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PREFACE

Preface: Hydrogeology and human health

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In the mid-1800s, Dr. John Snow (1813–1858), an obstetrician and anaesthesiologist, theorised that cholera, a highly infectious gastrointestinal infection associated with extremely high rates of mortality, was caused by faecal contamination of water supplies (Donaldson and Scally 2009). During the summer of 1854, a significant cholera outbreak occurred in the Soho district of London (UK), resulting in the deaths of 616 people. As part of this first modern epidemiological investigation, Dr. Snow noted that "within 250 yards of the spot where Cambridge Street joins Broad Street there were upwards of 500 fatal attacks of cholera in 10 days (…) suspected some contamination of the water of the much-frequented street-pump (a public well) in Broad Street." Snow subsequently developed what is now referred to as "The Ghost Map", a geographical grid indicating where and when cholera cases and associated mortalities occurred in relation to the public well (Hempel 2007). Not only did the map confirm that almost all cases related to drinking water from the pump, but also that specific residential clusters were not associated with infection; for example, workers in an adjacent brewery did not contract the illness due to their daily allowance of beer. Later research discovered that the hand-dug well had been constructed just 0.9 m from a defunct septic tank/cesspit (Johnson 2006; Hempel 2007). Thus, it might be said that the science of epidemiology, considered the cornerstone of public health and defined as "the study and analysis of the patterns, causes, and effects of health and disease conditions within a specific population" (Porta 2008), has its very roots in hydrogeology and the subsurface.

Historically, many assumed that natural groundwaters were free of (geogenic and anthropogenic) chemical contaminants; however, this is not the case, with this presumption potentially resulting in an unfounded and potentially hazardous sense of security among owners, operators and users of water wells—for example, in an effort to reduce waterborne gastrointestinal illness in developing regions of southern Asia, the international community heavily promoted a shift from using surface water to presumably cleaner groundwater sources during the 1970s (Flanagan et al. 2012). However, at the time, high rates of naturally occurring arsenic via concurrent biogeochemical and hydrologic processes in many of these regions had not been recognised, resulting in a widespread failure to assess the chemical quality of newly developed groundwater sources (Mukherjee et al. 2006). Four decades later, the associated health crisis continues; recent figures suggest that over the coming decades, 1 in 10 adult deaths in Bangladesh may be attributable to arsenic-associated cancers, with over 700,000 people in Southeast Asia known to have been affected by arsenic-related diseases to date (Fendorf et al. 2010). High levels of geogenic arsenic have been detected in groundwater supplies from approximately 70 countries, potentially affecting up to 140 million people (Mukherjee et al. 2006).

The objective and scope of this special issue, *Hydrogeology and Human Health*, has been borne of myriad issues and pressures pertaining to global groundwater resources, some longstanding and some more recently acknowledged. Among them, climate change, exponential population growth, increasing urbanisation, increasing food production and waste

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management requirements, and inconsistent regulation perhaps stand the tallest. Groundwater resources have never been more valuable or necessary, nor have they been under such strain. Accordingly, the editors have endeavoured to assemble a collection of papers that seeks to provide the reader, not only with a new perspective on the topic of medical geology, or as coined by Rehman (2009) "geomedical engineering", but also with information that solidifies the role and importance of hydrogeology and hydrogeologists in global public health. This special issue is aimed at anyone with an interest in waterborne infection, groundwater contamination, or "hydro-epidemiology", from undergraduate students and new postgraduate researchers, to those with decades of experience. As such, the issue comprises 22 peer-reviewed papers, of which 15 pertain to subsurface pathogens, and 7 focus on the human health effects of geogenic and anthropogenic chemical contaminants. Several excellent global and regionally focused review papers are included, in addition to research papers covering myriad countries, climactic regions, and hydrogeological settings, including Italy, Canada, Ireland, Vietnam, sub-Saharan Africa, India, and Vietnam, to name but a few. The collection is inherently multidisciplinary in nature; however, the invited papers are organised into two sections that reflect the nature of the associated human health effects, namely, (1) groundwater pathogens (acute effects), and (2) chemical contaminants (chronic effects).

Groundwater pathogens

Groundwater pathogens comprise numerous taxa, each of which requires a specific, and often complicated, laboratory assay to assess pathogen presence, and where possible, concentration. In lieu of this required effort and expertise, public health officials have relied for decades on more easily assayed non-pathogenic microbes, aka the faecal indicator organisms (FIOs), to indicate the sanitary quality of water. Definitively linking these indicators with a specific human health outcome necessitates expensive and labour-intensive epidemiological methods. As a default, investigators often evaluate an indicator's utility by characterising its co-occurrence with one or more pathogens via standard tests of association. Combining data on human enteric viruses and FIOs from 12 international groundwater studies, **Fout et al.** present the full suite of information necessary to evaluate virus and indicator co-occurrence; they estimate the elevated likelihood of detecting a virus when each of six frequently employed indicators are detected, in addition to estimating the four standard performance measures of any diagnostic test: sensitivity, specificity, positive predictive value, and negative predictive value. Finding the most effective indicator for pathogens in groundwater remains one of the 'Holy Grails' of public health microbiology, with the paper duly providing a new map for the quest.

Between the point at which a microbial contaminant begins its subsurface journey and arrival at its final (unfortunate) destination, be it a public or private well, or an aquifer, many processes affect the fate and transport of microbes, primarily retention, release, growth, and decay. Efforts to improve scientific understanding of these processes at the most fundamental levels are driven by the promise of prediction and being able to use microbial transport principles to establish truly effective setback distances that prevent contamination from potential contamination sources. Two papers in this special issue address this topic. **Hunt and Johnson** bring their two scale-dependent perspectives together from field-level hydrogeological transport to nanoscale mechanisms of particle and surface interactions. As such, their article takes an important first step in developing the conceptual framework for scaling up microbial transport principles from laboratory to the field. Following this, **Bradford and Harvey** combine years of experience and influential work on microbial transport in the laboratory and field, and present a veritable goldmine of ideas on which research directions will move the discipline significantly forward. Together these two papers encompass the salient issues at the intersection of subsurface microbial transport and human health.

Pharmaceuticals, and more specifically antibiotics, are now considered emerging contaminants of global concern, not least due to their environmental fate, potential toxicity, and the increasing prevalence of antibiotic resistant infections, both in nosocomial and community settings. **O'Dwyer et al.** present results of the first study from the Republic of Ireland to examine the presence of antimicrobial resistance among *E. coli* isolates recovered from private groundwater sources. A panel of commonly prescribed human and animal antibiotics was assessed, with multiple antimicrobial resistance frequently encountered, particularly among the veterinary panel, and specifically among the aminoglycoside antibiotics. Their paper concludes that septic tanks, infant residents, and livestock density are primary drivers of resistance and horizontal gene transfer in the subsurface.

Another emerging contaminant of major health concern that seems to raise its treacherous head every few months is the brain-infecting amoeba *Naegleria fowleri*. Fortunately, infection is rare; regrettably, so are data on the factors influencing the amoeba's occurrence, particularly in groundwater and hot springs. **Bright and Gerba** review reports of *N. fowleri* infections related to groundwater exposures and discuss future research needs of *N. fowleri* ecology in groundwater, and speculate that its geographic range could expand northward with climate change.

Dissolved organic carbon (DOC) is to hydrogeology as silica is to petrology, a crucial constituent that, due to its ubiquity, often disappears from the scientific consciousness. **Regan et al.** raise DOC awareness and present a novel overview of several potential relationships between groundwater

DOC and human health. To make this connection, indirect effects must be considered, for example, the role of DOC in generating disinfectant by-products, its potential effects on subsurface pathogen mobility and other colloidal contaminants, and inhibition of the polymerase chain reaction, a common molecular method for assessing microbial contamination of groundwater that, if inhibited, could produce false-negative results.

Several previous studies have shown that high-intensity and/or long duration precipitation events are frequently followed by increased rates of acute gastrointestinal illness. **Uejio et al.** look into the future and consider climate change projections for precipitation volumes and what this could mean for levels of infection in children residing in groundwater-supplied communities without disinfection. While the most deleterious consequences of these events are likely to befall small rural communities that rely on non-disinfected groundwater, their work shows that if these communities were to rapidly adopt drinking water treatment technologies, approximately 80% of the predicted increase in illness could be prevented.

Staying with this theme, it is no secret within the fields of epidemiology and public health that groundwater is perhaps the least understood environmental transmission route for enteric pathogens. The questions frequently asked, yet very rarely answered, are “what fraction of acute gastrointestinal illness in a population or region is attributable to pathogen-contaminated groundwater?” and of the acute illnesses attributable to groundwater, “how many go on to cause severe infection and possibly death?” **Murphy et al.** provide what is perhaps the most comprehensive critical assessment of this massive topic to date by reviewing over 110 articles and almost seven decades of global information on groundwater supply types, groundwater-related infections and outbreaks, the types and frequency of pathogens found in groundwater, and the study designs employed in epidemiology and risk assessment. Their paper can serve as a guide to future scientific studies focusing on assessing enteric disease (acute gastrointestinal illness) and its relation to groundwater. Additionally, the authors offer their ideas for future research on groundwater pathogens.

Among those working in the area of groundwater pathogens and waterborne infection, few are unfamiliar with the infamous Walkerton outbreak, which occurred in the small community (population ~5,000) of Walkerton, Ontario (Canada), during May 2000, and resulted in approximately 2,300 infections and seven mortalities. Numerous studies have shown that the outbreak occurred due to several intersecting factors including heavy rainfall, treatment failure, and budgetary restrictions (Auld et al. 2004; Salvadori et al. 2009). Almost two decades on, **Worthington and Smart** present previously unpublished results of electrical conductivity profiling within the Palaeozoic carbonate aquifer. Findings indicate that significant flows occur through bedding-plane fractures and large-aperture fracture networks, highlighting the dual-porosity nature of the formation, in addition to associated rapid groundwater flow and high hydraulic diffusivity. As stated in the paper, pathogenic and non-pathogenic bacteria are frequently present in carbonate aquifers, notwithstanding the absence of karstic features.

Likewise, **Bucci et al.** present an overview of findings to date from an ongoing 10-year study of carbonate aquifers in southern Italy. These investigations are characterised by their use of emerging biomolecular technologies, an approach that is steadily developing a foothold in hydrogeological investigations. As such, their paper provides an overview of the many potentially useful molecular approaches now available, and how they may be effectively coupled with traditional hydrogeological, hydrochemical, isotopic, and geophysical methods for analysis of subsurface microbial dynamics and groundwater vulnerability. Numerous research questions have been addressed as part of the overall project, for example, (1) the influence of rainfall regimes on spring breakthrough in mountainous regions, (2) the influence of pyroclastic topsoil on microbial migration, and (3) the efficacy of groundwater microbes as natural tracers. The work has found that migration of a significant volume of bacterial cells through topsoil and underlying carbonate rocks permits the use of microorganisms as effective natural tracers, which may be considered in parallel with other “classic” tracers to study recharge and other flow processes.

A wealth of superb research work relating to groundwater contamination (particularly enteric pathogens) and human health has emanated from the Nordic/Scandinavian region. This is unsurprising due to extremely high levels of groundwater reliance in these countries—for example, >99% of Danish water supplies utilise a groundwater source, while 85% of Swedish waterworks are associated with groundwater (Guzman-Herrador et al. 2015), with artificial groundwater recharge also widely employed. Continuing in this trend, there are three Nordic/Scandinavian papers included in this special issue. **Kløve et al.** provide a thorough overview of groundwater sources, water-supply systems, and associated microbial pollution, in Finland, Norway and Iceland. The distinctive characteristics of Nordic climate, geology, and hydrogeology, and particularly the unique recharge regime, are presented, along with the subsequent issues relating to contamination vulnerability. The extent, importance, and issues associated with managed aquifer recharge are summarised, in addition to the levels and types of water treatment employed. Most groundwater-related outbreaks that occur in this region are typically associated with norovirus and *Campylobacter* spp. **Krog et al.** subsequently describe findings from a field study undertaken on a Late Weichselian glacial moraine in northern Denmark. This study sought to quantify the leaching potential of three enteric viruses and three faecal indicator organisms to tile drainage systems due to slurry spreading. Whereas previous studies have examined the leaching potential of *E. coli*, this represents the first to study leaching patterns of multiple potentially pathogenic microorganisms, with a comprehensive suite of chemical, microbial and molecular methods employed for identification. A finding of particular relevance in the context of the special issue is the isolation of virus genomic material in monitoring wells up to 2 months after slurry application, thus highlighting the potential adverse human health impacts of these activities, particularly in areas with shallow water tables. Staying with the topic of groundwater viruses and the Nordic climate, **Mayotte et al.** examine a new approach to fitting virus inactivation models, namely General Likelihood Uncertainty Estimation (GLUE), and investigate the effects of sand and organic matter on microbial dynamics at low temperatures. While GLUE has been used since the early 1990s to optimise hydrological models via quantification of prediction uncertainty (Beven and Binley 1992), this is perhaps the first example of its use for modelling virus dynamics (bacteriophage MS2) in the subsurface environment. Findings suggest that GLUE produces similar parameter estimates to those of the more traditionally employed least-squares technique, and therefore represents a viable alternative. Results from static batch inactivation experiments indicate that increased DOC concentrations concur with increased virus inactivation, i.e. presence of organic carbon, encourages augments inactivation.

Perhaps nowhere are groundwater resources so precious as in sub-Saharan Africa, a region characterised by historically low levels of access to safe water supplies and sanitation, and a rapidly increasing population. The UN predicts that the regions population will increase to 1.5–2 billion over the next three decades (United Nations 2015). While access to clean water has increased within the region, there is a notable urban/rural divide, with urban areas unable to keep pace due to high levels of residential growth. The resulting human health effects are clear (MacDonald et al. 2009). This special issue includes two articles from urbanised areas within this region. **Engström et al.** present a new geostatistical approach to elucidating groundwater microbial contamination mechanisms, with the method developed and employed in Juba, South Sudan. The developed approach integrates conventional probit regression modelling with spatial autocorrelation, and employs hydrogeological, land-use, and socio-economic variables. Findings indicate that statistical assessments of groundwater contamination, which are becoming a method of choice (e.g. Howard et al. 2003; Hynds et al. 2012), should consider spatial interactions when wells are situated in close proximity, particularly in urban and peri-urban areas. **Lapworth et al.** provide a comprehensive overview of the chemical and microbial status of groundwater across a range of source types and hydrogeological settings in sub-Saharan Africa, and specifically within the context of climate change and future requirements. Based upon previous work by those authors, the vulnerability of lower storage basement terrains is given particular attention, not least because these underlie many large urban conurbations in the region. Future research requirements and an assessment of the association between groundwater nitrate and inherent contamination risk in the region are also presented.

Hydrogeologists are not the only scientists who find anisotropy and heterogeneity problematic in fractured bedrock aquifers; these inherent aquifer properties also make it difficult for microbiologists to understand pathogen migration in these formations. **Allen et al.** present a pathogen vulnerability assessment of the fractured dolostone aquifer that supplies drinking water to residents of Wellington County in Ontario. Using statistical approaches, their research shows that pathogens are more likely found in wells with longer open intervals, with pathogen concentrations in these wells negatively related to well depth and open interval length. Moreover, results indicate that the cumulative amount of precipitation preceding sampling by 2–3 weeks is related to higher pathogen concentrations. Despite the inherent uncertainty of flow paths in fractured bedrock aquifers, their conclusions show it is possible to identify the factors leading to pathogen contamination of wells in these aquifers.

Chemical contaminants

Arsenic is widely distributed throughout the environment with one of the major sources of groundwater arsenic being natural processes such as dissolution of arsenic-containing minerals. Arsenic is of particular concern to public health due to its significant toxicity and global ubiquity. Investigations of arsenic transport and geochemical mechanisms in the subsurface are key to understanding its distribution. **Kuroda et al.** study the effect of the sedimentary environments of Pleistocene and Holocene deposits, and associated recharge systems, on groundwater arsenic pollution in Vietnam. They report that groundwater arsenic concentrations in the Pleistocene confined aquifer are significantly higher, with these elevated concentrations likely being caused by vertical infiltration through the arsenic-rich and organic-matter-rich overlying Holocene estuarine sediments. Vertical groundwater movement in the sediments have resulted from massive groundwater abstraction from the Pleistocene confined aquifer. They propose several countermeasures to prevent further concentration increases in the Pleistocene confined aquifer.

Moving to the Indian subcontinent, **Choudhury et al.** present a study of the spatial distribution of arsenic along three classified hydrogeomorphological zones in the Brahmaputra River Valley in Assam. In order to examine the geochemical processes controlling arsenic mobilisation, they chemically analysed 150 groundwater samples from shallow and public water supply wells, finding a notable decrease in redox conditions along the runoff and discharge zones. Additionally, systematic changes in arsenic concentrations along the three hydrogeomorphological zones illustrated that areas of active recharge with high hydraulic gradients potentially represent “low-arsenic aquifers”.

As mentioned earlier in this preface, myriad human health problems associated with groundwater arsenic contamination have been reported from many countries. **Chakraborti et al.** investigate groundwater arsenic contamination and its health effects in India, with their findings based on a comprehensive 28-year longitudinal field survey in seven states, six of which comprise major river floodplains. More than 170,000 tubewell samples were analysed as part of the study, with approximately half of the samples associated with an arsenic concentration > 10 μg/L. The paper reports that 4.5% of children from the studied areas have presented with mild to moderate arsenical skin lesions, and also show that the population associated with severe arsenical skin lesions are more likely to contract numerous multiple cancers in the long term.

In order to prevent further health problems associated with arsenic, understanding mechanisms of arsenic removal from groundwater is crucial. Accordingly, **Chanpiwat et al.** investigate the effects of phosphate, silicate and natural organic matter on arsenic removal by ferric chloride. They carried out a series of batch co-precipitation experiments over a wide pH range using synthetic hard and soft groundwaters, similar to those found in northern Vietnam, and found that PO_4^{3-}, SiO_4^{4-} and natural organic matter in groundwater significantly decrease arsenic removal efficiencies from water by co-precipitation with $FeCl_3$; thus, they recommend the use of other remediation processes, such as membrane filtration technologies in order to ensure the future safety of drinking water in affected regions.

Aside from arsenic, countless other dissolved chemicals in groundwater have the potential to cause major human health threats. Selenium, for example, which is frequently present in both surface water and groundwater, is an essential human micronutrient; however, it can cause adverse health impacts at high levels of exposure. A review paper by **Bailey** focuses on the fate and transport of selenium in groundwater within the context of potential human health impacts. As selenium is consumed primarily via plant and animal products, migration and distribution of selenium in soil and groundwater systems play an essential role in determining the effect of selenium on human health. The paper presents a review of over 190 articles focusing on the relationships between selenium and human health, in addition to providing a summary of selenium distribution in soil-aquifer systems.

In addition to inorganic chemicals (e.g. arsenic and selenium), organic chemicals, including organic compounds released from coal deposits, are frequently (and increasingly) encountered groundwater contaminants. **Chakraborty et al.** examine the organic composition of groundwater along the Carrizo-Wilcox aquifer in East Texas (USA) to investigate the potential health and environmental effects of organic compounds derived from low-rank coals. They identify a variety of organic compounds, many of which are geogenic and originate from groundwater leaching of young and unmetamorphosed low-rank coals. Whereas a proportion of the organic compounds are potentially toxic to humans, the research finds that these are unlikely to cause acute human health problems. The study recommends that further studies of the human health effects of low-level chronic exposure to coal-derived organic compounds be undertaken both locally and more broadly.

Conclusion

Over the past 50 years, significant progress has been made in improving scientific understanding of the extent and potential consequences of groundwater contamination, with research advancing on several fronts including groundwater sampling methods, laboratory detection methods, subsurface transport (and microbial survival) as it relates to hydrogeological concepts and colloid filtration theory, and the role of environmental factors such as temperature and precipitation. Nonetheless, data and knowledge gaps remain, necessitating significant continued research in this area. Many excellent studies have been undertaken on the occurrence of pathogens and chemicals in groundwater; however, the data tend to be biased towards specific geographical regions and pathogen/chemical types. In the USA, for example, groundwater pathogen studies are over-represented in the upper Midwest, whereas few studies have been conducted in the south-eastern region. Subsurface pathogen studies have tended to focus on groundwater viruses, but there is a paucity of data on groundwater contamination by protozoan pathogens, with the same being true for many emerging organic contaminants including pharmaceuticals, endocrine disruptors, and microplastics. A significant proportion of studies on groundwater microbial contamination are conducted via laboratory microcosms or groundwater mesocosms. Such study designs likely do not adequately represent the direct and indirect effects on pathogen survival from attachment to aquifer sediments, predation from invertebrates and protozoa, bacterial pathogen growth from nutrient inputs to the aquifer, and the complex interactions with native microbial communities. The subsurface represents an extremely complex environment, characterised by significant spatial and temporal variability, and is almost impossible to accurately replicate. Thus, further studies are needed that seek to adequately account for the abiotic and biotic conditions found in natural groundwaters, as these will likely yield the most accurate measurements of microbial subsurface survival.

The recently proposed field of socio-hydrology, described by Sivapalan et al. (2011) as an exploration of the “…

coevolution and self-organisation of people in the landscape with respect to water availability…" may perhaps provide us with the first step. As previously eluded to, many of the current pressures on groundwater yield and quality are anthropogenic in nature, including population growth, agricultural and industrial intensification, increasing waste and wastewater production, and a paucity of effective regulation. Thus, effective communication and engagement are key, particularly with non-expert groundwater source owners and users. Hydrogeologists are central to these efforts, as the frequently complicated hydrogeological concepts and equations of importance (e.g. hydraulic conductivity, hydrodynamic dispersion, colloid filtration theory, etc.) are derived from, and should be informed (and simplified) by the hydrogeological community. In taking the "dual receptor" approach developed by Hynds et al. (2013), while it is undoubtedly possible (albeit often difficult) to improve, remediate, and thus protect a groundwater source (Receptor 1), it is also possible to empower well owners and users (Receptor 2) via education and awareness, and in doing so, achieve similar goals, i.e. an increasingly appreciated and protected natural resource.

The invited articles comprising this special issue and the broad, multi-disciplinary range of issues they encompass thoroughly demonstrate not just the global significance and inherent complexities associated with subsurface contamination and subsequent human health effects, but also the underlying interest and fascination the subject has for many. Perhaps most importantly, this special issue of *Hydrogeology Journal* shines a light on the critical role played by hydrogeologists and groundwater researchers in safeguarding current and future generations. Hydrogeologists possess an inherent understanding of the complex and unpredictable nature of groundwater contamination, and thus in collaboration with microbiologists, epidemiologists, geochemists, medical practitioners, and policy makers, have an opportunity to help achieve global public health goals.

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