Faster and Safer: Research Priorities in Water and Health

Prepared for: *International Journal of Hygiene and Environmental Health*

Authors: Karen Setty,[a]* Jean-Francois Loret,[b] Sophie Courtois,[b] Charlotte Christiane Hammer,[c] Philippe Hartemann,[d] Michel Lafforgue,[e] Xavier Litrico,[f] Tarek Manasfi,[g,h] Gertjan Medema,[i,j] Mohamed Shaheen,[k] Vincent Tesson,[l] Jamie Bartram[a]*

*Corresponding authors

[a] The Water Institute at University of North Carolina at Chapel Hill, Department of Environmental Sciences and Engineering, CB #7431, Chapel Hill, NC, 27599-7431; ksetty@live.unc.edu, jbartram@email.unc.edu

[b] Suez, Centre International de Recherche sur l'Eau et l'Environnement (CIRSEE), 38 rue du President Wilson, 78230, Le Pecq, France; jean-francois.loret@suez.com, sophie.courtois@suez.com,

[c] Norwich Medical School, University of East Anglia Faculty of Medicine and Health Sciences, Norwich, NR4 7TJ, UK; c.hammer@uea.ac.uk

[d] Université de Lorraine, Faculté de Médecine, EA 7298, ERAMBO, DESP, Vandœuvre-lès-Nancy, France; Philippe.Hartemann@univ-lorraine.fr

[e] Suez Consulting, Le Bruyère 2000 - Bâtiment 1, Zone du Millénaire, 650 Rue Henri Becquerel, CS79542, 34961, Montpellier Cedex 2, France; michel.lafforgue@suez.com

[f] Suez, Tour CB21, 16 Place de l'Iris, 92040 Paris La Defense Cedex, France; xavier.litrico@suez.com

[g] Aix Marseille University, CNRS, LCE UMR7376, 13331, Marseille, France; tarek.MANASFI@univ-amu.fr

[h] Institut Ecocitoyen Pour la Connaissance des Pollutions, Centre de vie la Fossette RD 268, 13270, Fos-sur-Mer, France

[i] KWR Watercycle Research Institute, Groningenhaven 7, 3433 PE, Nieuwegein, The Netherlands; gertjan.medema@kwrwater.nl

[j] Delft University of Technology, Stevinweg 1, 2628 CN, Delft, The Netherlands

[k] School of Public Health, University of Alberta, 3-300 Edmonton Clinic Health Academy, 11405 - 87 Ave, Edmonton, AB T6G 1C9, Canada; mshaheen@ualberta.ca

[l] French National Institute for Agricultural Research (INRA), UMR 1114 EMMAH, 228 route de l'Aérodrome, CS 40 509, 84914 Avignon Cedex 9, France; tesson.vincent@gmail.com

Abstract

The United Nations' Sustainable Development Goals initiated in 2016 reiterated the need for safe water and healthy lives across the globe. The tenth anniversary meeting of the International Water and Health Seminar in 2018 brought together experts, students, and practitioners, setting the stage for development of an inclusive and evidence-based research agenda on water and health. Data collection relied on a nominal group technique gathering perceived research priorities as well as underlying drivers and adaptation needs. Under a common driver of public health protection, primary research priorities included the socioeconomy of water, risk assessment and management, and improved monitoring methods and intelligence. Adaptations stemming from these drivers included translating existing knowledge to providing safe and timely services to support the diversity of human water needs. Our findings present a comprehensive agenda of topics at the forefront of water and health research. This information can frame and inform collective efforts of water and health researchers over the coming decades, contributing to improved water services, public health, and socioeconomic outcomes.

Keywords

Water, Wastewater, Humans, Public Health, Environmental Monitoring, Nominal Group Technique

Introduction

To promote public health and wellbeing, the United Nations' Sustainable Development Goal (SDG) 6 seeks to "ensure availability and sustainable management of water and sanitation for all" by 2030 (UN Water, 2018). Many entities are scaling up efforts to address this challenge, including responses to the new aspects of SDG 6 as compared to the earlier Millennium Development Goals (1990–2015). These aspects include universality, inclusivity, cooperative participation, and "safely managed" services, as well as improved coordination with environmental protection efforts to support integrated water resource management. A strong evidence-informed decision-making (EIDM) is a common goal in many service provision sectors, including water, sanitation, and hygiene (WaSH). Barriers to the use of EIDM in WaSH policy and practice have included a weak enabling environment, bounded by relatively low political priority, lack of mutual accountability, poor coordination, insufficient financing, and limited data availability or relevance (SWA, 2018). Because the transition to SDG 6 is accompanied by new evidence needs, it requires review of corresponding research priorities (Setty et al., 2018b).

Research on water and health involves both quantitative and qualitative studies, generating and matching data from a complex mixture of disciplines, such as environmental science, engineering, epidemiology, economics, hydrology, chemistry, microbiology, toxicology, human biology, sociology, anthropology, statistics, and geospatial mapping. Interventions to change processes or behaviors to improve public health are often complex. Unlike medical trials, it can be difficult to implement WaSH interventions in a controlled way, or to blind researchers and participants to randomized assignment. Some of these challenges are exacerbated in low-income settings, leading to weak main effects and strong contextual influences (Hamilton and Mittman, 2017). The resulting evidence base is characterized by heterogeneity with highly variable effects dependent on site-specific characteristics. The state of evidence in WaSH may exasperate decision-makers, who look for clear, usable, and immediate guidance when policy windows open (Brocklehurst, 2013; Rose et al., 2017).

A number of international events focus on EIDM around water and health topics, including World Water Week in Stockholm, the rotating International Water Association World Water Congress and Exhibition, and the Water and Health conference in Chapel Hill, North Carolina. These events draw hundreds to thousands of participants. Since 2009, the multinational utility company Suez has likewise organized an International Water and Health Seminar annually in Cannes, France to promote meaningful exchange between researchers and practitioners. It invites senior academic experts and junior scientists (typically finishing PhD students) into a smaller forum with greater contact time. Participating experts form a standing scientific committee, and new student participants apply to attend each year. Typically, the scientific committee selects 16–20 PhD students to maximize geographical and topic diversity. Attendees have come from countries including Australia, Brazil, Canada, China, Denmark, Egypt, England, Finland, France, Germany, Hungary, Iceland, South Africa, Spain, Sweden, Switzerland, Tunisia, the United States, and Wales.

We set out to explore water and health research priorities by harvesting the perspectives of participants at the 2018 International Water and Health Seminar. All participants joined a simplified nominal group technique (NGT) exercise that explored drivers, adaptation needs, and perceived research priorities. Ideally, research priority setting should be transparent, consider context, take a comprehensive stance, establish focal criteria, and include multiple categories of stakeholders (Viergever et al., 2010). The NGT approach is often used in quality improvement, business, and other group settings to engender active and equal participation, and to achieve prioritization and consensus (CDC, 2006; Tague, 2004).

Methods

We applied a simplified and slightly modified NGT (CDC, 2006; Tague, 2004) including all participants at the 2018 International Water and Health Seminar held in Cannes, France. This in-person, participatory method was selected as a structured and inclusive way to develop consensus among a fairly large and mixed group of researchers and practitioners (water and sanitation service providers). It aimed to achieve theoretical saturation (comprehensive exploration of research themes) by not limiting the number of submissions per person and triangulating concepts through multiple rounds of inquiry (Saunders et al., 2018). The technique was adapted because of time constraints, and used a color indicator for paper submissions to confidentially record, and permit analysis of, differences in perceptions among the three types of participants: academics, students, and practitioners. We also examined past programs and prepared summary statistics to compare results to presentation topics from the first ten years of the seminar (2009–2018). Owing to the expansive topic, data interpretation included a group-based narrative review (Dijkers, 2009) was focused on the most pertinent literature relevant to each research theme.

Data collection

Thirty-three participants (8 senior academic researchers, 10 Suez research staff members, and 15 doctoral or postdoctoral scholars) attended the seminar. All agreed to participate in the NGT exercise. No compensation was offered, nor any penalty for choosing not to participate. Most participants came from Europe, with representatives from the US, Canada, and Australia; names, classifications, and institutions of participants are listed in the acknowledgements. The students were at an advanced trainee level in their careers, pursuing pre- or postdoctoral research, while the academics held advanced degrees and professorships and were generally late career. Professional attendees ranged from early- to mid- to late-career and were permanent or contract employees of research and development branches within Suez, a large multinational utility group headquartered in France. The seminar and NGT sessions were conducted in English, which was a second language for some participants. In consultation with the University of North Carolina at Chapel Hill Office of Human Research Ethics, the study was not submitted for formal IRB approval because the information gathered related to the research needs assessment rather than the participants themselves.

Five days before the seminar, all participants received an email with written instructions concerning the exercise. Participants were asked to consider questions about water and health research priorities, but not to share their ideas with others. The scope of "water and health" was deliberately not defined, as the scope of understanding of the term was itself of interest. The instructions requested feedback at the seminar on research themes separately from research questions, but during the exercise these categories were merged and a new question was added on adaptations to the underlying drivers.

At the seminar, two sessions of NGT were conducted. In each, no prior knowledge of the instructions was assumed and participants were briefly introduced to the question(s) to be tackled. Ten to twelve minutes were dedicated to "silent idea generation" in which participants recorded each of their ideas on sticky note paper, with different colors to differentiate ideas from different participant groups (students, academics, and practitioners). The practice of writing responses before sharing ensured accountability to the original idea and equal participation, to prevent cognitive "anchoring and adjustment" or reporting bias based on what others shared with the group. The facilitator (JB) served as a participant in accordance with good practice for NGT.

Method modifications of standard NGT (CDC, 2006; Tague, 2004) included (a) accepting clustered contributions after the first round, and (b) performing counting for prioritization afterwards, following electronic data entry. One round of round-robin idea presentation was conducted in which each participant described one idea from their sticky notes and the note was added to a display board. Notes were loosely organized into categories, typically proposed by the person who first raised a new idea, and grouped by joining similar submissions as themes emerged. Subsequent rounds proceeded similarly, except that to conserve time, individuals were permitted to offer up notes duplicative of or similar to an idea being presented at any time, without waiting for their next turn, keeping them in the same grouping with the original idea. Rounds continued until all ideas were exhausted. Participants then checked the results on the boards, discussed, and modified the idea organization and groupings. The outcome was adopted by informal consensus and transcribed into an electronic record.

The first round involved all groups of participants (students, academics, and practitioners) and lasted approximately two hours. It addressed two questions (drivers and research questions), and participants indicated at the time of presentation whether the idea they were presenting was a driver or a research question/theme. The second session took place two days after the first, and lasted approximately two hours. It addressed practical adaptations to the drivers and involved only the academics and practitioners, as students were assumed to have less applied experience.

Data processing

We inductively compared responses based on the three different approaches using different questions (Figure 1) to identify prominent research priorities, underlying drivers, and adaptations. A research agenda was constructed primarily using input on research questions, with cross-comparison for sensitivity to drivers and adaptations. The participant input was similarly cross-compared with prior program topics gleaned from annual programs from 2009–2018. This data triangulation helped to ensure missing topics and perspectives were covered. Several authors separately assessed data via conventional qualitative content analysis (Hsieh and Shannon, 2005), using line-by-line (in vivo) coding in most cases, to evaluate the frequency of subthemes as a basis for presentation of findings and discussion.

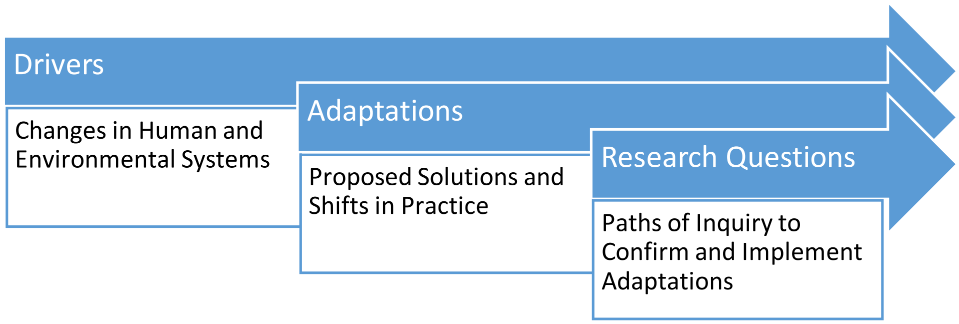

Figure 1. Relationship between three lines of inquiry pursued using the NGT method to support data triangulation and comprehension.

The relatively rapid sorting into themes at the in-person sessions was supplemented with follow-up checks involving two authors (JB and KS). Using the submitted research priorities and categorical organization as the primary input, category wording was harmonized to create a set of distinct concepts related to the umbrella of water and health. First, alternative categorization schemes were explored to determine which best fit the data. Second, categories with three or fewer nominated research topics were merged into other larger categories, and dominant subcategories were elevated to categories to create a relatively even distribution of topics. Third, each category assignment was reviewed and some research topics were reassigned, using the original wording of the submission and giving deference to the original category assignment if wording was unclear. Categories were ordered by frequency of topic nomination, counting each entry as one "vote," as a means to convey overall prominence. Finally, the wording of each submission was revised to correct minor spelling and grammar errors, to help clearly convey the intended topic. In some cases, for example when inferring the meaning of acronyms, the most probably meaning in common use was assigned, although alternative meanings were possible.

Input based on submitted drivers and adaptations were reviewed and cross-compared with the research priorities, to identify gaps and novel insights. Additionally, the research priorities were compared with topics from the 10-year history of the Cannes seminar, to offer insight as to trends over time. This involved assignment of topics to themes by year by a third author (JFL). All participants were offered a follow-up opportunity to help with data interpretation and contribute to manuscript preparation. As a result, the draft results were shared with a sub-group of participants who volunteered, to continue to validate and refine understanding of the results in a participatory manner. This team-based approach engendered a narrative literature review of the most relevant references on each topic, to aid communication and uptake of the findings.

Results

Participation

We tracked participant type, numbers of submitted "ideas," and average per-person idea generation rates to characterize representation (Table 1). Since no limit was assigned, the estimated number of submissions per individual ranged from approximately five to 25.

Table 1. Number of participants and responses submitted at the seminar workshop by respondent type and round of questioning

	Number of participants	Total number of responses submitted	Mean responses per person
Round 1 (Drivers)			
Students[1]	15	33	2.2
Academics[2]	8	23	2.9
Practitioners[3]	10	33	3.3
Total	33	89	2.7
Round 1 (Research Questions/Themes)			
Students	15	31	2.1
Academics	8	34	4.3
Practitioners	10	55	5.5
Total	33	120	3.6
Round 2[4] (Adaptation Needs)			
Academics	8	21	2.6
Practitioners	10	40	4.0
Total	18	61	3.4

[1]Twelve current doctoral students and three who had recently received doctoral degrees (students did not have an opportunity to participate in the second session)

[2]Professors or Professors-emeritus at universities or research institutions in France, UK, USA, Germany, and the Netherlands

[3]Permanent or contract staff of Suez water and wastewater utilities focused on research and development, including scientists and managers

[4]Round 2 included only academics and practitioners, as students were assumed to have less applied experience.

Research priorities

Refinement of the draft topic categorization initiated at the in-person sessions helped to solidify eleven major themes capturing water and health research priorities (Figure 2). A somewhat broad category about the social, political, economic and other context in which people use water was of greatest concern, reflecting increased attention toward sustainable global development and soft science in addition to engineering approaches. Next, some traditional disciplines such as water quality, water treatment, and water microbiology were prominent. Risk assessment and management, sanitation, and water resources held a moderate position. Less frequent emergent categories included information and artificial intelligence, real-time or rapid methods, water reuse, and the water-energy nexus. Some key subthemes also emerged across categories or nested within categories. These included technological innovation, metagenomics, "one health," and disinfection.

Socioeconomy of water (17)

- Human factors
- Governance
- Interdisciplinarity

Water quality (16)

- Microplastics
- Disinfection byproducts (DBPs)
- Antimicrobial resistance
- Toxicity detection
- Water safety and security

Water treatment (13)

- Cost-effectiveness
- Avoidance or removal of chemical additives, DBPs, and emerging contaminants
- Pathogen removal or disinfection
- Ecological sustainability

Water microbiology (13)

- Microbiomes and biofilms
- Stability versus regrowth
- Metagenomics

Risk assessment and management (11)

- Management tools for combining risks
- Extreme weather
- Political instability
- Uncertainties and unknowns

Sanitation (10)

- Access
- Improved service
- Pathogens and micropollutants

Water resources (10)

- Quantity and quality stressors
- Management solutions

Information and artificial intelligence (9)

- Data transmission, integration, safe storage, and modeling
- Instruments and management systems

Real-time/rapid methods (9)

- Early, real-time, online, and point-of-use contaminant detection

Water reuse (8)

- Technologies
- Health risks
- Public acceptance

Water-energy nexus (5)

- Resource rarefaction
- Decentralized and renewable solutions
- Energy-efficient and safe water treatment

Figure 2. Identified water and health research priorities, with themes and subthemes in order of frequency of research question submissions (in parentheses)

Triangulation

Using three different approaches (i.e., requesting research priorities directly versus asking indirectly about prevalent drivers and adaptations) allowed triangulation of the data from multiple perspectives. Similarities and differences among responses contributed to the framing of the research agenda. Overall, they revolved around protecting human health in the face of global changes as a critical underlying concept. Pure environmental (including wildlife and domestic animal) protection played a lesser role. Although deemed important by a number of participants, ecological sustainability represents a newer aspect of WaSH development goals. In many cases, environmental science, agriculture, and public health fields have traditionally had separate regulatory and research-funding structures, which may fail to promote disciplinary overlap. Shifts toward unified planetary health were recognized during participatory review of the study as a newer paradigm that will ultimately affect research drivers.

Drivers

Drivers fell into seven categories: demographic change, climate, chemicals, microbes, infrastructure, nexus systems, and socio-political demands. In comparing drivers to the research themes, the perspective of drivers emphasized the health concerns underlying the research topics, which largely focused on water and sanitation services. Some categories overlapped with the research questions and themes. For instance, nexus-related topics captured energy (Figure 2) as well as trends in food production, soil conditions, and shifting plant life. Climate change appeared as a prominent driver for weather-related risks, and was also mentioned under risk assessment and management (Figure 2). Shifts in chemical production, especially of micropollutants, likewise linked to research questions under risk assessment and management, water quality, and water treatment.

Other driver topics were less prominent among the research questions. Sociopolitical shifts, such as increasing attention to equity and changing international relations, indirectly matched with the socioeconomy of water category, and thus might underlie all research themes. Commonly-referenced drivers for changes in service needs and water-related health vulnerabilities included demographic trends, such as population growth, aging populations, and migration (especially to urban areas). The research themes overlooked some drivers such as antimicrobial resistance and emerging diseases, both of which should fall under the water microbiology category. Aging infrastructure appeared as a prominent driver, but was mentioned less frequently as a research need, relative to information and artificial intelligence as well as water treatment.

Adaptations

Due to the smaller group size, the adaptations had fewer submitted ideas and in-seminar groupings. The main overlap with the research questions was a category called knowledge management and data science, corresponding to the information and artificial intelligence research category. Additional analysis revealed that the draft groupings of adaptations could be broken down further, and all research categories related to at least one adaptation idea submission. Secondary groupings related to the use of science to inform policy and regulations, as well as improved service provision. Subthemes included integration across systems, sectors, and exposures (e.g., engineering for complex systems with interdependencies and trade-offs); decentralization (e.g., of treatment infrastructure and monitoring capabilities); safety and surveillance, and responsiveness (e.g., to crises or situations of increased demand like migration or local droughts). In connection with sanitation, human biomonitoring (e.g., via sewage) emerged as a human health-oriented complement to established environmental health monitoring approaches. Such bridges address traditional divides between environmental protection and human health regulations. Surveillance responsibilities may be siloed among different entities, though, limiting rapid and effective communication and response.

Topics from prior seminar programs

Though presentation topics varied widely over the past ten years of the seminar (2009–2018), four primary categories could be identified: microbiology, chemistry, general topics (e.g., policies, modeling, risk management), and technology (Figure 3). Subcategories further broke down these classifications. For water microbiology, *Legionella*, amoeba, and intra-amoebal pathogens were the most popular topics. For water quality, occurrence and treatment of micropollutants were prevalent in past seminars. Epidemiology and public health surveillance took the lead for the general category, mirroring the NGT adaptation topics. Biofiltration and biodegradation took the lead under technology. Additional prominent subcategories included pharmaceuticals and endocrine disruptors, antimicrobial resistance, nanomaterials, virus occurrence and treatment, perfluorates, and biofilms. Many of these topics matched those raised in the NGT sessions in 2018, although the prevalent terminology may have evolved over time. For instance, the microbiome and metagenomics appear more frequently in recent years, building on concepts prominent in earlier years such as biofilms and "viable but not culturable" bacterial cells.

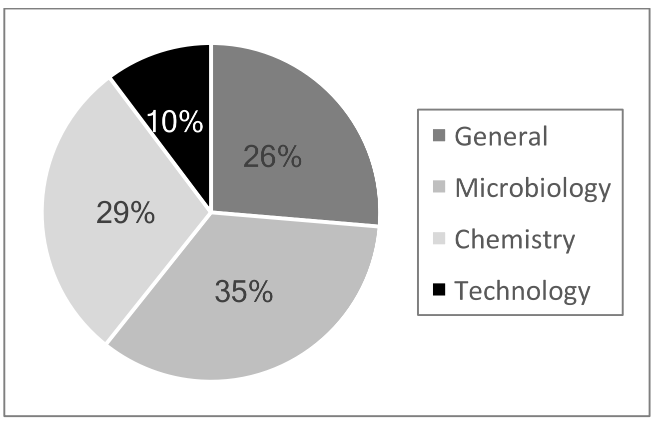

Figure 3. Broad categorization of past seminar topics (2009–2018, inclusive)

Some previous presentation topics not mentioned in the NGT included specific viruses (e.g., Ebola, adenovirus, norovirus), parasites (e.g., *Cryptosporidium*), and bacteria (enterotoxigenic *Escherichia coli*, *Shigella*, *Helicobacter*), as well as perfluorinated chemicals, biofiltration, biodegradation, advanced oxidation, and recreational waters. These might reflect oversights, actual shifts in attention, or the wider stance requested for the exercise versus the specificity of individual research presentations, as these topics remain globally prominent. The focus on single pathogens, contaminants, or treatment approaches may also have given way to more holistic approaches to water safety, with the understanding that biological and chemical threats are constantly evolving. Surprisingly, the SDGs were not explicitly mentioned in the NGT, perhaps because they were recognized implicitly. Terrorism was a more prominent topic in past years, but in 2018 was included as one type of risk under risk assessment and management.

Contributors

The classification of submissions as coming from students, academics, or practitioners permitted observations about similarities and differences in perspective among stakeholder groups. In general, practitioners submitted more ideas than the academics or students, who provided roughly the same number of submissions. Past seminar topics were not broken down by contributor type, but came predominantly from academic and student attendees at the seminar, and reflected somewhat narrower topic specificity than the NGT.

Regarding *drivers*, students did not raise infrastructure issues. Among *adaptations,* few trends or contrasts were apparent in the diversity of suggestions by practitioners and academics. Within the knowledge management and data science category, practitioners dominantly raised real-time security. Within the *research questions*, all submissions on development of rapid or real-time monitoring methods and most submissions on the water-energy nexus and water reuse came from practitioners. Few students at the NGT expressed ideas about risk assessment and management or sanitation, although former students covered these topics in past seminars. Few academics addressed the socioeconomy of water, which may reflect a greater degree of specialization in other areas.

Discussion

Within the umbrella topic of water and health, we present discussion around key themes and subthemes in order of decreasing frequency of participant submissions (Figure 2). Aspects introduced through the data triangulation methods are integrated within the same thematic areas. The scope of participants' understanding of "water and health" appeared to match the scope of the event itself, which focused on natural, social, and health sciences connected to water and wastewater services. It delved less frequently into water policy. Due to the natural overlap among these thematic categories, some topics were assigned to the closest fit while others appear in multiple contexts.

Socioeconomy of water

The socioeconomy of water concerns interactions of sociology, behavior, culture, and economics with water needs. Socioeconomic issues underlie many other water usage and safety concerns, as they make up the wider contextual structures in which water systems operate. This theme presents an opportunity to identify synergies among topics and issues, and traverse traditional disciplinary fields of research. Integration of different fields and novel combinations of viewpoints such as political ecology, international security, and anthropology can enhance understanding of the complexities of socio-economic, socio-cultural, and broader water research questions, as well as their impacts on water safety and resilience. Integrated approaches can help to model complex systems ripe with interdependencies and trade-offs. Within this topic, contributions from participants broadly fit into three key subthemes: human factors, governance, and interdisciplinarity. Based on drivers, this theme must consider shifting international relations, demographic trends, and transboundary issues, such as increased migration. Considering the drivers and adaptations, aging infrastructure was another reality that will require added long-term investment and efficient planning (Value of Water Campaign, 2017).

Human factors consist of attitudes, cultures, and practices. They include broad philosophical approaches towards the meaning of water (Lycan, 2010) as well as applied issues such as perceptions and attitudes towards water conservation (Tarlock, 1987; Hermanowicz, 2008) and wastewater reuse (Po et al., 2003; Hartley, 2006). Further research in these fields should accompany future technological advances and socio-political changes, considering both their empirical and ethical implications for complex water systems. For instance, community-based and public participation in research processes may help redress inequities perpetuated by prevalent power dynamics in science (Kemmis et al., 2016). Equity and social and environmental justice topics were underrepresented at the seminar, but may be a vital component of research context in both low- and high-income settings (e.g., Stillo and MacDonald Gibson, 2017). These contextual factors are likely to affect the selection and implementation of water and public health system interventions.

Governance issues include diverse settings from industrialized smart cities to resource-poor settings such as slums. In this field, research has focused on issues such as equitable and affordable access to safe water, which remains integral to accomplishing global development goals (Onda et al., 2012). This subtheme spans access to piped water and wastewater disposal, as well as the health outcomes of limited access, for instance stemming from water carriage over large distances (Geere et al., 2018; Sorenson et al., 2011). Water governance broadly encompasses situations of limited water (Kummu et al., 2010) and increasing pressures from climate change across different world regions as diverse as Australia (Dijk et al., 2013), the Middle East (Hadadin et al., 2010), South Africa (Mukheibir, 2008), China (Cheng et al., 2009), and North America (Gober and Kirkwood, 2010). Associated challenges for water conservation thus interact with many of the human factors mentioned above.

The third field concerns interdisciplinarity, transdisciplinarity, and the integration of social sciences, natural sciences, engineering, and operational research. This is at the forefront of many fields, especially in the context of "One Health" (Min et al., 2013; Manlove et al., 2016), planetary health (Galway et al., 2016), nutrition (Picchioni et al., 2017), and other fields (Morillo et al., 2003). Brown et al. (2015) mapped out how such an approach can lead to fruitful collaboration within and beyond the field of water research by forging a shared mission, developing "T-shaped" researchers, nurturing constructive dialogue, offering institutional support, and bridging research, policy, and practice. These approaches are especially important in water and health research due to the inherent integration of scientific inquiry with applied solutions in a complex socio-political environment. One example is the relationship between water and wastewater pricing and human behavior, where microeconomics (traditionally a business field) informs good water provision practices (Nauges and Whittington, 2017).

Water quality

The notion of water quality, defined as measurement and understanding of how compounds and organisms in water can influence human and environmental health, has evolved alongside scientific and technical progress. It was essentially limited to organoleptic descriptors (color, odor, taste and temperature) until the early 19th century (Symons, 2006). The emergence of epidemiology and bacteriology resulted in the development of water disinfection and microbial indicators as new quality parameters, representing substantive public health achievements (CDC, 1999, Sedlak, 2014). Developments in analytical chemistry during the second half of the 20th century led to an increasing number of new chemical parameters (Trussel, 2006). The consciousness raised by a series of popular works (e.g., Carson, 1962; Colborn et al., 1996) likewise contributed to expanding the lists of quality parameters to encompass pesticides, pharmaceuticals, and endocrine disruptors. To measure and understand how compounds and organisms in water can influence human health, NGT participants recommended continued improvement in analytical methods for chemical and microbial contaminants.

Subthemes raised by participants included microplastics, disinfection byproducts (DBPs), antimicrobial resistance, perfluorinated chemicals, toxicity detection, Water Safety Plans, and security issues. Microplastics have recently been an area of intense activity, especially in marine waters, but questions regarding their potential health effects on humans and the significance of waterborne exposure remain unanswered (Rocha-Santos, 2018). DBPs remain major concern in drinking and recreational waters, with increased attention on understanding formation from different precursors, toxicity, and strategies to reduce or eliminate formation (Li and Mitch, 2018; Manasfi et al., 2018). Antimicrobial resistance represents a major and increasing threat to public health, and the role of waste and drinking waters in the transmission of resistance genes needs to be clarified (Manaia, 2017, Wuijts*,* et al*.*, 2017). Perfluorinated compounds such as PFOA and PFOS have gained increased public attention due to the potential health effects of levels found in source water and drinking water (Morrison, 2016).

In-vitro bioassays for toxicity detection used for more than half a century to assess the safety of water reuse schemes have demonstrated their usefulness for the assessment of complex mixtures of pollutants. Their application, however, is still limited by lack of demonstration of the linkages between in-vitro and in-vivo response, and difficulty in interpreting results (Leusch & Snyder, 2015). Water Safety Plans (incorporating water quality and security issues) have been recommended by the World Health Organization (WHO) since 2004 (WHO, 2004) and are being deployed worldwide. Their application should lead to improved ways of assessing water quality using real-time parameters and on-line sensors for operational control (e.g., turbidity at filter outlet or intrusion detection), in addition to typically lengthier time-to-result laboratory analyses used for compliance.

Water treatment

Water treatment includes technology, infrastructure, and methods for ensuring safe water supply. Since water treatment technologies may be tailored to a range of sources including surface water, groundwater, marine water, stormwater, and recycled wastewater, this thematic area overlaps with water resources, water reuse, and sanitation. Ensuring safe water supply requires a holistic perspective and attention to four main subthemes: cost-effectiveness of treatment and treatment upgrades (e.g., membranes); avoidance or removal of chemical additives, DBPs, and emerging contaminants; alternatives for pathogen removal or disinfection; and ecological sustainability (e.g., safe disposal of brine waste from seawater desalination). An additional participant contribution focused on updating treatment technologies for distributed (cellular) systems and water reuse. In reference to drivers and adaptations, much of the world’s water treatment infrastructure was constructed in the latter half of the twentieth century, and is increasingly in need of repair or replacement (Moe and Rheingans, 2006).

Updates to water treatment systems must take into account the best available technology, as well as cost, resilience, and environmental constraints. Cost-effectiveness and cost-benefit analyses require accessible methods (e.g., Whittington and Hanemann, 2008) that consider costs and benefits accrued beyond the utility, for instance to the public and the environment. Such plans are especially pertinent when planning to replace or repair infrastructure that can flexibly meet needs (e.g., for a growing or declining population) over a multi-decadal lifespan. In addition to disinfection methods using chlorine, ozone, or ultraviolet light (UV), novel disinfection methods might include induction of autolysis of bacteria in water systems, for instance using quorum-sensing particles or bacteriophages. Limiting the formation of DBPs was recognized as a driver for this subtheme (Li and Mitch, 2018). While new approaches are constantly under development, consideration of the health impacts of pathogen reduction by various methods and degrees would help to support decision-making. The extension of the

SDGs to serve all, including remote populations in unique environments, requires added attention to water treatment decentralization and conservation via onsite reuse (Insight et al., 2017).

Water microbiology

Water microbiology research concerns microbial communities and their effects on water resources and human or animal health. Microbes can float freely in water, attach to particles, aerosolize, or live in biofilms (slimy matrices that form on surfaces). Knowledge about pathogenic microorganisms in water and wastewater has saved millions of lives over the last century from enteric disease outbreaks such as cholera (Rosen, 2015; Schlipköter and Flahault, 2010) and typhoid. The drinking water microbiome may comprise up to 40 phyla, which change during various stages of water treatment and distribution (Proctor and Hammes, 2015). The primary global burden of disease is associated with enteric pathogens spread via water and food, particularly rotavirus, Cryptosporidium, Shigella, and Enterotoxigenic *Escherichia coli* (ETEC) (Kotloff, 2017). Microbes and their pathogenicity are constantly evolving in response to environmental stimuli, which can lead to antimicrobial resistance and emerging human diseases. Topics raised by participants included interaction within microbiomes and biofilms, community stability or regrowth (e.g., in distributed or stored water), and investigative tools such as metagenomics.

Among biological hazards to human health, water treatment processes have traditionally targeted enteric pathogens only (Fewtrell and Bartram, 2001) and these continue to be critical for safety (Setty et al., 2018a). More recently, disease outbreaks associated with treated water and other water systems, such as cooling towers, show a significant increase in respiratory diseases caused by water-based opportunistic pathogens such as *Legionella pneumophila* (Beer et al., 2015; Gargano et al., 2017). Effective and safe drinking water distribution systems and plumbing systems in large buildings (Cunliffe et al., 2011) are crucial to protect and improve health. Water treatment processes, nutrients, disinfection residuals, DBPs, and the abiotic factors of distribution systems and on-premises plumbing (e.g., stagnation of water, temperature) have significant impacts on the microbial community of tap water and associated water quality (Wang et al., 2018). Moreover, free-living amoebae and some other protozoa present in distribution systems protect certain bacterial pathogens from disinfectants and support intracellular growth of pathogens like *Legionella* (Balczun and Scheid, 2017; Lu et al., 2014; Pagnier et al., 2015).

Microbial quality and chemical quality interact, especially where chemical disinfectants used for microbial inactivation give rise to added chemical hazards. One primary concern has been the health effects of DBPs, since many are considered carcinogenic (Richardson et al., 2007). Some suggest adapting treatment processes to select for bacteria such as *Rhodococcus* and *Mycobacterium,* which are capable of biodegrading DBPs (Sharp et al., 2010; Gerrity et al., 2018). Yet, another concern is inadvertent selection of disinfectant-resistant bacteria such as mycobacteria or antimicrobial resistant bacteria that can opportunistically cause infection in immunocompromised people (Von Reyn et al., 1994; Whiley et al., 2012; Gerrity et al., 2018; Liu et al., 2018; Potgieter et al., 2018; Stüken et al., 2018). Thus, manipulation of microbial ecology to promote "beneficial" microbes is an important area of continuing research.

Advancement in gene sequencing methods provide exciting new insights and opportunities for water microbiology research, although the presence of nucleic acids does not translate directly to infectivity (Tan et al., 2015). Future research might target biological processes in water treatment, use of metagenomics to characterize occurrence and fate of antimicrobial resistance genes, the virome of wastewater, or microbial ecology. Understanding microbial ecology is important to design sustainable and safe water systems. Some studies suggest that tap water bacterial composition depends primarily on treatment processes rather than source water (Wang et al., 2013; Zhang et al., 2017). Thus, the microorganisms and DBPs present in treated drinking water could alter the microbiota in the human gut, which would ultimately influence human health (e.g., Von Hertzen et al., 2007). A better understanding these relationships could inform the best drinking water management approaches for achieving public health benefits.

Risk assessment and management

Risk assessment and management consists of technologies, methods, behaviors, and processes that support conversion of evidence about risk to planning and mitigation among stakeholders. This often involves ranking different hazards harmful to people at different life stages, taking into account mortality, illness (disability-adjusted life years or DALYs), and other types of consequences. Subthemes of participant contributions on this topic included: (a) management tools for combining multiple types or measures of risk under a common framework, (b) risks related to extreme weather events, (c) security in the face of political instability (e.g., war or terror attacks), and (d) accounting for uncertainties and unknown risks. An additional submission related to the water microbiology and information and artificial intelligence categories suggested using burgeoning data availability (e.g., metagenomics and other "omics") to inform risk management. Changing demographics represented a relevant driver, as this may lead to shifts in the sensitivity or receptivity of populations to various hazards.

Multiple risk management tools and approaches were raised as potential options for water systems, including synthesis frameworks such as Water Safety Plans (Bartram et al., 2009), quantitative microbial risk assessment (QMRA; Petterson and Ashbolt, 2016) for microbial pathogens, as low as reasonably achievable (ALARA; Lindhe et al., 2010) principles for contaminant reduction, and geospatial modeling (e.g., Lafforgue et al., 2018). One issue may be how to combine data-driven management of multiple risk categories (e.g., water quality, financial risk, reputational risk). Risk management programs such as Water Safety Plans have been actively piloted and evaluated in recent years (WHO and IWA, 2017), demonstrating potential benefits to public health (Gunnarsdóttir, et al., 2012; Setty et al., 2017), but work remains to facilitate an enabling implementation environment in both low-middle and high-income countries (Baum and Bartram, 2018). While most efforts in past decades were dedicated to managing chemical hazards, emerging risks are more often linked to microorganisms (Rusin et al., 1997). Based on prior seminar topics, risk assessment related to nanotechnology is needed as compounds may be more or less toxic at the nanoscale (Rocha-Santos, 2018). Climate extremes are expected to become more severe in coming decades (IPCC, 2014), leading to a great deal of research among water suppliers, environmental managers, and public health officers around mechanisms for planning, adaptation, and resilience (Deere, 2017).

Regarding security, the terrorist attacks on September 11, 2001 led to greater awareness around water supply vulnerabilities (Camarillo et al., 2014). Safety largely requires responsiveness to both urgent and subtle water crises, including those with non-malevolent causes such as long-term drought or shifting water demands. In the NGT exercise, hospitals were mentioned as a particularly vulnerable type of institution, mirroring newer findings of poor attention to water, sanitation, and hygiene systems in settings with greater-than-average immunocompromised populations at risk of infectious diseases (WHO & UNICEF, 2015). Loss of hospital water supplies (e.g., due to a crisis or intermittent service) puts patients at greater risk and often requires compromises in sanitary procedures or physiologically stressful patient transfers. Approach and methodology options for addressing uncertainty and unknown risks include the precautionary principle, expert consultation, probabilistic inference, sensitivity tests, fuzzy-set theory, value-based weighting preferences, or conditional rules (Almaarofi et al., 2017; Dominguez-Chicas and Scrimshaw, 2010; Petterson and Ashbolt, 2016). Automated data production, management, and decision-support systems may aid in earlier detection of risks, enabling faster response times.

Sanitation

Sanitation considers management of human excreta, wastewater, and solid waste to lessen negative human, animal, and environmental consequences. Within this area, key subthemes raised by participants included access to sanitation services and improving their quality, especially using decentralized wastewater treatment systems (DEWATS). Priorities also included improving knowledge of pathogens and micropollutants in liquid and solid waste disposal, particularly for risks associated with their persistence, removal from wastewater, and the sanitary, environmental, and occupational implications. In sum, these topics complement the water resources and socioeconomic subthemes, and create synergies for enhancing usability of freshwater and marine resources.

Ensuring availability and improvement of sanitation systems has been an area of intense activity. The WHO and United Nations Children's Fund (UNICEF) Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) reported that more than 2.1 billion people gained access to improved sanitation between 1990 and 2015 (WHO and UNICEF, 2017). Still, more than 2.4 billion people had no access to improved sanitation and 1 billion remained without any sanitation system. Taking into account the ambitious new service norm of "safely managed" sanitation, meaning a household has an improved facility with in-situ excreta disposal or transport and treatment offsite, a whopping 5.3 billion people lacked coverage (WHO and UNICEF, 2017). Decentralization appears as a logical evolution for handling increasing loads of wastewater and urban stormwater. A study published by the Organisation for Economic Co-operation and Development (OECD) demonstrated the potential for sustainable decentralized water resource management in urban environments, with better flexibility and at a lower cost than current sanitation systems (Water and Cities, 2015). In addition, many urban centers continue to seek solutions for managing concentrated urban runoff, in some cases by facilitating treatment of discharge collected by separate or combined sewer systems (Barbosa et al., 2012).

Better knowledge of the fate of pathogens and micropollutants from wastewater represents a valuable addition to the research docket, as it will improve understanding and management of subsequent risks to public health (Campos et al., 2016; Gavrilescu et al., 2015). Along with molecular methods and chromatographic methods, the addition of high-throughput sequencing and mass spectrometry has enabled more rapid analysis of their transport, dissemination and persistance in environment. Still, researchers limited information on both the long-term effects of micropollutant cocktails and their relationship with the emergence of new bacterial and viral pathogens (Jekel et al., 2013; Sano et al., 2016). Concerning the implications of waste disposal, some studies have addressed wastewater reuse and solid waste disposal (Kellis et al., 2013; Kinnaman, 2017; Maimon et al., 2010), but more attention is needed to determine method effectiveness and pollutant persistence. Seminar participants felt that wastewater reusability (e.g., for water, energy, nutrients) and mastery in pollutanst removal were critical components of waste management for the next 5-10 years. Forward-looking commentary on adaptations and the potential use of wastewater revolved around the public health surveillance via human biomonitoring (Joas et al., 2017).

Water resources

Water resources refers to conservation of existing and potential new ambient water supplies for human and ecological use. Research priorities primarily fell into two subthemes: (a) water supply quantity and quality stressors and (b) water management solutions. Quantity stressors included shortage, drought, and water loss. Quality stressors related to industrial, agricultural, and other pollutant sources that lead to groundwater contamination and fecal pollution in watersheds. Regarding management solutions, participants cited protection, conservation, improved management planning at the watershed level, and attention to irrigation practices. To achieve SDG 6, the 2018 United Nations' world water development report emphasizes nature-based solutions tapping wastewater as an underused resource (WWAP/UN-Water, 2018), consistent with the sanitation theme above.

Water resources planning and accounting will require projection of suspected stressors, such as climate change (Olmstead, 2014). Accounting concepts include a water footprint, defined as the total volume of freshwater used directly and indirectly by a nation or a company, or in the provision of a product or service (Chenoweth et al., 2014). Economic approaches such as payment for environmental services (PES) represents a potential option to protect water quality at the watershed scale (Lafforgue, 2016). Bioremediation and source tracking methods were similarly raised as management tools to address pollutant fate and movement within surface and groundwater. Overlapping with the water reuse category, an additional submission had to do with considering the circular economy of water resources in which uncontaminated water circulates in closed loops, allowing repeated use (Eneng et al., 2018) rather than traditional collection, use, and disposal into the environment.

Information and artificial intelligence

This category revolves around data collection and processing to enable better informed decision-making. Few submissions were repetitive or demonstrative of trends, suggesting a wide array of needs in this research area. Data modeling was a research need for holistically considering contaminant sources, pathways, effects on water quality, and control options at a systems level inclusive of the watershed, infrastructure, and receptors (e.g., Lafforgue et al, 2018). Other needs included management, transmission, integration, and safe storage of large amounts of data from diverse sources (e.g., watershed, water supply and treatment, public health, open data, video streams, social media). Appropriate instrumentation and centralized management systems should be developed to accomplish these tasks. Speed was of key concern, for example using artificial intelligence as an alternative to long, difficult, and costly epidemiology studies.

Experts recognize care should be taken in communicating the potential for artificial intelligence to replace existing methods. For instance, Google Flu Trends (Ginsberg, 2009) was released in 2006, but withdrawn after a few years due to its tendency to over-predict influenza infections based on Google search data. Despite some limitations, data analytics and artificial intelligence will be considered useful and necessary tools to explore data and contribute to better management of water systems in the future. Participants recommended data systems both to survey ongoing performance shifts and to detect or diagnose abnormalities (e.g., in infrastructure integrity). Optimization exercises can help to solve complex water network design or health hazard problems, taking into account many different criteria, and leading to better solutions than manual design (e.g., Maier et al., 2014).

Real-time/rapid methods

Real-time monitoring of drinking water systems includes the technologies and data systems that help managers to maintain safety and respond quickly to accidental or malevolent incidents. Participant feedback dealt with early, real-time, online, and point-of-use contaminant detection, spanning both chemical and biological parameters. In addition to informing water treatment processes, participants anticipated deployment of sensors in source water, distribution systems, and at the point of use to maintain active surveillance and problem detection.

Research interest has been growing in online monitoring for both chemical and biological water quality, including harmful algal bloom (HAB) toxins (Storey et al. 2011; Lopez-Roldan et al. 2013). Online monitoring equipment can be installed as an early warning system for the water intake, treatment process monitoring and main entry points to the distribution system. In ambient waters, real-time and rapid methods also concern water-contact and other recreational uses. Complexity derives from the current impossibility of constructing a single sensor to detect all contaminants or pathogens. Studies investigating the performance of various water quality sensors on different contamination patterns suggest monitoring changes to conventional parameters, such as pH, temperature, turbidity, electrical conductivity, and free chlorine concentration, may sufficiently address concerns associated with health risk, customer perceptions (aesthetic taste and odor), and asset management (Hall et al. 2007).

Such monitoring systems should distinguish abnormal changes from normal variations. Thus, event detection models are required for exploring the time series of each water quality parameter and detecting anomalies in water supply systems and networks (Housh & Ostfeld 2015). The cost for sensor deployment and operation limits the number of locations that can be monitored in real time. Future studies will likely aim to develop low-cost and miniaturized sensor technologies to make continuous and complete monitoring possible throughout a water system. In addition to treatment facilities, participants raised installing sensors in distribution pipes (such as sensor chips attached to pipe walls), consumer taps, and individual water meters.

Water reuse

Water reuse refers to safe reuse and recycling to enable sustainable water supplies for human and ecological use. Increasing water supply challenges, aggravated by human population growth and climate change, have driven interest in water reuse as a main component of the new era of water management (Hering et al., 2013). Within this area, key subthemes raised by participants included: technologies for the treatment and reuse of wastewater or alternative water sources, health risks associated with water reuse in particular for potable purpose, and public perception and acceptance of water reuse for potable and non-potable (e.g., agriculture, industry, toilet flushing) purposes.

Research into engineered treatment technologies has been intense, including membrane filtration and oxidation treatment to eliminate microbial and chemical contaminants (Tang et al., 2018; Zodrow et al. 2015). Recent advances in membrane technology, particularly reverse osmosis (RO), have played a key role in producing highly purified recycled water and driving an increase in water reuse projects worldwide. This research aims to achieve cost-effectiveness and reliability in removing microbial and chemical contaminants (Tang et al., 2018). Since some chemical contaminants (e.g., certain DBPs, pharmaceuticals) can cross RO membranes, post-RO oxidation treatments capable of removing these contaminants have been integrated into treatment schemes. Traditionally, advanced oxidation processes that generate hydroxyl radicals have been used, and electrochemistry-based oxidation treatment has been attracting increasing attention (Feng et al., 2016). The degree of adoption of any technology will depend on its effectiveness, energy demands, feasibilty, and integration into future water treatment systems (von Gunten, 2018). Nature-based solutions such as managed aquifer recharge (MAR) and biofiltration similarly show promise for promoting water reuse (Water JPI, 2016).

To enhance understanding around the safety of water reuse, further toxicological and epidemiological studies are warranted (NRC, 2012). In exposure circumstances where toxicological and epidemiological dose-response data are lacking, risk assessment can account for uncertainty and use the best available knowledge to support design of safe reuse systems (NRC, 2012). Further, quality assurance of treatment schemes with regard to elimination of chemical and biological contaminants, economic effectiveness, and feasibility of integration into water systems must be resolved to demonstrate usefulness of novel treatment approaches, for example via studying the scaled-up engineering designs (Lazarova et al, 2013). Water reuse may be an especially efficient option in water-scarce contexts, where regulation permits reuse and other options cost more (Lafforgue and Lenouvel, 2015).

In sum, water reuse complements other efforts to increase water availability (e.g., conservation, desalination) and appears as a critical component of ongoing sustainable water management. Some participants mentioned public perception of water reuse, which overlaps with the socioeconomy of water. Public acceptance of water reuse is a prominent factor in determining the future of water reuse, as it significantly influences political decisions on water reuse projects (Dolnicar et al., 2011).

Water-energy nexus

The water-energy nexus refers to the study of how energy use interacts with provision of sustainable water services. Within this area, key subthemes raised by participants included resource rarefaction (water, energy, raw materials) and how to counteract this phenomenon by developing synergies between water-energy-waste cycles, redefining water and sanitation using decentralized and renewable energy-based solutions, safe water treatment at a low energy cost, and microbial fuel cells for sustainable energy production.

Water rarefaction is increasing due to long-term increases in water abstraction, declining resource availability (Damiana et al., 2017; 2030 Water Resources Group, 2009), and the projected effects of climate change. Research focuses on three main options: increasing water production by desalination, reducing abstraction by recycling urban waters, and reducing water consumption and water losses. However, desalination and water recycling frequently use energy-intensive membrane filtration, replacing a problem by another one. Singapore, for example, is an island city-state faced with this issue (Lenouvel et al., 2014). An integrated perspective would account for such risk substitution.

For instance, the Water and Wastewater Companies for Climate Mitigation (WaCCLIM) roadmap to carbon neutrality in urban water recommends research into low-energy options to produce, transfer and purify water (Ballard et al., 2018). One option is to recover or produce energy from water (e.g., hot water recycling, energy-neutral wastewater treatment, hydropower production in water networks, microbial fuel cells). Another option is to save energy (e.g., low-energy membrane filtration, pumping and pressure optimization, reduction of water consumption, early leak detection). Water recycling in short loops using nature-based solutions may improve water management and save energy (WWAP/UN-Water, 2018; Lafforgue and Lenouvel, 2015; Kavvada et al., 2016). OSMOSUN® solar desalination units are one example of a technology combining renewable energy and water production. Similar recommendations are included in the International Water Association Principles for Water-Wise Cities being adopted around the world (IWA, 2016).

In sum, NGT participants felt that water-energy synergies, water short loops, and renewable energy emerged as prominent options to investigate resource rarefaction. Flexible solutions require time and development, as they are very context dependent (Lafforgue et al., 2014). Investigative tools for structuring and testing potential water-energy option combinations (e.g., Urb'Advanced) may be useful.

Comparison to other studies

With increased activity around the SDGs, WaSH professionals have renewed efforts to examine high-priority research areas (UN Water, 2018; WHO and UNICEF, 2017). Needs assessments are a valuable step in structuring research, policy, and practice responses. This study is one of several efforts to gather data on water and health knowledge needs, for instance via literature review (Hutton and Chase, 2016), electronic survey (Setty et al., 2018b), review of meeting abstracts (Kogevinas, 2017), and knowledge translation activities (USAID, 2017). While the framing differs among agenda-setting methods and studies, these synergistic efforts contribute to capacity building to support global goals toward safe water and sanitation for all.

In connection with WHO-Europe efforts to set priorities for environmental health research, Kogevinas (2017) recommended dialogue between researchers and stakeholders rather than algorithms or semi-quantitative grading to non-prescriptively assess potential research topics against novelty, importance to people, impact on policy, and technical innovation and development. The WaSH research prioritization survey in collaboration with the Sanitation and Water for All partnership (Setty et al., 2018b) was structured around SDG 6 targets, with heavy representation from African partners, whereas the present effort garnered representation primarily from high-income regions. The literature review

(Hutton and Chase, 2016) looked retrospectively at peer-reviewed and gray literature, in contrast to the forward-looking expert elicitation used here. Both the literature review, which is subject to publication bias, and our in-person approach, requiring costly travel, likely underrepresent researchers from low- and middle-income countries.

While the results of these studies overlap in many ways, research policy and the financing of research were not considered in this study. Similarly, while hygiene and associated behavior change were not excluded topics, they did not emerge as a substantive focus during the NGT exercises. Though not explicitly discussed during the NGT sessions, the context for the study was set in an era of shifting priorities, as the SDGs set out more challenging expectations for water and health professionals, and unlike similar development initiatives in preceding decades, the SDGs explicitly apply to countries at all stages of development. The targets for SDG 6 (UN, 2018) comprise:

- Achieve universal and equitable access to safe and affordable drinking water for all
- Achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
- Improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
- Substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
- Implement integrated water resources management at all levels, including through transboundary cooperation as appropriate
- Protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes
- Expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies
- Support and strengthen the participation of local communities in improving water and sanitation management

Equity represents a central component of SDG 6 and also appeared as an underlying driver of research needs in this study. Many aspects of SDG 6, such as “safe,” “affordable,” and “participation” were mentioned using similar wording under the socioeconomy of water category, which dominated the research priorities; however, subthemes addressed neither transboundary management nor capacity building. Untreated wastewater management features in both the SDG 6 targets and the sanitation category of the research priorities, although the SDG 6 focus on ending open defecation was reflected as increasing access to sanitation. The water resources and water reuse categories corresponded well to the SDG 6 targets, including remediation of polluted ecosystems and desalination, respectively. The research agenda presented here paid less heed to the specific needs of women and girls (e.g., for physical safety and menstrual hygiene management).

Limitations

The NGT approach was appropriate for including all ideas (rather than just the majority), accommodating heterogeneity of experience in the group, and ensuring equal footing for underrepresented voices in research planning (CDC, 2006; Tague, 2004). Although the results provided sufficient information for the study's purposes and saturation was achieved via subsequent data triangulation, limitations to internal validity include adaptations of the process used to fit time constraints. Limitations of NGT include the need for conformity within a somewhat mechanical process. The group sizes (33 or 18 participants) were large by NGT standards (Taylor et al., 1958). While unlikely to have restricted idea generation, this might have hampered full-group discussion and clustering of ideas. We sought to overcome this by more thoroughly reviewing the categorization afterward, using multiple reviewers. Normally, NGT includes scoring and ranking after grouping (CDC, 2006), but we accomplished this afterward using simple frequencies and requested member checking remotely several months following the sessions.

While an effort was made to consider ten years of data and multiple categories of water and health professionals, the methods inherently rely on a sample of professionals, which limits external validity and generalizability. As is the case with focus groups, the viewpoints captured may not represent all members of a certain demographic. Since participants need to travel to attend the conference in person, representation skewed toward a small number of high-income countries especially in vicinity of France. Furthermore, the scientific committee and practitioners were invited, and this method of "sampling" is more likely to result in a cohesive group that shares similar viewpoints. The student participants, in contrast, can openly apply to attend, and are intentionally selected to increase diversity. Water and health topics specified on the event announcement aim to attract student expertise in the area of emerging waterborne pollutants and pathogens, epidemiology, microbiology, toxicology, analytical chemistry, risk assessment, water treatment, water hygiene, public health, and sociological aspects of risk management. Advertisement and marketing is generally limited and likely does not reach all possible candidates.

Recommendations

Research planning processes often stem from independent primary investigators, either in isolation or in collaboration with others, typically with a goal of achieving publication in a peer-reviewed journal. In many cases, research planning and execution is closely determined by funding availability on specific topics, for example via requests for proposals (Setty et al., 2018b). Mechanisms for accountability to the public, governments, and practitioners are less well established in academia, although applied, translational, and implementation research has gained traction in recent decades (Hering, 2018). Setty et al. (2018b) found stakeholders outside of academia (e.g., governmental and civil society organizations) sought but perceived fewer opportunities to engage in learning and training events. Making research relevant to potential end users and decision makers recommends cross-sector communication about research priorities (Kogevinas, 2017; Roux et al., 2006). Although not inclusive of all possible stakeholder types, this project offered one approach to eliciting practitioner and potentially other stakeholder group perspectives on research planning.

Broad, inclusive processes are recommended for research planning (Setty et al., 2018b), including scientists as well as other stakeholder types, with attention to underrepresented voices. Such processes are more likely to identify a mix of short- and long-term priorities as well as diverse perspectives and needs. The SDG process, for instance, provide an example of inclusive priority setting, which can be used to justify research efforts from 2016–2030 (UN General Assembly, 2015). Another example comes from the US National Science Foundation's Advisory Committee for Environmental Research and Education in 2018, which invited input from members of the Association of Environmental Engineering and Science Professors, an international group of professors educating on environmental protection, science, and technology topics (NSF, 2018). They sought to identify environmental research and education directions that would further advance national security and economic competitiveness. This direct solicitation took place in tandem with a public comment period over about two months.

Conscientious, structured exercises such as NGT can bolster equity, transparency, and inclusivity of research planning processes (Viergever et al., 2010). This and other approaches may be adapted to fit case-specific constraints and needs, although users should document adaptations to consider how they might alter effectiveness (Allen et al., 2017; Bartunek and Murninghan, 1984). Depending on organizational needs, periodic reflective exercises can be timed to fit into research planning cycles (Weichselgartner and Kasperson, 2010). In practical terms, participation in research prioritization exercises can be time-consuming. At a macro level, doing an exercise in conjunction with an existing collaborative event created minimal additional cost and labor. At a micro level, grouping similar responses together as they came up likewise offered a time advantage.

Conclusions

High-priority research areas (in order of frequency) included the socioeconomy of water, water quality, water treatment, microbiology, risk assessment and management, sanitation, water resources, real-time and rapid methods, water reuse, and the water-energy nexus. Each of these themes housed a range of more detailed research subthemes and questions. Underlying drivers of water and health research included social inequity, shifting international relations, demographic trends, aging infrastructure, antimicrobial resistance, and emerging diseases. To support attainment of the SDG targets for water and sanitation, water and health professionals will need to integrate efforts across environmental and health systems, sectors, and exposures; decentralize infrastructure and monitoring capabilities; and adopt more advanced processes for safety, surveillance, and responsiveness. The study methods and findings may prove useful for planning research funding offerings, projects, practicums, and quality improvement efforts among a variety of organizational types focused on water and health issues.

Declaration of interest

Authors include employees and contractors of Suez, who received remuneration for their time and travel expenses to attend work functions such as the seminar where this study took place. Senior academics on the scientific committee were similarly reimbursed for travel expenses to attend the seminar. Students accepted to the seminar received accommodations and meals for the duration of the seminar. Some participant institutions have received separate funding from Suez for specific research projects.

Acknowledgements

Our gratitude extends to all participants in the 2018 International Water and Health Seminar in Cannes for their enthusiastic collaboration. We are especially indebted to the meeting coordinators for

arranging the session logistics. Suez provided financial sponsorship for the meeting, and student travel was in many cases made possible by their respective sponsors and institutions.

Workshop participants

Academics

Jamie Bartram, The Water Institute at UNC
Elke Dopp, IWW Water Center
Martin Exner, University of Bonn
Philippe Hartemann, University of Lorraine
Paul Hunter, University of East Anglia
Gertjan Medema, KWR Water Cycle Research Institute
Mark Wiesner, Duke University
Michael Wilhelm, Ruhr-University Bochum

Practitioners

Reynald Bonnard, Suez
Sophie Courtois, Suez
Jerome Enault, Suez
Michel Lafforgue, Suez Consulting
Xavier Litrico, Suez
Jean-François Loret, Suez
Pierre Pieronne, Suez
Olivier Schlosser, Suez
Daniel Villessot, Suez
Flavia Zraick, Suez

Students

Claire Bertelli, University of Lausanne*
Helena Bielak, IWW Water Center
Nadratun Chowdhury, Duke University
Christina Fiedler, University of Natural Resources and Life Sciences, Vienna
Charlotte Christiane Hammer, University of East Anglia
Tarek Manasfi, University of Aix-Marseille*
Manon Michaut, University of Rouen
Laura Palli, University of Florence
Yoann Perrin, University of Poitiers
Nicholas Rogers, Duke University
Sydney Rudko, University of Alberta
Mohamed Shaheen, University of Alberta
Sohan Shrestha, University of Queensland
Esther Sib, University of Bonn
Vincent Tesson, French National Institute for Agricultural Research
**postdoctoral scholar*

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Supplemental Information: List of submitted research questions/themes

Research Category	**Research Question/Theme**
Socioeconomy of water	Access to safe water
	Cultural constructs such as the meaning of water and understanding of water quality
	Public information and participation
	Social acceptance of new issues in water and health
	Water-saving culture
	Water governance
	Training and human resources: change in profile of system operators with "smarter" systems
	Integration of technology and life science research with social sciences
	Getting populations "on the grid" of water and wastewater services
	How can we ensure equitable access to water and sanitation?
	Socio-economic factors affecting affordability of water and sanitation
	Water management in slums
	Water treatment and reuse on the household scale
	Water and the one-health concept: ensuring water is good for health
	Implementation science and operational research
	Water-wise smart cities
	Improving public acceptance of wastewater reuse
Water quality	Epidemiological effects of substances remaining in water on human health
	Health risk of micropollutants and methodologies for studying mixtures
	Control of antimicrobial resistance in water
	Influence of different kinds of organic matter on disinfection byproducts, microbial growth, etc.; goal and criteria for organic matter limits in produced water
	Which thresholds to use in the absence of micropollutant regulation
	"Silent" pollution of surface waters (e.g., with endocrine disruptors)
	Eutrophication and cyanobacterial toxins
	Sediment contaminants
	Oxidation byproducts
	Assessment of micropollutants and mixtures
	Improved techniques for micropollutant detection (e.g., time required, volume needed, limit of detection)
	Non-targeted analysis of chemicals and microbes in aquatic systems
	In-vitro bioassays
	Defining water toxicity and using online monitoring to measure it
	Innovative, simple, and cost-effective methods for detection of effects in water samples
	Analytical progress to assess significance of very low contaminant concentrations and exposure levels (including cocktail effects)
	Costs vs. health benefits of water treatment methods

Water treatment	Drinking water production from seawater; solutions for safe disposal of concentrated brine waste
	Cost-efficiency of membrane treatment
	Chemical-free drinking water treatment chemical free
	Which disinfection byproducts are really harmful? How can they be avoided?
	Health-related advantages of water disinfection
	Sustainable alternatives for drinking water treatment
	Reducing environmental impact of water treatment
	Treatment technologies for distributed (cellular) systems and water reuse
	Pathogen removal in drinking water
	Induction of autolysis of bacteria in water systems (e.g., using quorum sensing particles or bacteriophages)
	New technologies for emerging contaminant removal
	Low-cost technologies for upgrading infrastructure
Water microbiology	Environmental microbiomes
	Relationship between bacteria, viruses, and eukaryote cells
	Inter-kingdom or inter-species communication
	Stopping the transmission of pathogenic microbes from water systems to humans and animals
	Biological stability of stored water
	Legionella prevention approaches, sources, spread, and pathogenicity
	Growth pathogens
	Amoebae and other reservoirs for pathogenic bacteria and viruses
	Bacterial regrowth and the long-term consequences of using disinfectants to control it
	The "good biofilm": a good way to fight bad bugs
	Unpredictable bacterial contamination from biofilms
	Application of metagenomics to sewage surveys of population health, detection of pathogens, and understanding and control of microbial treatment processes
	Metagenomics and high-throughput sequencing
Sanitation	Water and solid waste impacts on public health
	Health and occupational implications of waste and residue disposal
	Sanitation (access to toilets)
	Improved sanitation systems
	Decentralised solutions for water sanitation
	Transition from centralised towards decentralised solutions for water distribution and sanitation
	Legionella and sewage treatment plants: consequences for river ecology, legionellosis, and risk regulation
	New methods to reduce pathogenic microbes (and genes) from wastewater
	Identification, detection, and removal of persistant, mobile, toxic (PMT) substances
	Innovative techniques for removal of micropollutants (contaminants) from wastewater
	Tertiary wastewater treatment to remove contaminants

Risk assessment and management	Risk assessment methods for obligate pathogens versus facultative (opportunistic) pathogens, and using QMRA (quantitative microbial risk assessment) versus ALARA (as low as reasonably achievable) principles
	Combined risk assessment for chemicals and microorganisms
	Uncertainties of health risk assessments
	Water Safety Plans that can be used in a broad context
	Management of water following crisis events (hurricanes, floods, etc.)
	Resilience in war and terrorist attacks and [consequence] for water in hospitals; New conception of civil defense
	Improved security in water distribution
	What improvement to health risk assessment may be provided by metagenomic and other "omics"
	Unknown risks
	Adaptation to weather extremes
Water resources	Industry- or agriculture-driven groundwater contamination
	Protection of drinking water resources
	Water conservation and scarcity
	Water shortages and drought
	Water loss minimization technologies
	Droughts as a consequence of irrigation practice
	Circular economy for water, using short or recycling circuits
	Watershed management plans
	Microbial source tracking
	Ex-situ and in-situ bioremediation of polluted soil and aquatic systems
Information and artificial intelligence	Integration of epidemiological or health systems data with water quality data
	Data scraping and informatics for monitoring public health
	Water and health risk assessment: how to define alternatives to long, difficult, and costly epidemiology studies using artificial intelligence and data management (cf. Google, etc.)
	Generation of large datasets and analysis of big data
	Instrumentation to support digital solutions
	Water quality modeling
	Integrative models of contaminant sources and environmental pathways and control options
	Informatics for monitoring and diagnosing infrastructure integrity and performance
	Safe and effective information transmission to support centralized management systems
Real-time/rapid methods	Real-time monitoring
	On-line water monitoring for pathogens
	On-line water monitoring for micropollutants
	Real-time risk management
	Water treatment plant operation: risk management in real time
	How to have real-time guarantee of safe drinking water?
	Early detection systems

	What measures or analyses could be incorporated into water meters to guarantee safe water?
	Rapid detection of contamination
Water reuse	Health risks associated with increasing water reuse
	Health risks of direct potable reuse
	New water resources, such as desalination or wastewater reuse
	Safe water reuse for agriculture
	Safe water reuse approaches and pilot studies
	Increasing water reuse
	Water reuse: different water quality for different uses
	Safe wastewater reuse
Water-energy nexus	Safe water treatment at a low energy cost
	Resource rarefaction (water, energy, raw materials)
	Redefining water and sanitation using decentralized and renewable energy-based solutions
	Synergies between water-energy-waste cycles
	Microbial fuel cells for sustainable energy production