ASSESSING GROUNDWATER QUALITY: A GLOBAL PERSPECTIVE

Importance, methods and potential data sources

Friends of Groundwater in the World Water Quality Alliance (WWQA)

Friends of Groundwater in the WWQA

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Importance, methods and potential data sources

Executive summary

This perspective paper by the Friends of Groundwater (FoG) group aims to give a compelling argument for the importance of groundwater quality for human development and ecosystem health. It also provides a global overview of the current knowledge, with focus on data coverage, gaps and technological advances. It is a building block towards a future global assessment of groundwater quality as part of the United Nations Environment Programme (UNEP) World Water Quality Assessment (WWQA).

Groundwater is an essential global resource and provides the largest store of freshwater, apart from the ice caps. Current groundwater abstraction represents 26% of total freshwater withdrawal globally, to supply almost half of all drinking water and 43% of the consumptive use in irrigation. In arid and semiarid regions, groundwater is the only reliable water resource. In the environment, groundwater makes an important contribution to river flow and groundwater dependent ecosystems. For drinking water supply, one of the advantages of groundwater is that it is naturally protected from many contaminants. With drought and climate change, people in water-scarce areas will increasingly depend on groundwater, because of its buffer capacity and resilience to rapid impacts. However, groundwater quality, as well as quantity, may be impacted by climate change.

A global groundwater quality assessment is needed because human activities and climate variability increase the pressure on groundwater resources, but it is an invisible resource that remains out of sight and out of mind for most people. Protection of our groundwater resources is necessary for protecting human health, maintaining food supplies and conserving ecosystems. Many regions and countries rely on naturally clean groundwater as advanced water treatment is economically infeasible. Knowing where to source clean groundwater, as well as understanding threats to this resource, is therefore important.

The principal objectives of this perspective paper are to present the importance of groundwater to meet the Sustainable Development Goals (SDGs), notably SDG3, SDG6 and SDG7, describe the threats to groundwater quality from anthropogenic and geogenic contaminants, discuss the challenges of providing a global overview of groundwater quality, present key messages to summarise current knowledge and capacity and outline a Work Plan to develop a global groundwater quality assessment network, including protection and management of groundwater quality.

The key messages from this perspective paper are that:

1. Increased attention to water, and specifically groundwater quality, is of utmost importance for the achievement of the Sustainable Development Goals, especially related to water security (SDG 6), health (SDG 3), and food production (SDG 2). Groundwater quality is under increasing pressure due to human development and the impacts of climate change posing risk to human consumption and affecting to a large extent disadvantaged vulnerable groups in society.
2. A dedicated global groundwater quality assessment is necessary and timely. It will provide a comprehensive and coordinated overview of the knowledge base pertaining to groundwater quality, including mapping of main drivers, pressures, trends and impacts, as well as current and prospective management approaches.

3. There is a large variety of anthropogenic and natural (geogenic) chemical and microbiological contaminants that are found or move into aquifers across the globe. The range of characteristics and behaviour in the groundwater systems requires expert knowledge.
4. Groundwater systems are heterogeneous, three-dimensional water reservoirs in porous and fractured rock formations. Groundwater contaminant distributions are therefore particularly challenging to map. Also, contaminant transport and remediation of pollution in these systems often involves long timescales. Hence, groundwater quality is more complex to understand, assess and remediate than surface water quality.
5. Information and data on groundwater quality are very variable across the globe, with often less information available in countries of the Global South. For a comparable global assessment, substantial efforts are needed to i. Improve data collection, ii. Develop the capacity and the knowledge base, with particular focus on developing countries and iii. Develop international standards.
6. Groundwater quality needs to be understood at various scales depending on the key risks, *e.g.* related to the size and vulnerability of the aquifers and receiving water bodies, the inherent or external pollution loads, land use, waste handling, and the demand on the resource. There is a need to consider groundwater quality for different uses: *e.g.* drinking water, ecosystems, food (particularly irrigation), energy production and other industries.
7. Groundwater monitoring programmes need to be targeted and designed according to the purpose of the monitoring, *e.g.* specific contamination tracing and remediation, short-term campaigns to understand local contamination issues, and longer-term larger-scale systematic monitoring programmes to identify general spatial patterns and long-term temporal trends in groundwater quality.
8. Besides traditional groundwater monitoring programmes involving water sampling in wells (points in space), upstream (soils), and downstream (receiving streams, springs, wetlands and coastal areas) need to be considered. Important new technologies and practices are developing, *e.g.* earth observations and GIS, Citizen Science, machine learning, and numerical modelling of contaminant fate and transport. Due to general lack of in-situ data, the new technologies can help extrapolate knowledge from regions with good data to areas with less information, giving an understanding of potential risks and vulnerabilities. Vulnerability and pollution load mapping are critical factors in tracing potential groundwater pollution and designing monitoring programmes on groundwater quality.
9. Most monitoring programmes for groundwater quality are based on national level legislation and regulations, where these exist. Special attention is required for groundwater quality challenges in transboundary aquifers. To fill knowledge gaps and prepare an improved and fair basis for transboundary cooperation requires development of comparable standards for the aquifers, data sharing and joint capacity development programmes.
10. Local-to-global partnerships and investments in research, capacity development and evidence-based policymaking are required to make the step change required to manage groundwater quality sustainably.

The Friends of Groundwater (FoG) group has developed this perspective paper with great professional enthusiasm and without a dedicated budget, but the planning of future activities depends on motivation and budget. The FoG specialists are fully aware of the importance of regional and global groundwater quality assessment and this assessment needs to remain a focus of the group. To establish this critical flow of information and feed into the science policy interface assisting countries to achieve SDG 6 targets and namely to address the water related equality dimensions in a gender perspective “leaving no one behind” budget is critical for a global groundwater quality and quantity appraisal, for raising awareness and ensure impact. To leverage the substantial in-kind investment of FoG in the World Water Quality Alliance that enabled this report ; a follow up budget needs to be secured (section 8).The main objective is to continue this targeted FoG activity and evolve it from setting the stage and scoping towards a full global assessment and an outreach interface to users. Since the FoG activities are a part of the WWQA, and shall contribute to World Water Quality Assessment of UNEP it is expected that the core budget can be raised collectively with alliance support to enable the implementation of the workplan sketched out below and in section 8.

In the Work Plan, the principal short and the long-term activities are:

- A global GQ Assessment Portal is already under development. It will be the FoG main window to the world to be a focal point and link to all portals and activities relevant to GQ assessment at the regional/global scale. The portal will include this perspective paper, a reference database, a graphical interface for spatial/geographic presentation, activities of FoG, etc.
- The global GQ Assessment Network will be progressively developed by including new information and current activities in the portal, through active contributions of the specialists and institutions involved. The network will grow further, alongside development of an overview of national GQ monitoring programmes. This will build on the existing work of GEMS/Water in connection with SDG target 6.3.2.
- A systematic overview of GQ Monitoring Programmes at national level will be prepared, including institutions, purpose, parameters, methodology, availability and accessibility. This activity will reveal additional information about the state and trends of GQ at national level.
- Contributing to a World Water Development Report 2022 “Groundwater: Making the Invisible Visible”. The draft annotated Table of Contents was circulated for comment in November 2020 and the call for contributions is expected before the end of the year.
- Organising and participating in other activities relating to groundwater quality for World Water Day 2022
- Contributing to the World Water Quality Assessment under preparation by UNEP with partners for the 6th Session of the United Nations Environment Assembly (Feb 2023) and featuring in the UNGA mandated “midterm comprehensive implementation review of the International Decade for Action, ‘Water for Sustainable Development’ 2018-2028” (UN-Water Conf. NY, March 2023).
- Assistance to national GW assessment programmes: advocacy through embedding GQ in societal, economic and other environmental issues in water programmes of international, national and UN funding agencies, multinationals, trust funds, etc.; acquisition, preparation and execution of projects; raising awareness and providing incentives through webinars, videos, tailored information and kits for schools, academia, NGOs, etc.; promoting innovative approaches and technologies (*e.g.* low cost sensors).
- Upscaling and regionalisation of local assessments are the main FoG research activity. It includes regional/global modelling (*e.g.* using machine learning), inclusion of “use cases” into regional assessment (*e.g.* case-based reasoning), remote sensing, Citizen Science, etc. When presenting and reporting on GQ at regional scale, distribution of pollutants with depth and possible behaviour in time will be taken into account where possible.

The FoG Work Plan will be further developed according to budget availability and preferences of FoG members and other specialists to contribute to global groundwater quality assessment.

Table of Contents

1. Objectives:

This perspective paper aims to give a compelling argument for the importance of groundwater quality for human development and ecosystem health. It also provides a global overview of the current knowledge, with focus on data coverage, gaps and technological advances. It is a building block towards a future global assessment of groundwater quality as part of the United Nations Environment Programme (UNEP) World Water Quality Assessment (WWQA).

The principal objectives of this perspective paper are to:

a. Present the importance of groundwater and in particular good quality groundwater to meet the Sustainable Development Goals (SDGs), notably SDG 6, SDG 3 and SDG 2
b. Describe the main threats to groundwater quality from anthropogenic activities
c. Consider natural (geogenic) pollutants and their importance in certain regions, especially arsenic (As), iron (Fe)/manganese (Mn), fluoride (F) and radionuclides
d. Discuss the challenges involved in trying to provide a global overview of groundwater quality, including the three-dimensional nature of groundwater flow and the long-time scales involved
e. Make proposals on data sources and possible ways forward for assessing global groundwater quality
f. Present key messages, which provide a synthesis of the current knowledge and capacity base, with recommendations on focus areas for future work
g. Outline a Work Plan with both short-term and long-term activities for development of a global groundwater quality assessment network, including consideration of protection and improved management of groundwater quality.

2. Introduction

Groundwater is an essential resource from a global perspective and provides the largest store of freshwater, apart from the ice caps.

Current groundwater abstraction represents approximately 26 % of total freshwater withdrawal globally (Van der Gun, 2012) . Groundwater supplies almost half of all drinking water in the world and 43 % of the global consumptive use in irrigation (Siebert *et al*., 2010). It is also important for industry and as an energy source. In arid and semiarid regions of the world, groundwater is the only reliable water resource. In the environment, groundwater makes an important contribution to baseflow in rivers and support groundwater dependent ecosystems.

For drinking water supply, one of the advantages of groundwater is that it is naturally protected from many contaminants. For example, special conditions of soil, climate, structure of the aquifer and groundwater flow can favour denitrification, naturally attenuating high concentrations of nitrates and other contaminants of anthropogenic origin (Box 1). During droughts and with climate change, people in water-scarce areas will increasingly depend on groundwater, because of its buffer capacity and resilience to rapid impacts. However, groundwater quality, as well as quantity, may be impacted by climate change, which needs to be taken into account in groundwater assessments.

There are many reasons why a global groundwater quality assessment is needed:

- Human activities and climate variability are increasing the pressure on groundwater resources, but groundwater is an invisible resource that remains out of sight and out of mind for most people.
- Protection of our groundwater resources is necessary for protecting human health, maintaining food supplies and conserving ecosystems.
- Some regions and countries rely on naturally clean groundwater as advanced water treatment is economically infeasible. Knowing where to source clean groundwater, as well as understanding threats to this resource, is therefore important.

3. Threats to groundwater quality

The quality of groundwater is determined by the initial quality of water infiltrating the subsurface, its interaction with the subsurface environment and the impact of anthropogenic activities at the surface (agriculture) or in the subsurface (*e.g.* oil and gas exploration). Therefore the 'governing factors' determining the potential threats to the quality of groundwater are the composition and reactivity of the subsurface strata (geogenic contamination) and contaminant sources from land use and other human activities (anthropogenic contamination) (Figure 1). As a result, much like surface water, there may be multiple groundwater quality challenges at any given location.

The groundwater environment differs significantly from surface water in ways that are important for the fate of natural and anthropogenic contaminants. It is dark and has no photosynthesis (but bioactivity exists, even though groundwater is aphotic), has a nearly constant temperature, has limited inputs from the surface (*e.g.* oxygen) and contains 10^2 to 10^6 times fewer bacterial organisms (Ghiorse & Wilson, 1988). The main source of natural groundwater recharge is precipitation. Most importantly, the groundwater zone has long water residence times, typically years to millennia compared to weeks for streams and rivers (see Box 1). This allows the groundwater time to react with rocks and minerals, which is important for reactions that are often slow. Some reactions, depending on mineralogy, may lead to geogenic contamination (As, Fe, Mn, F, radionuclides, etc.) but in other cases may facilitate natural attenuation of contaminants from the surface. The spatial scale of groundwater contamination largely depends on whether the contamination originates from point sources (*e.g.* factories) or diffuse sources of regional origin, for example of agricultural or atmospheric origin (Figure 1).

Several physical and chemical factors in groundwater may control processes and therefore the fate and mobility of contaminants.

Acidity is a key characteristic of groundwater. Acidity, measured as pH, in natural groundwater is controlled by the balance between carbonic acid (H_2CO_3) and buffering by dissolution of alkaline rocks. Besides controlling the precipitation and dissolution of minerals that may contain contaminants, the pH controls the mobility of a range of electrically charged contaminants by changing the surface charge of clays, oxides and organic matter (OM), solids whose surfaces promote sorption. This means that cationic contaminants like heavy metals (lead – Pb, zinc – Zn, cadmium – Cd, etc.) may be mobile at low pH values, while anionic contaminants, such as oxyanion forming elements (As, selenium – Se, etc.), may be mobile at neutral to high pH values. Similarly, organic contaminants may be adsorbed by naturally present organic matter, slowing the rate of contaminant transport in the groundwater (retardation).

The groundwater environment typically has low oxygen content because of slow, diffusion-controlled exchange with the atmosphere and because of the presence of natural organic matter in the groundwater aquifers, which consumes oxygen. The redox potential is a measure of the relative concentrations of dissolved oxidised and reduced species and is largely controlled by the balance of oxygen and labile organic matter. As for pH, the redox potential may indicate the degree of mobility for some groups of contaminants or the potential for natural attenuation of others. Typically, reducing conditions (*i.e.* high OM content) lead to an increase in dissolved Fe, Mn, hydrogen sulphide (H_2S), As and ammonia (NH_4). If dissolved sulphide is present, then a range of trace metal forming sulphide minerals may have very low mobility. Reducing conditions may also indicate a potential for the natural attenuation of nitrate and some organic contaminants.

High total dissolved solids (TDS but often measured as electrical conductivity EC) are associated with processes such as saltwater intrusion; dissolution of salts from highly soluble rocks and evaporites; high rates of evaporation in arid and semi-arid environments; or highly mineralised (old or deep) groundwater. High TDS are linked to high concentrations of major ions and sometimes geogenic contaminants (*e.g.* As, F, uranium – U). High TDS result in a high ionic strength and formation of soluble complexes that may lead to increased mobility for some ionic contaminants. High TDS is in itself a water quality issue.

Some water quality issues may result from a complex interplay of physical and inter-linked chemical processes. For instance, groundwater drawdown due to abstraction in rocks or sediments containing pyrite (FeS_2) may lead to its exposure to the atmosphere and oxidation. In unbuffered environments the oxidation will cause acidification which in turn will lead to mobilisation of trace metals. The understanding of such linkages is a prerequisite for a sensible interpretation of international groundwater quality assessments.

Figure 1 – Groundwater pollution threats (Villholth et al., 2011)

Box 1 – Water resource and water quality characteristics of groundwater and surface water

Feature \ Resource	Groundwater resources/aquifers	Surface water resources (rivers, lakes, wetlands)
Accumulated storage volume	Very large	Small to moderate
Resource areas	Extensive, widely available below the earth surface	Restricted to water bodies
Flow velocities	Low	Moderate to high
Residence times	Decades/centuries	Weeks/months
Drought propensity	Generally low	Generally high
Evaporation losses	Low and localized	High in dry/warm climates
Resource evaluation	Higher cost and significant uncertainty	Lower cost and often less uncertainty
Abstraction impacts	Delayed and dispersed	Immediate with impact on downstream areas
Natural water quality	Generally good (but not always)	Variable
Vulnerability to pollution	Less vulnerable, but natural protection varies	More vulnerable, largely unprotected
Persistence of pollution [a]	Pollution more long-lasting	Pollution more transitory
Natural resource recovery from pollution	Slow to restore	Quicker to restore
Remediating pollution	More costly and complex	Less costly and less complex

[a] Persistence of a temporary pollution load

3.1. Anthropogenic contaminants

Groundwater faces many threats from the effects of agricultural intensification, urbanisation, population growth and climate change. The following section provides an overview of key groups of anthropogenic contaminants, and groundwater contamination that is exacerbated by anthropogenic activities, with a global footprint.

Elevated groundwater **salinity** can result from a range of processes, including natural water-rock interactions and recharge in areas dominated by evaporation. However, many groundwater salinization processes are exacerbated by anthropogenic activities; these include salinization from irrigated agriculture, over-pumping mobilising geologically old saline water, seawater intrusion into coastal aquifers and hydrocarbon production. Groundwater salinization can be exacerbated by excessive irrigation and shallow groundwater levels due to salt accumulation which is subsequently leached to groundwater (MacDonald *et al*., 2016; Zhang *et al*., 2014). In certain cases, leaching of agricultural drainage water to groundwater increases concentrations of specific ions such as sodium and magnesium with deleterious effects to crops irrigated with sodium- and magnesium-rich groundwater. This issue is intensified in arid and semi-arid regions where there is inadequate flushing of ions due to limited rainfall recharge (Foster *et al*., 2018).

Groundwater pumping may enhance the subsurface inflow of seawater, referred to as 'coastal intrusion' or 'seawater intrusion', due to over-pumping of fresh groundwater in the coastal zone. With time, this can lead to increasing salinity levels in the abstracted groundwater and, can render the groundwater unsuitable for public supply and crop irrigation. There are many examples of this process in coastal regions globally (Alfarrah & Walraevens, 2018; Hussain *et al*., 2019). In some settings, pumping may enhance mobilisation, typically upward, of underlying paleo-groundwater with a higher salinity, referred to as 'upconing', which can also lead to increasing salinity in the abstracted groundwater.

Groundwater salinization is also linked to climate change and rising sea levels (Mirzavand *et al*., 2020; Nogueira *et al*., 2019). In low rainfall areas, salt moves up from shallow groundwater to the soil and root zone. For instance, salinization may link to changes in the intensity of tidal surges and coastal flooding in low lying regions, *e.g.* in polders of Bangladesh, where soils and shallow groundwater may become rapidly contaminated by episodic seawater flooding. Many of the world's most densely populated regions are coastal, and groundwater beneath these regions will continue to be impacted by coastal salinity issues. By 2060 it is projected that 1.8 billion people will live in coastal regions, with over half of these in in Asia (Post *et al*., 2018).

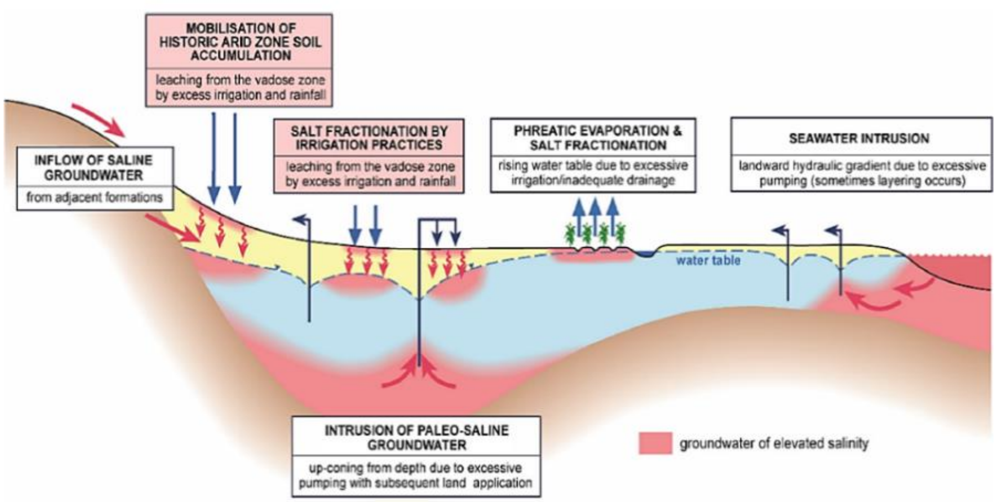


Figure 2 – Processes leading to groundwater salinization (Foster et al., 2018)

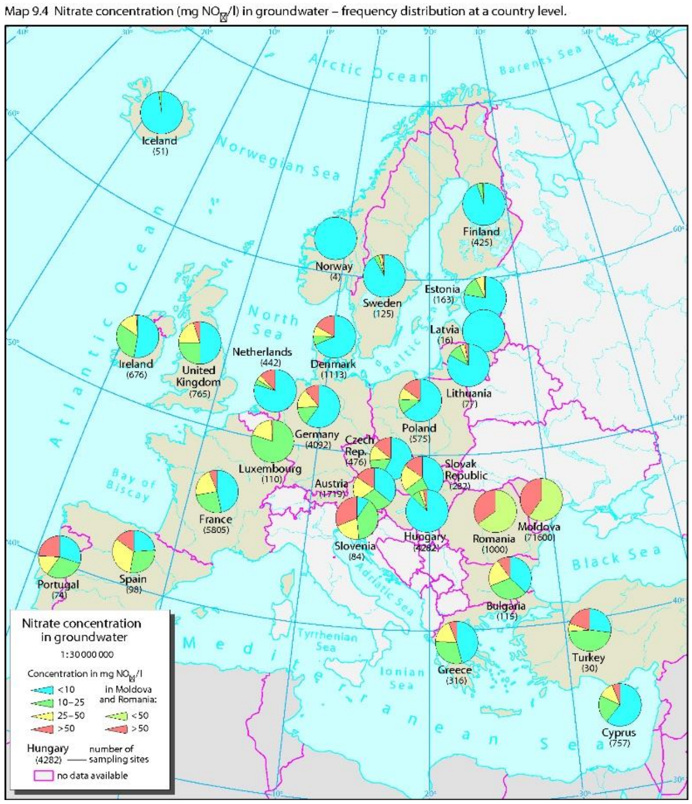


Figure 3 – Nitrate concentrations in European groundwater source: (https://www.eea.europa.eu/legal/copyright). Copyright holder: European Environment Agency (EEA).

Worldwide, aquifers are experiencing an increasing threat of **nitrate** pollution from agricultural activities, urbanization and industrial development. Nitrate (NO_3^-) is the most ubiquitous nonpoint source (NPS) contaminant of groundwater resources worldwide (Spalding & Exner, 1993). This well documented problem is largely driven by intensive agriculture and growing global demand for food production (Galloway *et al*., 2008). After fertilizer applications, surplus nitrogen (N) can rapidly move in to groundwater systems (Foster & Crease, 1974; Foster & Young, 1980; USEPA, 1987). Nitrate is highly mobile in groundwater and there is only limited potential for denitrification (Rivett *et al*., 2008). Nitrate pollution is responsible for the majority of water quality exceedances in Europe (Figure 3) and other regions where it is routinely monitored (Foster & Custodio, 2019; Strebel *et al*., 1989).

Because groundwater flow is usually slow there is often a significant time lag (years-decades) for pollution to become apparent in aquifer systems (Ascott *et al*., 2017; L. Wang *et al*., 2013, 2016). As a result, the impact of N pollution in groundwater sources and rivers sustained by baseflow may be delayed for many decades relative to the time of N inputs and last for a long time (Ascott *et al*., 2017; Howden *et al*., 2010). Elevated nitrate concentrations in rivers and wetlands, due to baseflow contributions from groundwater, may lead to excessive algal growth, which results in oxygen deficiency causing fish kills, toxic algal blooms and a decrease in biodiversity (Rhee, 1978; Whitehead & Hornberger, 1984).

Nitrate is a common groundwater contaminant in drinking water sources and at high concentrations can cause health problems in infants and animals (Boy-Roura *et al*., 2013; Fennessy & Cronk, 1997; Knobeloch *et al*., 2000). This is particularly important in peri-urban areas where untreated wastewater is used for irrigation and where groundwater is pumped for drinking purposes.

Globally, two billion people consume water contaminated with faeces (WHO, 2019). Groundwater is often assumed free from **microbiological contamination** which is not necessarily the case; indeed in the USA, up to half of all groundwater supplies have shown some evidence of faecal contamination likely resulting in many cases of waterborne transmission and illness (Macler & Merkle, 2000).

Bacteria, viruses and protozoa (*e.g.* cryptosporidium spp.) are widely detected in groundwater systems (Chique *et al*., 2020; Hunt *et al*., 2010; Hynds *et al*., 2014; Stokdyk *et al*., 2020). Faecal bacteria contamination is largely assessed through the use of faecal indicator organisms, thermotolerant (faecal) coliforms (TTC), or specifically *Escherichia coli*. A recent review (Murphy *et al*., 2017) identified that five pathogens were responsible for most outbreaks linked to groundwater use: Norovirus, Campylobacter, Shigella, Hepatitis A and Giardia. It was estimated that between 35.2 and 59.4 million cases of acute gastrointestinal illness per year globally could be attributed to the consumption of groundwater. Pollution by microbes is especially common in private household wells, since these are often shallow, poorly located and constructed, and they generally lack water treatment (Murphy *et al*., 2017). Access to 'improved' drinking water sources, such as deeper boreholes, may provide some protection, but does not guarantee water free from faecal contamination (Bain *et al*., 2014).

A range of pathogenic microbes are found in groundwater, particularly in vulnerable shallow groundwater supplies where high detection rates are possible (Borchardt *et al*., 2003; Ferguson *et al*., 2012). On site sanitation (pit latrines) and open defecation are major sources of faecal contamination in groundwater (Graham & Polizzotto, 2013), but there is limited evidence to suggest pit latrine density alone is a good predictor of faecal contamination in shallow groundwater supplies (Back *et al*., 2018; Lapworth *et al*., 2017; Sorensen *et al*., 2016; Wright *et al*., 2013). In areas where there is a low sanitation coverage, other factors such as rainfall have been shown to correlate with groundwater contamination (Howard *et al*., 2003; Lapworth *et al*., 2020), and significant seasonal trends are evident across a range of groundwater sources (Kostyla *et al*., 2015).

Contamination is often driven by poorly constructed or un-maintained groundwater sources which are then vulnerable to surface ingress of enteric bacteria and viruses (Pedley & Howard, 1997; Sorensen *et al*., 2015). There have been a number of Cholera outbreaks in recent years, and untreated vulnerable groundwater has been shown to be a potentially important risk factor in some of these (*e.g.* (Nanzaluka *et al*., 2020), confirming earlier anecdotal links to contaminated groundwater (Pedley & Howard, 1997). In contrast, deeper well-constructed sources, such as boreholes, and other improved sources provide drinking water with significantly less contamination (Bain *et al*., 2014; Parker *et al*., 2010). Recent evidence suggests that more attention needs to be paid to reducing contamination around the immediate vicinity of the well head (*e.g.* (Lapworth *et al*., 2020; Ravenscroft *et al*., 2017). Bacterial contamination in groundwater may be a greater barrier to achieving targets set for improved drinking water quality under the SDG 6 than other contaminants (Lapworth *et al*., 2020).

The issue of anti-microbial resistance (AMR) in vulnerable groundwater systems, driven by a range of chemical and environmental stresses, is an important emerging challenge (Anderson & Sobsey, 2006; Sapkota *et al*., 2007; Szekeres *et al*., 2018). This issue is intimately linked to other anthropogenic contaminant challenges that can lead to a cocktail of contaminants, which both facilitate microbial activity (*i.e.* nutrients) and stress microbes (pharmaceuticals, pesticides, etc.) leading to AMR in polluted groundwater systems.

Numerous **manufactured organic** contaminants are detected in groundwater, although on average at much lower concentrations than in surface water (Lapworth et al., 2012). Some of these are more commonly monitored and regulated in groundwater, *e.g.* pesticides and non-aqueous phase liquids, others such as pharmaceuticals are contaminants of emerging concern for which we have little information at present. These are emitted from a wide range of point and diffuse sources and are often very challenging to detect and treat. Concentrations can be very high in groundwater near point sources, such as fuel stations or legacy industrial sites, airfields and landfills. Industrial use of fluids (*e.g.* fuels and solvents) can locally cause very concentrated contamination levels through spills that form non-aqueous phase zones in groundwater. These zones may persist as a source of dissolved organic groundwater contaminants for many decades.

Pesticides are a diverse and ubiquitous group of organic contaminants (including herbicides, fungicides and insecticides) has been extensively studied in groundwater (Beitz *et al*., 1994; Chilton *et al*., 1998; Foster & Custodio, 2019; Kolpin *et al*., 1998). Pesticide contamination arises from both diffuse sources such as agricultural uses and point source applications in urban settings and on transport networks (*e.g.* herbicides used on roads, paths and railway lines). While the concentration of individual pesticide metabolites is usually low (typically <0.1 microgram per litre [µg/L]), their diversity in a sample can be large (Reemtsma *et al*., 2013). Legacy contamination in groundwater is widely reported where more persistent pesticides, such as atrazine and its degradation products, remain at detectable concentrations in groundwater for several decades (Vonberg *et al*., 2014; Wang *et al*., 2020). Pesticides can degrade in the soil and groundwater, however the degradation products can still be harmful and persist in groundwater and metabolites are often detected in groundwater at higher concentrations than parent compounds (Lapworth & Gooddy, 2006). Despite regulations to control their use, which differ significantly globally, pesticides remain a persistent issue for global groundwater resources.

Non-aqueous phase liquids (NAPLs) are hazardous and widely occurring point source contaminants in groundwater that can be classified as either light (L) and dense (D), according to their density relative to water (Mackay & Cherry, 1989; Pankow & Cherry, 1996). For example, benzene, toluene, ethylbenzene, and xylene (BTEX) are prominent examples of LNAPLs, while chlorinated solvents and heavy crude oil are examples of DNAPLs (Mayer & Hassanizadeh, 2005). The leached dissolved phase, as well as vapour phase processes, are important for transport and attenuation of NAPLs in the unsaturated zone (Rivett *et al*., 2011). Monitoring and treatment of soil and groundwater contaminated by NAPLS has been hugely costly to undertake, amounting to billions of dollars globally (Kent & Mosquera, 2001).

Organic contaminants of emerging concern (CECs) are not unknown substances, but rather groundwater pollutants about which relatively little information is currently available regarding their distribution and concentrations. Their emergence is related to the advent of suitably advanced analytical methods and sampling protocols. Associated with a wide range of anthropogenic sources of contamination, this large and diverse group of contaminants (*e.g.* pharmaceuticals, personal care products, perfluorinated compounds, wastewater treatment products, as well as nanoparticles and plastics) remains largely unmonitored and unregulated in groundwater. These compounds are typically detected at sub µg/L concentrations in groundwater (Lapworth *et al*., 2012). The sources and pathways of emerging contaminants in the groundwater are as various as their chemical make-up (Stuart *et al*., 2012).

Microplastics have been primarily considered a surface water pollutant, although pathways to groundwater do exist (Re, 2019), *e.g.* in a recent study microplastics were detected in karst groundwater (Panno *et al*., 2019). This finding is of importance because it is estimated that 25% of the world's population rely on karst aquifers for their drinking water supply.

3.2. Naturally occurring contaminants

Numerous elements that dissolve from the minerals of the aquifer matrix under natural conditions and accumulate in groundwater can pose a potential health risk, as well as operational issues for water supply. These are known as geogenic contaminants. Two of the most widely documented geogenic contaminants are arsenic and fluoride, although others include iron, manganese, chromium and radionuclides such as uranium, radium and radon. If these naturally occurring groundwater contaminants are present in sufficiently high concentrations, they can lead to serious health problems, such as cancer (*e.g.* arsenic) or dental and skeletal problems (*e.g.* fluoride). Elevated iron and manganese concentrations (in association with microbiological action) commonly have aesthetic (orange, red and black staining of clothes and walls) and operational (clogging of boreholes, pumps and water reticulation infrastructure) impacts, the latter of which plays a critical factor in the success of groundwater supply systems and wellfields.

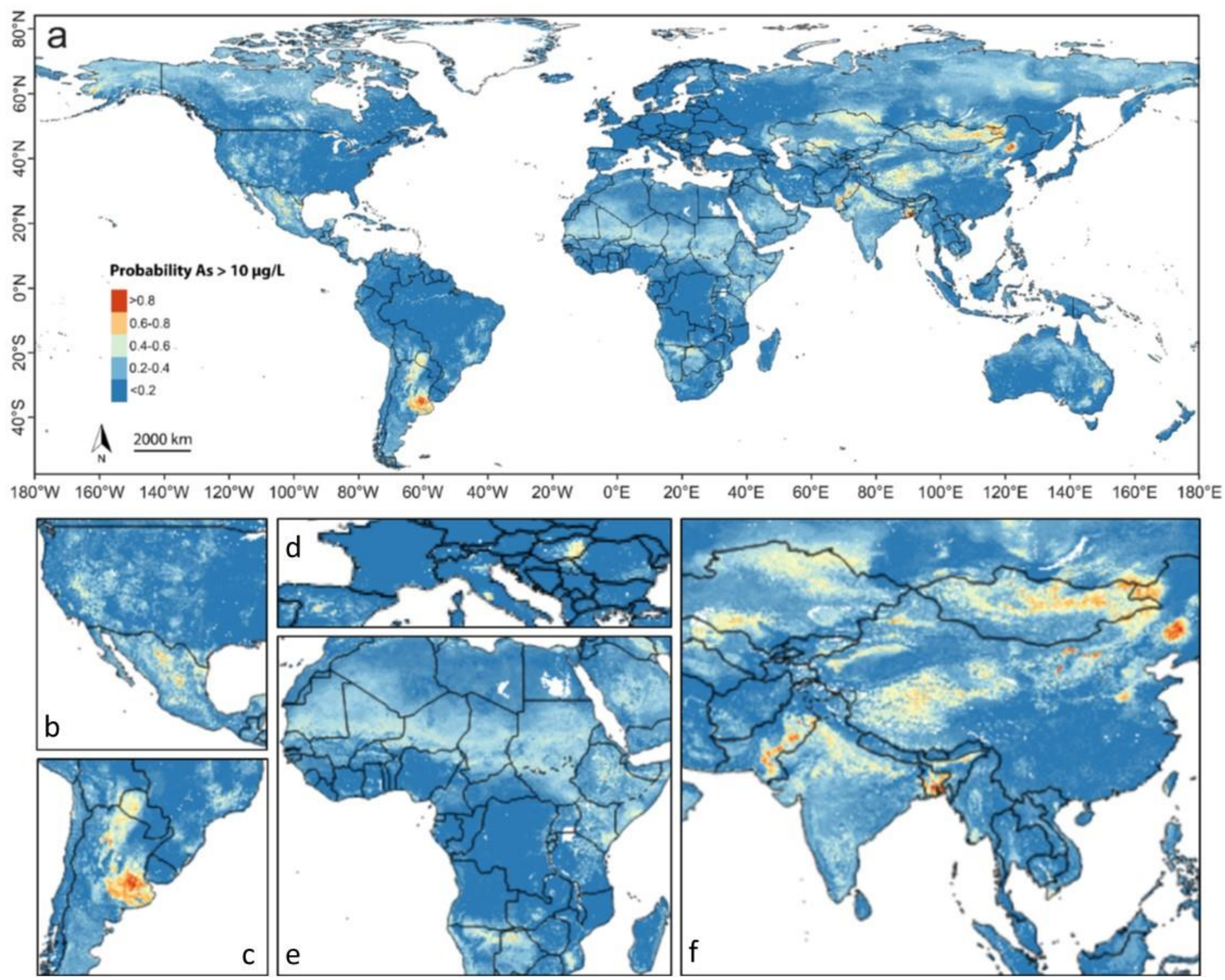


Figure 4 – Probability of naturally occurring arsenic in groundwater exceeding the WHO guideline of 10 µg/L (Podgorski & Berg, 2020) at the global scale (a). Hotspots are shown in North America (b), South America (c), Europe (d), Africa (e) and South and East Asia (f).

In recent decades, **arsenic (As)** in groundwater supplies has become increasingly recognized as a major health issue. Although not an essential element for humans and animals, exposure often occurs through food, but most commonly through its natural presence in groundwater used for drinking. The health effects of consuming relatively low doses of arsenic over an extended period of time include disorders of the skin and vascular and nervous systems as well as various cancers.

Arsenic is naturally found in generally low concentrations in rocks all around the world. Under certain geochemical conditions, it can become mobilized in aquifers, particularly in river basins and deltas containing recently deposited sediments (Smedley & Kinniburgh, 2002). Other geochemical settings leading to arsenic release include oxidation of arsenic-bearing sulphide minerals and release from arsenic-enriched geothermal deposits. The WHO guideline of 10 µg/L for arsenic in drinking water is exceeded on all continents (Figure 4a), with hotspots including parts of Mexico (Figure 4b), Argentina (Figure 4c) and South and Southeast Asia (Figure 4f). The number of people estimated to be exposed to arsenic concentrations exceeding 10 µg/L for drinking and household uses is 94-220 million (Podgorski & Berg, 2020).

Groundwater with high concentrations of arsenic that is used for irrigation can directly increase arsenic levels in crops as well as negatively impact crop yields (UNICEF & WHO, 2018). This is particularly true for rice, which is very efficient in incorporating arsenic into its grains. Furthermore, irrigation with high-arsenic groundwater raises the level of arsenic in the topsoil, which can remain available for crop uptake long after ending irrigation with high-arsenic groundwater (Huq *et al*., 2006). The issue of arsenic exposure through the groundwater-crop pathway is particularly relevant in South and Southeast Asia, where there is extensive irrigation with arsenic-contaminated groundwater and much rice is produced and consumed.

Fluoride (F^-) is found in relative abundance in various minerals throughout Earth's crust. It is widely present in groundwater as a result of geochemical interactions with fluoride-bearing minerals and the presence of geothermal fluids. Because of its small size and charge, fluoride is highly mobile in groundwater, and controlled by the availability of calcium and the pH of the water (Edmunds & Smedley, 2013).

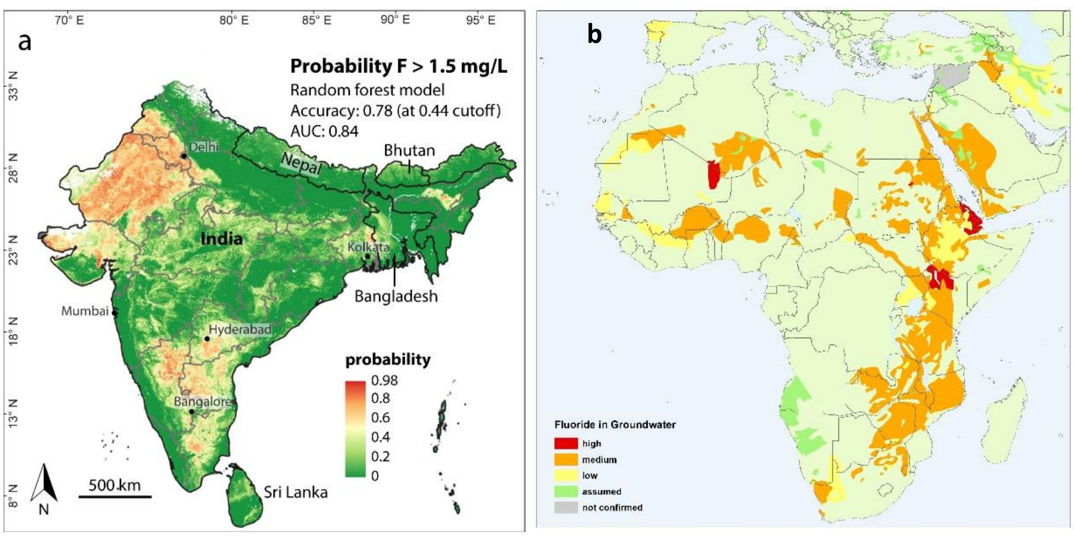


Figure 5 – Prediction of geogenic fluoride in groundwater ***(a)*** *exceeding the WHO guideline of 1.5 mg/L in India, Bangladesh, Bhutan, Nepal and Sri Lanka (Podgorski et al., 2018) and in* ***(b)*** *Africa* (IGRAC, 2004)

The main intake pathways of fluoride for humans are drinking water and food intake. Fluoride toxicity (fluorosis) occurs at higher levels of ingestion, which primarily consist of adverse effects on tooth enamel and skeletal tissue. In order to avoid excessive levels of fluoride, the WHO maintains a guideline for fluoride in drinking water of 1.5 mg/L. However, some countries, particularly in warmer climates, recommend a lower limit of 1.0 mg/L because of higher water consumption. Hotspots of groundwater fluoride include India (Figure 5a), Mexico and the East Africa Rift System (Figure 5b). It is estimated that 9% of the Indian population (120 million people) is potentially exposed to fluoride concentrations exceeding 1.5 mg/L (Podgorski *et al*., 2018), whereas the total population in the East African Rift affected by fluoride reaches 80 million (Kut *et al*., 2016), with more than 13 million people in Ethiopia living in high fluoride risk areas (Demelash *et al*., 2019).

Iron (Fe) and **manganese (Mn)** are two of the most abundant metals in the Earth's crust, and usually occur in association. Both elements are present in a range of rock forming minerals in igneous/metamorphic rocks and associated derived sediments and sedimentary rocks. Fe/Mn can also be introduced into various hard rock lithologies via hydrothermal oxide mineralisation in fractured zones, combined with later secondary supergene enrichment by groundwater flowing along preferential fracture paths (Figure 6). The form and solubility of Fe/Mn in groundwater is strongly dependent on the pH and redox potential of groundwater with Fe/Mn being mobile in either acidic or anaerobic groundwaters, with dissolved oxygen, dissolved organic carbon (and associated organic compounds such as humic, fluvic and tannic acids), salinity, sulphur and/or carbonate species also acting as controlling parameters.

Elevated Fe/Mn concentrations (usually above ~0.3 mg/L and ~0.1 mg/L respectively) can have a range of aesthetic and operational issues (with associated high investment, management and operation costs), if not removed through some form of in-situ borehole or post-abstraction groundwater treatment. Aesthetic problems from elevated Fe/Mn includes changes in the colour and turbidity of water (with an associated, unpleasant metallic taste), and the orange/black staining of laundry clothes and walls (following washing/irrigation and exposure to atmospheric oxygen). Most importantly from an operational aspect, elevated Fe/Mn can cause clogging/blockages of boreholes (Figure 6) and associated aquifer matrix/fractures (reducing borehole/aquifer yield), as well as water/sanitation/irrigation reticulation infrastructure. This clogging is a result of the development of Fe/Mn oxide/hydroxide precipitation (due to oxygen ingress into the borehole during pumping) and associated bacterial sludge (via biofouling *i.e.* accumulation of Fe/Mn bacteria biofilms, which can also cause microbial-induced corrosion) (Figure 6). Biofouling of boreholes, pumps and water reticulation infrastructure requires expensive periodic cleaning in order to ensure the continued functionality, operability and viability of groundwater abstraction systems.

There are no immediate health risks of elevated Fe in drinking water (WHO has no Fe drinking water guideline, although some countries *e.g.* South Africa have chronic health limits of <2 mg/L for Fe). Toxic symptoms are only observed after massive intake *e.g.* Fe concentrations of ~10-30 mg/L can have chronic health effects in young children and sensitive adults such as haemochromatosis (where tissue damage occurs as a consequence of Fe accumulation). Long term health impacts are increasing at Fe concentrations of ~30-100 mg/L. Mn toxicity can potentially occur in humans, and the WHO drinking water guideline is <0.4 mg/L. Elevated Mn can cause respiratory (*e.g.* lung embolisms and bronchitis) and neurological (*e.g.* hallucinations, nerve damage and Parkinson's disease) problems. Elevated Fe concentrations above 5 mg/l may cause foliar damage to plants due to Fe precipitation, whereas elevated Mn can be toxic to various plant types (with Mn concentration toxicity dependent on the plant species).

a) 

b) 

Figure 6 –a) Iron and manganese hydrothermal mineralisation within fractured quartzitic sandstones of the Table Mountain Group (TMG) near Cape Town, which results in highly elevated Fe (>30 mg/L) and Mn (>5 mg/L) concentrations within deep fractured TMG aquifer groundwater; b) Iron biofouling from a production borehole within the primary dune sediment Atlantis Aquifer near Cape Town (where iron-coated quartzitic sediment is derived from iron-rich TMG lithology), indicating clogging of pump and water reticulation infrastructure (photos Umvoto Africa).

Another potentially hazardous but infrequently monitored geogenic contaminant is **chromium (Cr)**, which is also found in localized anthropogenic contamination associated with industrial activities or mining. In natural settings, high chromium concentrations are found predominantly in mafic aquifers, with mobility being influenced by pH (Oze *et al*., 2007). Geogenic chromium has been reported in aquifers in Europe and North and South America (Coyte *et al*., 2020). Although an essential element, high doses of chromium can possibly be carcinogenic, thus the WHO has a set a provisional guideline value of 50 µg/L (WHO, 2017).

Rock and soil contain trace amounts of naturally occurring radioactive substances that can accumulate in groundwater and negatively affect its utilization. Most relevant natural radionuclides of concern for water supply are the water-soluble products of the uranium and thorium radioactive series (Figure 7) of **uranium (^{238}U, ^{234}U), radium (^{228}Ra, ^{226}Ra) and radon (^{222}Rn)**. However, individual cases of other radionuclide anomalies in groundwater such as highly toxic **polonium (^{210}Po)** have also been reported (Seiler *et al*., 2011). Due to its short half-life ($t_{1/2}$) of 3.8 days and volatility, ^{222}Radon might be of concern only when the time between groundwater extraction and its use is short.

Dissolved uranium is often present in groundwater because of its moderate mobility, long half-life and relative abundance in the earth's crust. The chemotoxicity of uranium is generally more significant than its radiotoxicity. However, in the presence of other radionuclides its contribution to gross activity concentrations might result in an excess of screening or guidance levels (WHO, 2017). Uranium concentrations exceeding the WHO guideline (30 µg/L) for drinking water have been found all over the world and are generally observed for oxic groundwater. Uranium concentrations strongly correlate with calcium and carbonate. The formation of uranyl carbonate complexes may allow uranium to be mobile at concentrations over 1 mg/L (Gascoyne, 2004). Elevated dissolved uranium concentrations may originate from ore–grade deposits in sedimentary, granitic and volcanic host rocks, (Fujii & Swain, 1995) as well as uranium-enriched sedimentary facies associated with marine phosphorites that occur throughout North Africa and the Middle East (Smith *et al*., 2000).

The radium nuclide ^{226}Ra is the fifth member of the ^{238}U-decay series and the most abundant radium isotope in the environment in terms of mass due to its half-life of 1602 a. The second member of the ^{232}Th-decay series is ^{228}Ra ($t_{1/2}$ 5.8 a). Due to expensive and time-consuming radiochemical analysis, radium is generally not part of groundwater quality monitoring programmes. Nevertheless, a wide range of radium activity concentrations in groundwater has been reported worldwide. Anomalously high radium activities exceeding 10 Bq/L have been found in the United States (Herczeg *et al*., 1988; Kitto *et al*., 2005), Europe (Dragović *et al*., 2012), the Middle East (Arabi *et al*., 2006; Kiro *et al*., 2015; Smith *et al*., 2000), and Africa (Ajayi & Owolabi, 2008; Post *et al*., 2017). Activity concentrations are generally related to uranium content in underlying sediments and bedrock and the geochemical environment. Dissolved radium is controlled by the availability of surface adsorption sites, which depends on the clay content and oxides in the aquifer rocks (Vengosh *et al*., 2009). The complex mechanisms resulting in radium mobilization and transport are not yet completely understood. The common assumptions that high dissolved radium occurs primarily in reduced, acidic, and/or saline groundwater is contradicted by observations in the Middle East where high dissolved radium concentrations occur in low-salinity, neutral-pH and oxygenated groundwater.

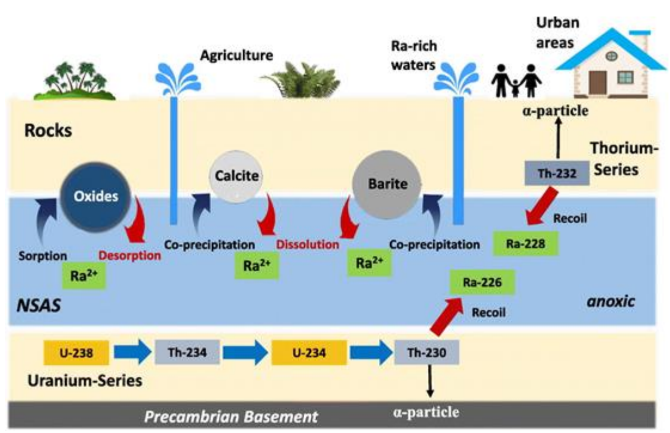


Figure 7 – Origin of Ra-isotopes and mobilization mechanism in groundwater of the Sinai peninsula (NSAS: Nubian Sandstone Aquifer; (Sherif et al., 2018))

3.3. Climate change

Groundwater quality may be impacted by climate change, which needs to be taken into account in groundwater assessments (Burri *et al*., 2019). A well-known mechanism is through rise in sea levels and its impacts on coastal groundwater resources through coastal flooding and/or accelerated seawater intrusion (Delcour *et al*., 2015; Ranjan *et al*., 2006). This may be exacerbated through increased pumping in coastal areas and by concomitant land subsidence (Post *et al*., 2018). The combination of higher sea levels and more intense weather systems under future climate makes lower lying coastal regions more susceptible to episodic flooding/inundation, storm surges, tsunamis, and salinization. Certain regions, such as deltaic settings and smaller low-lying islands with naturally thin freshwater lenses underground, are particularly vulnerable (Comte *et al*., 2014; Khan *et al*., 2011; Oude Essink *et al*., 2010).

Other impacts may be due to changes in land use that are brought about, in part, as a response to changes in climate (Scanlon *et al*., 2005). Examples include the intensification or expansion of agriculture, and the associated increased use of fertilizers and plant protection products (*e.g.* pesticides) (Bloomfield *et al*., 2006; Delcour *et al*., 2015; Stuart *et al*., 2011). Both of these changes can be driven by changes in climate, bringing new and different pests as well as putting more pressure on existing agricultural land. One of the drivers for urban migration is climate change (Hugo, 2011; McLeman & Hunter, 2010; Tacoli, 2009), and the increases in population may lead to increased urban groundwater contamination in some regions.

Intensification of seasonal rainfall, resulting in increased flooding risk, is projected for many regions globally (Prein *et al*., 2017). This has the potential to impact groundwater quality in several ways (Delpla *et al*., 2009; Levy *et al*., 2016; Taylor *et al*., 2013). Firstly, directly through increased surface ingress of faecal and other surface-derived contaminants to shallow, more vulnerable groundwater sources such as springs and shallow hand-dug wells (Howard *et al*., 2003; Sorensen *et al*., 2015). Increased surface flooding may cause highly vulnerable groundwater sources to become unsafe for human consumption (Brouwer *et al*., 2007; Schreider *et al*., 2000; Ward *et al*., 2021). Secondly, long-term changes in hydrology due to changes in rainfall intensities may render sites which are today only rarely affected by surface flooding unsuitable for water supply in the future. Thirdly, rapid recharge processes, for example via focussed recharge from ephemeral surface water bodies, through fissure flow in some basement and karstic terrains, may be intensified (Cuthbert *et al*., 2019), and with that there is risk of increased contaminant loading to groundwater (Butscher & Huggenberger, 2009). Intensified and prolonged droughts, likewise projected under climate change, may increase the use of non-sewered sanitation in less developed or serviced areas, which can indirectly enhance the contamination load to groundwater (McGill *et al*., 2019).

Changes in global temperatures may impact on groundwater quality, *e.g.*, changing survival times for groundwater microbes, changing physical and biochemical reactions in the subsurface linked to carbon breakdown, dissolution processes, denitrification and trace element mobility (Hunter, 2003; McDonough *et al*., 2020). Higher concentrations of algae and other microbial populations in surface water due to higher temperatures may likewise provide recharge water of relatively poorer quality (Delpla *et al*., 2009). The character and mix of contaminants may also change with climate change, due to new requirements for materials, substances, pharmaceuticals, and personal care products (Balbus *et al*., 2013; Redshaw *et al*., 2013). Through the processes described above the groundwater contaminant and treatment challenges of today may change and potentially intensify under projected climate change.

4. Challenges and opportunities for a global groundwater quality assessment

4.1. Methodological challenges

4.1.1. What are priority parameters?

Based on the discussion in Section 3, priority contaminants include salinity (usually monitored as electrical conductivity, EC), acidity (pH), major ions, nitrate, microbiological pollutants, contaminants of emerging concern (CECs – pharmaceuticals, etc) and geogenic parameters, notably arsenic, iron, manganese, fluoride and radionuclides. However, a major question is: what groundwater quality parameters can be brought into a global water quality assessment, which are scientifically sound and can easily be "upscaled" to a global assessment, while bearing in mind that many/most groundwater quality issues are local? The work of the GEMS/Water project in contribution to the UN-Water Integrated Monitoring Initiative focused on SDG 6.3.2 (ambient water quality) is relevant here: the core groundwater parameters are EC, pH and nitrate, whilst the full set constituting this indicator parameters also include phosphate and oxygen relevant in addition in surface waters.

Whatever parameters are monitored, it is essential to ensure that the data are as accurate and reliable as possible. This includes using appropriate field and laboratory sampling, storage and analysis methods; applying proper quality assurance protocols; taking care in data entry and data transfer within and between databases, etc. Often laboratories performing the chemical analysis are accredited and have established quality procedures. However, the field sampling and analysis rarely has this level of quality assurance. Frequently forgotten in the context of sample quality is the suitability and condition of site infrastructure (bores or wells) for sample integrity.

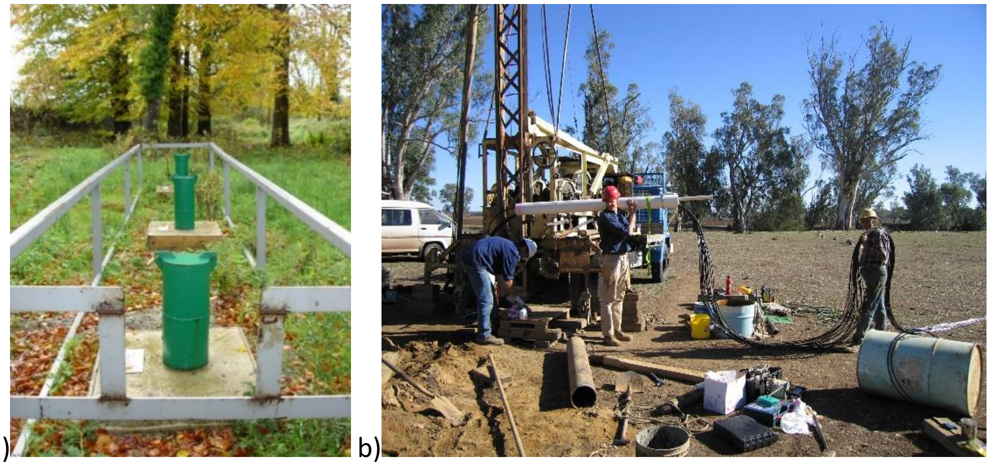
4.1.2. Upscaling local studies to regional assessments

Many pollution sources are localised, in addition to the significant natural variations in geology and hydrogeology across the aquifer systems of the planet. This means that pollution impacts on wells are often site-specific, making regional upscaling of results difficult.

Local studies will need to be upscaled to regional assessments, but how should this be done? There are some potential ways forward, for instance the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) proposed a machine-learning approach at a larger, possibly global level (see Section 5.1). Machine learning has been also used at the African scale (Ouedraogo *et al*., 2019) with good results, for geogenic contaminants such as fluoride. These types of approaches still require more research before they can be applied at a global scale for contaminants introduced, or at least mobilised, by human activities, including salinity (EC), chloride, microbes, nitrates, phosphorus, trace metals, trace organic compounds, etc.

4.1.3. The 3rd (3-D flow) and 4th (time) dimensions

One major complexity of assessing groundwater quality arises from the 3-D nature of flow systems. Groundwater systems are often highly heterogeneous, meaning that samples from wells in close proximity may produce very different results, especially if they are taken from different depths. Well construction may also impact on the groundwater quality data: for example, two wells of identical depth may produce contrasting groundwater quality results if one of them is constructed with a grouted upper well casing and the other is not. It is therefore necessary to monitor groundwater quality at different depths using special borehole designs such as clusters, piezometer nests or using multi-level devices (Misstear *et al*., 2017). Figure 8 shows an example of a cluster of boreholes constructed to allow water samples to be collected from specific depth intervals.



a) b)

Figure 8 – a) Cluster of boreholes to monitor groundwater level and quality at different depths (source: B. Misstear), b) Multi-level sampling device being installed at a site in Australia (source: M. Andersen)

The impact of the 3-D nature of groundwater flow on pollution pathways is illustrated in Figure 9. On the left-hand side of the diagram, the geology comprises a low transmissivity, poorly productive fractured bedrock aquifer overlain by clayey soils and subsoils. Here, flow pathways and hence pollutant transport mainly occurs in the shallow fractured and weathered bedrock layers, or in local permeable zones within the subsoils. On the right-hand side of the diagram, in contrast, the subsoils and aquifer are more permeable, and contaminants may follow deeper pathways. The design of the monitoring system must thus take account of these hydrogeological and contaminant characteristics.

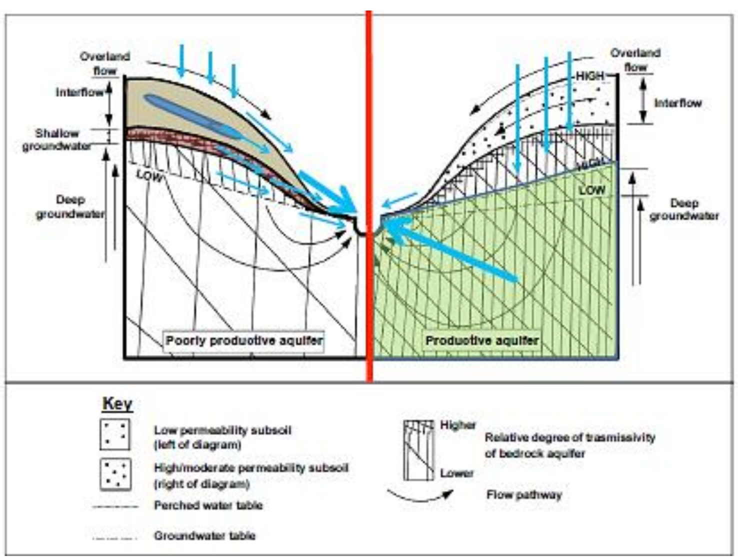


Figure 9 – Contaminant pathways present in low transmissivity poorly productive aquifers (left) and productive aquifers (right) (Archbold et al., 2016).

Other complexities are the long transport times involved in many groundwater flow systems. Groundwater pollution and rehabilitation may take place over considerably longer timescales than a surface water contamination problem. For example, nitrate currently stored in the unsaturated zone may result in contamination of the underlying aquifers for many decades (Ascott *et al*., 2017). Thus, present day land use and industrial practices may leave long-term legacy issues relating to groundwater pollution. As well as long term issues, groundwater quality may vary seasonally, or respond to local short-term rainfall. Microbiological contamination of wells, for example, is often closely related to individual rainfall events. Hence monitoring programs should be designed to collect groundwater quality data at the required frequency to show the temporal changes.

4.1.4. Poor sampling or analysis procedures; poor monitoring well construction

For river systems, sampling downstream along the river gives an integrated picture of the water quality pressures from the catchment, but this is not the case with groundwater systems. Often boreholes designed for monitoring water levels are subsequently adopted for measuring water quality, even though their location and construction may be unsuitable or suboptimal for this purpose. Moreover, groundwater sampling data may be unrepresentative because of poor sampling or analysis procedures (Section 4.1.1).

Boreholes for monitoring groundwater quality need to be sited carefully, and to be constructed to permit collection of water samples at the required depth intervals (Fetter et al., 2018). The construction materials, sample collection and handling procedures must be chosen to avoid reporting “false positives” and “false negatives”. This is especially important when dealing with contaminants that are redox sensitive (unstable in air), volatile or present in groundwater in trace concentrations, including the contaminants of emerging concern (Section 3). The materials therefore must not sorb contaminants from the water sample, nor leach contaminants. Field personnel need to be trained to a high level to ensure that they can obtain representative samples.

4.2. Mandate and use of national data sources

Currently data on groundwater quality is scarce due to the lack of national monitoring programmes for groundwater quality in many countries and the limited public accessibility of data from those who have national monitoring networks. With exceptions such as the requirements of the European Union (EU) Water Framework Directive (WFD), many states and national agencies are not required to make available data and information on groundwater quality. Even if data is publicly available, questions arise about its reliability, representability and quality, unless there was a quality assurance process to international standards.

Additional challenges arise from existing monitoring programmes that are focused towards drinking water quality (for human health) or irrigation water quality and less frequently for ecosystems. All of these require different standards of “good” water quality. Especially in the Global South, existing monitoring programmes may focus on few basic quality indicators of palatability (*e.g.* major ions) with less capacity to measure parameters of health concern (As, F and bacteria) (Kreamer & Usher, 2010). The impacts of groundwater quality on the operation of groundwater abstraction schemes and wellfields is also rarely accounted for or monitored. Once again this is especially the case in the Global South, where poor groundwater management (*e.g.* incorrect borehole pumping regimes) can lead to clogging of boreholes (resulting in declining yields) and failure of abstraction infrastructure as a result of iron/manganese oxide/hydroxide precipitation, and the consequential “failure” of groundwater supplies.

For interpretation, individual monitoring data need to be seen in the context of the sampling methods, locations, sampling wells or boreholes, depths, sampling protocols and lab analyses performed. Often this additional information is not available. Additionally, data may be stored at different institutions and not in a central national repository or at one institution responsible for keeping and making available groundwater quality data.

Public accessibility of groundwater quality data is further hampered by national restrictions to make groundwater data available for research or multi-lateral reporting and assessment purposes. There are, however, examples of international norms that offer guidance how such data can be better made available for the public (*e.g.* United Nations Economic Commission for Europe [UNECE] Aarhus convention, EU WFD, etc). Additionally, incentives can be developed to encourage academia and industries to contribute to regional and national assessments.

Most monitoring programmes for groundwater quality are based on national level legislation and regulations, where these exist. Special care is required for groundwater quality challenges in transboundary aquifers. To fill knowledge gaps and prepare an improved and fair basis for transboundary cooperation requires development of comparable standards for the aquifers, data sharing and joint capacity development programmes.

4.3. Opportunities to use Citizen Science to monitor groundwater quality

Attempts to monitor the quality of groundwater resources in most regions of the world reveal huge data gaps (San Llorente Capdevila *et al*., 2020). Citizen Science, the collection and analysis of data by members of the public as part of collaborative efforts with scientists (Buytaert *et al.*, 2014), is an innovative approach to the generation and monitoring of groundwater quality data. However, several attributes of citizens and the conceptualization of Citizen Science activities can affect the success, including knowledge, technical capacity and awareness of environmental issues of citizens, incentive structures for participation, and the weight given to empowerment of local stakeholders versus capturing data for the main purpose of science (San Llorente Capdevila *et al*., 2020). The variation of these attributes across different regions calls for standardized and regionally contextualized Citizen Science approaches. Graham & Taylor (2018) suggest that with appropriate training, facilitation and support, most of the inhibiting factors can be overcome even in resource-constrained environments such as South Africa.

Examples of Citizen Science approaches in gathering groundwater quality data are growing but still scarce. The advantage is that a small subset of easily measurable water quality indicators (conductivity, temperature, turbidity) can serve as a starting point, and the motivation due to the tangible effects of water quality deterioration on the health and wellbeing of environments and citizens could help spark the interest of scientists and citizens to jointly implement Citizen Science. However, the need for proper sampling of groundwater bodies and water wells pose extra challenge in using Citizen Science for groundwater quality monitoring. The use of generally available mobile phone technology to collect and share data among scientists and citizens makes it attractive in most contexts.

The vast majority of Citizen Science based groundwater quality data gathering is currently conducted in North America and Europe (Baalbaki *et al*., 2019). A growing number of cases of Citizen Science based monitoring of groundwater quality have been deployed elsewhere, showing that data quality was similar to the quality achievable through monitoring by scientists (Baalbaki *et al*., 2019; M. Graham & Taylor, 2018; WES NET INDIA, 2006). Notably, in developing nations, youth groups are becoming actively engaged in Citizen Science.

4.4. Earth Observations

Remote sensing Earth observations, which are widely used to assess surface water quality, also have groundwater applications.

For groundwater applications, satellite-based gravity measurements have been widely used to evaluate changes in groundwater storage, highlighting global regions vulnerable to unsustainable groundwater depletion (Rodell *et al*., 2018). However, the coarse spatial resolution of current satellite-based groundwater assessments is insufficient for local-scale management (Scanlon *et al*., 2015). For example, satellites have helped highlight the unsustainable groundwater depletion in northern India and Pakistan, but higher-resolution in situ groundwater quality data reveal that contamination is an even larger problem, with more than 60% of the aquifer restricted by excessive salinity or arsenic (MacDonald *et al*., 2016).

Thus, there is a significant need for global understanding of groundwater quality data to complement our increasing ability to measure global groundwater storage. Although Earth observing satellites do not provide direct measurements of groundwater quality, recent research shows that they can produce proxies related to groundwater contamination processes and thereby provide indirect insights. (Poulin *et al*., 2020) showed that Earth observations about population density, road density, precipitation, temperature, and landcover in Uganda and Bangladesh were strongly correlated with microbial contamination levels in shallow groundwater. The authors produced country-level maps of a "microbial groundwater contamination index" derived from Earth observations.

More generally, Earth observations can support predictive modelling efforts as they can provide additional variables to include in predictive models. For example, predictions of nitrate and herbicide concentrations in groundwater rely on information about anthropogenic activities (*e.g.*, landcover, population density), which can be derived from Earth observations (Anning *et al*., 2012; Stackelberg *et al*., 2012). Similarly, information on soil salinity can be retrieved from Earth Observations and input to predictive models of groundwater salinity (Taghadosi *et al*., 2019). Vulnerability mapping can be derived from Earth observations and available spatial datasets. The Cape Town Aquifer Use Case (see Box) provides a local scale example.

Furthermore, several studies have employed Earth observations, or products derived from them, to develop continental- and global-scale models of geogenic groundwater contamination by arsenic (Ayotte *et al*., 2017; Podgorski *et al*., 2017, 2020; Podgorski & Berg, 2020; Rodríguez-Lado *et al*., 2013; Wu *et al*., 2020) and fluoride (Amini, Mueller, *et al*., 2008; Podgorski *et al*., 2018).

Sources of large-scale geospatial datasets, including Earth observations, that can serve as explanatory variables in predictive models of groundwater quality are listed in Appendix A2.

Box 2 – Lessons learned from UNEP WWQA Use Cases – the case of the Cape Town Aquifers

At the 2018 Inception Workshop in Geneva, the WWQA decided to pilot and demonstrate current capabilities and future water quality information services through three use cases in Africa, aiming to build the "use cases" contributing both, to a global water quality assessment (GWQA) and to establishing engagement with water sector stakeholders to co design water quality improvement products/pathways. One of these cases focuses on the aquifers in and around Cape Town: Atlantis, Cape Flats and the Table Mountain Group aquifers.

The Cape Flats Aquifer (CFA), reported specifically here, is a sedimentary primary aquifer in an urban setting that is highly vulnerable to pollution from current land use activities, including small-scale agriculture (mostly irrigated), landfill sites, cemeteries, industrial areas, sand mining and informal settlements without proper sanitation.

The urban setting of the CFA results in salinization and anthropogenic contamination with nutrients, microbiological and industrial compounds, including hydrocarbons and potentially emerging organic contaminants.

- The salinity in some areas of the aquifer is above expected and guideline values, with elevated EC values of 3000-7000 µS/cm possibly due to stormwater ingress and irrigation return flow. The extensive abstraction and further wellfield development pose an additional risk of saline intrusion.
- Nitrates are generally low with no evidence of diffuse fertilizer contamination within the agricultural areas. Elevated concentrations are linked to point sources such as poorly functioning wastewater treatment plants and cemeteries. Higher N-concentrations are also found in some canals and rivers.
- Presence of elevated contaminants such as hexavalent chromium and trichloroethylene in CFA groundwater is shown near industrial areas and landfill sites.

The extensive in-situ monitoring data collected over the three-year period (2017 – 2020), as part of the City of Cape Town's groundwater development project, was supplemented with remote-sensing EO data to provide a detailed land-use map identifying potential pollution sources and GIS-based vulnerability mapping that confirms the in-situ data and links the identified hotspots to pollution sources and high aquifer vulnerability.

Numerical groundwater flow and transport modelling assisted in developing groundwater protection zones around the current wellfields to stop further water quality deterioration. The ongoing stakeholder engagement was crucial for the water quality assessment and development of an aquifer protection plan, comprising a risk assessment regarding potential pollution and delineation of protection zones with associated restrictions on land use activities.

These findings can be extrapolated to other urban centres with similar geological settings, and the approach can be adopted for more regional groundwater quality assessments.

5. What sources of data and information already exist?

Groundwater data and information exist at different scales (global, regional, national, local), and can also be derived from alternative sources (*e.g.* modelling, land use data), as covered in Section 4.4.

Regional data can be found as part of regional studies or via regional organisations. For instance, the European Environmental Agency provides a map of nitrate in groundwater by country and WFD groundwater bodies (EEA, 2014). Another example is the study from (Ouedraogo & Vanclooster, 2016) where around 250 studies on nitrate contamination in Africa were compiled and combined with other variables to model the presence of nitrate in groundwater at the African scale.

5.1. Global sources of information

Global sources include assessments, overviews, studies and data portals. Some examples are the assessments of the probability of excessive concentrations of arsenic and fluoride produced by the International Groundwater Resources Assessment Centre (IGRAC) in 2004 (Brunt *et al*., 2004a, 2004b). IGRAC produced two more overviews on arsenic and fluoride in 2007, which included an evaluation of removal methods (Feenstra *et al*., 2007; Feenstra & Erkel, 2007) and a global overview of saline groundwater occurrence (van Weert *et al*., 2009). Another global assessment was made by Griffioen *et al*. (2004) which compared status among regions and differences in the contaminated status from the natural one. The study was based on publicly available information on the internet, publications, reports and maps, including environmental state reports such as the ones prepared by the UN Environment Programme, and other national and non-governmental organisations.

More recent developments come from EAWAG, that hosts the Groundwater Assessment Platform – GAP (EAWAG, 2020), a free interactive web-GIS platform and knowledge hub for groundwater quality (Figure 10). The portal contains several groundwater quality prediction maps: two global maps of probability of arsenic concentration in groundwater exceeding the WHO guideline of 10 µg/L (Amini, Abbaspour, *et al*., 2008; Podgorski & Berg, 2020), a global map on global population density at risk of exposure to arsenic in groundwater exceeding 10 µg/L (Podgorski & Berg, 2020), a global map on probability of fluoride concentration in groundwater exceeding the WHO guideline of 1.5 mg/L (Amini, Mueller, *et al*., 2008) and a variety of national maps, such as the prediction map of arsenic in groundwater exceeding 10 µg/L for Pakistan (Podgorski *et al*., 2017), and an arsenic prediction map for China (Rodríguez-Lado *et al*., 2013). These maps are the result of studies based on modelling techniques. For instance, the study of Podgorski & Berg (2020), with the goal of creating a global prediction model of the occurrence of geogenic arsenic, utilized machine learning modelling to relate 11 spatially continuous environmental parameters of climate, geology, soil and topography with more than 200,000 groundwater arsenic measurements. Combined with country-level statistics of urban and rural groundwater usage, 94-220 million people were estimated to be potentially exposed to hazardous concentrations of arsenic in drinking water.

Moreover, GAP includes two global maps of arsenic and fluoride concentrations.

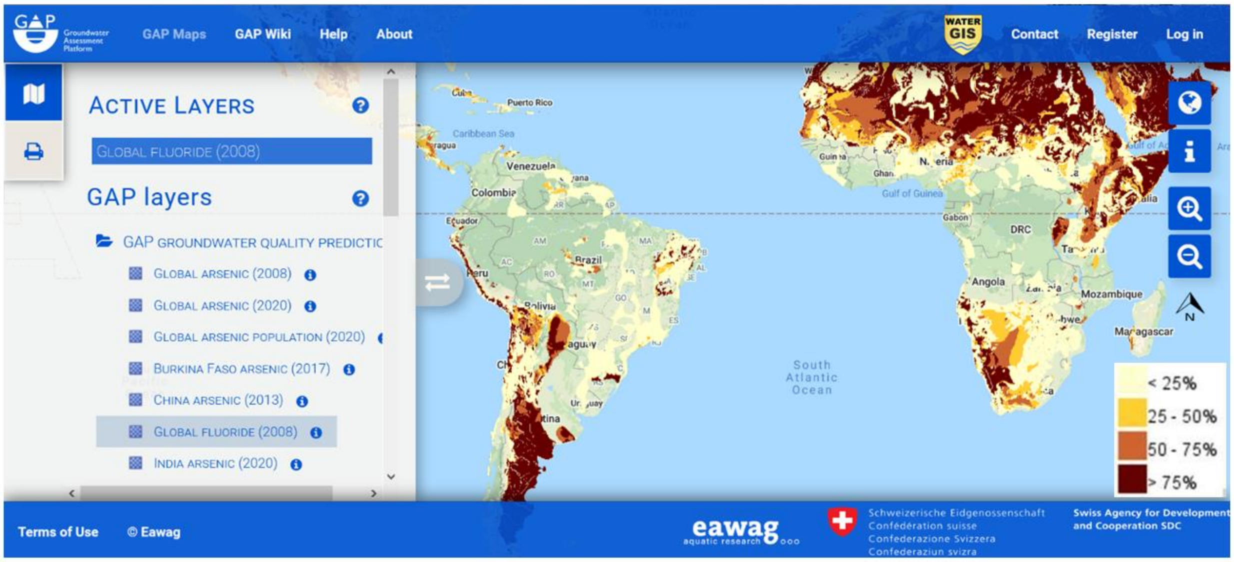


Figure 10 – GAP Platform (EAWAG). Map of probability of fluoride concentration in groundwater exceeding the WHO guideline of 1.5 mg/L (Amini *et al*., 2008).

Another source of global data is GEMStat (GEMS/Water, 2020), the Global Freshwater Quality Database hosted, operated and maintained by the International Centre for Water Resources and Global Change, ICWRGC in Koblenz, Germany, within the framework of the GEMS/Water Programme of UNEP and in cooperation with the Federal Institute of Hydrology of Germany. GEMStat provides scientifically sound data and information on the state and trend of global inland quality. Currently, the database contains more than 7 million entries for river, lakes, reservoirs, wetlands and groundwater systems from 75 countries, and groundwater quality data from 2,544 stations. Parameter groups considered are organic and inorganic compounds, temperature, coliforms, and more.

An additional United Nations (UN) portal is the SDG 6 Data Portal (UN-Water, 2020), which brings together data on all the SDG 6 global indicators and other key social, economic and environmental parameters. Most of the data comes from countries and is globally compiled by the UN. Related to groundwater quality, the portal presents data on the proportion of groundwater bodies with good water quality. However, only 26 countries reported on the status of groundwater, which is not sufficient for a global overview.

There are other sources of global groundwater quality data but without open access. One example is the Global Water Chemistry Database – GLOWACHEM (UHH, 2020) maintained by the University of Hamburg (UHH), which is used together with the Helmholtz-Institute Climate Service Science, (HICSS) to identify the impact of climate and land use change on groundwater. The database includes major compounds, trace elements, isotope, nutrients, as well as environmental information on lithology, climate, soil, land-use, etc. Another example is the data collected by the International Atomic Energy Agency (IAEA) using isotope techniques, such as the study by the Bangladesh Atomic Energy Commission (BAEC) from 2016 to 2019 to identify groundwater free of arsenic and sea water intrusion (Peeva, 2020), and the IAEA technical cooperation in the Sahel Region that studied and mapped five transboundary aquifer systems (Jarvis, 2018). IAEA also hosts the Global Network of Isotopes in Rivers – GNIR (IAEA, 2013) which is aimed at a better understanding of stream-aquifer interactions. Part of GNIR data is online via WISER (Water Isotope

System for Data Analysis, Visualization and Electronic Retrieval), but it is only accessible for selected users (part of NUCLEOUS – IAEA internal system).

5.2. Alternatives sources of information

As many contaminants are linked to specific uses (*e.g.* agricultural or industrial), a land-use database may provide an indication of the presence of potential contamination sources. In addition, a database holding commercial registration of companies can be used to assess potential groundwater contamination sources. Combined with insights from the hydrogeological system, potentially impacted zones can be derived, based on groundwater flow direction and rate.

Since groundwater systems are often connected to local surface water systems, surface water quality data may help to provide an indication of the quality of groundwater near surface waters. One source of surface water quality data is the Joint Monitoring Programme, JMP global database jointly managed by WHO and UNICEF, which includes around 5,000 national databases, with parameters related to drinking water, sanitation and hygiene.

As shown in Section 4.4, Earth observation data can be used as a proxy for certain aspects of groundwater quality monitoring. Appendix A2 presents a list of datasets that can be used for groundwater quality modelling.

In conclusion, there are several sources of data (both directly on groundwater quality and "proxy" data) but more data and effort is needed to facilitate the integration of different sources, methods and scales.

6. Groundwater Quality Management

The groundwater quality aspects and concerns highlighted in the previous sections can and should be managed to avoid these concerns developing into problems, stop the increase of the pollution, and reduce the impacts of the water quality issues on the environment and human health.

For instance, the South African National Water Act identifies several functional approaches to provide adequate protection and efficient management of groundwater quality:

- A source-directed approach to prevent and minimize, at the source, the impact of development on groundwater quality by imposing regulatory controls and providing incentives. This can be enforced by developing and implementing standards, monitoring protocols, on-site management practices and certain requirements and permits that pertain to the protection of groundwater quality.
- A resource-directed approach to groundwater quality management by implementing measures to protect the aquifer and ensure sustainability and suitability for beneficial use. Vulnerability mapping, development of groundwater protection zones and associated land-use planning provide the basis for the decision-making and setting resource-quality objectives. With respect to geogenic water quality issues, measures such as restricted usage, limited drawdown to avoid ingress of water with different water quality and other operational requirements to minimize the risk of water quality deterioration can be defined and implemented.

- A site- and needs-specific approach to the remediation of degraded groundwater. These can include source removal, pump-and-treat options, interruption of pathway, in-situ treatment and bio- or phyto-remediation.

A water quality assessment is the first step for developing a framework to protect the water quality of an aquifer. Several procedures need to be deployed to achieve this, including:

- Location of abstraction borehole(s)/wellfield(s) and or sensitive receiving ecosystems,
- Demarcation of groundwater protection zones (GPZ) based on the available hydrogeological information on groundwater flow, recharge, discharge and travel time,
- Vulnerability mapping to guide future spatial and land-use planning, *e.g.* deciding the future placement of potential contaminating activities.
- Identification of existing potentially contaminating activities (PCAs) that may be considered a possible origin of microbial and/or chemical contamination within a groundwater source area.

GPZs are put in place to ensure the integrity of the groundwater quality within the aquifer. They are generally subdivided into four different zones, based on the risk imparted on the drinking water source (Figure 11). Each zone requires different assessment, protection, and management measures. The risk of groundwater contamination has a direct link to land-use and increases with human activity. GPZs aim to protect drinking water sources by controlling land-use in the capture zone. A summary of the zones used internationally are listed below:

- A zone adjacent to borehole to prevent the rapid ingress of microbial and direct chemical contamination. This zone represents the highest risk to the groundwater quality.
- An inner zone based on the expected time needed for a reduction in pathogen presence in groundwater.
- An outer zone based on the expected time needed for the dilution/attenuation of slowly degrading inorganic compounds.
- The groundwater catchment, whereby all water will eventually meet the abstraction point. This zone represents the lowest risk to the groundwater quality.

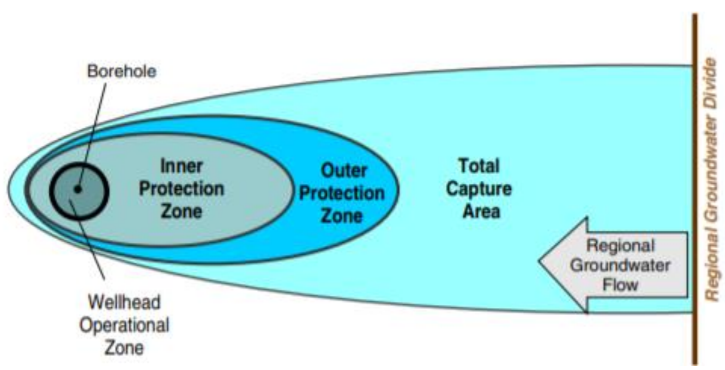


Figure 11 – Groundwater Protection Zones around a production borehole (Rajkumar & Xu, 2011).

There are many methods available for assessing groundwater vulnerability, each with its own unique application and data input requirements. A common method is the vulnerability assessment DRASTIC (also known as pollution potential) set out by the US Environmental Agency (Aller. *et al*., 1987). DRASTIC takes its name from: D = Depth to water table, R = Net recharge, A = Aquifer media, S = Soil media, T = Topography, I = Impact of the vadose zone, C = Hydraulic conductivity.

The vulnerability map is then overlaid with the GPZs and PCAs to identify areas that are at high risk of contamination. In areas of concern, different management strategies can be deployed to help mitigate contamination issues.

Groundwater quality management instruments include:

- Water quality assessment as described in previous chapters,
- Vulnerability mapping, protection zoning and land-use spatial planning that considers groundwater quality and protection as an integral part,
- Development of a green economy and promoting water sensitive urban design to minimise risk of pollution, including local by-laws and financial incentives,
- Legal and regulatory instruments such as permits for waste discharge or operating PCAs, fines for transgression or pollution, requirements for monitoring and enforcement, and
- Cooperative governance across all spheres of government and private sector.

7. Key messages

This perspective paper aims to provide a compelling argument for the importance of groundwater quality for human development and ecosystem health. It also provides a global overview of the current knowledge, with focus on data coverage, gaps and technological advances. It is a building block towards a future global assessment of groundwater quality. The following key messages are a synthesis of the current knowledge and capacity base, while recommending focus areas for future work. The key messages are meant to help inform the process and further building blocks required to move towards a coordinated global assessment of groundwater quality.

1. Increased attention to water, and specifically groundwater quality, is of utmost importance for the achievement of the Sustainable Development Goals, especially related to water security (SDG 6), health (SDG 3), and food production (SDG 2). Groundwater quality is under increasing pressure due to human development and the impacts of climate change posing risk to human consumption and affecting to a large extent disadvantaged vulnerable groups in society.
2. A dedicated global groundwater quality assessment is necessary and timely. It will provide a comprehensive and coordinated overview of the knowledge base pertaining to groundwater quality, including mapping of main drivers, pressures, trends and impacts, as well as current and prospective management approaches.
3. There is a large variability of anthropogenic and natural (geogenic) chemical and microbiological contaminants that are found or move into aquifers and groundwater systems across the globe. Their large range of characteristics and behaviours in these systems requires expert knowledge.
4. Groundwater systems are heterogeneous, three-dimensional water reservoirs in porous and fractured rock or sediment formations. Groundwater contaminant distributions are therefore particularly challenging to map. In addition, contaminant transport and remediation of pollution in these systems often involves long timescales. Hence, groundwater quality is more complex to understand, assess and remediate than quality of surface waters.

5. Information and data on groundwater quality are very variable across the globe, with often less information available in countries of the Global South. For a comparable global assessment, substantial efforts are needed to i. Improve data collection; ii. Develop the capacity and the knowledge base, with particular focus on developing countries and iii. Develop international standards.
6. Groundwater quality needs to be understood at various scales depending on the issues, *e.g.* as related to the size and vulnerability of the aquifers and receiving water bodies, the inherent or external pollution loads, land-use, waste handling, and the demand on the resource. There is a need to consider groundwater quality in relation to different end uses: *e.g.* drinking water, ecosystems, food (particularly irrigation), energy production and other industries.
7. Groundwater monitoring programmes need to be targeted and designed according to the purpose of the monitoring, *e.g.* specific contamination tracing and remediation, short-term campaigns to understand local contamination issues, and longer-term larger-scale systematic monitoring programmes to identify general spatial patterns and long-term temporal trends in groundwater quality.
8. Besides traditional groundwater monitoring programs involving water sampling in wells (points in space), upstream (soils), and downstream (receiving streams, springs, wetlands and coastal areas) need to be considered. Important new technologies and practices are becoming more commonplace, *e.g.* earth observations and GIS, citizen science, machine learning, and numerical modelling of contaminant fate and transport. Due to general lack of in-situ data, the new technologies can help extrapolate knowledge from regions with good data to areas with less information, giving some initial understanding of potential risks and vulnerabilities. In addition, vulnerability and pollution load mapping are critical factors in tracing potential groundwater pollution and designing monitoring programmes on groundwater quality.
9. Most monitoring programmes for groundwater quality are based on national level legislation and regulations, where these exist. Special attention is required for groundwater quality challenges in transboundary aquifers. To fill knowledge gaps and prepare an improved and fair basis for transboundary cooperation requires development of comparable standards for the aquifers, data sharing and joint capacity development programmes.
10. Local-to-global partnerships and investments in research, capacity development embracing gender equality and community level engagement as well as and evidence-based policymaking are required to make the step change required to manage groundwater quality sustainably.

8. Proposal for Work Plan

The Friends of Groundwater (FoG) group has developed this perspective paper with great professional enthusiasm and without a distinct, dedicated budget. The planning of urgently required future activities to position groundwater central in the discourse towards achievement of the 2030 Agenda for Sustainable Development very much depends on awareness and a global sense of urgency supported by expert engagement and adequate budget allocation. The FoG specialists convene as a high standard community of practice and has by each of its members raised awareness of the importance of regional and global groundwater quality assessment to serve human and ecosystem health. This assessment needs to remain a priority focus of the group which aims to provide the expert nucleus for a work programme and to contribute to the achievement of the SDG 6. Several other groundwater quality aspects – apart from regional/global assessment - also require increased attention (such as emerging contaminants, monitoring, thresholds, etc.) however, those need to be coordinated elsewhere (*e.g.* by setting up working groups under the IAH Commission on Groundwater Quality).

This Perspective Paper is developed through in-kind contribution of FoG specialists. Seed Funding for WWQA Work Streams is well placed to support important elements of a world groundwater quality assessment, namely the knowledge base and the assessment (upscaling) procedure. At the same time FoG specialists will continue to provide in-kind contribution. Since an assessment can be conducted at various levels of detail and accuracy, a total budget for a global assessment should be estimated separately, also in discussion with possible donors about their expectations. Since the FoG activities are a part of the WWQA, it is expected that a budget for the assessment will be raised through collective resource mobilisation with support of the World Water Quality Alliance.

In the Work Plan the short and the long-term activities will be defined. Among the short-term activities (i.e. within next year), the most prominent are completion/refinement of this paper and development of the portal, which is already being developed (see below). In the long-term, building a global Groundwater Quality (GQ) Assessment network and upscaling (*i.e.* regionalisation of local assessments) are the most important activities. Some of the main activities are described below.

- A global GQ Assessment Portal is already under development. It will be the FoG main window to the world with a main purpose of being a focal point and link to all (FoG members and others) portals and activities relevant to GQ assessment at the regional/global scale. The perspectives paper will be included in the portal, along with a reference database, a graphical interface (in particular for spatial/geographic presentation), activities of FoG and other relevant activities, etc.
- The global GQ Assessment Network will be progressively developed by including new information/current activities in the portal, through active contributions of the specialists and institutions involved. The network will grow further, alongside development of an overview of national GQ monitoring programmes. This will build on the existing work of GEMS/Water in connection with SDG target 6.3.2.
- A systematic overview of GQ Monitoring Programmes at national level will be prepared, including institutions, purpose, parameters, methodology, availability and accessibility. This activity will reveal additional information about the state and trends of GQ at national level.
- Contributing to a World Water Development Report 2022 "Groundwater: Making the Invisible Visible". The draft annotated Table of Contents was circulated for comment in November 2020 and the call for contributions is expected before the end of the year.
- Organising and participating in other activities relating to groundwater quality for World Water Day 2022.
- Contributing to the global groundwater assessment as a complementary component to the World Water Quality Assessment under preparation by UNEP with partners for the 6th Session of the United Nations Environment Assembly (Feb 2023) and featuring in the UNGA mandated "midterm comprehensive implementation review of the International Decade for Action, 'Water for Sustainable Development' 2018-2028" (UN-Water Conf. NY, March 2023)
- Assistance to national GW assessment programmes, advocacy (embedding GQ stronger in societal, economic and other environmental issues) at various levels (water programmes of

international and national funding agencies, UN agencies, multinationals, trust funds, etc.), acquisition, preparation and execution of projects, raising awareness and providing incentives (webinars, promotion videos, tailored info and kits for schools, academia, NGOs, etc.), promotion innovative approaches and technologies (*e.g.* tech/low cost sensors), and similar.

- Upscaling and regionalisation of local assessments are the main FoG research activity. It includes regional/global modelling (*e.g.* using machine learning), inclusion of "use cases" into regional assessment (*e.g.* case-based reasoning), remote sensing, Citizen Science, etc. When presenting and reporting on GQ at regional scale, distribution of pollutant in depth and possible behaviour in time will be taken into account as much as possible.

To summarise, the FoG aims to further develop as a focal point for regional/global groundwater quality assessment within WWQA, provide advice, guidance and scientific leadership. This Work Plan will be further developed accordingly, taking in consideration countries feedback, priorities of potential donors, fellow specialists in related fields and the public.

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Appendix A – Data sources

A.1 Regional data in Africa

Groundwater is a crucial natural resource supporting the development of the African continent, but it is subjected to many pressures. In this regard, (Gaye & Tindimugaya, 2019) affirms that groundwater resources in Africa face increasing threat of pollution from urbanisation, industrial development, agricultural and mining activities, and from poor sanitation practices and over-exploitation due to increasing demand to meet human and agricultural needs. Furthermore, according to (Xu & Usher, 2006), the degradation of groundwater is the most serious water resource problem in Africa. The two main threats are overexploitation and contamination (MacDonald *et al*., 2013). Nitrate is a common chemical contaminant of groundwater and the level of contamination also increases in many African aquifers (Puckett *et al*., 2011; Spalding & Exner, 1993). Indeed, based on a review of 29 papers from 16 countries, (Xu & Usher, 2006) have identified major groundwater pollution issues in Africa, considering the following order of importance as follows: (1) nitrate pollution, (2) pathogenic agents, (3) organic pollution, (4) salinization, and (5) acid mine drainage. As illustrated in the recent study of (Ouedraogo & Vanclooster, 2016) , nitrate contamination of groundwater is a problem that commonly occurs in Africa. Contamination of groundwater with nitrate poses a major health risk to millions of people around Africa. Nitrate ingestion has been linked to methemoglobinemia, adverse reproductive outcomes, and specific cancers (M. H. Ward *et al*., 2005). Nitrate contamination is therefore very informative for overall groundwater quality. Also, nitrate is often a proxy of other possible pollutants of groundwater. Nitrate contamination of groundwater is however a space-time variable property and the level of contamination depend on many space-time variable environmental and anthropogenic attributes. Therefore, to support Africa's policy in groundwater management in such a context of groundwater pollution, it is important to identify which aquifer systems/groundwater resources and settings are most vulnerable to degradation. In this regard, (Ouedraogo *et al*., 2016) addressed a significant knowledge gap for groundwater pollution at the continental scale in Africa by developing methods for assessing groundwater pollution risk at the African scale (*See Figure 1*). The main lesson to remind from this great contribution is that shallow groundwater poses a pollution problem for Africa. The maps designed in the study of (Ouedraogo *et al*., 2016) can increase awareness of citizens and regulators in areas where groundwater pollution is likely to be significant.

Furthermore, using the meta-analysis approach to build a database of groundwater quality, (Ouedraogo *et al*., 2016; Ouedraogo & Vanclooster, 2016) found that groundwater contamination by nitrates is reported throughout the African continent, except for a large part of the Sahara desert. The observed nitrate concentrations range from 0 mg/L to 4625 mg/L. The mean nitrate concentration varies from 1.26 to 648 mg/L. The sample mean of this mean nitrate concentration is 54.85 mg/L, its standard deviation was 89.91 mg/L and its median was 27.58 mg/L. The minimum nitrate concentration varies between 0 to 185 mg/L while the maximum concentration varies from 0.08 to 4625 mg/L (Table 1). Despite the data scarcity and bias issues of nitrate data collected, (Ouedraogo, 2017) used a novel application of machine learning (random forest techniques) to modelling groundwater nitrate contamination at the African continent scale. Using the nitrate parameter as a proxy for groundwater degradation, this author has demonstrated that the nitrate pollution in groundwater is strongly linked to the variable of population density (*e.g.* urban areas, agricultural activity, mining activities).

The research presented by (Ouedraogo, 2017) represents an important step toward developing tools that will allow us to accurately predict the distribution of nitrate contamination in groundwater in the climate change context. Such a conclusion could prompt national/regional (ECOWAS, OSS, IGAD, GWP, etc.) or international authorities to foster targeted local investigations. It yields also important baseline information for monitoring progress in the implementation of the United Nations Sustainable Development Goals (UN SDGs) for water. Because, according to (Saruchera & Lautze, 2015), transboundary water cooperation has emerged as an important issue in the post-2015 United Nations (UN) Sustainable Development Goals (SDGs).

Table 1 – Summary statistics of nitrate data in Africa (modified from Ouedraogo and Vanclooster, 2016).

Statistic	**Maximum NO_3^- concentration**	**Mean NO_3^- concentration**	**Minimum NO_3^- concentration**
Number of data (-)	206	82	185
Minimum (mg/l)	0.08	1.26	0
Maximum (mg/l)	4625	648	180
Median(mg/l)	73.64	27.58	0.55
Mean(mg/l)	190.05	54.85	8.91
Variance ((mg/l)^2	183778.94	163.92	537.07
CV (-)	225.56	8085.08	260.08
Standard Deviation(mg/l)	428. 69	89.91	23.17

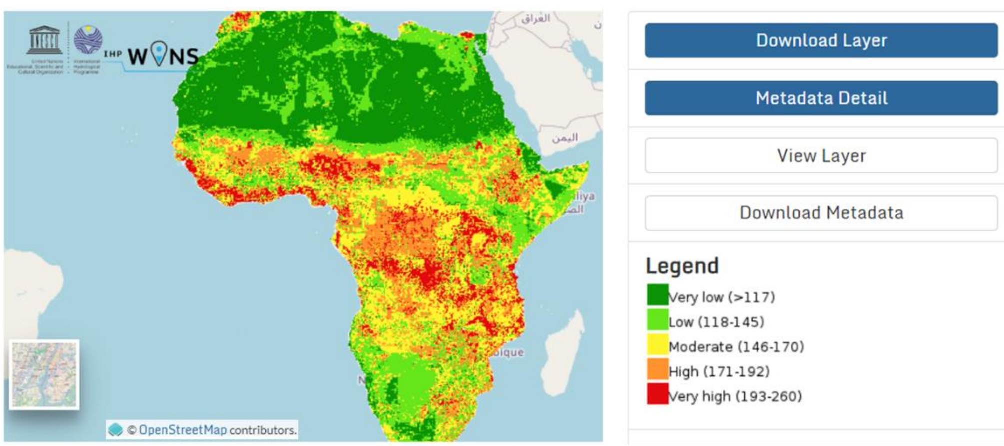

Figure 12 – Groundwater pollution (focus in nitrate) in Africa (Ouedraogo et al., 2016). *http://ihp-wins.unesco.org/layers/geonode:gwpollriskafrio*

Literature data for several countries in Africa:

For a large part of Africa, there is very little, or no systematic monitoring of groundwater. In the absence of a data systematic monitoring program, Ouedraogo, 2017 compiled nitrate pollution data at the African scale from different literature sources (Figure 13). More details can be found in Ouedraogo, 2017.

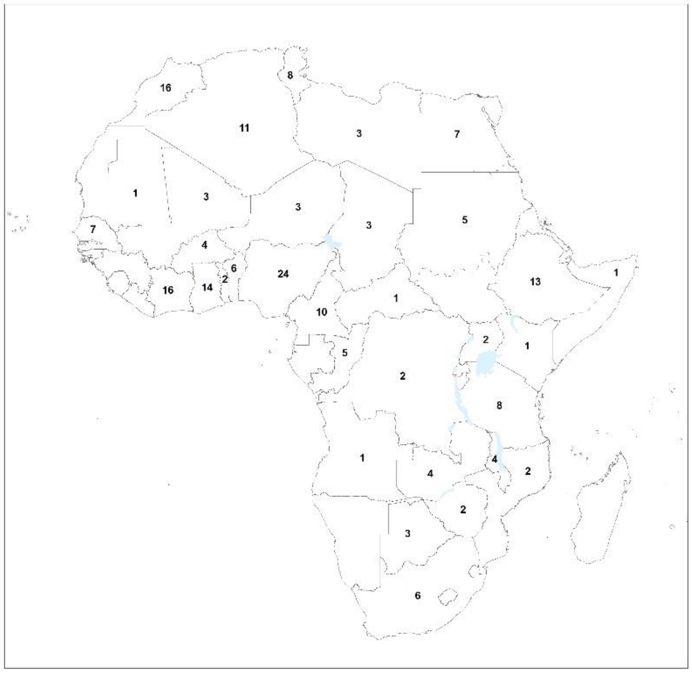

Figure 13 – Distribution of nitrates studies identified across Africa (Ouedraogo & Vanclooster, 2016)

<u>Box: Water quality data issues in Africa.</u>

Groundwater quality data in the World are not collected consistently and is often spatially and/or temporality limited. In Africa, many authors have highlighted the data availability problem (Carter & Bevan, 2008; Robins *et al*., 2006). have found that there is a lack of systematic data and information on groundwater monitoring across Sub-Saharan Africa. According to these authors, studies in this region occur on an ad-hoc basis and without strategic oversight or coordination (cited in Pavelic *et al*., 2012). In the study entitled '*Monitoring groundwater use in Sub-Saharan Africa: issues and challenges*', (Adelana, 2009), mentions that: 'modelling groundwater management scenarios suffers from a paucity of reliable data with which to calibrate and validate numerical models'. Other authors, such as (Allaire, 2009) and (Foster *et al*., 2006), found that groundwater monitoring is limited or absent, and that groundwater monitoring systems for gathering, collating and analysing information have failed in several countries, despite numerous amounts of wells drilled each year.

According to (Pavelic *et al*., 2012), data remains scarce and the information that is gathered is being done in an unsystematic manner. Recently, (Comte *et al*., 2016) affirm that groundwater information services (*i.e.* databases) and systematic long-term monitoring are non-existent or fragmented and of inadequate quality. (Adelana & MacDonald, 2008) argue that the reasons behind this are numerous and complex, including lack of clear institutional arrangements and responsibilities, inadequate resourcing, lack of technical expertise, and the absence of (or disconnection from) database management and retrieval systems.

(Baisch, 2009) affirms that Africa is not only suffering from water shortage but also data shortage. Furthermore, according to Fan *et al*. (2013), Africa is the most data-poor region with limited records (<0.001 %) of global shallow groundwater records. Hence, it is not possible to collect data for all African countries.

A.2 Datasets available for groundwater data modelling

Table 2 – List of large-scale geospatial datasets available for groundwater quality modelling

Explanatory variable	Unit	Raw resolution (pixel size)	Data source	Spatial scale	Description
Climate					
Precipitation	mm/hour	30x30 km^2; monthly 30x30 km^2; daily	TRMM_3B43 (TRMM, 2011a) TRMM 3B42 (TRMM, 2011b)	Global	Satellite imagery
Temperature	Kelvin	5x5 km^2; monthly 1x1 km^2; daily	MOD11C3 Modis (Wan et al., 2015b) MOD11A1.006 Modis (Wan et al., 2015a)	Global	Satellite imagery
Anthropogenic activities					
Livestock density	Head/km^2	1x1 km^2	GeoWiki (Robinson et al., 2014)	Global	Reported livestock (sheep, cows, chickens, ducks, pigs) statistics combined with statistical modelling
Population density	People/ha	0.1x0.1 km^2	World-pop (Stevens et al., 2015)	Global	Semi-automated dasymetric modelling approach that combines detailed census data and satellite imagery (land cover, digital elevation data, observed lights at night, road networks)
Time to city	minutes	1x1 km^2	Weiss et al., 2018	Global	Model taking into account urban centres of more than 50,000 people (extracted from the Global Human Settlement Grid of high-density land cover (GHS-HDC)), road type, land cover, and topography.
Land cover (cropland, forest, settlement or artificial, grassland/herbaceous, wetland, shrubs)	% of land cover	0.03x0.03 km^2 0.1x0.1 km^2	Servir East Africa (RCMRD, 2015) Copernicus (Buchhorn et al., 2020)	East Africa Global	LandSat satellite imagery using supervised classification. Derived from Sentinel-2 satellite imagery.
Hydrology – Hydrogeology					
Runoff	mm/month	50x50 km^2; monthly	UNH-GRDC Composite runoff Field (Fekete et al., 2002)	Global	Climate-driven water balance model (WBM) combined with river discharge observations

Groundwater resources and recharge of the world	mm/year	1:25 000 000	WHYMAP (Richts et al., 2011)	Global	Groundwater recharge rates are derived from simulations with the Global hydrologic model Water GAP, and refer to the period 1961 -1990
Global groundwater vulnerability to flood and drought	Vulnerability index to drought and flood	1:25 000 000	WHYMAP (Richts et al., 2011; Richts & Vrba, 2016)	Global	Based on aquifer type and annual groundwater recharge.
Soil properties for Africa	Organic carbon, bulk density, Cation Exchange Capacity (CEC), pH, soil texture fractions and coarse fragments	0.25x0.25 km^2	ISRIC (Hengl et al., 2015)	Global	Combination of data sets and spatial prediction on soil properties
Depth to groundwater	Meters below ground level (mbgl)	5x5 km^2	British Geological Survey (Bonsor & MacDonald, 2011)	Africa	Depth to groundwater was modelled using an empirical rules-based approach considering rainfall, proximity to rivers, and aquifer type
Groundwater storage	Water depth in mm	5x5 km^2	MacDonald et al., 2012	Africa	Estimated by combining the saturated thickness and effective porosity of aquifers.
Groundwater productivity	Aquifer productivity l/s	5x5 km^2	MacDonald et al., 2012	Africa	Has been estimated using borehole yield data as a proxy
Surface water salinity map	mS/m	10x10 km^2	World Bank, Quality unknown	Global	They measured the impact of water salinity on agricultural productivity using regression analysis.
Groundwater vulnerability to pollution	Vulnerability index to pollution	15x15 km^2	Ouedraogo et al., 2016	Pan-Africa scale	Derived from 7 different hydrogeological parameters
Soil salinity	EC ds/m	0.01x0.01 km^2	Taghadosi et al., 2019	Qom Province, Iran	Sentinel 2 multispectral imagery – methodology paper
Aquifer type, productivity and geology		1:5 000 000	Africa Groundwater Atlas by the British Geological Survey		Aquifer type, productivity and geology of 38 countries in Africa

Appendix B – Regional Challenges

B1 Case of Africa: Addressing the Challenges of Groundwater Quality: Science, Knowledge, and Capacity

As highlighted in the study of (Ouedraogo, 2017), groundwater pollution problems are a growing threat to African continental development and urgently need to be addressed. The maps designed in this study show an interpretation of the groundwater resources map of Africa in terms of groundwater sensitivity and exposure to pollution. Because, until now, no general groundwater vulnerability map is available. To fill this existing gap, our study, we assess the vulnerability of groundwater at the pan-African scale. This study could help in many management domains.

Raising awareness: large-scale vulnerability maps could raise the awareness of policymakers and water managers about the vulnerability of this precious water resource system and increase the overall concern to develop appropriate protection programmes. It is also useful to scientists in government agencies and consulting companies.

Smart groundwater monitoring: Improving the assessment of water quality at a large-scale should be based on the appropriate monitoring. This assessment is needed to evaluate the compliance of different countries with overall political commitments, such as the commitment to reach sustainable water management in the WFD in Europe or to reach the SDG at the UN level. Hence, smart monitoring of water quality at a large scale is needed. We believe that smart monitoring of groundwater quality should be based on vulnerability. Monitoring should be concentrated primarily in vulnerable areas. Hence, vulnerability maps can help to optimise the smart large-scale monitoring programme. For example, in 2016, in the article Accidental infrastructure for groundwater monitoring in Africa published by Oxford University, the researchers tested the potential of using Africa's (Kenya as an example) accidental infrastructure to harmonise groundwater monitoring systems with rural water-security goals. They affirm that their study has the potential to be scaled up across Africa, meaning that every time water is pumped data could be harvested from the handle vibration help monitor Africa's groundwater resources. They say that smart hand pumps can help monitor Africa's groundwater resources.

In this respect, the groundwater vulnerability could serve as a good example for establishing a pan-African groundwater network like the strategies employed in Europe and the USA to establish large-scale groundwater monitoring networks and groundwater protection programmes. Groundwater protection and alleviation at the pan-African scale are not optional and acknowledging the role of groundwater is paramount to successfully implementing the SDGs. Remediation should be developed at both the continental and regional scale. The solutions that can be proposed to mitigate and improve the situation of groundwater quality issues have been partially addressed by (Xu & Usher, 2006):

i. Political will: Groundwater quality protection is closely related to the government policy towards economic development and the political will for sustainable development and utilisation of resources. Our study may increase support for AMCOW (African Ministerial Council on Water) to proceed with groundwater protection programmes at the pan-African level. For example, the implementation of resolutions at the Pan-Africa Conference on Water (December 2003 in Addis-

Ababa/Ethiopia) organized by AMCOW, are a good start for correct regulation of policies for the successful protection of water resources.

ii. Capacity building and technical skills: Africa has little capacity to challenge groundwater degradation and there is a need to boost this capacity through appropriate capacity building programmes. As an example, capacity building can be increased by (a) the establishment of more formal networks of African universities working on water and sanitation; and (b) improving communication by increasing access to internet facilities.
iii. Knowledge dissemination: Awareness of groundwater resources in Africa is low. There is a need to improve the knowledge of groundwater systems for decision-makers and for the broader public. This study may contribute to the increase of groundwater awareness. For example, in Africa, the number of technical people involved in groundwater studies is small.

In addition to these 3 main solutions above, which we recommend to decision-makers, we think that the African decision-makers for water resources must urgently elaborate groundwater protection programmes that are based on groundwater monitoring and data management. Such programmes can be boosted through a multilateral organisation such as the African Groundwater Commission or SADC, ECOWAS, the Nubian Aquifer Regional Information Systems (NARIS), The North Western Sahara Aquifer System (NWSAS) (better known under the acronym SASS for its French name “Système Aquifère du Sahara Septentrional”). Various institutions are working in many countries, but they are scattered, isolated and uncoordinated. Groundwater management organisations should be created and connected with existing river basin organisations. Cooperation between neighboring countries is, therefore, a requirement if we are to reduce the risks of degradation and allow the sustainable use of these shared resources.

Also, groundwater monitoring in Africa needs to be addressed as a matter of priority. Based on the research conducted in this thesis, several factors for nitrate pollution have been highlighted. Of great concern is the fact that for many of these factors, the currently available datasets show that very little attention has been paid to the constituents in most groundwater monitoring programmes. Two sources of nitrate pollution are highlighted: urban areas and agricultural domains. High nitrate concentrations have been found to occur from sources ranging from agricultural fertilisers to pit latrines to explosives companies. There is no directed programme to monitor nitrate in urban and peri-urban areas and hence there is a gap in information.

The pan-African map is intended for continental or sub-regional (*e.g.* ECOWAS, SADC, IGAD region) use and has several limitations because it does not reflect local conditions. Each map type should only be used for the purpose for which it was produced (Vrba & Zaporožec, 1994)). Areas of high risk on the map have a high potential for nitrate contamination but are not necessary contaminated. A low vulnerability does not mean that there is no risk of contamination; it simply means that the geology and hydrogeology of the area provide more natural (or intrinsic) protection to the groundwater resources. Despite the issue of possible bias and uncertainties noted in the dataset collected for this dissertation, we are very optimistic about the robustness of the models for predicting contamination at the continental scale. The random forest machine learning model results presented in this research show that this is a promising technique for modelling groundwater degradation because of its ability to provide meaningful analysis of nonlinear and complex relationships such as those found in hydrogeological studies. The explained high variation of the random forest paves the way for creating water quality maps at the continent scale. Such maps are considered essential tools for developing groundwater management and development programmes, including transboundary groundwater management.

Notwithstanding some limitations related to data, the simple Dynamic Vulnerability Index (DVI) model allowed modelling the temporal dynamics of groundwater pollution risks at the pan-African scale using public available data. This is therefore an important tool for sustainable groundwater resources management in Africa. The DVI could be used to monitor the achievement of SDG Goal 6 in Africa which includes a focus on preserving freshwater resources for potential future threats.

All methodologies presented in this study can be easily applied both to larger areas, and small areas, and used as a decision support tool for evaluation of legislative and management measures, aiming to reduce groundwater contamination risks. Although the present work was directed toward the vulnerability of groundwater to agricultural chemicals, of which nitrate was the exemplar, the methods developed in the course of this study are not specific to agricultural chemicals in groundwater. The same approach could easily be applied to other forms of pollution such as fluoride and arsenic.

aquaya

British Geological Survey

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

eawag aquatic research

International Association of Hydrogeologists
the World-wide Groundwater Organisation

igrac
International Groundwater Resources Assessment Centre

CGIAR
RESEARCH PROGRAM ON Water, Land and Ecosystems
LED BY: IWMI International Water Management Institute

KWR

NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

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UNU-INWEH
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U-FDG

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