Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action

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Abstract

Climate change represents the most significant challenge of the twenty-first century and poses risks to water and sanitation services. Concerns for water supply include damage to infrastructure from flooding, loss of water sources due to declining rainfall and increasing demand, and changes in the water quality of water sources and within distribution of water. Sanitation concerns include damage and loss of services from floods and reduced carrying capacity of waters receiving wastewater. Key actions to reduce climate risks include the integration of measures of climate resilience into water safety plans, as well as improved accounting and management of water resources. Policy prescriptions on technologies for service delivery and changes in management models offer potential to reduce risks, particularly in low-income settings. Water and sanitation services contribute to greenhouse gas emissions. Choice of wastewater treatment technologies, improved pumping efficiency, use of renewable sources of energy, and within-system generation of energy offer potential for reducing emissions. Overall, greater attention and research are required to understand, plan for, and adapt to climate change in water and sanitation services. As with many other climate change adaptations, the likely benefits from no-regrets solutions are likely to outweigh the costs of investment.

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INTRODUCTION

Climate change is the most significant challenge of the twenty-first century with the potential to cause significant human and economic damage (1). The 21st Conference of the Parties to the United Nations Framework Convention on Climate Change, held in Paris in December 2015, saw a commitment by states to keep the increase in temperature to no more than 2°C compared to preindustrial levels and to attempt to limit the increase to 1.5°C (2). Even if this is achieved, significant changes are likely to occur, posing increasing threats to communities and infrastructure.

The increase in temperature, even if restricted to 1.5°C, is expected to result in significant changes in precipitation patterns (3). These changes in precipitation will impact local hydrology and consequently groundwater (4–6). More frequent extreme weather events are likely, and these coupled with land-use change are likely to lead to increased frequency of flood events and with growth of settlements, to increase exposure of people to these events (7, 8).

There is more uncertainty when considering the impacts on water resource availability. Global projections often suggest greater scarcity, as a consequence of changes in precipitation, increasing temperature, increasing demand, and reduced quality of resources due to pollution (9, 10). These assessments, however, do not account for the available groundwater storage (11, 12) and the growing evidence that groundwater recharge may increase in future climate scenarios (6). Population growth, economic growth, and urbanization will all place greater pressure on water resources. Niang et al. (13) conclude that for Africa, at least, these other drivers will be more significant than climate change.

As the magnitude and complexity of the threats to water resources posed by climate change become increasingly well-understood and documented, there is increasing emphasis on more adaptive management (5). However, relatively little attention has been placed on how these threats will impact drinking water and sanitation services and their management, despite their importance to human health (14, 15).

World leaders agreed on a new framework for development in 2015—the Sustainable Development Goals (SDGs)—which include a goal on water (SDG 6) with ambitious targets for universal access to drinking water and sanitation (targets 6.1 and 6.2, respectively) by 2030. Achieving sustainable universal access under the influence of climate change will be a defining challenge for the SDG period. The SDGs also call for a focus on higher levels of service associated with much higher quantities of water (16, 17), which will create further challenges. In addition to the targets on drinking water and sanitation services, SDG 6 also includes targets to improve water quality (6.3), improve water-use efficiency (6.4), implement integrated water resources management (IWRM) (6.5), and restore water ecosystems (6.6). All of these will be impacted by climate change and in turn have important influences on the resilience of drinking water and sanitation services.

THE IMPORTANCE OF WATER AND SANITATION

The provision of water and sanitation, with associated sustained behavior change, is critical to improved public health (14). Ensuring that these services remain functional and deliver public health protection is a priority for national policy worldwide.

The evidence on the health consequences of inadequate water and sanitation is strong. There are a large number of diseases that result from poor water and sanitation, although diarrhea is the most important and most extensively studied. Recent estimates show that nearly 1,000 children under five die every day as a result of diarrhea caused by poor water and sanitation (18). This is a significant reduction in previous estimates (19, 20), a trend primarily explained by a global decline in global diarrheal deaths between 2000 and 2012.

Systematic reviews have looked at the ways in which water and sanitation services and hygiene behavior affect health (21–25). The consistent finding in relation to endemic diarrheal disease is that reasonably well-designed improvements in one or more of water supply, water quality, sanitation, or hygiene are all likely to lead to up to a one-third reduction in diarrheal disease (14). The most recent reviews show that in water supply, it is the provision of safe and continuous piped supplies that offer the greatest reductions in diarrhea (24). Freeman et al. (25) note that handwashing can deliver very significant reductions in diarrhea but that less than 20% of the global population routinely wash their hands at critical times such as before eating and after defecating. Under outbreak conditions, there is a well-established relationship between water and diarrheal disease (15).

It has been suggested that improvements in the availability and quantity of drinking water are more important than improving the quality of water sources (22, 23); however, there is very little high-quality literature on which to base reviews. This finding potentially supports the idea that improved water availability supports better personal hygiene, which would be consistent with the significantly greater reductions in diarrhea associated with water piped into the home (14, 16). It may also reflect the fact that there are few longitudinal assessments of water quality and few studies that account for the critical role of reliability of supply in reducing exposure to contaminated drinking water. Hunter et al. (26) note the importance of reliability of supply in determining risks of disease, highlighting that interruption in supplies of even short duration can greatly increase risks to health. Thus studies into water quality may overestimate the extent to which quality has been improved and the seeming lower impact on diarrhea is a consequence that contamination still occurs.

CURRENT LEVELS OF ACCESS TO WATER AND SANITATION

Monitoring coverage of drinking water and sanitation is undertaken at the global level by the Joint Monitoring Programme (JMP) for Water Supply and Sanitation of the World Health Organization (WHO) and the United Nations Children's Emergency Fund (UNICEF). The JMP has identified a set of technologies that studies show provide better water quality in water supplies and better separation of excreta in sanitation and thus provide relatively safe water and sanitation. This is questionable, however, for some technologies, for instance the large number of sewer connections with no or inadequate treatment of wastes. Estimates of coverage to safe water and sanitation are based on the use of these technologies (27).

It is estimated that in 2015, at the end of the Millennium Development Goal (MDG) period, 91% of the global population used an improved water supply (27), with 2.6 billion people gaining access to improved water between 1990 and 2015. The MDG target of halving the proportion of the population using an unimproved water source or supply was met in 2010 (28). This still left 663 million people lacking access to an improved water supply, with most of these people living in rural areas. The proportion of the global population with a water supply piped onto their premises, the level of service at which significant health gains accrue (16), stood at only 58%. Urban populations were far more likely to have access to piped water on their premises than those in rural areas (29), although the gap decreased over the MDG period.

A systematic review of studies on water quality indicated that 1.8 billion consume water that is fecally contaminated (30). Given the number of people relying on unimproved sources would account for only one-third of these people, this study suggests that more than 1 billion people are using "improved" water sources that are contaminated. In reality, this is likely to be an underestimate because there are few longitudinal studies and the importance of seasonality in affecting water quality is poorly represented (31). Furthermore, there are relatively few studies in low-income and slum environments where contamination would be expected to be more common.

The MDG sanitation target was missed by a very large margin despite 2.1 billion people gaining access between 1990 and 2015 (27). Only 68% of the world's population has access to improved sanitation, with sub-Saharan Africa, South Asia, and Oceania continuing to have very low levels of access. Lack of access to improved sanitation is primarily a rural phenomenon, with only slightly more than half of all rural dwellers having access to improved sanitation. Open defecation remains a major public health concern, and its elimination has been explicitly targeted in the SDGs. The majority of the remaining 1 billion people who practice open defecation are found in South Asia and sub-Saharan Africa, with two-thirds in India alone.

A small portion of the population with improved sanitation can be sure that their waste is effectively treated before being released back into the environment. Baum et al. (32) found that 35% of the people who have access to sanitation defined as improved by the JMP actually have connections to sewerage systems with no treatment. Many of the people using onsite sanitation in urban areas similarly have no access to systems of fecal sludge management (FSM) that include treatment of waste before final disposal (33).

SUSTAINABILITY OF SERVICES

The sustainability of many water and sanitation services is questionable, although estimates of sustainability have to be treated with a degree of caution as definitions vary and few longitudinal studies are available. A variety of reports have looked at the continued functionality of water supplies in different environments. The most widely cited study indicated that at any one point in time approximately 40% of hand pumps installed in Africa are nonfunctional (34). A more recent survey indicated that 25–40% of water points in Africa and 10–23% of those in South Asia were

Table 1 A typology of reasons why water supplies fail (38)

Category of cases	Examples
Primary causes	Mechanical failure, resource depletion, water quality problems
Secondary causes	Poor siting, lack of spare parts, basic management, poor local governance
Underlying conditions	Institutional, financial, and social factors moderated by cultural norms shaping environments when failure is more likely
Long-term trends	Changes in water demand, evolution of governance, reduction in resource availability, climate change, changes in water quality

nonfunctional (35, 36). In both regions, measures of overall service quality showed that effective service (involving estimates of reliability and quality) were even lower.

Sustainability is not simply an assessment of operational functionality at any one point in time, but needs to be considered as a wider set of institutional, financial, and environmental issues (37). Even in the context of operational functionality of water supplies, the cause of the problem can often be unclear. There are a number of reasons for operational failures; **Table 1** provides a categorization of the types of failure (38). The different categories of failure are interlinked, and many of the underlying conditions and long-term trends will directly influence secondary and primary causes of failure. Nonetheless, the typology is useful in understanding the nature and causes of failure in a rounded way.

CLIMATE CHANGE AND WASH-RELATED DISEASE

The links between events associated with climate change and disease are increasingly well-documented (18, 39). Increases in global temperature have been linked to increasing rates of diarrheal disease (40). Carlton et al. (41) found positive relationships in all-cause diarrhea and diarrhea caused by bacterial infections and increases in ambient temperature. There was no relationship between viral infections and increases in ambient temperature. There was significant regional variation, with bacterial infections being most strongly related to increases in temperature in tropical zones. Carlton et al. note that this requires further evaluation as many of these settings have low access to water and sanitation and pre-existing high rates of infection. WHO (42) estimates that climate change will cause an additional 48,000 diarrheal deaths in 2030. A systematic review and meta-analysis by Philipsborn et al. (43) found that an increase of 1°C in mean monthly temperature was associated with an 8% increase in incidence of diarrheagenic *Escherichia coli* (*E. coli*).

In a review of extreme water-related weather events, Cann et al. (44) concluded that outbreaks were commonly associated with contamination of drinking water supplies. In a systematic review of the relationship between flooding and health, Alderman et al. (45) found that infectious disease outbreaks are much more likely in areas with poor water and sanitation services. They found infectious disease epidemics tended to occur only when there was mass population displacement by floods and that there was good evidence of increased water-related disease after floods. Leptospirosis was identified as causing epidemics during floods and as a key postflood pathogen with cholera, hepatitis A and E, and pathogenic *E. coli* outbreaks postfloods. Davies et al. (46) suggested that the poor quality of water and sanitation was responsible for the statistically significant impact of floods on diarrheal disease in only 2 of 16 provinces in Cambodia. Carlton et al. (47) found that rainfall was associated with diarrhea incidence in Ecuador and that water treatment reduced incidence, with sanitation and hygiene having no impact.

Wade et al. (48) found that there was a significant association between patients presenting at emergency rooms in Massachusetts with gastrointestinal disease and floods. This was significant for the time period 0–4 days postflood and most significant in the 6–18 and over-64 age groups. Schwartz et al. (49), in an analysis of four flood-related outbreaks in Bangladesh, found that *Vibrio cholerae* (*V. cholerae*) was the predominant pathogen and, although there was some variability, they concluded that other pathogens also contributed, notably rotavirus and enterotoxigenic *E. coli*. Akanda et al. (50) found that climate change was likely to result in increases in cholera outbreaks in the Bengal Delta, as greater inundation of land by brackish water would allow the vibrios to survive longer in a viable but nonculturable state, and increased freshwater flooding would wash them into water supplies. Other studies also point to the association of outbreaks of disease with periods of drought, for instance cholera outbreaks in inland Africa (51).

Some authors have also suggested that climate change may also affect impact noncommunicable disease. Khan et al. (52) found hypertension was increased among pregnant women drinking tubewell water with high levels of sodium in coastal Bangladesh. Chong et al. (53) note the potential risks of increased salinity in drinking water as a consequence of sea-level rise and transport of salt water up rivers due to storm surges in cyclones. However, other factors such as overpumping may be more important in causing increased salinity.

CLIMATE IMPACTS ON WATER AND SANITATION SERVICES

The majority of the literature regarding the impact of climate change on water deals with water resources, but the literature is growing on the specific threats to drinking water and sanitation services. Howard et al. (54) and Howard & Bartram (55) provide a global assessment of the resilience of water and sanitation technologies and management systems. They provided assessments of the robustness of technologies under a number of climate scenarios (see **Figures 1** and **2** for examples).

There are increasing numbers of studies on specific threats, for instance the risks posed by climate change to secure water supply in glacierized basins in the Andes (56). A study in Nepal (57) highlighted the role that groundwater storage plays in increasing the resilience of small,

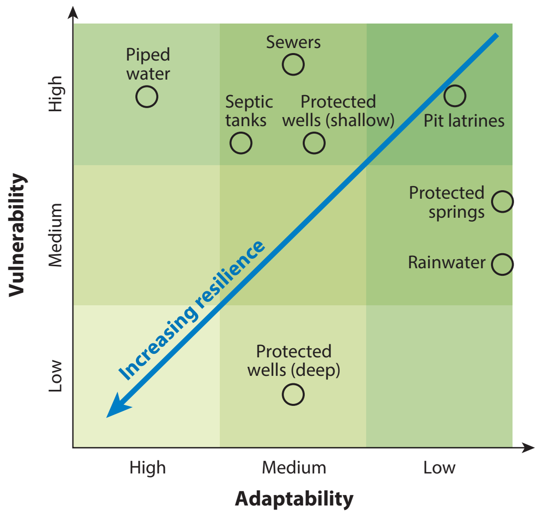

Figure 1

Water and sanitation technology resilience under increased intensity of rainfall. Adapted from Howard & Bartram (55).

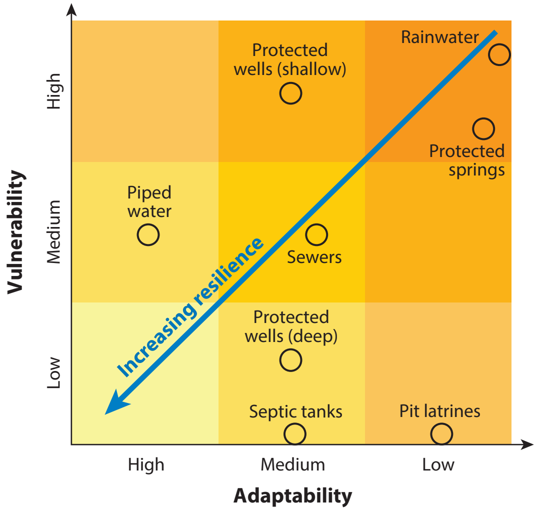

Figure 2

Water and sanitation technology resilience under decreased rainfall. Adapted from Howard & Bartram (55).

community-managed water supplies to climate change. In elevated catchments, snowmelt and rainfall provide high streamflow during the monsoon, but groundwater storage sustains flows to springs throughout the year, offering a reliable, though much reduced, supply.

The threats from climate change relate to changes in temperature and in precipitation, leading to changes in hydrology and water demand, as well as to storm events that damage water and power supplies (8). The nature of the threats relates to increasing unpredictability in surface water flows and a consequent change in demand for groundwater, as well as floods and declining water availability. These changes may be experienced in the same location at different times. Changes may be experienced through short-term, unpredictable events and slow-onset events.

Short-term threats include flash flooding and storm surges, where it may be possible to predict the areas that are vulnerable and to some extent when specific events may occur. Once underway, however, these events offer very limited time for action to be taken. For these types of events, reducing risks requires prior planning and investment in both structural and nonstructural measures, consistent with the accepted principles of disaster risk reduction. Slow-onset threats include sea-level rise, drought and water scarcity, changes in water quality, as well as some types of flooding. Although the impact on services of these events can be similar to those of short-term events, planning responses may be different and operate over different timescales. Preventive action should be possible, and for individual events there may be time to tailor responses to the specific nature of the event. The threat from flooding is most acute when flash floods occur, primarily because of their destructive force and limited warning, but slow-onset flooding can also be hugely challenging, as was found in the United Kingdom when the Mythe pumping station was inundated and water supply for 350,000 people was interrupted (58).

Loss of water sources may occur because of reduced rainfall, because of overabstraction, or because intakes or reservoirs are destroyed in flood events. Distribution infrastructure may be damaged by floods. Droughts may increase concentrations of chemicals and pathogens. Contamination may also occur because water treatment systems, source protection measures, or distribution infrastructure fail, or because of disruption to transport and power systems that may cause water supplies to stop functioning or prevent delivery of treatment chemicals.

Climate-related threats interact with other aspects of the environment and the current levels of service provision, as the volume of water used by households varies depending on the level of service (16). Where climate change results in declining water availability, utilities serving populations with water piped into homes may find securing sufficient water challenging. Households with access to water sources outside the home commonly use multiple sources of water to meet needs year-round (59–61), posing major problems in maintaining adequate quality and quantity in a wide range of sources.

In some cases, the simple technologies used for lower levels of service are more vulnerable than the complex systems used to deliver higher levels of service. This is primarily because the latter typically have better and more sophisticated management systems, greater access to finance and technical resources, and often better quality construction at the outset (54).

CLIMATE IMPACTS ON SURFACE WATER SOURCES

Changes to surface water sources from climate change will have significant impacts on drinking water supplies and waters receiving wastewater. Where rainfall becomes more concentrated into heavy events, the need for storage and conveyance may increase to help smooth out variability in rainfall and river flows between areas, and over time to ensure supply. Bates et al. (5) note that changes in climate have already resulted in changes in water flows in different parts of the world. Furthermore, they demonstrate that events such as the El Niño–Southern Oscillation, North Atlantic Oscillation, and Pacific/North American teleconnection pattern already cause significant variation in river flows, and that climate change will increase this variability.

Investment in water storage in many low- and middle-income countries is a long-standing need for dealing with current climate variability (62, 63). Brown & Lall (62) suggest that insufficient water storage capacity from built infrastructure (e.g., reservoirs) hampers economic development and makes poor countries more vulnerable to climate change. Grey & Sadoff (63) further demonstrate the urgent need to invest in improved water security, including through built storage, and point out the economic costs in poor countries associated with both floods and droughts. Sadoff & Muller (64) suggest that these are costs that could be avoided with greater investment in hydraulic infrastructure.

This is disputed as some commentators argue that it is economic growth that leads to water resource development and not the other way around (65), and that a focus on growth alone distorts decision making in relation to poverty reduction (66). Foster & MacDonald (12) argue that for many poorer countries, using the existing natural storage available from groundwater is a first step to improving water security. This may require building ponds to store infiltration water. However, this can also be achieved by allowing controlled flooding into polders that recharge groundwater, or by reducing groundwater levels prior to flood events to encourage greater recharge along rivers. Other commentators argue that the role natural infrastructure plays in buffering rainfall variability and adapting to longer-term change is also overlooked (67, 68).

Where surface water storage is developed to cope with increasing variability, this must take into account increasing challenges from more intense rain events as storage volumes may need to be greater in order to capture sufficient water. This in turn may increase evaporative losses from larger water bodies. Increasing intensity of rainfall, when combined with land-use change that reduces vegetation cover, will also increase the risks of sediment accumulation in reservoirs. This emphasizes the need for combined and carefully sequenced investments in natural and built infrastructure for climate change adaptation. The creation of reservoirs has been linked to adverse health outcomes, including increased rates of malaria and schistosomiasis, where protective measures have not been taken.

Predicting future availability of surface water is further complicated where resources are fed in part from glacierized basins and where the majority of basins may be ungauged. Current understanding is that increased warming is already leading to increased meltwater from glaciers, and in the long term this will impact the seasonality of flows; thereafter, when individual glaciers reduce to a critical volume, meltwater will reduce (69). Other sources of runoff, such as precipitation, snowmelt, and groundwater flows, are then likely to dominate, changing the timing and magnitude of flows within the rivers. This long-term reduction in the role of glaciers as flow regulators will fundamentally change the nature of these rivers.

Most of the large rivers of Asia are fed in part by glacier melt, although for the Ganges and Brahmaputra this contributes a very small proportion, and rainfall within the basin is the primary source of water (70). For these rivers, glacier loss will have an impact on local water sources but more limited impact on the main stems. For the Indus, however, snow and glacier melt may be 1.5 times greater than precipitation occurring downstream (70), and therefore changes to glacier mass will have a greater impact. Using an approach that applied glacier mass-balance assessment with recorded river flows downstream, Immerzeel et al. (71) found that precipitation at altitude in the Upper Indus Basin has been significantly underestimated. At present, this precipitation falls as snow and supports glaciers in a reasonably steady state, ensuring fairly consistent streamflow. With temperature increases, the proportion of precipitation falling as rain can be expected to increase, reducing natural storage of water. This will increase risks of seasonal flooding and scarcity, posing direct challenges for water and sanitation.

IMPACTS ON SURFACE WATER TREATMENT

Increases in suspended solids loads in rivers may mean drinking water treatment systems are unable to cope without significant upgrading. Where coagulation is used, doses can be adjusted to cope with higher suspended solids but may reach a point where the suspended solids load exceeds removal capacity and the works must be shut down. Failure to shut down coagulation units in a timely manner will lead to breakthrough of suspended solids into subsequent filtration units, which is likely to cause clogging, underperformance, and ultimately breakthrough into the final water tanks and distribution system.

Treatment units (in developed or developing countries) that are either not permanently staffed or are operated by relatively unskilled members of a community may struggle to cope with short-term changes, leading to failures in water quality (8, 54). High suspended solids loads will reduce the effectiveness of chlorination and other disinfection systems (72). Even short-term failures in treatment may result in elevated public health risks (26, 73). The key management response to these risks is often to link failures to rapid (often automatic) shutdown in order to prevent substantive breakthrough. Such systems are the norm in high-income developed countries but not in many developing countries, even in large utility supplies. The use of automated systems able to shut down systems in low-resource settings could reduce risks.

Multistage filtration may also be at risk from increasing suspended solids loads (54). This again can be managed through improved controls to shut down water intakes with increasing sediment loads and also through physical measures that cause units to stop working, for instance by having a finer layer close to the inlet of prefilters that clogs relatively quickly.

Increasing temperatures may favor survival of pathogens associated with piped drinking water supplies and may potentially extend their range. Higher temperatures favor development of biofilms containing pathogens such as mycobacteria, *Legionella*, and *Pseudomonas*. As the numbers of households with water piped into homes increase and in-house water systems become more complex, the risks from these pathogens will likewise increase.

Khan et al. (74) note that climate change may lead to increased risks of cyanobacterial blooms and consequent risks to public health, particularly in health facilities offering dialysis where there is a lack of specific additional treatment for water. This is associated with increases in temperature, but in addition to direct increases there are a number of other processes that may favor the development of blooms. Jöhnk et al. (75) showed that increased temperatures favor greater stability in the water column of lakes and reservoirs, reducing vertical turbulent mixing and shifting the competitive balance in favor of buoyant cyanobacteria. The season during which high temperatures occur may also be significant. In a study in Switzerland, Anneville et al. (76) found that warm winters were associated with high abundance of cyanobacteria, whereas warm autumns promoted blooms in two mesotrophic lakes, but they did not in an oligotrophic lake. Warm summers were not associated with blooms.

Decreasing flows are likely to lead to increased concentrations of pollutants (10). Changes in temperature and precipitation may change dissolved organic carbon and lead to an increase in the precursors of disinfectant by-products (77). Wildfires have also been identified as a risk in dry areas (notably Australia, but also parts of the United States and the Mediterranean), causing changes in nutrient concentration and dissolved organic carbon, which lead to increasing challenges to water treatment (74).

Surface waters used as drinking water sources may face additional water quality challenges where they receive wastewater upstream of water supply intakes. The most obvious impact will be increasing concentrations of pollutants if river flows decline. However, where combined sewers are used risks may also increase with more extreme rain events due to storm water overflows. For instance, Jaliffer-Verne et al. (78) found that the major causes of water quality deterioration in rivers in Quebec (Canada) were associated with spring snowmelt that preceded river peak flow and extratropical storms. They note that in the coming decade population growth and urban development are likely to be the primary causes of water quality deterioration, and after this climate impacts will be increasingly felt.

CLIMATE IMPACTS ON GROUNDWATER SOURCES

Groundwater resources are widely expected to be less affected by climate change, and it is widely believed that groundwater will form the basis of adaptation programs, as it buffers against more unpredictable rainfall (8, 79). Groundwater resources are therefore likely to be impacted as much by increases in demand for groundwater as by any changes to groundwater recharge (80).

Kundzewicz & Döll (79) note that global groundwater recharge is unlikely to change by more than 10%, although in some already dry areas (such as the Northeast region of Brazil and Southwest Africa) this may have important consequences. The development of groundwater resources has been identified as important to the resilience of community water supply, particularly in Africa (81). This is a result of the considerable buffering effect of groundwater due to the storage capacity of aquifers that smooth out short-term variations (e.g., seasonal or annual) in water availability (82).

Kundzewicz & Döll (79) note that overall knowledge of groundwater resources remains limited, and as a consequence drawing firm conclusions regarding the potential for groundwater to sustain water supplies in a given area is difficult. MacDonald et al. (11), in a review of groundwater data in Africa, highlight larger than anticipated groundwater resources but point out the patchy nature of available data for the continent. They conclude that groundwater in Africa is sufficient to maintain basic levels of drinking water supply at a communal level and much higher abstraction in some places. However, they conclude it is far from clear whether groundwater could on its own support higher levels of drinking water service, let alone significantly increase development for irrigation.

Calow et al. (83) highlight the lack of data on groundwater conditions and trends, and the dearth of data on levels and patterns of groundwater use.

There remains substantial uncertainty about how changes in precipitation will impact groundwater recharge (6). Kundzewicz & Döll (79) suggest that groundwater recharge could decline. However, Taylor et al. (80) report that based on analysis of 55 years of data from an aquifer in central Tanzania, the majority of recharge for the highly productive aquifer actually occurred in highly episodic and possibly decadal events. Recent reviews of stable isotopes in groundwater in semiarid areas point to a bias toward high-intensity rainfall events in driving groundwater recharge (84).

Coastal groundwater resources may be at increasing risk of saline intrusion as sea levels rise, often exacerbated by overabstraction. Increasing salinity of drinking water is already noted as an emerging problem in countries as diverse as Bangladesh and the Netherlands (85, 86). However, overabstraction and pollution by agrochemicals play a greater role in increasing salinity than sea-level rise for many coastal groundwaters (8, 80).

In mountainous areas, shallow groundwater in fractured rock or small aquifers coupled to rivers may be the only reliable sources of drinking water (83). Changes in the balance of snow and rainfall, or the length of the dry season, could increase pressure on these already vulnerable water supplies. Research in the middle hills in Nepal (57), for instance, suggests that most highland communities are dependent on groundwater for part of the year, and that these resources become stretched when demand increases for irrigation as well as for domestic purposes.

IMPACTS ON WATER SUPPLY INFRASTRUCTURE

Climate change is likely to lead to increasing risks on the infrastructure used in service provision. Howard et al. (54) provide an overview of the likely risks and vulnerability of those technologies considered "improved" by the JMP (27), as shown in **Figures 1** and **2**. Studies focusing on particular technologies have also been carried out for sanitation (87), and have mapped populations exposed to flood, drought, and cyclone hazards (88).

For water supply infrastructure, there are significant threats from damage to infrastructure, poor sanitary completion, poor operation and maintenance, and disruption of essential power systems. A number of studies have shown that in small water supplies, often community managed, the risks of microbial contamination can very often be ascribed to failures in maintenance of source protection and water distribution systems rather than diffuse pollution (89–92). Heavy rainfall events have been particularly associated with peak contamination (89, 93). The consequences have at times been substantial for public health, as shown by the Walkerton incident in Canada (94).

Such problems are not limited to small systems, and there are examples of failures within the operation and maintenance of utility treatment plants and distribution systems that have resulted in contamination and in some cases outbreaks of disease. The overall importance of good operation and maintenance led to the development of risk-based approaches to water safety management through water safety plans and hazard analysis critical control point (HACCP) plans (72, 95–97).

IMPACTS ON SANITATION

The impacts of climate change on sanitation infrastructure are a mix of positive and negative, depending on the nature of the changes likely to occur with climate change and changes in the types of technologies demanded by households. The literature on climate impacts on sanitation is extremely sparse, even though the impacts will be at least as significant as those for water supply and in some circumstances may have greater impact.

In countries likely to become drier, the impact on simple onsite sanitation infrastructure may be positive, as groundwater pollution risks may reduce as the distance between the base of pits and groundwater (and hence travel time for pathogens) increases (98). Drying environments may also mean that seasonal groundwater flooding of pits will be less frequent (87). Even so, such technologies may be vulnerable to damage and destruction from short-term flood events. By contrast, both declining water availability and increased flooding will pose major threats to sewerage and septic systems reliant on water. Securing sufficient water to ensure conventional sewers function as designed may be problematic and, even for modified sewerage, securing sufficient volumes of water for flushing and operation may be challenging (54). Declining water flows may adversely impact water quality in rivers receiving wastewater, although at present the low rates of treatment in sewerage systems indicate that other factors may be more important than climate change for the foreseeable future (32).

Where annual rainfall increases or there is a shift to higher intensity events, the impacts on sanitation may be more profound. For onsite sanitation, the risks are primarily related to flooding and may have very serious public health implications. All onsite systems are vulnerable to flooding, and under more severe conditions this may result in widespread spillage of fecal matter in the environment and to contamination of drinking water supplies (54). In a review of sanitation technologies, Sherpa et al. (87) concluded that only dry urine-diverting latrines could be considered resilient, mainly because the absence of water made construction of watertight tanks fully aboveground feasible. Howard et al. (54) considered pit latrines more resilient because of the adaptations that are feasible. Septic systems were considered vulnerable not only because of flooding and discharge of the tank contents into the environment, but also because of the risk of flotation due to increased groundwater levels.

Fecal sludge management (FSM) chains may be vulnerable to climate impacts. In urban areas in particular, FSM as a system is gaining traction as the demand for low-cost toilets drives the demand for simple pit latrines, but space constraints preclude approaches used in rural areas (replacing latrines once a pit is full). Typically, FSM chains involve collection and transportation of waste in vehicles, with disposal in a treatment facility. Clearly, risks of flooding will impact the ability of emptying vehicles to access communities if roads become impassable.

Sewer systems are highly vulnerable to greater rainfall, particularly where combined sewers are used. Even when sewers are not combined, the risk of damage to sewers during flood events is high and higher for modified sewers that are typically laid at shallower depths (87). Wastewater treatment works may also be adversely affected because they are often low-lying and next to rivers that are likely to flood.

EVIDENCE OF APPROACHES TO MANAGING AND PREVENTING IMPACTS

The literature that deals with the likely impacts and consequences of climate change on water and sanitation facilities is much more extensive than that dealing with the potential means to managing risks. Most of the guidance offered with regard to climate change and water and sanitation emphasizes the need for a good understanding of the resources that supply water. In most developed countries there is a good understanding of the available resources and typically long-term commitments to monitoring and research to improve this understanding. Although not perfect, many utilities in high-income countries have access to significant good-quality data from which they can develop future scenarios in light of expected changes in climate. In very many low-income countries, basic data on existing water resources and patterns of use are not available. This means that assessing future risks from climate change is extremely difficult and bounded by very large margins of uncertainty.

WATER RESOURCE ASSESSMENT AND CLIMATE SCREENING

Increased investment in water resources assessment and accounting, particularly for groundwater, is an urgent priority for most low-income countries (11, 83). Artificial recharge of groundwater will increase availability of water and may also help to reduce quality problems, such as salinity in coastal areas, as freshwater can help dilute brackish water (99, 100). Low-cost technologies such as sand dams have been shown to be effective technologies in arid areas (101–103).

In regions at threat of drought, a key action will be to reduce water consumption, especially in "closing" basins where further appropriation of water for human use is not possible within sustainable limits. In these areas, investment in basic water accounting is key for decision makers to develop an understanding of what is being withdrawn, where water is going, what fraction is consumed or recycled, what is happening to pollution loads, and the timing and location of return flows as water is recycled and reused (104). Understanding the difference between withdrawals and consumption is key, as only those interventions that reduce nonbeneficial evaporation and transpiration, or that minimize losses to saline or polluted bodies, generate real savings (105, 106).

A number of authors have highlighted screening of climate risks as a key approach to identifying the vulnerability of particular water and sanitation services. Heath et al. (107) present case studies from three African cities in which a rapid climate adaption assessment tool was applied. These cities all had a substantial low-income population, with multiple climate and weather-related vulnerabilities and water and sanitation service typified by low-cost technology and management. The authors looked at how climate was expected to change in each city and, using material developed as part of the "Vision 2030" study (55), were able to identify where specific vulnerabilities lay. Heath et al. (107) found that flooding risks outweighed drought risks. They noted that many of the mitigation options identified were relatively straightforward and in many cases used what should be considered best practices in flood- or drought-prone areas. They stress, however, that addressing climate change is not business as usual, with heavy rainfall events particularly requiring much more consideration.

Oates et al. (108) provide case studies from three low-income countries where assessing climate risk was found to be feasible. The authors argue for a stronger focus on ensuring the reliability and protection of drinking water sources and simple changes to latrine design under current conditions of climate variability as a first step toward adaptation. They go further and apply value-for-money assessment to options for improving the resilience of services as a key element in decision making.

OPERATIONAL AND SUPPLY DESIGN CONSIDERATIONS

The use of climate-resilient water safety plans as a risk management tool has been identified as an effective approach for climate resilience in water supplies (74 , 109). Khan et al. (74) note the ability of risk management tools designed for water safety to capture risks associated with climate change and to therefore lead to action. They note, however, that to date this has had limited success and clearer guidance on how climate risks can be effectively captured within the water safety plan approach is required. Under a program to support climate resilience in water and sanitation, WHO has used experiences from four developing countries to update guidance on integrating climate risks into water safety plans, as shown in **Figure 3** (109). The Global Water Partnership

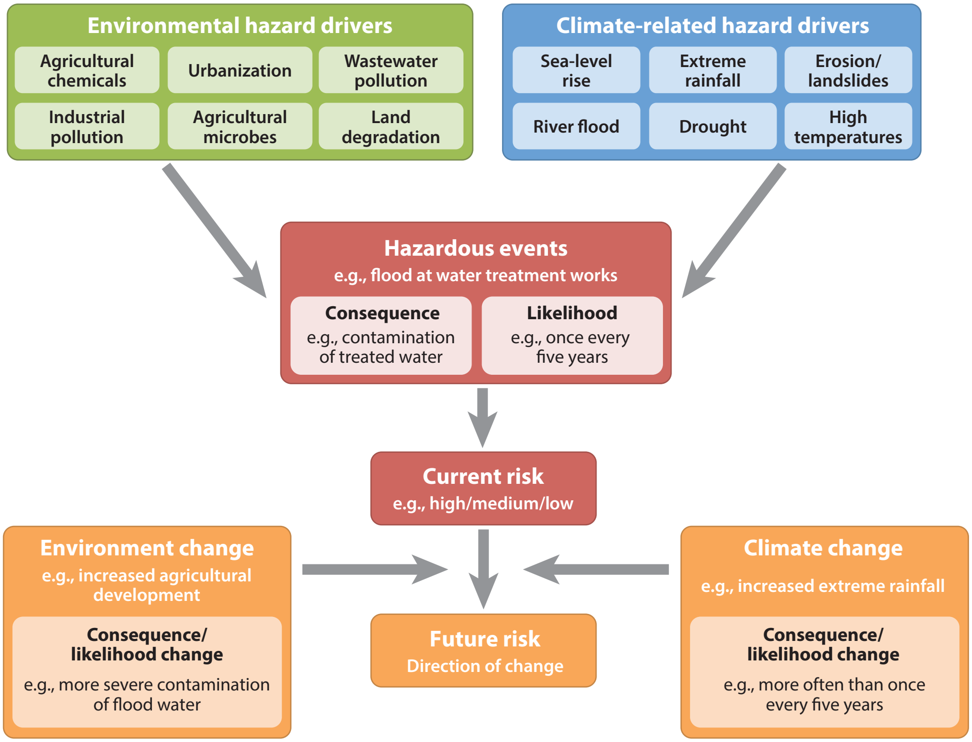

Figure 3

Conceptual flow of activities in water safety plan risk assessment, extended to consider changes in climate and environment. Figure adapted from WHO 2016 (109), with permission.

& UNICEF (110) jointly developed a strategic framework, and as with the guidance and tools developed by WHO, much of what is included is based on good operational management.

In urban areas, diversifying sources of water is an important strategy for larger utilities (54, 111). This may be the development of new freshwater sources as noted by Howard et al. (54), but importantly may also include reuse of treated wastewater in blended systems and possibly desalination. Danilenko et al. (111) refer to examples from Windhoek and Singapore where reclamation of water has been instrumental in securing potable water for cities. Wastewater use may also reduce competing demands on freshwater; for example, Ensink et al. (112) show that in Egypt, India, and Pakistan the use of treated wastewater in small-scale agriculture has reduced demand on freshwater sources, thus making these more available for drinking use.

Danilenko et al. (111) note the use of market instruments as important and particularly relevant for utilities. They point to the use of such approaches in Australia in the Murray–Darling basin and cite experience in Tucson, Arizona, where the cost of buying water rights from agricultural users was found to be cheaper than long-distance conveyance costs. They also note that developing countries may need to develop such approaches, although this will be dependent on whether a transparent system of tradable water rights can be instituted and on the degree of understanding of water resources. The technical and institutional hurdles to doing this are considerable, and trades should ideally be based on consumptive use not diversions. In Australia's Murray–Darling basin, perhaps the best-known example of formal water trading, codifying water rights in a system that was already well managed and orderly, took several decades. Only once this process was complete was it possible to introduce a system of trading (113).

POLICY RESPONSES

There are a number of policy responses available to address resilience of water and sanitation services. Howard et al. (54) note several areas where policy responses may be effective for low- and middle-income countries, based on an assessment of the resilience of technologies and management approaches commonly used.

In rural areas of low- and middle-income countries, where small supplies continue to be the norm, key policy decisions revolve around which technologies are acceptable in terms of resilience. In their assessment of the range of technologies categorized by the JMP, Howard et al. (54) suggested that some, such as dug wells, are less resilient because of vulnerability to contamination, susceptibility to drought or long-term reduction in water volume, or difficulty in preventing damage during flooding. Others are less vulnerable because of adaptations that have been shown to be effective, for instance raising the wellheads of tubewells.

Although such decisions should be made on a case-by-case basis, policy prescription on acceptable technologies is one way to help build resilience. Such an approach would be very much in line with other risk management approaches, such as the specified technologies approach to health-based targets described in the WHO's (72) *Guidelines for Drinking Water Quality*. Although the evidence may be clearer for water supply technologies, the same approach could, in principle, also be applied to sanitation.

In order to apply a specified technology approach, the current and likely future trends in key climatic and other variables should be assessed to establish how the technology performs against current threats and what future threats may challenge the technology. This must be based on local conditions and trends rather than simply transferring practice from elsewhere. For instance, although it is true that dug wells are vulnerable mainly because of the difficulties in protecting against contamination under existing climates (91, 92), this may not be the case in all environments, and adaptations may be available that could reduce vulnerability (54).

Similarly, although Howard et al. (54) concluded that tubewells were a resilient technology, with adaptations available, Luby et al. (114) found that during flood events in Bangladesh, contamination in tubewell water could not be linked to the sanitary risks of the technology itself, but were likely to have resulted from more diffuse and widespread fecal contamination of the aquifer; they conclude that actions taken to reduce sanitary risk of the tubewell itself may not eliminate this risk. Threats from reducing water tables from declining recharge and/or overabstraction may be different for the same technology in different circumstances; however, again, a general rule will be that shallower groundwater and smaller surface water catchments will be more vulnerable than deeper groundwater or larger catchments. However, the aquifer type will influence the nature of the threat. Shallow alluvial aquifers will be highly vulnerable to dropping water tables caused by declining recharge and overuse, but this may not be true for fracture aquifers as it will depend on where the recharge occurs and there is no guarantee deeper aquifers will have any greater storage than shallow ones (81).

APPROPRIATE MANAGEMENT MODELS

Management approaches and in particular the level of decentralization of management will have an important impact on resilience. Community management is still the most common approach in rural water services despite evidence of significant variation in its success (115, 116). Community management can be robust where some central support, for instance from surveillance programs, is provided (90, 117). Given the current problems with sustaining community-managed supplies, Howard et al. (54) concluded that the challenge would be likely to increase significantly with increasing climate threats.

The available literature points to the benefits of more organized utility management in developing climate resilience (54, 111). This is because the technical, human, and financial resources are usually sufficient to permit the integration of climate issues within management plans, provided the will to do so exists. However, as noted by Evans et al. (118), in reality many utilities lack the capacity to do this in practice.

There is good emerging evidence of how utilities in developed countries have developed plans of action to address climate change. For instance, WHO (109) presents case studies of how utilities in Australia (for the entire country and specifically for Western Australia) and the Netherlands have started to build climate resilience. These case studies highlight the range of events that will pose a risk to the quality of water services and the options available for reducing risks. There is a significant emphasis on alternative source development to produce lower-risk source waters, although in the Australian national case study, the risks associated with some alternative supplies, specifically rainwater, in promoting other diseases (in this case dengue fever) were flagged. By contrast, there is limited evidence of how utilities in developing countries are addressing risks from climate change, despite arguably facing a greater range of risks from climate change.

Johannessen et al. (119) note the potential value of public–private partnerships in building resilience in water, sanitation, and hygiene (WASH) systems, including through investments in disaster risk reduction, delivery of services to the unserved, and use of microfinance and microinsurance. They point to the still greatly underdeveloped potential for private investment in WASH systems in developing countries, a view that is supported by Sy et al. (120), who suggested the potential market for private suppliers of water and sanitation services in developing countries is huge. In formalizing existing, informal arrangements, there is significant potential to improve the ability of governments to regulate services and to improve their quality and resilience.

There is similarly limited experience in use of microfinance and microinsurance in the water and sanitation sector. Microfinance, for instance, has the potential to support the greater acquisition of hygienic latrines and move households up the "sanitation ladder." Whether this potential can be realized depends in part on whether the benefits of acquiring a latrine can be sufficiently well-articulated to encourage poor people to take on debt. There is very limited uptake of the use of microfinance for water supply, although it has potential application in promoting household water treatment. Problems in sustaining effective use, however, may limit the resilience of this technology. Microfinance could be used to encourage the uptake of connections to utility piped schemes, which could offer benefits to both the households who have access to more water and the utility, which would have a larger customer base and therefore greater resources to invest in reducing vulnerability to climate-related hazards.

The alternative in both water supply and sanitation could be to use conditional cash transfers (CCTs) available solely for the use of acquiring a water supply connection or improved toilet. Juillard & Opu (121) reported a scoping study on the use of CCTs as an emergency response for water and sanitation and note that CCTs are being increasingly used, but documentation of experience is largely lacking. CCTs have been shown to be effective in other sectors including nutrition and health, and as a means to encourage girls to attend schools.

The microinsurance approach is less well-tested in water and sanitation. Its most obvious application is in regions regularly affected by flooding where services are supplied by households themselves or at the community level. However, implementing such schemes is likely to be problematic. Even in countries with a tradition of homeowners insurance, extending this to cover replacement of basic services may well be considered unacceptable by many people affected.

The use of IWRM that permits more transparent allocation of water across all its uses and promotes participation of all stakeholders will support improved management of water services. IWRM can be applied at all levels, and its uptake is explicitly called for under SDG target 6.5.

WATER AND SANITATION AS GREENHOUSE GAS EMITTERS

Water and sanitation services are contributors to greenhouse gas emissions because of the need for energy to power piped water systems and managed water and wastewater treatment plants. For instance, Twomey & Webber (122) found that 5% of the United States' primary energy production and 6% of its electricity is used in public water supply.

Sanitation systems directly produce greenhouse gases from the breakdown of excreta. Howard et al. (54) note that using technologies with lower energy requirements should be considered a priority in reducing the carbon footprint. It will also be critical that improvements in management, particularly in reducing unaccounted-for water, are realized as this reduces the amount of water required and consequently reduced energy demands.

Human excreta, as with other organic material, is a potential source of greenhouse gas emissions, although waste (solid and wastewater combined) accounts for less than 5% of global emissions (123). Fischedick et al. (124) note that greenhouse gas emissions from industry and waste/wastewater doubled between 1970 and 2010 and that waste/wastewater emissions amounted to 1.4 Gt CO_2 eq in 2010.

Where wastewater treatment is used, Cakir & Stenstrom (125) conclude that aerobic processes released lower greenhouse gas for low-strength influent wastewater (based on biochemical oxygen demand), but that at higher strengths anaerobic systems provided lower emissions. The Intergovernmental Panel on Climate Change noted that the greenhouse gas emissions from septic tanks, latrines, and open-air defecation remain largely unquantified and a global systematic assessment is needed (5, 123, 124).

Emissions from wastewater are expected to rise by almost 50% up to 2020 under a business-as-usual approach, with the primary contributors being in developing countries. It is not clear how much would be related solely to human waste and how much to industrial waste also treated in municipal wastewater treatment plants. Good wastewater management does reduce greenhouse gas emissions and therefore it is reasonable to expect that, with increasing sanitation coverage, these levels of emissions may decrease (126, 127). Future decisions on technology should give some consideration to measuring or estimating greenhouse gas emissions, and further research is needed to quantify the absolute and relative greenhouse gas emissions from the available sanitation options.

A number of studies have looked at specific utilities and locations to determine likely greenhouse gas emissions from water and sanitation services. Santos et al. (128) found that sewage treatment was the main source of emissions from a utility in Bahia state in Brazil. Freidrich et al. (129) concluded that in South Africa, use of onsite sanitation systems where possible was likely to produce less greenhouse gas than sewerage and wastewater treatment, mainly because of lower energy requirements. This study also found that sanitation options that recycled water to meet increasing demand had the lowest carbon footprint when using a lifecycle assessment approach compared to the base condition or construction of new infrastructure. Qi & Chang (130) also applied a lifecycle assessment approach and showed how carbon footprint could be integrated with cost to assess alternatives for expansion for drinking water systems in Florida. Fischedick et al. (124) provide a summary of alternative methods of wastewater treatment that would produce fewer emissions and where energy could be generated directly from waste.

The water and sanitation sector has significant potential to generate much of its energy requirements from within its systems and potentially to be a net contributor to energy, thus making systems energy positive (124). This in part is related to the use of biogas generators linked to treatment of sewage from septic systems but also includes the potential to use microhydro systems within pipes to generate electricity (131). Given the potential for choices that will reduce emissions and the obvious climate-development cobenefits, there is a strong case for more climate finance to flow to the water and sanitation sectors.

CONCLUSIONS

The evidence is increasing of the potential risks to water and sanitation services posed by climate change. There are multiple risks derived from both changes in precipitation and increases in temperature, which relate to damage to infrastructure leading to the loss of services and environmental contamination and to deterioration in water quality, impacts that will increase risks to health. It is clear that these risks are widespread, affecting both poor and rich countries, and countries in temperate and tropical environments. There is good evidence that impacts on water and sanitation services from climate change will lead to direct impacts on health. This is primarily derived from infectious disease, particularly diarrhea, but there is some evidence that noncommunicable disease risks will also increase.

Different technologies and management approaches have very different resilience to climate change. Strategies to manage the impacts of climate change are beginning to emerge; however, there remains much to be done, particularly in low-income countries and for small supplies in all countries. Building climate resilience into existing risk management approaches such as water safety plans appears to offer one of the most cost-effective approaches to managing climate risks, and similar approaches have potential in sanitation. However, in some cases investments in new infrastructure or catchment management will be required. Water and sanitation services also represent important sources of greenhouse gases, although their overall contributions remain poorly quantified and this is an important research need. Nevertheless, choices can be made to minimize emissions through selection of technologies and through sound management. Given that development benefits are likely to arise from actions to build climate resilience, more water and sanitation, programs should consider accessing climate finance in the future.

DISCLOSURE STATEMENT

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