in more detail. Several contributions in this special issue address these more emerging threats, including microbiological contamination and remediation, and contamination from pharmaceuticals and other emerging organic compounds.

4. Opportunities for groundwater development and assessment

While there is considerable evidence from many regions globally that over-abstraction is depleting groundwater stores (Wada et al., 2010), there are many regions with underutilised groundwater potential (MacDonald et al., 2012; Cobbing and Hiller 2019). There are large humid regions in Africa for example, that have sufficient recharge and groundwater stores to support more abstraction and adaptation to climate impacts (MacDonald et al., 2019; 2021). Many of these regions are relatively sparsely populated, have had more limited surficial contaminant loads compared to many other regions (e.g. Europe) with a long legacy of use of synthetic fertilisers and plant protection products, and generally contain groundwaters with good water quality even when drinking-water quality standards are used as the criterion for assessment (Silliman et al., 2007; Anku et al., 2009; Rivett et al., 2018; Lapworth et al., 2013; 2019). Many shallow basement and sedimentary aquifers contain groundwater with low total dissolved solids contents due to the nature of recharge and water-rock interactions and are suitable for irrigation use (e.g. Lapworth et al., 2021; 2020; 2017b). However, often assessments of the suitability of groundwater for irrigation ignore groundwater quality (Altchenko and Villholth 2015) or only feature once water quality problems are well documented and widespread (e.g. Feng et al., 2005). In basement settings, it is often water quantity and the rate of replenishment that may constrain development of groundwater for a range of uses (MacDonald et al., 2021). While there is a critical role for deeper groundwater resources in settings where shallower sources are contaminated it is important to monitor abstraction and changes in water quality to ensure that there is no contaminant breakthrough from shallower aquifers as a result of abstraction or poor borehole construction (Ravenscroft et al., 2018; Lapworth et al., 2018a, 2018b).

A range of Managed Aquifer Recharge (MAR) schemes exist at different scales which can potentially enhance groundwater recharge and quality locally. Many schemes have taken water quality considerations into account, either through the use of the unsaturated zone or though pre-treatment technologies prior to injection or infiltration into aquifers. However, where this has not been factored in or where there is opportunity for rapid by-pass flow it is possible that groundwater quality may be compromised under such schemes – this is a particular risk for direct injection schemes (Dillon et al., 2020a). MAR may in some circumstances promote the improvement of groundwater quality (Dillion et al., 2020b) through changes in redox conditions and subsequent denitrification or sorption of contaminants, or through dilution in regions impacted by salinity.

Groundwater of varying natural quality can be used for different purposes, for example industry, aquaculture, irrigation and livestock all have different water quality considerations. As such, there may be opportunities to exploit groundwater for livelihoods even if it is not suitable for human consumption without prior treatment. A wide range of existing and new technologies (e.g. filtration methods, osmosis, new membrane technology and the use of nanotechnology) to improve water quality and remove or reduce bacteria, arsenic, fluoride, iron and salinity, to name a few examples are available (WHO 2009; Boving et al., submitted; Richards et al., submitted). These new technologies represent an opportunity to increase the use of groundwater and develop new groundwater resources and is the topic of some of the contributions to this special issue.

The use of machine learning and other statistical methods have, in some cases, enabled regional- or global-large-scale assessments to be made, but these are still constrained by the availability of reliable observations and the use of proxy input data sets (Podgorski et al., 2018; 2020). The use of sensors can also improve our understanding of particular threats to groundwater quality and may enable more high-resolution data (in both space and time) to be gathered rapidly for selected parameters such as nitrate, salinity (e.g. Dulaiova et al., 2010; Opsahl et al., 2017) and threats from faecal contamination (e.g. Sorensen et al., 2016; Ward et al., 2020). However, there is still a fundamental issue of poor coverage of groundwater-quality data and limited availability in many regions (much of Africa, parts of Asia and S America), as well as data bias in certain regions and for certain parameters (e.g. S

Asia for arsenic and parts of Europe and N America for many parameters), which limit assessments undertaken at scales comparable to those for rivers and lakes.

4. Concluding remarks and future outlook

Groundwater quality treats arise due to due to human activities and due to naturally occurring geogenic sources of contamination. Anthropogenic activities can also both enhance and mitigate threats to groundwater quality. Groundwater should also be recognised as an opportunity and underutilised resource in some settings with enormous adaptive potential. The recent World Bank assessment of global water quality (Damania et al., 2019) highlights the critical need for more emphasis on groundwater quality as an important aspect of water resource assessment. It also demonstrated the limited visibility of both global groundwater quality threats and opportunities. Very few studies have been able to make truly ‘global’ assessments of groundwater quality (e.g. Ascott et al., 2017; McDonough et al., 2020; Thorslund and van Vilet 2020; Podgorski and Berg, 2020) and for those which have, there are clearly large data gaps for many regions. There is an urgent need to improve data coverage in some regions such as Africa and parts of Asia and South America and to coordinate initiatives focussed on making data more accessible (WWQA 2021).

Good groundwater quality underpins progress on a range of Sustainable Development Goals and can provide safe and resilient water supplies, able to buffer changes in climate extremes as well as other anthropogenic pressures such as land-use change. The adage ‘you can only manage what you know’ is true in many senses regarding groundwater quality. It is probably fair to say that while there has been massive progress in the last three decades on the understanding of groundwater quality threats, their complexities, as well as the opportunities groundwater quality brings, a great deal remains to be done on this topic.

There are many potential threats to groundwater quality that we are aware of and which are well understood, and other ‘emerging threats’ that we are only just starting to investigate. There continue to be rapid advances in analytical techniques, statistical methods and treatment technology which will, over the coming years broaden our understanding of groundwater threats and also provide potential solutions. Large stores of shallow groundwater with water quality suitable for a range of uses still have the potential to be utilised, these include humid regions with high annual recharge, as well as less humid and more water-scarce regions where groundwater is the only reliable source of water (MacDonald et al., 2021). However, water quality and quantity assessments are rarely undertaken in parallel to allow a more complete assessment of water security, and this is clearly an area where improvements can be made. The quality of groundwater is key to assessing groundwater resources at a range of scales from local to global and this assessment needs to be improved if we are to realise their potential.

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