Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services

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ABSTRACT

Drinking-water supply and sanitation services are essential for human health, but their technologies and management systems are potentially vulnerable to climate change. An assessment was made of the resilience of water supply and sanitation systems against forecast climate changes by 2020 and 2030. The results showed very few technologies are resilient to climate change and the sustainability of the current progress towards the Millennium Development Goals (MDGs) may be significantly undermined. Management approaches are more important than technology in building resilience for water supply, but the reverse is true for sanitation. Whilst climate change represents a significant threat to sustainable drinking-water and sanitation services, through no-regrets actions and using opportunities to increase service quality, climate change may be a driver for improvements that have been insufficiently delivered to date.

Key words | climate change, decadal forecasts, drinking water, less developed countries, Millennium Development Goals (MDGs), sanitation

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INTRODUCTION

The effects of climate change will be felt particularly through changes in the water cycle, with increasingly unpredictable rainfall leading to less predictable water flows and recharge, more droughts and floods and changes in the capacity and nature of key water stores such as glaciers (Stern 2006; Xu *et al.* 2007; Bates *et al.* 2008). In addition, sea-level rise will increase the risks of permanent or seasonal saline intrusion into groundwaters and rivers, impacting on quality and potential usability of water sources for domestic, agricultural and industrial uses. There is therefore a need to adapt current practices and to build greater resilience in water-using sectors to minimise adverse impacts. Such measures will be required to ensure the functioning of these sectors and have wider implications in terms of the ability of countries and communities to cope with future climate changes.

Drinking water supply and sanitation are critical water uses for human survival, health and prosperity (WHO 2004). Almost 900 million people lack access to an improved water supply and 2.6 billion to basic sanitation (WHO & UNICEF 2010). WHO and UNICEF consider improved water supplies to be those technologies that

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provide water of an acceptable quality and quantity and improved sanitation and sanitation facilities to be those technologies that hygienically separate faeces from human contact. The details of those technologies considered improved is available in WHO & UNICEF (2010). It is people in the developing world, and primarily the poor, who lack access to services and are also expected to be most vulnerable to the impacts of climate change. The sustainability and quality of the services provided to those people who have achieved access in many countries is already highly questionable. The risks from climate change are likely to further undermine sustainability unless services can be made resilient, which will in turn further increase risks of water-related disease (Confalonieri *et al.* 2007).

The threats from climate pose major risks to the quantity of water available for use. There will be a need to ensure that water resources required to supply drinking water are safeguarded and that sufficient water to meet these needs is prioritised. For drinking water and sanitation, equally great climate risks are associated with the impact of extreme events, particularly floods, that damage infrastructure and cause temporary or permanent loss of supply and gross environmental contamination. Further challenges will arise from changing source water quality that renders water unsafe and increases treatment requirements.

Water supply and sanitation infrastructure and management systems are vulnerable to current climate-related threats. Floods cause widespread damage and loss of access to infrastructure on a regular basis in both the developed and developing world. For instance, the floods in Bangladesh in 2006 meant that large numbers of water supplies and sanitation systems were unusable for a period of weeks and there was widespread contamination of tubewells by faecally contaminated surface waters (Luby *et al.* 2008). In the 2007 floods in the UK, flooding led to the Mythe pumping station being put out of action, removing access to piped supplies for 350,000 people in Gloucester (Pitt 2007).

Decreasing rainfall, particularly when combined with increasing temperatures will increase the risks of blooms of cyanobacteria as surface water flows decrease and nutrient loads become more concentrated. Decreased rainfall also reduces carrying capacity, particularly of surface waters, thus increasing the concentration of chemical and other pollutants. Increasing rainfall will lead to increased loads of suspended solids. Saline intrusion into aquifers and surface waters represents a further significant threat to water and sanitation technologies. All these will make the production of safe drinking water more expensive and difficult, requiring more sophisticated technologies and management systems.

The influence of climate change will be felt alongside population growth, economic development, changing land-use and urbanisation, all critical driving forces affecting water availability, quality and demand (Human Development Report 2006).

Although the risks from climate change are significant, it is also important to acknowledge that building resilience to climate change may also provide incentives for the drinking-water and sanitation sectors to improve policy, investment and operation to prevent and limit climate impacts alongside those caused by increased competition for a declining resource. Technologies and management systems capable of adapting to a wide range of potential climate scenarios need to be identified and prioritised.

Most freshwater abstraction is for agriculture, while domestic water supply accounts for some 15% globally, but considerably less in many developing countries (Gleick 2008). The wider water resources management implications of climate change have been comprehensively dealt with elsewhere (Arnell 2004; Bates *et al.* 2008; Sadoff & Muller 2009) but climate change impacts on drinking water and sanitation services and the scope for adaptation have thus far received little attention. This is particularly the case for low and middle income countries which are likely to be most adversely affected by climate change and where progress has been most limited in the delivery of drinking water and sanitation services.

This paper presents the first assessment at a global scale of the resilience of the currently used technologies and management of drinking water supply and sanitation services to projected climate changes in the short to medium term. An assessment was made of the resilience of water and sanitation systems to climate change by 2020 and 2030. These time horizons reflect work in other water-using sectors and are relevant to investment decision-making (Lobell *et al.* 2008). The year 2020 indicates the potential for climate change to undermine investments already made and committed towards achievement of the

Millennium Development Goal (MDG) targets; and 2030 provides for responses in technology selection and planning to expected climate changes.

METHODS

Technology resilience

The resilience of technologies and management approaches to key climatic threats was assessed through literature review and collection of data from sector professionals. An extensive review of the published and grey literature was undertaken using key databases and linking to professional networks to access grey literature. An electronic questionnaire, running between July and September 2008 on surveymonkey. com was used, targeted at professionals working in the water and sanitation sector who had experience with a range of drinking-water supply and sanitation facilities in the field. The questionnaire used both open and closed questions with single and multiple answers and was pre-tested to ensure clarity, relevance and comprehensibility.

Semi-structured telephone interviews using a detailed interview were conducted with a selected group of international water and sanitation experts. The topic guide was pre-tested before use. All interviews were recorded and transcribed in full and the transcripts were checked for accuracy by a second internal reader, then sent to the interviewees for verification. The transcripts of the interviews were analysed for responses, views and experiences that fell within each of the main themes of the interview guide. The questionnaire and interview guide can be accessed from www.rcpeh.com and the results are the subject of a forthcoming paper. The data from the literature review, questionnaire and semi-structured interviews were used to categorise the resilience based on evidence of resilience and vulnerability to current climate variability and ability to withstand forecast future changes.

Changes in coverage

To assess the scale of impact of resilience of the different technologies and management approaches to climate change, forecasts of coverage were undertaken using data derived from the WHO and UNICEF Joint Monitoring Program. This used linear regression for countries where at least two survey data points were available and spaced five or more years apart. If the extrapolated regression line reached 100% coverage or beyond, or 0%, a flat line was drawn from the year prior to the year where coverage would reach 100% (or 0%).

Where insufficient data exists for linear regression, the slope of the regression was assumed to be zero. When this occurred the projection was made up to a maximum of six years forwards and backwards in time from the data point. When coverage was at 95% or above, or at 5% or below, the projection was made without limitations, as described in WHO & UNICEF (2004). The proportion of the population using a particular type of improved water supply or sanitation facility was also forecast. For this, individual facilities were forecast as the proportion of total population using improved facilities. These forecasts were scaled so that the sum of the individual facility usages, where there was data for more than one facility, was equal to the total coverage.

Climate predictions

Predictions for expected changes in the average precipitation and the frequency of 5-day heavy rainfall events were undertaken using the decadal prediction system (DePreSys). DePreSys predictions are started from observed conditions which specify the current phase of variability of the climate on interannual (and decadal, or multi-decadal) timescales (Smith *et al.* 2007) and use the HadCM3 climate prediction model (Gordon *et al.* 2000). The forecast used in this study was a 10-member ensemble started from conditions observed on 10 consecutive days in March 2007. The climatology of the model is provided by a mean of 4 simulations for 1979 to 2001 made using HadCM3, which include natural and man-made influences on the climate system. The regions used are those defined by Giorgi & Francisco (2000) for regional analysis of climate model simulations. A set of hindcasts using DePreSys was created to help assess the skill of the system by comparison with observations. The hindcasts are 4-member ensembles (started from consecutive days), with start dates at 3-month intervals, from initial conditions created by assimilating observations.

The external forcings applied to the system are derived from concentrations of greenhouse gases and sulphate aerosol provided by SRES scenario B2[2] (see IPCC 2007), observed volcanic aerosol decayed from the initial value with one-year timescale and solar forcing obtained by repeating the previous 11-year solar cycle. In addition, two 10-member hindcasts were initialised 10 years apart, in 1965 and 1975 respectively, and run for 30 years each, with external forcing similar to those used for the shorter hindcasts. Observations were used for converting predicted percentage changes into amount changes and for evaluating the model's performance in reproducing the observed precipitation variability from 1979 onwards. For the period since 1979 data from the Global Precipitation Climatology Project (Adler *et al.* 2003) were used for annual, seasonal and monthly averages, and data from the CPC Merged Analysis of Precipitation (Xie & Arkin 1997) were used for 5-day averages; for the period prior to the satellite era data from the Goddard Institute for Space Studies (Dai *et al.* 1997) the Climate Research Unit (Hulme 1992) and the Variability Analysis of Surface Climate Observations (Beck *et al.* 2005) project were used.

RESULTS AND DISCUSSION

Technology resilience

The potential resilience of each technology was classified as high, medium or low. Highly resilient technologies are expected to function under most expected climate conditions, medium resilience under a significant number of climate conditions, and low resilience under a restricted number of climate conditions. The potential resilience of drinking water supply technologies is shown in Table 1.

When considering piped water supplies as a technology, they were found to be inherently highly vulnerable because of their size and complexity. As a consequence they are exposed to multiple threats from the source, through treatment systems (if deployed) and subsequent distribution. The quality and protection of water sources and available treatment processes exert a significant influence on vulnerability. These are inter-related issues as changing source water quality exerts a significant impact on treatment efficiency and requirements, leading to significant changes in treatment plant design and process selection.

The large spatial spread of pipes crossing environments with significant hazards and numerous joints (points of weakness for breaks and contaminant ingress) greatly increase vulnerability. This is increased further by leakage, intermittent supply and critical points (such as pumping stations or in-system storages) whose failure may affect large numbers of people.

There are a number of technical adaptations that would reduce vulnerability including the use of multiple sources, innovations in treatment, more robust pipe material and leakage reduction. However, as noted below, implementing such innovations is largely a function of the management and depends on the financial position of the managers of the water supply.

Table 1 | Resilience of drinking water supply technologies

Technology	Resilience	Key issues
Tubewells	High	Motorised pumping may pose challenge in drying environments
Dug wells	Low	Problems with water quality and securing year-round supply already problematic
Protected springs	Low-medium	Water quality threats from increased rainfall and reduced flow in drying environments
Household roof rainwater	Low	Reduced frequency but more intense rain and drying environments pose threats
Treatment processes	Medium	Processes are resilient, but climate change may increase performance requirements
Piped water	Low	High inherent vulnerability, with critical points where damage may lead to impacts on large populations

Tubewells (boreholes) were found to be highly resilient to most impacts of climate change on freshwater systems, but were less resilient to issues of saline instruction resulting from sea-level rise. Their vulnerability to freshwater changes brought about by climate change was relatively low because of adaptations available on existing water supplies, such as raising wellheads, but also because new or replacement supplies can also often be sunk in new locations close to existing water supplies. Saline intrusion from rising sea levels may represent a more long-term problem and drying environments may make shallow tubewells less viable. Sinking deeper tubewells, particularly where these are separated from shallower aquifers by aquicludes in the case of saline intrusion, offers a potential solution but will change the cost-effectiveness of tubewells.

Household-level rainwater harvesting and protected shallow springs are less resilient to climate change. Both are inflexible as their location is determined by the outlet of spring or the roof catchment. Both have limited adaptability in design and are rapidly susceptible to rainfall changes, although the less commonly found artesian springs are less vulnerable. Household rainwater harvesting rarely delivers a year-round supply and the yield of many springs declines during dry periods, particularly where the springs emerge from shallow renewable groundwater resources. Without good operational management, both these sources of water are vulnerable to microbial contamination. Although adaptations exist to improve the performance of both these technologies, for instance through changes in filtration media for protected springs or increased size of storage tanks, improvements are generally limited.

Dug wells have very low resilience because of high vulnerability to reducing quantity of water and microbial contamination following rainfall. Dug wells are more difficult to protect against microbial contamination than other groundwater sources, such as protected springs or tubewells. The construction method makes it difficult to prevent ingress of water from the upper parts of the lining and experience suggests that these supplies are unable to deliver water of acceptable quality without chlorination. In dry and drying areas, dug wells have limited adaptations. Deepening options are likely to be limited because of limits on safe depth of construction and collector wells have been used to increase yields in very dry environments.

No sanitation technology with low resilience was found (Table 2). The high potential climate change resilience of pit latrines derives from the availability of adapted designs (that reduce the impact of flooding and risk of environmental contamination), which can be introduced relatively rapidly and build on existing investments. Flooding remains a major threat for pit latrines and can result in very significant environmental contamination. However, the nature of latrine technology means that changes can be made after flooding that reduce vulnerability to subsequent events.

In environments that are getting drier and where groundwater levels decline, pit latrines will be highly resilient because of the increasing potential for the attenuation or death of pathogens. There may be increases in nitrate concentrations, but the overall burden of disease associated with nitrate is much lower than other threats to the health of households only able to afford a pit latrine. Soil stability and hence pit stability could decrease in drying environments, but relatively simple adaptations exist to reduce this risk, by lining pits using local materials.

Table 2 | Resilience of sanitation technologies

Technology	Resilience	Issues
Pit latrines	High	Many adaptations possible; flooding represents a particular challenge
Septic tanks	Low-medium	Vulnerable to flooding and drying environments
Modified sewerage	Medium	Less vulnerable than conventional sewerage to reduced water quantity, but flooding a threat
Conventional sewerage	Low-medium	Risk from reduced water availability and flooding of combined sewers
Sewage treatment	Low-medium	Vulnerable to increases and decreases in water and treatment requirements may increase as carrying capacity reduces

Pour–flush latrines have a slightly lower resilience than dry pit latrines. In environments that are getting wetter, low-flush systems are more likely than dry latrines to cause groundwater contamination because use of water, even in small quantities, can significantly increase pathogen breakthrough. In environments that are drying, the requirement for any water at all will reduce resilience, although the typical volume associated with pour–flush latrines (1–3 litres at most) means that the impact would be relatively limited.

Septic tanks are less resilient than pit latrines and in areas of increasing flooding and groundwater level rise are vulnerable to flotation and causing widespread contamination. Flooding of household premises is also a significant risk when flooding of septic tanks occurs, resulting in significant public health risks to the inhabitants. There are adaptations to septic tanks to reduce discharge during floods, including installing sealed covers and fitting non-return valves to pipes to prevent back flows. In drying environments, the volumes of water required to keep a septic tank functioning may be difficult to sustain.

Unconventional sewerage (including 'condominial' and small bore sewerage) is more resilient that conventional sewerage. Small-bore and condominial sewers use less water than conventional sewerage and as a consequence they are less vulnerable to decreasing water availability. Modified sewers will still be at risk from damage from floods and other extreme events.

The resilience of conventional sewerage systems to climate change varies widely. Where combined sewers are used, overflows disperse pathogens and other pollutants and may become more frequent where intense rainfall events increase and there is increasing evidence that past flood criteria in terms of return floods may become increasingly unreliable. Heavy rain events may also cause back-flooding of raw sewage into houses, with consequent significant risks to public health. Flood events cause physical damage to sewer infrastructure, resulting in leakage of sewage into the environment.

In drying environments, all forms of sewerage will become less sustainable because they depend on reliable water inputs and prolonged drought can cause differential ground settlement and damage to the sewer. Increasing water scarcity will affect sewers, as water flows may be reduced leading to greater deposition of solids and consequent blocking of sewers. This may be particularly problematic because conventional sewers typically carry non-faecal solids from both domestic and commercial properties, which may cause greater blockages. In many coastal areas, sewer outfalls discharge into the sea, either as short or long sea outfalls. As sea levels rise in the future, water levels in the sewers may rise in response, causing wastewater to back up and flood through manholes in roads and the toilets and washbasins of homes and buildings. Shut-off valves can prevent such back-flow, but in many cases in developing countries these have not been installed.

There are adaptations that build greater resilience into sewer systems, but these are often expensive and technically demanding. Adaptations include deep tunnel conveyance and storage systems that intercept and store the combined sewer overflow water until it can be conveyed to the wastewater treatment works. Re-engineering sewer systems to separate out stormwater flow using sustainable urban drainage systems or providing additional storage for stormwater will increase resilience of sewers. Other strategies include the introduction of special gratings and restricted outflow pipes.

Management resilience

Management was found to be critical in determining resilience of drinking water, particularly for piped supplies. Larger, utility-managed piped supplies are potentially highly resilient because of human resources (numbers and skill level) and access to finance to implement adaptations. Such utilities have the potential to develop new sources of water, improve treatment processes and replace broken or worn pipes and fittings. This depends on their ability to raise finance–whether through tariffs, government support, donors or from private capital markets.

Small town and particularly community-managed piped water supplies have much lower potential resilience because of limited human resources and restricted ability to raise capital to fund adaptations and improve operation. For small towns the capital available for upgrading and rehabilitation is limited, and money raised through tariffs is unlikely to be sufficient to fund large-scale investment.

Small towns also typically lack a large, well-trained and skilled workforce, and thus some of the key mechanisms to improve resilience, which demand rapid and skilled operational responses and proactive maintenance, may in fact not be currently feasible.

For community-managed supplies finance raised typically fails to cover the costs of operation and maintenance and there is virtually none available for upgrading or capital works. Furthermore, community-managed supplies typically rely on unpaid volunteers often with limited training. This is not a problem confined to the developing world, although it is more acutely felt there, but it is also found in many small water supplies in developed countries. For these reasons, such supplies have been the focus of outbreaks of disease.

The resilience of sanitation is not as management-driven as drinking-water. In urban areas, sewerage utilities should logically benefit from similar advantages to utility-run drinking water supply. However, in practice unit costs are often higher; financing has been more difficult and management is less effective in counter-acting the low resilience of the technology. Simple technologies, such as pit latrines, are largely built and maintained by households and even very poor households rapidly adapt designs. Thus the resilience of the technology can overcome apparent weaknesses in management.

Climate predictions

The climate predictions are best estimates of mean values of broad distributions at each location. The forecasts for 2020 show large-scale, spatially coherent changes that continue to 2030. Following conventions used by the IPCC, best estimate predictions, based on ensemble-mean values, were evaluated only at points where at least 66% of ensemble members agreed on the sign of the change. The changes predicted for 2030 (Figure 1) are generally consistent with trends identified by the IPCC for 2050 and beyond. As a guide to uncertainty and levels of variability, predictions from DePreSys indicate that in most parts of the world there is at least a 10% chance that, for any year around 2030, the change in annual mean precipitation may be of opposite sign to that of the predicted best estimate. The clearest signals are: decreases in annual mean precipitation in southern Africa, the Mediterranean basin and north-eastern South America; and increases over south Asia, parts of central Africa and the high latitudes of both the northern and southern hemispheres.

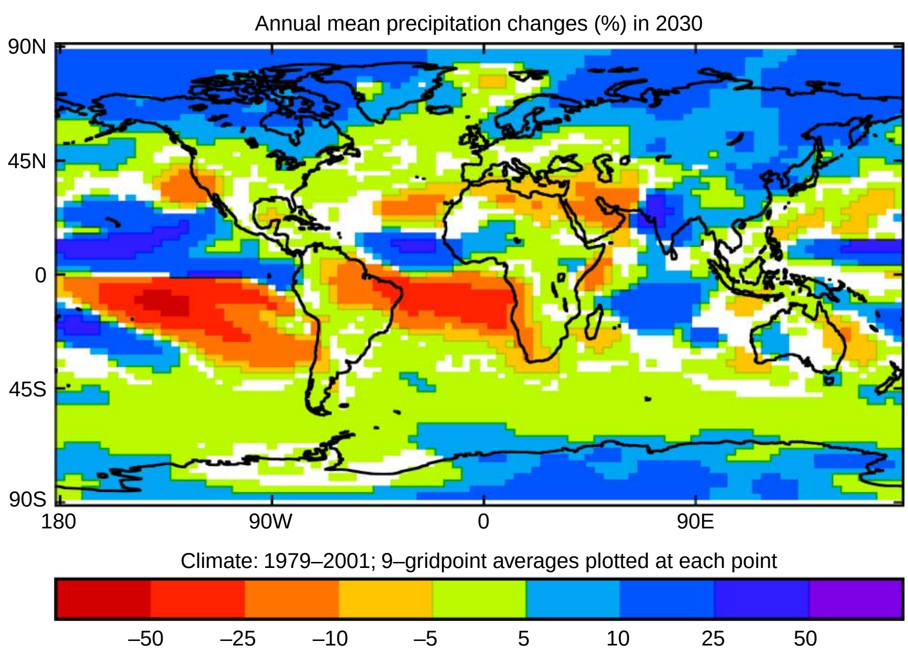

Figure 1 | Changes in precipitation (as percentage of present-day climatology) predicted for the 2030s.

Estimates of changes in the intensity of very wet 5-day large-scale events were also generated. Results indicate that uncertainty, even in the sign of the predicted change, is high in most places. Areas of relatively high risk include parts of southern and eastern Asia and parts of the northern temperate latitudes. Areas of relatively low risk include northern and south-western Africa, north-eastern South America, eastern Australia and parts of the eastern Mediterranean. The decadal forecasting in this work does not extend to specific forecasts of flood risk. However, regions where seasonal mean rainfall is predicted to increase (especially during the peak rainfall season) or regions with an increasing intensity of 5-day wet events are likely to experience increased risks of flooding. This suggests that south Asia and parts of east Asia may experience higher rates of flooding than currently experienced. Taking the regional climate changes identified above, an indicative list of appropriate technologies by region can be identified. These are shown in Table 3.

Coverage

Water supply and sanitation coverage is projected to significantly increase by 2020 with most regions having over 75% access, but developing regions continue to have lower coverage than developed regions (see Table 4). Technologies used vary and of concern is the high level of household water connections and sewers in regions likely to experience drying, notably the eastern Mediterranean, north-eastern south America and parts of north and southern Africa.

In South Asia, widespread use of tubewells and low-flush pit latrines is projected, suggesting services should be resilient at least in rural areas, although urban piped supplies will remain under threat. Water supplies in central and east Africa are vulnerable as there is a greater use of dug wells, but sanitation is resilient given widespread use of pit latrines. East Asia is dominated by piped water supply and thus resilience will depend on management, but there is widespread use of waterborne sanitation and so lower sanitation resilience. Piped supplies in both south Asia and the parts of Africa at risk from flooding are likely to have low actual resilience, but are potentially adaptable to climate change.

DISCUSSION

There is an urgent need for critical reflection on planning and management of drinking-water supply and sanitation because of the long time horizon of investment in infrastructure with limited adaptive capacity. The implications are of concern to sustaining achievements made towards Millennium Development Goal 7 Target 3. There are also reasons for concern in developed nations where high levels of access depend on technologies with limited climate change resilience.

Comparison of technology resilience and projected technology coverage indicates that a significant fraction of global water and sanitation infrastructure is not sustainable in the face of climate change. The difference between potential and actual resilience for most real systems indicates a need to review the resilience of systems and facilities on a case-by-case basis and institute measures to increase resilience.

An effective response to increase climate change resilience in the drinking water and sanitation sector—whether at local, national or international level—will include: promoting resilient technologies, adapting or updating technical norms and regulations and enhancing management of services. Where reliable safe water and sanitation are not universal it will also imply reviewing policy and management on progressive upgrading of services and reflection on policy targets and their monitoring. Many of these changes are no-regret solutions and have been consistently advocated within the water sector for many years.

It is essential that in future technology choice is based on a sound understanding of resilience to climate change, in addition to social or cost grounds. Priority should be given to technologies that are climate resilient. Less resilient technologies should only be used where local conditions either dictate that more resilient technologies cannot be deployed or local assessment demonstrates sufficient resilience to current climate or expected climate changes. The indicative technologies identified in Table 3 as suitable by region provides some initial thinking on this but is primarily designed to promote discussion within the sector, and to encourage more detailed local and regional assessments.

Table 3 | Indicative list of technologies suitable by region

Region	Category 1	Category 2	Category 3
South-western Africa–getting drier	All	Protected springs, community-managed piped, small-bore and shallow sewers appropriate Conventional sewers and septic tanks will be less appropriate as rainfall declines	Dug well use will require local information on shallow groundwater response to declining rainfall Household roof-catchment harvesting only appropriate as a supplementary source
Central and East Africa–likely to have more flooding	All	All appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug well not appropriate
Rest of sub-Saharan Africa–limited change	All	All appropriate	Appropriate provided local conditions permit
Northern Africa–getting drier	All	Protected springs, community-managed piped and unconventional sewers appropriate Conventional sewers and high volume septic systems not appropriate	Dug wells where local conditions permit Rainwater not appropriate
South Asia–likely to experience more flooding	All	All appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug wells not appropriate because of microbial contamination threat
SE Asia–likely to experience more flooding	All	All appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug wells not appropriate because of microbial contamination threat
Central Asia	All	All appropriate	Both appropriate
East Asia–likely to experience more flooding	All	All appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug wells not appropriate because of microbial contamination threat
Central America	All	All appropriate, but additional safeguards against flooding required	Rainwater appropriate, dug wells not appropriate
NE South America	All	Protected springs, community-managed piped and unconventional sewers appropriate Conventional sewers and septic tanks not appropriate	May be appropriate, but will face long-term drying trends
Rest of South America	All	All appropriate	Both appropriate
Eastern Mediterranean and West Asia	All	Water supplies and unconventional sewers appropriate Conventional sewers and septic tanks not appropriate	Dug wells appropriate, rainwater not appropriate
Pacific Islands	All	Appropriate depending on local conditions, but sewerage and septic tanks unlikely to be appropriate	Both feasible depending on local conditions

Table 4 | Forecast water supply and sanitation coverage (%) by 2020

	Water supply						Sanitation			
Region	Piped home	Public taps	Wells	Prot. springs	Rain-water	Total	Sewerage	Septic system	Pit latrines	Total
Western Asia	79	3	10	1	0	93	54	33	4	91
Sub-Saharan Africa	18	16	28	5	2	70	8	10	36	54
South-East Asia	42	6	34	4	8	94	5	56	20	81
South Asia	23	20	53	0	0	96	7	36	11	54
Oceania	18	0	4	11	8	41	5	5	36	47
Northern Africa	86	3	4	0	0	93	71	5	17	93
Latin America & Caribbean	89	2	5	1	1	98	62	22	7	91
Eurasia	66	7	19	1	0	92	47	8	40	95
Eastern Asia	83	0	17	0	0	100	35	31	23	88
Total developing regions	50	10	30	2	1	93	24	29	19	72
Developed	95	1	2	1	0	100	78	18	2	98
Total	51	10	29	2	1	93	28	28	18	74

For drinking-water, the role of management in determining resilience allows inherently vulnerable piped supplies to be resilient provided appropriate management systems are implemented. However transforming potential resilience into actual resilience at the utility level remains a major challenge in most developing countries. Achieving more resilient utilities will require action to ensure adequate cost-recovery in water and sanitation services and to ensure greater equity in access to services. Rural supplies worldwide are community managed and weaknesses in their management result in poor sustainability and vulnerability to climate related impacts as well as disease outbreaks (Carter *et al.* 1993; Harvey & Reed 2006; Kabir & Howard 2007). Climate change will aggravate this further.

Management versus technology as determinants of resilience influence the potential for decentralisation to increase resilience, which is a fundamental policy issue. For drinking water, decentralisation of infrastructure is important to reduce flood and drought risks and reducing 'critical' points reduces vulnerability. In contrast, centralisation of management (or management support) contributes substantively to resilience. In general terms much greater emphasis needs to be given to supporting management systems becoming more adaptive in light of climate change.

Whilst some of this will come through the wider application of systems such as water safety plans that can effectively assess and manage risk (Bartram *et al.* 2009), there is a need to develop and test tools that are better able to provide guidance to dealing with uncertainty. Of greatest importance is to support water and sanitation programme managers in developing more flexible approaches to responding to climate risks and in using scenario-based planning.

'Surveillance' systems have been shown to be effective in supporting decentralised and centralised infrastructure (Lloyd & Bartram 1991; Howard & Bartram 2005), but remain poorly developed worldwide. Prioritising the development of surveillance programmes is likely to be critical to promoting more effective and resilient water supplies, but will require the development of new tools to support climate adaptation. This would facilitate local level assessments that ultimately will be required to help build resilience and identify adaptations.

Although the potential resilience of utilities is high, in practice many have low resilience because of poor management, corruption, and poor staff training and retention. As a consequence, they cannot raise finance and do not have the right numbers and type of staff. Evans *et al.* (2009) notes that in some regions utilities are poorly prepared for climate change. Nonetheless, with reform, experience suggests that larger utilities are able to attract financing and undertake significant improvements in supply, indicating an adaptive capacity.

Securing source water that is capable of continuing to supply the demands placed on piped systems may be under threat in countries and regions likely to experience a reduction in rainfall and in areas where rainfall may increase or stay the same, but become increasingly intensified through shorter, heavier rain events. This is particularly the case given the current high rates of water losses in most piped systems in developing countries. Ensuring adequate storage of water, whether through reservoirs or natural and enhanced storage (for instance through artificial groundwater recharge) will be a critical adaptation measure. The current lack of water storage potential developed in Africa and parts of Asia suggests that this will significantly reduce the resilience of piped water supplies.

A specific issue of concern is water supply and sanitation in coastal areas where a quarter of the world's population lives, many of which are already water stressed and experiencing rapid population growth. Increasing sea levels predicted to occur as a result of climate change will increase the threat of saline intrusion and are of particular concern for low-lying small island states, such as the Maldives, and coastal areas of low-lying countries such as Bangladesh. The combination of over-abstraction from shallow aquifers and rising sea level has been identified as a key climate change threat in Bangladesh (Shamsudduha *et al.* 2009). In some areas, landward migration of the brackish or saline water front up surface waters could be very significant, at least seasonally. Models for Bangladesh suggested that up to two thirds of the country could experience increased salinity in rivers as a result of rising sea level combined with poor upstream management of the freshwaters in the Ganges–Brahmaputra–Meghna basin.

For technologies such as tubewells, simple adaptations further enhance resilience. For instance wellheads can be raised to reduce risks from flooding (Luby *et al.* 2008) or by extracting water from deeper aquifers and casing off shallower contaminated aquifers (MacDonald *et al.* 1999). There are existing threats from natural contaminants such as arsenic and fluoride in some countries, which may limit the potential to use tubewells. In environments that are getting drier, there may be threats to tubewells if water tables start to decline. This will be exacerbated where there is over-abstraction from other sectors, particularly agriculture. It may be possible to sink deeper tubewells, which may mean shifting from handpumps to motorized pumping for domestic supply, but a more effective response is likely to be action to reduce abstraction from other sectors. Declining water tables may also lead to water quality problems, as deeper aquifers with more chemical contamination are exploited. This may require additional treatment being applied, for instance aeration to remove iron or manganese.

For dug wells available adaptations to some possible climate changes, such as collector wells (MacDonald & Davies 2000) have not been widely used. Dug wells are vulnerable to microbial contamination (Godfrey *et al.* 2006; Howard *et al.* 2007) and despite recommendations for routine chlorination of such supplies (Hira-Smith *et al.* 2007) there has been limited success in reducing water quality threats (Gelinas *et al.* 1996; Godfrey *et al.* 2006; Mahmud *et al.* 2007). There are very limited adaptations possible to protected springs and these are particularly vulnerable to microbial contamination, which be expected to be exacerbated in environments getting wetter or where more intense rainfall occurs (Howard *et al.* 2003; Taylor *et al.* 2009).

There are also limited adaptations available for rainwater harvesting at a household level. Larger-scale rainwater collection from ground catchments may be an effective response, and in dry countries such as Yemen is a current adaptation to an arid climate. The degree to which such approaches remain viable for the future will depend on the degree to which the climate becomes drier, as well as changes in the timing and intensity of rainfall. Household rainfall collection may become increasingly viable in regions receiving more rainfall. But if the rainfall increase is essentially an intensification of monsoonal rain, then the limits on storage may result in no improvement in year-round supply and thus the technology may not be climate-resilient. Roof catchment rainwater harvesting as the principal source of water is likely to become less viable in parts of the globe expected to get drier, as insufficient water can be captured.

In coming decades significant investments will be made in increasing service level for populations already benefiting from basic access. For drinking-water 50% of the world's population has a tap at their home (WHO & UNICEF 2008) and this study predicts a modest increase by 2020. In-house water supply provides much greater health benefits than a community source (Howard & Bartram 2003) and also supports poverty reduction (Fass 1993). Achieving higher levels of service which are also resilient to climate change implies new approaches, for example for rural areas of sub-Saharan Africa. There needs to be evidence as to whether households would use the same amount of water as from a household tap and thus accrue similar benefits. To support the significant policy and operational shifts needed to build resilience, increase service quality and extend access, much better hydrological and hydrogeological information is required in southern countries.

The resilience of sanitation is determined more by technology than management. Worldwide, most sanitation takes the form of a latrine, directly managed by the household. Simple sanitation technologies appear to be highly resilient, in part because they can be readily adapted to increase resilience. Flooding can be a particular risk for pit latrines, leading to widespread contamination (Cairncross & Alvarinho 2006), although simple adaptations including construction of temporary facilities in very highly vulnerable areas are effective. These include using raised latrines or constructing smaller pits that require more frequent emptying (Franceys *et al.* 1992; Ahmed & Rahman 2007).

In areas that are highly vulnerable, it may be more appropriate to build low-cost temporary sanitation facilities that can be easily moved and re-built, rather than building permanent structures. In environments likely to get wetter, increasing rainfall may lead to rising groundwater levels, flooding of pits and contamination of shallow groundwater. Changes in design, for example to vault latrines (Franceys *et al.* 1992) and the implementation of simple risk-based approaches to defining separation distances and the selection of appropriate groundwater technology may all reduce these risks leading to greater resilience (ARGOSS 2001; Chave *et al.* 2006). Septic tanks are more vulnerable because they typically are connected to high volume flush water. They are also at risk from flood events and flotation when groundwater levels rise (Cairnscross & Alvarinho 2006; Reed 2008).

Where conventional sewers are used or planned, of particular importance is separating stormwater from sewage flows, particularly in tropical climates where monsoonal storm flows frequently overwhelm poorly managed sewer systems. Sewage treatment remains often poorly managed and is not resilient, suggesting that improving treatment technology is important. In urban areas, there is a critical technology gap concerning acceptable alternatives to conventional sewerage for sanitation in dense urban settlements that provide the same level of service, with lower requirements for water and inflexible infrastructure.

Responding to climate change implies possible changes in sanitation technology application that may itself have implications for greenhouse gas emissions. There is therefore a need to quantify greenhouse gas emissions from sanitation systems, particularly on-site systems for which very little data currently exist (Bogner *et al.* 2007; Bates *et al.* 2008) despite some evidence that these would provide lower emissions (Freidrichs *et al.* 2009).

For all technologies and management approaches, it is important to document adaptations that prove successful and in particular to capture autonomous adaptations by communities that will provide insights beyond those of professionals. This will be of particular relevance to sanitation systems that are largely household-provided and managed.

It is predicted that the MDG target for drinking-water supply will be met while that for sanitation will be badly missed (WHO & UNICEF 2008). This monitoring does not account for climate change resilience. If this were to be done, the current figures for coverage would be revised downward and the world would be badly off-track for both the drinking-water and sanitation components of MDG 7. There is a strong rationale that post-2015 global policy, targets should focus on access to an at-house level of drinking-water service and should account for sustainability (Bartram 2008). This suggests to that post-2015 targets and monitoring need to take a more graduated approach and move away from universal categorisations of technology adequacy, towards identifying regionally acceptable technologies.

The forecasts of climate change undertaken in this project show limited changes in precipitation are forecast for significant parts of the developing world by 2030. While this may imply limited impact on currently used technologies, it also suggests a need for more detailed climate assessments at a regional or country scale. Whilst all climate forecasts and predictions have a degree of uncertainty, this study has highlighted key hotspots where there is a high degree of confidence in the predictions for climate change and where action is warranted. The forecasts for south Asia suggest that flooding may become more likely. This will represent a significant challenge for most water supplies, but in particular for the use of dug wells, which are reasonably widely used in arsenic affected areas. It will require either a switch to tubewells exploiting deeper aquifers or improvements in dug well design. In east Africa and the parts of central Africa where increased flooding may also occur, there is likely to be continued reliance on point source water supplies. In these regions, a shift away from dug wells to boreholes with handpumps is likely to be advisable unless research can show effective ways to improve the protection and rehabilitation of dug wells.

In Central America and north-eastern South America there are indications of an overall drying of the climate, and these regions may face significant problems with drought. This combined with predicted increasing piped water coverage, which is already over 75%, suggests that the region will be faced with significant future problems. A more detailed regional assessment of likely changes in climate would be valuable to inform this thinking. The eastern Mediterranean is also predicted to get drier and may face increasing water scarcity problems, although there remain sufficient reserves of fossil water to supply water for some decades. However, a challenge may well be to preserve those waters for domestic use in the face of competing demands. In these areas, desalination is already more common than in most other regions and this is likely to continue. However, as energy requirements are typically high, developing new sources of energy (for instance solar-powered desalination plants) is likely to be a priority.

CONCLUSION

Climate change represents a significant future threat to sustainable drinking-water and sanitation services, which are essential in protecting public health. Large numbers of people today lack access to these basic services and without action to improve policy, planning and delivery, reversals in coverage could be expected by 2030. For both drinking-water supply and sanitation, few technologies are resilient to most climate change scenarios. These should be prioritised in future investments. Those technologies with a medium resilience can clearly be deployed in locations with climates and expected changes to which they are resilient. Technologies with only low resilience should be considered as supplementary technologies, or as interim measures within progressive upgrading. Further research would also be warranted on improving technology resilience, especially for medium-resilience technologies in order to increase their applicability. In many cases adaptations available such as reducing losses and preventing contamination are ‘no regrets’ responses–they are desirable regardless of climate change. Building more resilience services will take determined action to ensure that service providers are better equipped to deal with uncertainty as well as more quantifiable risks. Building resilience to climate change offers opportunities, for example by creating a stimulus to aim for higher levels of service for the unserved without passing through the intermediate step of communal levels of services. Concerns about adapting to climate change also create stronger pressure to rationalize the promotion of technologies to prioritise sustainability in service delivery. Thus climate change may in fact be a driver for improvements that have been insufficiently delivered to date.

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