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Groundwater Quality and Public Health

Xianjun Xie,[1,2] Jianbo Shi,[1,3] Kunfu Pi,[1] Yamin Deng,[1]
Bing Yan,[1] Lei Tong,[1] Linlin Yao,[3] Yiran Dong,[1]
Junxia Li,[1] Liyuan Ma,[1] Chunmiao Zheng,[4]
and Guibin Jiang[3]

[1] State Environmental Protection Key Laboratory of Source Apportionment and Control of Aquatic Pollution, School of Environmental Studies, China University of Geosciences, Wuhan, China

[2] State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Wuhan, China

[3] State Key Laboratory of Environmental Chemistry and Ecotoxicology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China;
email: gbjiang@rcees.ac.cn

[4] State Environmental Protection Key Laboratory of Integrated Surface Water-Groundwater Pollution Control, School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China

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Abstract

Groundwater deterioration due to enrichment with contaminants of either geogenic or anthropogenic origin has adversely affected safe water supply for drinking and irrigation, with pervasive impacts on human health and ecosystem functions. However, the spatiotemporal evolution and public health effects of groundwater quality remain unclarified, posing a grand challenge for the safe and sustainable supply of global groundwater resources. This article provides a state-of-the-art review of the complexity and dynamics of groundwater quality, as well as the impacts of various groundwater substances on human health. In particular, knowledge is growing about the health impacts of key substances ranging from nutritional elements (e.g., Ca^{2+}, Mg^{2+}) to pollutants (e.g., heavy metals/metalloids, persistent organic pollutants, and emerging contaminants) and, further, to pathogenic microorganisms to which the human body can be exposed through multiple patterns of groundwater use. Proliferating concerns at the same time call for enhancing science-based governance directives, economic policies, and management strategies coordinating groundwater quality. We propose that safeguarding groundwater-dependent public health needs concerted efforts in source control, cross-scale rehabilitation, and social hydrology-based groundwater governance.

Contents

1. INTRODUCTION

As the most sizable and accessible freshwater resource on Earth, groundwater is foundationally important to safeguarding human health, economic development, and ecosystem services (1, 2). This is particularly true considering that society is demanding an exponentially increasing amount of clean water, scilicet, water good enough for drinking, municipal use, and irrigation. Unfortunately, the deterioration of groundwater quality due to enrichment with geogenic and anthropogenic contaminants or potentially harmful chemicals and pathogenic microorganisms exerts significant, yet invisible in most cases, impacts on water supply from small communities to large cities (3, 4). As a consequence, public health and ecosystem functions may suffer due to direct or indirect access to deteriorated groundwater (5–7).

Naturally, the composition of groundwater varies for many reasons (e.g., the hydrogeological conditions) (4), which, from the perspective of hydrogeochemistry, can be collectively considered a result of water-rock interaction (WRI) (8). As our understanding of the hydrogeochemical evolution of groundwater quality grows, the essentials of WRI have been immensely extended to the interactions of water, rock, soil, minerals, gases, and organisms that occur from local (e.g., the pore niches) to regional (e.g., the whole watershed) scales and from microseconds (e.g., radical formation) to millions of years (e.g., quartz dissolution) (**Figure 1**). Hence, by participating in the global water cycle, groundwater is closely linked to the biogeochemical cycling of elements that are significant to both human society and multiple groundwater-dependent ecosystems (9). In the course of these interactions, the groundwater components, present in dissolved, colloidal, or particulate forms, change alongside the variations of physicochemical parameters (e.g., temperature, redox

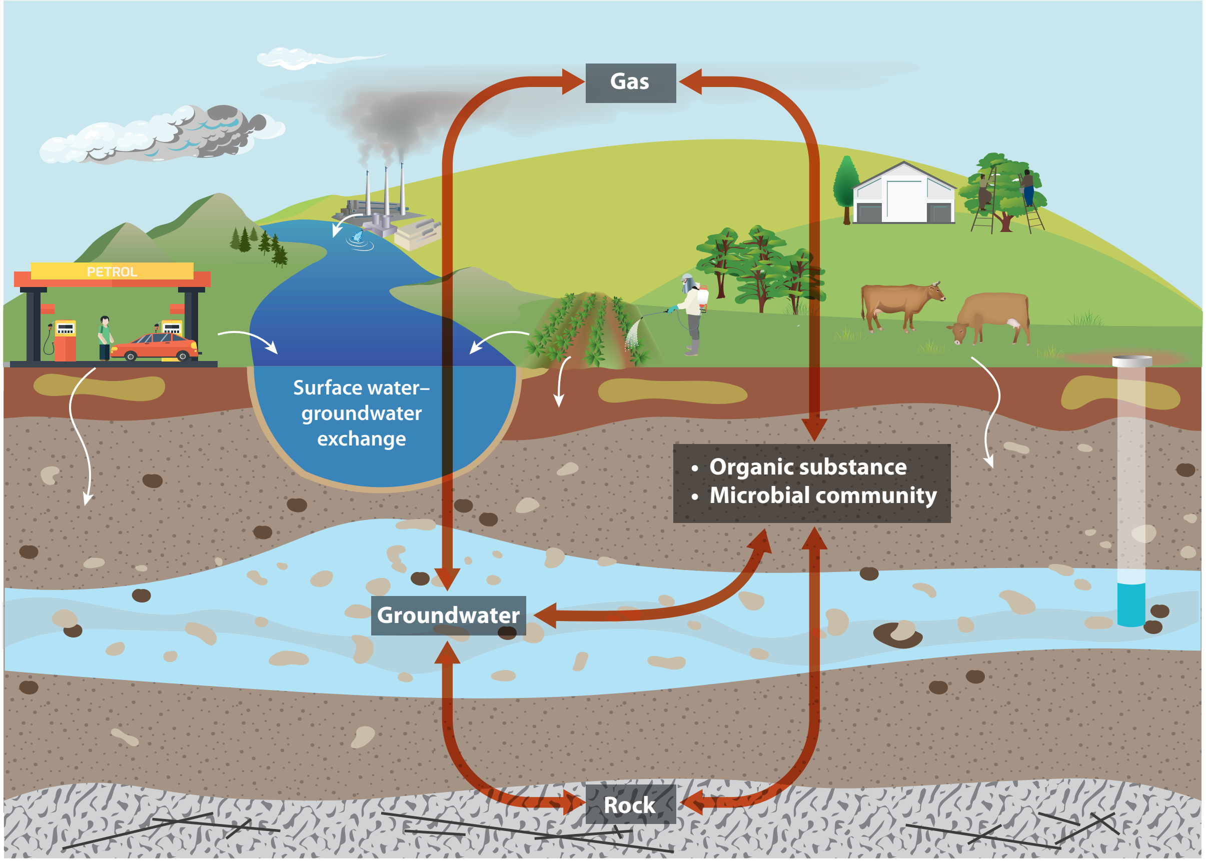

Figure 1

Water–rock–soil–gas–organic substance–microbial community interactions and consequences for groundwater quality. The groundwater represents a dynamic system that can exchange gaseous, liquid, and solid substances (and energy) with its surroundings. In particular, vertical infiltration and surface water–groundwater exchange are important pathways to introduce those substances to the groundwater system. As a consequence, nutritional elements, pollutants, and pathogenic microorganisms enter or leave the groundwater, leading to spatiotemporal variations of the groundwater quality. White arrows indicate vertical infiltration.

potential). Put simply, groundwater quality represents the evolving, joint consequence of hydrogeological, hydrogeochemical, and biogeochemical actions across scales for water in the subsurface.

In most cases, groundwater is clean, potable, and utilizable. It can deteriorate, however, due to natural processes and human activities (3, 10). In particular, geogenic enrichment of salts, hazards, and even essential elements for life is likely to occur as the groundwater systems evolve to late stages (11, 12). For instance, geogenic arsenic (As)-, fluorine (F)-, and iodine (I)-contaminated groundwater has been found in more than 100 countries/regions and is considered a public health emergency of international concern (3). What further incapacitates the resource attribute of groundwater is manmade perturbations to groundwater quality. These devastations, which in many cases are practically irreversible, range from the overexploitation-induced enrichment of harmful substances to the massive introduction of emerging contaminants (ECs) (13–15), increasingly risking a loss of balance between water demand and the sustainable exploitation of groundwater resources. This should put us on high alert.

Nevertheless, groundwater is invisible, and so is the deterioration occurring. The development of our society, in particular the acceleration of urbanization, is soliciting more clean groundwater from Earth to sustain water and food safety. Undoubtedly, groundwater deterioration has impacted and will continue to impact public health through the groundwater supply and food chain (5). In these processes, the human body can be exposed to key substances—representing, collectively, elements (including protons), nutrients, organic compounds, and microorganisms present in groundwater and biologically significant to human health—potentially causing health impairments, e.g., endemic diseases, in the short or long term (16). Some of the key substances, such as ECs including antibiotics, antibiotic resistance genes (ARGs), and pharmaceuticals and personal care products (PPCPs), may exert currently inconclusive health impacts but they attract growing concern due to scientific evidence on their harmfulness (6, 13, 17). More importantly, knowledge remains lacking about the combined effects of ECs, conventional contaminants (e.g., As), and pathogenic microorganisms on public health, given they are very likely to coexist in the groundwater that is accessed daily and to which the human body is coexposed frequently.

Although societal awareness of groundwater's importance has been escalating, our efforts toward protecting groundwater, especially ensuring groundwater quality, seem to lag behind the actions required to meet the global water challenge. Both the exploitation of good-quality groundwater and the remediation of contaminated groundwater call for not only comprehensive, quantitative understanding of the fate and routes of exposure to humans of key substances in groundwater but also actionable tools of management and policy-making specific to groundwater quality. Given the aforementioned issues in the field of groundwater quality science, we emphasize here the significance of groundwater quality for public health. It is not our intention to provide an all-inclusive, overly broad review of key substances in groundwater and their links to human health. Rather, this review helps to identify the complexity of groundwater quality, key issues in its health effects, and science-based solutions to the sustainable management of this precious resource for the sake of human well-being.

2. COMPLEXITY AND DYNAMICS OF GROUNDWATER QUALITY

2.1. Sources of Key Substances in Groundwater

Elements in groundwater can be sourced back to their existence in the solid Earth and accumulated in the water due to WRI (18). This also applies to the naturally occurring, yet undesired, enrichment of salts and trace elements, potentially causing harm to human and ecosystem health (19–21). On the regional scale, groundwater chemistry, in particular its temperature, pH, and concentrations of dissolved substances, is often a good reflection of the underlying geological settings, which include, among others, the crustal processes, hydroclimatic conditions, and geothermal activities (22). This is why not only the hydrogeologists but also scientists in the general field of Earth science show interest in groundwater geochemistry. For instance, the concentrations of strontium (Sr), calcium (Ca), and their stable isotopes can be altered by the chemical weathering of silicate and carbonate minerals either from water source areas or from the deposits in the flow path (23, 24). Therefore, the multiple Sr and Ca signatures are robust indicators of mineral formation and stratificational sedimentation. Likewise, the presence of elevated sulfur (S) and As in naturally hot water is characteristic of hydrothermal dynamics in the deep subsurface (25).

In addition to natural processes, human activities can bring additional naturally occurring substances and manmade contaminants into groundwater (10, 26). Leaching of heavy metals, for instance, from mining sites, including mine wastes and acid mine drainage, remains a great threat to the pH state and toxic/radioactive metal contamination of groundwater around the globe (27). At the same time, field monitoring in different regions clearly indicates the leaching of nutrients, pesticides, and insecticides from the farmlands, persistent organic pollutants (POPs) and petroleum products from the industrial plants and storage tanks, as well as flame retardants and PPCPs from our daily lives into the aquifers that supply our drinking water (28, 29). Conventionally, groundwater quality is defined by what it has, but nowadays more by what is added to it by the humans who use it.

2.2. Hydrobiogeochemical Controls on Groundwater Quality

Playing an integral role in WRI, hydrogeochemical processes change the concentrations, redox state, and speciation of the key substances, either natural or manmade, in groundwater. These processes include, among others, weathering and leaching of silicates and carbonates, redox transformation of metal oxides and sulfides, pH-dependent sorption and desorption, and dissolution and precipitation of secondary minerals (18, 30, 31). Although these processes may occur in any niches in the groundwater systems, critical interfaces including the surface water–groundwater interface (e.g., the hyporheic zone), the unsaturated-saturated transition zone, the groundwater-bedrock interface, and the submarine groundwater discharge zone are hotspots where the chemical gradients of key substances vary most intensively and frequently. This leads to remarkable alteration of groundwater quality in short timescales that are highly relevant to daily life. For example, the concentrations and speciation of dissolved As in the shallow groundwater of Jianghan Plain, central China, vary for two orders of magnitude over seasons (32). Consequently, the groundwater may be As-safe in winters but As-contaminated in summers, providing no warning signs for the local communities using it. Similar scenarios very likely occur with other redox-sensitive elements (e.g., I, N), and the hyporheic redox gradients are dynamically perturbed as the seasons shift (33, 34).

Biogeochemical modifications to groundwater chemistry represent an increasingly recognized constraint on groundwater quality. In reality, redox reactions taking place in the subsurface are mostly mediated by biological metabolisms, in particular by the microbial utilization of electron donors and terminal electron acceptors (TEAs) (35, 36). Here, reduced organic carbon, either buried along with the aquifer formation or externally introduced by groundwater recharge, can serve as a significant energy and/or carbon source for redox zonation that is characterized by a complex of TEA reactions from deoxygenation to methanogenesis (11). These reactions are usually kinetically controlled on the timescale of groundwater flow in the porous media and linked to the mobilization/immobilization of almost all redox-active substances in the groundwater (30). Furthermore, because biologically mediated redox reactions involve the generation of dissolved inorganic carbon and protons, the biogeochemical processes link to almost all nonredox reactions that simultaneously account for the migration of key substances in groundwater (37). Therefore, a network of hydrobiogeochemical processes often can be constructed to formulate and parameterize the fate of key substances in groundwater.

2.3. Spatiotemporal Variation of Groundwater Quality

Transport of the key substances in groundwater changes, as does groundwater quality, in response to the hydrogeological processes. The relative timescale of groundwater residence and WRI is a focal issue in interpreting the dilution or enrichment of concerning substances in groundwater (38). Hazardous substances may only accumulate to harmful levels when the groundwater flow is so slow as to allow adequate time for geochemical processes to take effect (37, 39). Due to the high heterogeneity of the aquifer structures (e.g., the porous media) and associated hydrogeological conditions (e.g., water recharge intensity) (40), however, the concentrations of groundwater substances are likely to vary substantially over space and time, from small to large scales (11). This is commonly observed for the concentrations of, for instance, As, F, and I in geogenic contaminated groundwater from fluvial-lacustrine basins, river deltas, or coastal floodplains. For example, total As concentrations in the Datong groundwater vary from <10 to >1,000 μg/L in shallow wells that are only a few hundred meters apart (41). The high spatiotemporal variability of key substances remains a big challenge for fully understanding groundwater quality dynamics and thus a frontier of environmental geoscience research.

In the context of global environmental changes, groundwater quality faces additional significant threats caused by sea level rise, glacial melting, and temperature increases that usually exert impacts on short time and regional scales (42). Consequences include the regional groundwater salinization and acidification occurring in the (semi)arid areas of the world that have already suffered from clean water shortages (43). Increased groundwater salinity and acidity are often associated with elevated concentrations of trace elements such as Cu, F, Se, B, and As (44, 45). Moreover, such devastating impacts may have been aggravated by increasingly intensified human perturbations. A typical example is the deterioration of groundwater quality in the North China Plain, where overexploration of groundwater from multiple aquifers generated a huge depression cone with a complex of problems including ground subsidence, seawater intrusion, and ecological degradation (46). In South and Southeast Asia, long-term, extensive groundwater pumping results in either the penetration of As-contaminated groundwater from shallow aquifers into the underlying and adjacent As-safe aquifers or the compaction-driven release of As-contaminated or saline pore water from circumjacent fine sediments into the aquifers (39, 47, 48). We are seeing more consequences for the coastal areas and still lack the capability to reliably predict the impacts of interrelated climate change and anthropogenic perturbations (49). More efforts are undoubtedly needed to tackle this significant issue, not only from groundwater researchers but also from all practitioners more generally.

3. IMPACTS OF GROUNDWATER QUALITY ON PUBLIC HEALTH

3.1. Essential Elements in Groundwater

A healthy human body requires approximately 20 essential elements to function soundly (50). Groundwater is a vital carrier of almost all essential macroelements (Na, K, Ca, Mg, Cl, S and P, in mg/day doses) and microelements (B, F, Si, Se, I, Mn, Fe, Co, Cu, Zn and Mo, in μg/day doses), although their concentrations vary depending on the sources and hydrogeological-geochemical processes (18). Drinking purified or demineralized water over the long term can be deleterious to human health by, for instance, raising the risk of acidosis and decreasing thyroid function and dental health (51). Instead, drinking groundwater adequately rich in essential elements provides an easy way, often unrecognized though, to counteract epidemiologically significant malnutrition on the regional and even national scale (52, 53). In reality, drinking water of groundwater origin contributes substantively to the recommended daily intake of essential elements and benefits increasingly human health, particularly considering that the global population is facing deficiencies of nutritional elements despite increasing caloric consumption (51, 54). When used for irrigation, groundwater delivers these elements to human beings via the food chain (**Figure 2**) (53).

Macroelements such as Na, K, Ca, and Mg constitute the "biochemistry of life" by participating in hard structure assembly, information transfer, enzymatic activation, and immune system buildup (50). Drinking water of groundwater origin is one of the major routes of exposure to these macroelements. When originating from aquifers characteristic of Ca-/Mg-bearing minerals (e.g., calcite and dolomite), groundwater with appropriate enrichment of Ca and Mg, together with dissolved bicarbonates as a pH regulator, is protective against cardiovascular diseases (CVDs), osteoporosis, cognitive dysfunction, diabetes mellitus, acidosis, and probably cancers (55). In addition,

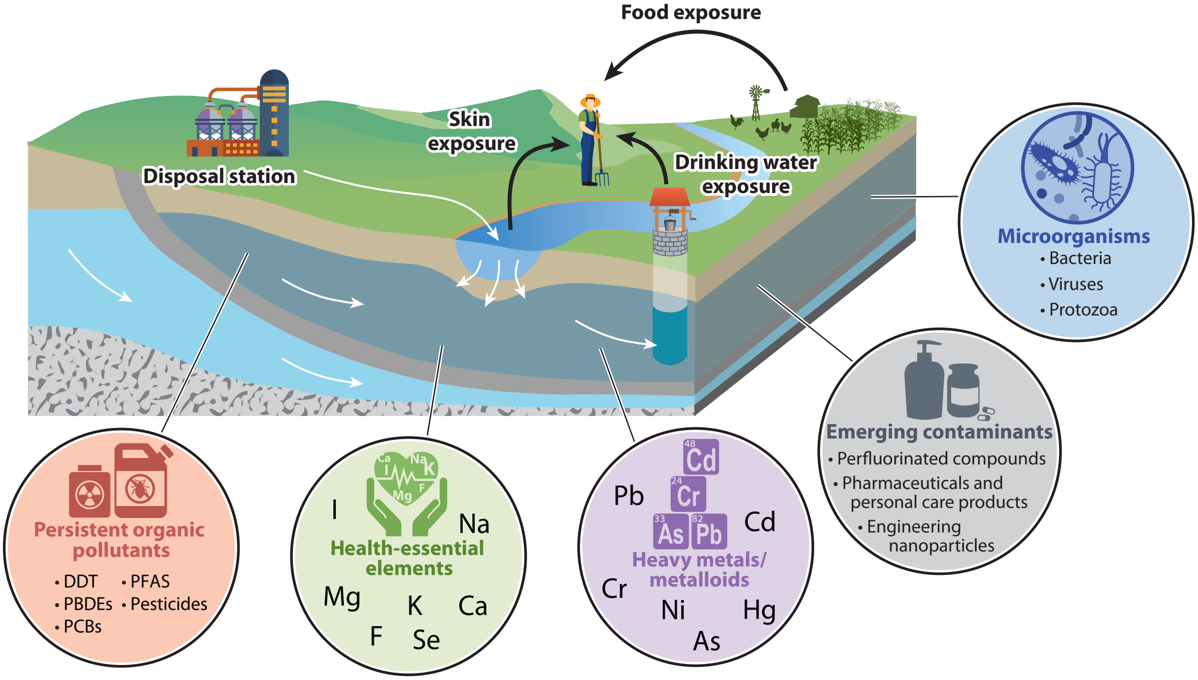

Figure 2

Schematic of causal links between groundwater quality and human health, showing the routes of human exposure to key substances from subsurface aquifers and consequent impacts on human health. While five main groups of key substances with known or potential health harms are illustrated, there are likely other elements and components, either geogenic or anthropogenic, in groundwater that could be accessed by humans via the three primary routes of exposure highlighted (skin, food, and drinking water). White arrows represent the transport of key substances to aquifers. Abbreviations: DDT, dichlorodiphenyl trichloroethane; PBDEs, polybrominated diphenyl ethers; PCBs, polychlorinated biphenyls; PFAS, perfluoroalkyl substances.

Ca and Mg are metabolic antagonists in cell incorporation and at proper concentrations are able to alleviate the toxicity of harmful elements (e.g., U, Cd) (51, 56). Therefore, an optimum balance of essential macroelements in potable groundwater is of equal importance to human health.

The health benefits, however, do not exclude the requirement of optimum ranges of these macroelements in groundwater. High concentrations of Na in saline groundwater may contribute significantly to daily Na intake of coastal populations and salinity-prone regions, posing a risk of increased blood pressure and CVDs (57). Excess ingestion of Ca and Mg from groundwater can cause coronary and vascular cerebral diseases and contribute to calculi that have plagued human health for centuries (19). In the “global stone belt,” the prevalence of urolithiasis shows a remarkable association with high Ca and Mg concentrations in the potable spring water (19, 58). Moreover, a loss in the balance of groundwater Ca and Mg (e.g., high Ca and low Mg) significantly increases the risk of acute myocardial infraction and urolithiasis (58).

Despite their complex functions in the biological systems, essential microelements are normally required within a narrow range, and both insufficient and excess intake can impair human health, even causing irreversible damage to the vital functions (50). Water-sourced access to these microelements depends largely on their geoavailability in groundwater systems. At optimum levels in groundwater for drinking, F is favorable for healthy teeth and bones and I provides prevention against goiter and hypothyroidism (51). Nevertheless, geogenic contaminated groundwater due to elevated (co)enrichment of F and I has been a worldwide public health concern for decades, causing devastating endemic fluorosis and iodism across the continents (3). Likewise, variable Se concentrations in groundwater (from <1 to hundreds of μg/L) lead to an array of health effects from the low-Se-related Keshan disease to endemic selenosis, particularly in seleniferous regions (59, 60).

For microelements sensitive to redox alternation (e.g., Se and I), the redox chemistry and speciation are crucial to biological interactions. Generally, the organic forms exhibit less toxicity than the inorganic forms, and biotoxicity also varies between different oxidation states (52, 59). For example, inorganic Se(VI) and Se(IV) are more soluble and bioavailable than Se(0) and selenide in groundwater. Health risks may occur at Se(VI) exposures well below the upper safe limit of drinking water Se recommended by the World Health Organization (WHO) (10 μg/L) (53, 61). Because of the high variability of redox and pH conditions, drinking water of groundwater origin possibly contributes most to the geographical variation in dietary intake of essential microelements in some countries (e.g., Denmark, Sri Lanka, and China) (52). Knowledge on the speciation and variation of microelements in groundwater and the connection with human health is, however, lacking.

Anthropogenic perturbations impact the dynamics of essential elements in groundwater and consequences for public health. Increases in daily salt intake from salinized groundwater can be a risk factor for hypertension and CVDs (62). Additional deleterious effects on crop production irrigated with Na- and Mg-rich groundwater could be intensified in (semi)arid regions with limited surface water recharge (63). Elevated levels of F, Se, and other microelements in groundwater can be specifically linked to industrial waste and agricultural fertilizers (59, 64). The interactions between natural mechanisms and anthropogenic perturbations complicate the groundwater-related exposure to essential elements and associated health effects. This gives rise to considerations in public health guidelines regarding the water quality standards for essential elements.

3.2. Toxic Metals and Metalloids in Groundwater and Health Impacts

Metals and metalloids absent from the list of essential elements can be toxic to humans even when present at trace levels in groundwater (**Figure 3**). Furthermore, these metals and metalloids can be enriched in groundwater by both natural processes and human activities (65–67). For anthropogenic inputs of these toxicants, the shallow aquifers seem more prone to contamination than the deep confined aquifers (29).

The health effects of toxic metals and metalloids in groundwater vary by concentration and dose. The trace essential metals (e.g., Mn, Fe, Cu, and Zn), likewise, can be health-harmful if their concentrations are elevated above recommended daily intake (68). Many metals are considered toxic or carcinogenic because they can generate reactive oxygen species (ROS) that disrupt the cellular antioxidant defense (69). Long-term chronic exposure increases ROS production and thus induces oxidative stress, which has been associated with different types of cancers, endocrine disruption, immune system suppression, sclerosis, muscular dystrophy, and Alzheimer's disease (66). At the same time, metabolism is compromised by reactions of those toxic metals with the sulfhydryl enzyme system (69). As a consequence, various organs including kidneys, lungs, liver, stomach, skin, esophagus, and prostate will be damaged (70). In China, heavy metal contamination of groundwater has been reported as causing severe endemic diseases characterized by damage to nervous activities, blood composition, and some key organs (71).

The human body can be subjected to all of the toxic metals and metalloids, primarily through ingestion of contaminated water or polluted food (e.g., cooking) or skin contact (e.g., bathing) (67). Among these different routes of exposure, drinking water and dietary intake are the major contributors, especially in regions where groundwater is the major water source (72). What should

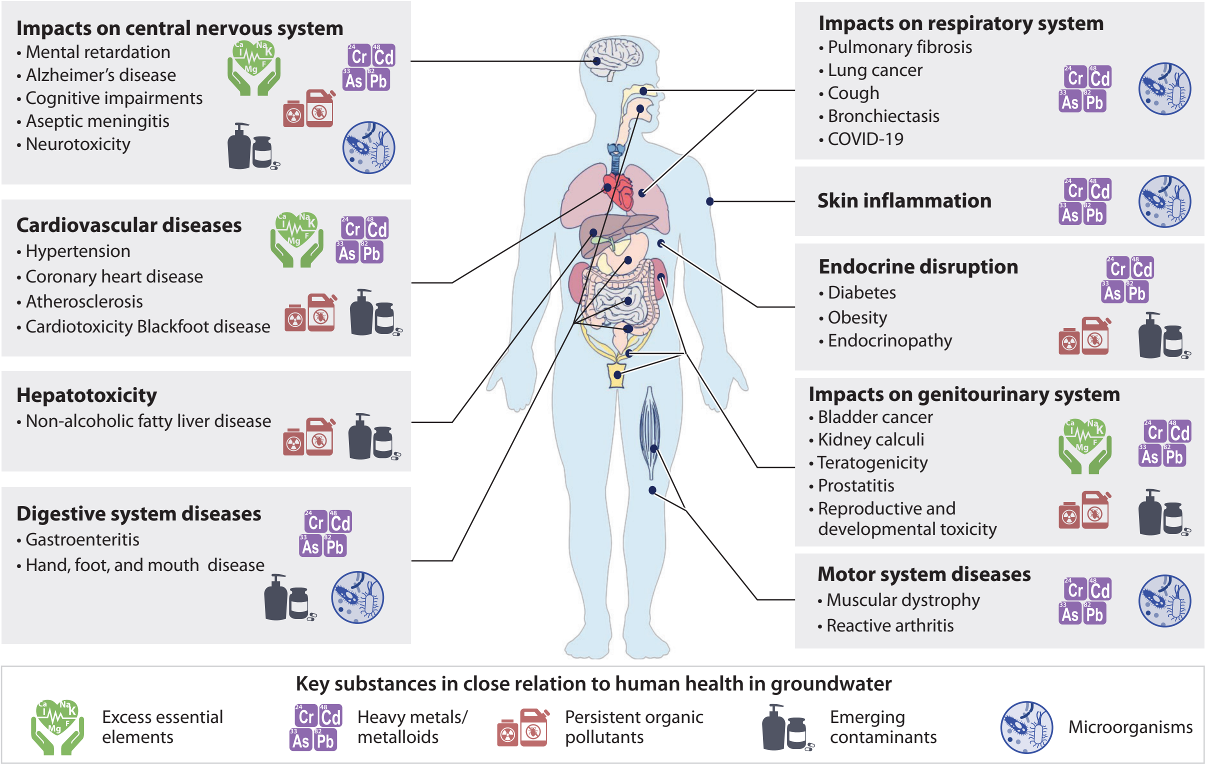

Figure 3

Potential health impacts of key substances in groundwater. Key substances in close relation to human health include, but could be not limited to, essential elements (e.g., Na, K, Ca, Mg), toxic metals and metalloids (e.g., As, Cd, Pd, Hg), persistent organic pollutants (e.g., dichlorodiphenyl trichloroethane, polybrominated diphenyl ethers, polychlorinated biphenyls), emerging contaminants (e.g., pharmaceuticals and personal care products, nanoparticles, microplastics), and microorganisms (e.g., pathogenic bacteria, viruses, protozoa). When taken in excess, for instance, via drinking groundwater, they do harm to various tissues and organs of human bodies. Note that the panel of endocrine disruption does not point to any specific organ because the endocrine system can be affected by multiple glands and organs of human bodies.

be more concerning is the bioaccumulation and biomagnification of toxic metals and metalloids through the food chain toward humans at the highest trophic level, even though they are present initially at only trace concentrations in the groundwater (73). For instance, when crops grown in contaminated lands are ingested, toxic metalloids can bioaccumulate in the living organisms, and subsequently migrate through the food chain (67). Once they enter the human body, they are transported to different organs depending on their species and the routes of exposure (67).

Among the toxic metals and metalloids in groundwater, As, Cd, Pb, and Hg are of major concern, in large part due to a high potential for them to occur at elevated concentrations and cause severe harms to public health after exposure to even low doses (70, 74). As per the WHO, the maximum contaminant limits (MCLs) of As, Cd, Pb, and Hg in drinking water are 10 μg/L, 3 μg/L, 10 μg/L, and 6 μg/L, respectively (68). Arsenic in groundwater exists mainly as inorganic and organic compounds (3). Among them, arsenite is considered most soluble, mobile, and toxic (67). Long-term exposure to As even at levels slightly above MCL is related to health problems of the skin (e.g., skin lesions, Bowen's disease), cardiovascular system (e.g., hypertension, coronary heart disease), neurological system (e.g., dysfunction of the central nervous system), genitourinary system (e.g., kidney and bladder cancers), and respiratory system (e.g., asthma, chronic cough, and bronchiectasis) (67). With the increase of As accumulation as well as the duration of chronic exposure, its adverse health impacts are strongly biomagnified (75). To date, As contaminated–groundwater related health issues persist in more than 100 countries and regions, threatening likely more than 200 million people (76); these issues are typically endemic in South, Southeast, and East Asia as well as in West Africa and South America (3, 48). In South and Southeast Asia alone, approximately 6.8 million people are at risk of groundwater As concentrations exceeding 300 μg/L, with an estimated 0.3 million deaths from As-responsive cancers (77). Drinking and cooking with As-contaminated groundwater are the two recognized main routes of As exposure to humans, whereas As can be simultaneously enriched in the rice we eat after agricultural irrigation with As-contaminated groundwater (78).

Due to their persistency and bioaccumulation in the human body, Cd, Pd, and Hg are the most harmful metals in groundwater (74, 79). Although they may exist in both inorganic and organic forms in groundwater, inorganic ionic complexes, even at low concentrations, are the main contributors to direct health risks (80). When accumulated in the human body, they can damage various organs, sometimes causing them to malfunction (70). For instance, long-term exposure to Cd may cause cancers in the prostate, lungs, and liver, as well as injuries to the pulmonary, testicular, and nervous systems (70, 73). Lead including its organic species is harmful to the kidney and nervous system, potentially causing mental retardation and cancers (81). It is estimated that elevated concentrations of Pd may have threatened approximately 26 million people worldwide, especially in developing countries (82). Exposure to Hg may damage the kidney, brain, reproductive system, and respiration system, causing symptoms such as cough, dyspnea, fever, gingivitis, renal tubular dysfunction, and neuropsychiatry disorders (83). Public health concerns about Hg and Cd in Japan, for example, include Minamata and Itai-itai diseases, which are attributed to contaminated fish and rice, respectively (84). Similarly, these metals come into contact with the human body mainly through consumption of contaminated water and polluted food.

When the living organisms are exposed to multiple toxic metals in groundwater, the toxicity of metal mixtures can be 10 to 100 times higher because of the biomagnification effects (70, 85). Available evidence suggests that exposure to binary mixtures of As and Cd, as well as Pd and Cd, adds more disruptions to cellular growth than individual metals and metalloids alone, leading to inflammatory response and cancers (79). With increasing reliance on groundwater resources, further attention needs to be on demand for public health impacts caused by toxic metal mixtures in groundwater.

3.3. Persistent Organic Pollutants in Groundwater and Health Impacts

POPs are persistent and bioaccumulative with the potential of long-range transport via multiple environmental media (86). Many POPs have been listed in the Stockholm Convention of the United Nations Environment Programme, and the list is growing (87). Among them, organochlorine pesticides (OCPs), polycyclic aromatic hydrocarbons (PAHs), perfluoroalkyl substances (PFASs), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers (PBDEs) are the most concerning POPs due to their high toxicity and health impacts, such as diabetes, cancers, endocrine disruption, and obesity (88), as well as significant adverse effects on ecosystems like bioaccumulation in animal tissues (89).

POPs enter the environment from a variety of sources, which include solid waste combustion, fuel emissions, cooking, iron and steel smelting, metal production, energy generation, and volatilization of electrical equipment or construction materials (90). They can then migrate to the groundwater environment through various pathways, such as soil leaching, accidental leaks, and surface water–groundwater exchange (91). Compared with surface water, the anoxic and reducing conditions in groundwater may lead to a longer duration of POPs.

OCPs are one type of the widely used POPs of earliest concern (92). Hexachlorocyclohexane (HCH) and dichlorodiphenyltrichloroethane (DDT), for example, are the dominant OCPs found in natural waters (93). Concentrations of HCH and DDT in the groundwater of the Yangtze River Basin were elevated to almost 2 μg/L (94). In the Saïss Plain (95) and Bolu (96), concentrations of HCH and DDT in groundwater show remarkable seasonal variations, with higher concentrations observed in summer. Similarly, contamination of groundwater with PAHs is ubiquitous around the world. For example, the concentrations of PAHs in groundwater in the middle and lower reaches of the Abou Ali River far exceed the MCL specified by the WHO (97). In the groundwater of Merida City in Mexico, the total concentrations of 16 PAHs, which came mainly from pyrolytic and petroleum products, were elevated to almost 25 μg/L (98). In China, PAHs have been detected in a large number of groundwater samples from a wide range of regions (99).

Aside from direct exposure via drinking groundwater (100), the use of POPs-contaminated groundwater in irrigation, aquaculture, and animal husbandry represents additional routes of exposure to POPs, causing unexpected threats to food security. In particular, skin contact with contaminated groundwater and inhalation of POPs-containing aerosols during agricultural activities lead to the nonnegligible exposure of farmers to groundwater POPs (101). In addition, by ingesting food produced with contaminated groundwater, POPs in groundwater can be ingested into and accumulate in the human body indirectly (102).

The accumulation and metabolism of POPs trigger various biotoxicities in vivo, which typically include reproductive and developmental toxicity, neurotoxicity, and immunotoxicity (103). It has been demonstrated that OCPs could adversely affect follicular development, ovulation, and steroid hormone synthesis in female animals, as well as genital malformation, sperm concentration, and sperm motility in male animals (103). Similar reproductive toxicity has been reported for PBDEs and PFOS (104). Exposure to POPs during pregnancy can affect the development of the offspring's reproductive system and impair reproductive function (105). Various POPs like PCBs, OCPs, PBDEs, and PFOS are able to cross the blood-brain barrier and cause injuries to the nervous system, resulting in cognitive impairment, impaired learning and memory functions, and motility dysfunction. The immunotoxicity of POPs lies in the disturbance of immune microenvironments, injury of immune cells, increases in ROS production, and damage to immune organs, which together weaken the immune system. In addition, some of POPs' metabolites are also toxic. Therefore, the organs that metabolize small molecules, such as the liver, are especially vulnerable to damage during in vivo exposure to and metabolism of POPs (106).

What makes POPs further deleterious to human health are the bioconcentration and biomagnification effects that lead to substantial accumulation of POPs in organisms and increase along with trophic levels. POP concentrations in the order of magnitudes of ng/g to μg/g have been detected in various organisms, including mollusks, fishes, the eggs of water birds, and whales (107). Perfluorinated compounds, PCBs, and OCPs have been observed in human body samples including breast milk, blood/serum, and urine (108, 109). The adverse biological effects and routes of exposure to POPs have together indicated that environmental POPs in groundwater exert serious harm to human health.

3.4. Emerging Contaminants in Groundwater and Health Impacts

ECs are referred to as detrimental contaminants that clearly exist owing to human activities but have not been regulated or adequately regulated by laws, regulations, and standards (110). Although ECs are present generally at trace concentrations in the environment, their potential impacts on human health and ecosystem functions are of broad concern. Recognized ECs include, among others, pesticides, antibiotics, PPCPs, plasticizers, endocrine disruptors, flame retardants, PFASs, nanoparticles, and microplastics (111). Antibiotics and endocrine disruptors are currently the two most concerning ECs for groundwater quality.

There are many potential sources of antibiotics in groundwater, such as sewage treatment plants, hospitals, agriculture, landfills, and sewer pipe leakage (6, 13). Antibiotic contamination of groundwater is closely related to human activities and functional zoning (13). In contaminated areas, tetracyclines, sulfonamides, quinolones, and macrolides are the main types of antibiotics detected in groundwater, with observed concentrations of 5–188 ng/L, 1–1,820 ng/L, 4–14,000 ng/L, and 1–2,980 ng/L, respectively (112).

Endocrine disrupting chemicals (EDCs) are ubiquitous in items for daily use, for instance, pesticides, metal food cans, and cosmetics (113). Surface water infiltration is considered the main source of EDCs in groundwater, but the specific pathways of transport are still unclear (114). Estrogen and bisphenol A are the most frequently observed EDCs in groundwater, with a wide concentration range of 1 to 20,000 ng/L reported, for instance, in Spain, Switzerland, the United States, and the United Kingdom (115).

Microplastics and plasticizer are two types of ECs associated with plastic use (28). Plasticizers can be desorbed from soil particles by rainfall or surface percolation and eventually transported to groundwater (116). Phthalate esters are the main plasticizers used in plastics production, and appreciable concentrations of phthalates were indeed detected in groundwater, for instance, in the range of 9–232 ng/L from the United States and Mexico (117). Similarly, microplastic particles were found in the aquifers of Australia, the karst groundwater system of the United State (118), the coastal groundwater of southern India (119), and the drinking water source area in northern China (120). Due to similar lipotropy, the routes of exposure to ECs in groundwater are similar to those for POPs. Drinking groundwater still represents one of the most direct exposure pathways for the receiving populations. Because of inadequate regulations and limited purification technologies targeting ECs in drinking water, however, both treated and untreated groundwater contaminated with ECs may enter the human body. Inhalation and skin contact via use of EC-contaminated groundwater pave way for additional direct exposures to ECs (121). The agricultural utilization of EC-contaminated groundwater and subsequent food supply lead potentially to the oral exposure to and digestive uptake of ECs by the human body.

Although the in vivo biotoxicity of ECs has not been adequately revealed, there are indeed observed toxic effects of EC exposure, including endocrine disruption, neurotoxicity, cardiotoxicity, immunotoxicity, hepatotoxicity, and reproductive and developmental toxicity. This is in part demonstrated by determining their occurrence in adipose tissue, breast milk, serum, and urine. For instance, alkylphenols, a type of surfactant metabolite, were detected in subcutaneous adipose tissue at concentrations of 0.05–1.1 μg/g fat weight (122). The average concentration of bisphenol A in urine samples from a cohort study of pregnant women was 0.92 μg/g creatinine (123). In replacing palm oil with plasticizers during the production of food and medicine, local populations exposed to plasticizers for years might suffer from reduced reproductive performance. In addition, prolonged exposure to phthalates even at low doses can induce the onset of atherosclerosis and elevated blood pressure in adolescents (124). It is worth noting that, however, the biotoxicity normally depends on the exposure dose and selected benchmark, which should be carefully considered in estimating toxic effects and health impacts of ECs on humans. Furthermore, the wide spectrum of EC biochemical properties likely means their health effects vary across patterns and populations. Overall, the relevance between EC exposure and human health problems has been tentatively demonstrated, highlighting the need for the further comprehensive investigation of the health effects of ECs in groundwater.

3.5. Pathogenic Microorganisms in Groundwater and Health Impacts

Although groundwater is generally regarded as an oligotrophic ecosystem, it offers vast habitats for diverse microorganisms, including pathogenic bacteria, viruses, and protozoa. The pathogens in groundwater prefer to embed in biofilms or attach to particles, which has important implications for their phenotype and survival (125). In contrast with viruses and protozoa, bacteria are able to actively form biofilms, providing comfortable habitats for the neighboring pathogens. The presence of pathogenic microorganisms in groundwater and associated water supply systems has posed a serious threat to the global public health. This is of particular concern for decentralized water supply systems and developing countries (126). If not treated or purified thoroughly, contaminated groundwater used in homes or agriculture will increase the risk of disease in animals and humans.

Bacteria are recognized as the most prevalent pathogens in groundwater, with highly diverse risks (127). Enteric bacterial pathogens, such as *Campylobacter*, *Enterotoxigenic Escherichia coli*, *Shigella*, and *Vibrio cholera*, are responsible for many waterborne outbreaks (128). Infection by these pathogenic bacteria occurs primarily in the small intestine in humans, causing gastroenteritis with watery diarrhea, cholera, or fever and dehydration in severe cases. For example, when humans ingest contaminated groundwater, *V. cholera* colonizes small intestinal epithelial cells via toxin-coregulated pili. After adhesion, the cholera toxin generated by *V. cholera* causes infections that can be asymptomatic or responsible for severe watery diarrhea known as rice water stools (129). Associated complications including reactive arthritis and the neurological disease Guillain-Barre syndrome (GBS) may occur simultaneously with gastroenteritis. In addition to *V. cholera*, several GBS cases (approximately 31%) are associated with *Campylobacter* infection, but the pathogenesis remains unclear.

Viral contaminants have been considered a more dangerous threat to groundwater quality than bacterial and protozoal pathogens (127). Their smaller size (0.02–0.2 mm), more diverse constituents (>5 groups and >140 stereotypes), longer survival times, and higher resistance to disinfection procedures than most intestinal bacteria may make viruses widespread and the most crucial candidate groundwater pathogens (130). Although viral pathogens and their concentrations vary significantly in aquifers over time and space, the unenveloped RNA viruses, Rotavirus, Enterovirus, Norovirus, and Hepatitis A virus, and enveloped Coronavirus were among the most frequently detected in groundwater (131). The major disease caused by Norovirus and Rotavirus is acute gastroenteritis. In comparison, polio-like illness, aseptic meningitis, epidemic conjunctivitis, and hand, foot, and mouth disease have been reported in Enterovirus-infected patients. The infection by Hepatitis A virus can lead to fever, nausea, jaundice and liver failure (132). Coronaviruses are a large family of viruses causing a spectrum of diseases ranging from the common cold to more severe diseases, such as Middle East Respiratory Syndrome and Severe Acute Respiratory Syndrome. The COVID-19 pandemic caused by SARS-CoV-2 and its variants was a public health emergency of international concern and has profoundly impacted all humans (133).

The most common pathogenic protozoa in groundwater include *Cryptosporidium parvum*, *Giardia lamblia*, and *Entamoeba histolytica*, which are the agents for cryptosporidiosis, giardiasis, and amoebiasis, respectively (126). Although infection by these parasitic protozoa can be self-limited in healthy individuals, they potentially cause life-threatening diseases such as severe diarrhea, encephalitis, and dysentery in vulnerable people (134). The life cycle of the parasitic protozoa begins with their cysts and oocysts, which exhibit high stability and maintain viability for up to 12 months in cold environments typical for groundwater (135). In the small intestine, each cyst produces two trophozoites, which multiply by longitudinal binary fission. The trophozoites remain in the lumen of the proximal small bowel. When they transmit toward the colon, encystation occurs to form a protective cyst wall around trophozoites, presumably in response to bile concentration. Both cysts and oocysts can be released into the external environment during defecation and may lead to a new round of infection (135).

Managed aquifer recharge: active methods of groundwater management that either recharge aquifers with clean surface water or use subsurface recharge technologies

The main route of exposure to pathogens in groundwater by the human body is drinking groundwater without adequate treatments (**Figure 2**). Infection by pathogenic microorganisms begins with ingestion of contaminated groundwater, contaminated food consumed by hand, or via fomite carried into the gastrointestinal tract, where microbial propagation and replication occur (136). The pathogenic viruses, however, can additionally pollute human blood through broken skin and mucous membrane. Artificial groundwater recharge in combination with bank filtration, subsurface dams, and artificial aquifers appears to be a highly effective pretreatment strategy in natural attenuation of pathogens for safe drinking water (137). This approach efficiently removes the majority of pathogenic bacteria, but viruses and cysts/oocysts of protozoa may pass through filtration systems due to their adequately small size. Taken together, ensuring groundwater quality—defined or updated in line with long-term safe and sustainable use of groundwater resources—should emphasize the potential public health impacts. To approach this goal, we need to seek strategies for regulating and mitigating these key substances of great scientific and general public concern.

4. MANAGEMENT AND REMEDIAL ACTION FOR GROUNDWATER QUALITY PROTECTION

As highlighted above, sustaining good-quality groundwater resources is an ongoing challenge with regard to not only the accumulation of potentially harmful ECs and pathogens in groundwater but also pressure caused by a changing climate, growing populations, increasing urbanization, and rising demands on agricultural water (4, 138). This essentially drives the governance of sustainable groundwater to take into account these factors. In accordance, directives on groundwater governance are informing policy-making by raising awareness about the critical role of groundwater resources in averting the imminent water crisis (139). Overall, six general governance directives have been launched with global consensus: (*a*) recognizing aquifers and groundwater as critically important, finite, valuable, and vulnerable resources; (*b*) halting the ill-controlled depletion of groundwater in aquifers on a global basis; (*c*) understanding aquifer systems as unique and groundwater as visible; (*d*) managing groundwater in a sustainable way within an integrated water resource framework; (*e*) increasing managed aquifer recharge globally; and (*f*) implementing effective groundwater management with robust stakeholder participation and community engagement (140). In addition, because groundwater and surface water are so interconnected that their links must be respected in achieving sustainable water management, the American Water Resources Association recommends the holistic management of groundwater on the basis of the principles of Integrated Water Resources Management (IWRM) (141). The following are the ten IWRM-recommended actions: (*a*) assess resources, (*b*) build partnerships, (*c*) align legal frameworks, (*d*) think groundwater, (*e*) maintain sustainability, (*f*) respect ecosystems, (*g*) engage stakeholders, (*h*) commit to understand, (*i*) protect the asset, and (*j*) utilize interdisciplinary approaches. Clearly, the IWRM-recommended actions are in high concert with the general governance directives mentioned above.

The limitation of large-scale self-renewal for groundwater renders IWRM to be a critical approach for guaranteeing the sustainability of this resource (142). Fortunately, a wealth of experience has been accrued over the years on IWRM. In the United States, the Clean Water Act and Safe Drinking Water Act have been enacted since 1972. These achievements strongly suggest that groundwater monitoring and assessment should be conducted using the hydrogeological unit as the base and that IWRM should be developed based on the spatial expansion of aquifers (143). Similarly, Australia has enacted the National Water Initiative and National Water Quality Management Strategy since 2006 and implemented IWRM following the ecological sustainable development principles. In particular, managed aquifer recharge has been pioneered to improve the amount and quality of groundwater resources (144). Member states of the European Union act for enhanced cooperation on groundwater quality monitoring, identification and removal of groundwater pollutants, and developed utilization of groundwater resources under the guidance of the Water Framework Directive and Groundwater Directive, especially for the widespread transboundary aquifers (145). China has enacted the new Regulations on Groundwater Management and Law of Prevention and Control of Water Pollution since 2017. These nationwide laws require that central and provincial governments organize routine groundwater surveys to provide guidelines for compensating groundwater overexploitation and for decontaminating groundwater. In brief, improving public awareness regarding groundwater resources protection could pave the road to sustainability-oriented regulations for IWRM and a more sound system of groundwater resources use.

In practice, economic policies may employ financial incentives and disincentives to better societal behaviors in order to encourage sustainable groundwater resource management (146). For example, tax and quota policies are commonly used tools to reduce the misallocation and overconsumption of groundwater resources. In this way, the tax policies can lead users to consider future resource value and added costs when deciding on groundwater withdrawals. Water use quotas are a policy alternative because they can reduce the uncertainties regarding the amount of water available to users (147). In addition, indirect pricing of groundwater is another potentially feasible economic policy, such as providing a certain amount of electrical energy per day through a flat energy tariff. Nonetheless, farmers receive electricity subsidies instead of direct water subsidies, which results in a significant overuse of both energy and water in groundwater-irrigated agriculture. To truly and effectively save water, subsidies that encourage the use of more efficient irrigation technologies may be a viable means (141). Overall, trial of economic tools requires the collection of good data on groundwater use, rights, and pricing.

The nature-inspired remediation technologies for groundwater contaminants play important roles in purifying groundwater and improving its ecological and societal values. They are applicable not only to the conventional geogenic contaminants, e.g., As, F, and I (148), but also to ECs and pathogens that require detoxification and purification to assure thorough water safety (111, 137). By learning from nature, we may be able to take advantage of redox reactions, adsorption, and biodegradation, among others, that are occurring in the subsurface to in situ immobilize or decompose those key substances to the levels safe for humans. This represents the environmentally friendly and efficiently active approaches in securing groundwater quality. Based on the hydrogeological structure and environmental conditions of contaminated aquifers, integrating multiple remediation technologies seems to maintain key substances in groundwater within safe concentration ranges more effectively.

5. PERSPECTIVES

As the global population is projected to rise in the coming decades, groundwater resources are likely to be increasingly relied upon for drinking, domestic use, and agricultural irrigation, making groundwater quality more crucial to ensuring water and food safety on regional to global scales. Nonetheless, groundwater quality, as defined by key substances related to human health that include essential elements, geogenic contaminants, toxic metals, ECs, and pathogens, shows signs of increasing deterioration due to evolving hydrogeological-geochemical processes and strengthening anthropogenic perturbations. In the meantime, global environmental changes and the insufficiency of groundwater sustainability–oriented policy-making challenges the safe and sustainable use of groundwater resources for the well-being of society. In particular, climate change is likely to exacerbate the toxicological aspects of essential elements, heavy metals and metalloids, and ECs in groundwater (149). This poses high pressure on groundwater quality for megacities. With projected increases in sea level rise and in the population living in coastal areas in the decades ahead, destruction of the nutritional properties of potable groundwater by intensifying tidal surges and coastal flooding in deltaic zones and low-lying islands needs our special attention due to its severe public health impacts (e.g., CVDs, diarrhea, and abdominal pain) (54, 62, 139).

In the Anthropocene, the impacts of interrelated natural and anthropogenic processes of groundwater contamination on public health represent a significant concern that deserves our attention. The increasingly recognized prevalence of ECs and pathogens in the vast aquifers are probably complicating the spatiotemporal variability of the groundwater quality for both decentralized wells and regional water supply. This likely makes the protection and rehabilitation of groundwater resources more difficult due to the high heterogeneity of the groundwater systems as well as our limited understanding of this high complexity. Although comprehensive interpretations of the behaviors, fate, and exposure routes of the key components in groundwater lay the scientific foundation for groundwater quality management, safeguarding groundwater-dependent public health still requires concerted efforts in source control, cross-scale rehabilitation, and social hydrology-based groundwater governance.

SUMMARY POINTS

1. As groundwater is a vital source of drinking and irrigation water, water and food safety depend increasingly on groundwater quality and its health effects.
2. Both natural and anthropogenic processes have contributed to the complexity and variability of groundwater quality on local to global scales.
3. Potable groundwater adequately rich in essential elements is favorable to life and human health; abnormally high concentrations, however, confer adverse health effects and severe public health issues around the globe.
4. The shallow aquifers that are frequently utilized as significant sources of clean water supply, in the past and at present, are more prone to contamination by toxic metals, organic pollutants, emerging contaminants, and pathogens than the deeper confined aquifers, and thus represent a major source of exposure to these harmful substances.
5. The adverse biological effects and exposure routes of persistent organic pollutants (POPs) suggest that POPs in groundwater risk causing severe harms to human health.
6. The pathogenic microorganisms in groundwater and associated water supply systems pose a nonnegligible threat to global public health, especially for the noncommunity water supply systems and the developing areas.
7. Concerted actions of groundwater governance directives, sustainability-oriented policy tools, and nature-based remediation may lead to long-term safety of groundwater quality for the sake of public health.

FUTURE ISSUES

1. Geogenic and anthropogenic contamination of groundwater has emerged as a global concern for the safe and sustainable use of groundwater resources. Attention should be paid to the interactions between geogenic and emerging contaminants (ECs) in groundwater and to the impacts, likely unexpected, on water and crop food safety.
2. Although the concentrations of ECs in groundwater are generally low, the persistence and prevalence of these contaminants as well as their impacts on the groundwater environment and human health require urgent, specific investigations.
3. Overall, there are no clear explanations of the mechanisms underlying correlations between health effects and intake of essential elements and ECs from groundwater. Future research on national and transboundary public health may delve deeper into medical hydrogeology to explore the mechanistic links between the spatiotemporal variability in exposures to the key components in groundwater and the health of all populations.
4. Considering the impacts of climate change and increasingly strong anthropogenic processes, how the conventional pollutants and ECs mobilize and are transported concurrently during groundwater-surface water interactions remains a big challenge for groundwater quality control.
5. The transport and transformation of key substances are further complicated by the anthropogenic perturbations, which through multiple ways exert significant influences on the hydrobiogeochemical conditions relevant to solute mobilization and transport. Future work is therefore needed to integrate multidisciplinary knowledge to achieve an in-depth understanding of the interactions between human activities and transport/transformation of key substances in aquifer systems.
6. Science-based directives and policies on groundwater management require continual awareness of the vital role of groundwater quality in the grand challenge of providing clean water supplies.

DISCLOSURE STATEMENT

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