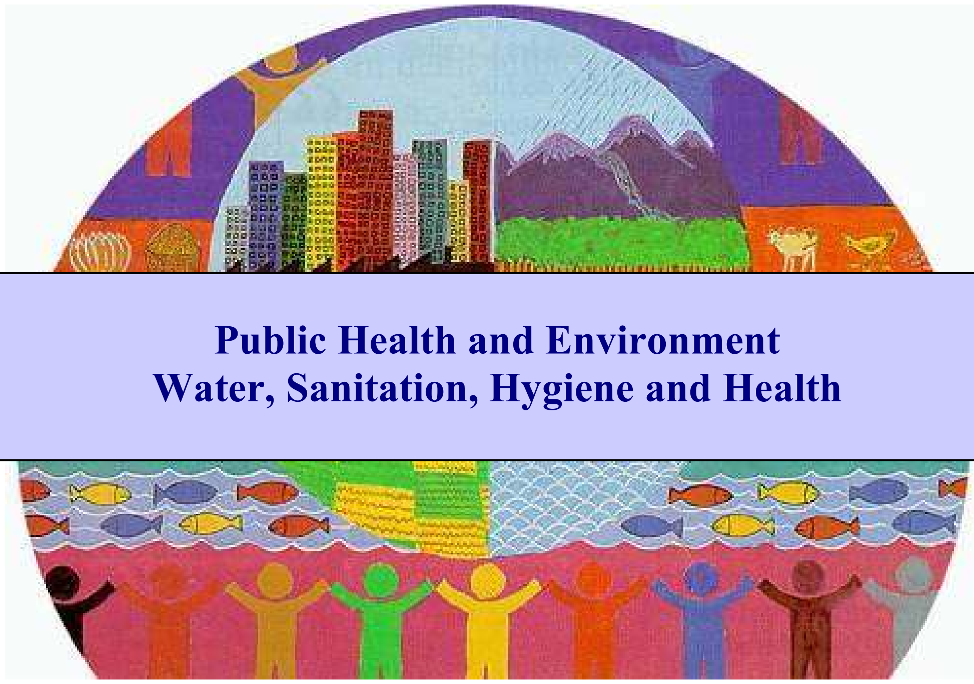
Vision 2030

The resilience of water supply and sanitation in the face of climate change

Technical report

Guy Howard
Jamie Bartram



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Executive summary

This report presents the findings of research into the projected impact of climate change on water and sanitation services by 2020 and by 2030. These time horizons are relevant to investment decision-making and have been used in other water-using sectors. Results for the year 2020 indicate the potential for climate change to undermine investments already made and committed towards achieving the MDG targets and towards improving access to safe-drinking water and sanitation beyond 2015; and estimates for 2030 provide for responses in technology selection and planning to expected climate changes.

This study represents the first attempt to address this issue at a global level. This report is particularly focused on low- and middle-income countries, but has global relevance. It provides an analysis of the resilience of water supply and sanitation technologies, and of management approaches. It also reviews the policy implications of the findings, identifies hotspots where attention is particularly needed and points to research needs. It draws on background studies into the resilience of water and sanitation technologies, decadal climate forecasts for 2020 and 2030, and projections of water and sanitation coverage by 2020. It is important for policy-makers and practitioners to understand the likely impact of short-term climate change on water and sanitation services.

The climate is changing, and this will be felt in different ways in different regions. Although the precise nature and extent of change are not yet certain, planners and policy-makers responsible for the water and sanitation sector need to start acting now to build for resilience and support adaptation to climate change in the sector. Waiting for certainty is not an option. By making water supplies and sanitation more resilient and adaptable to climate change there is the potential to improve how the sector performs. Therefore climate change is an opportunity as much as a threat. Because of inherent uncertainties in predictions of climate change, planning needs to allow for flexibility in responses.

The main technologies used for water supply and sanitation were assessed to determine resilience. They were categorized as to whether resilience was high (resilient to most possible climate changes), medium (resilient to a significant number of possible climate changes) or low (resilient to a restricted number of climate changes).

For the water supply technologies, tubewells were found to have high resilience, with protected springs having a medium resilience. Piped water, household rainwater collection and dug wells were considered to have low resilience as technologies. Management approaches were found to be critical to resilience for water supplies. Utility-run piped systems were found to have high resilience, thus management is able to overcome the low resilience of the technology. By contrast, small community-managed systems had low resilience. Dug wells and household rainwater collection should be considered primarily as interim or supplementary water supplies.

For sanitation, pit latrines were found to have high resilience, septic tanks and different forms of sewerage medium resilience, and no technology was found to have low resilience. In contrast to water supply, the management approach had a much more limited impact on resilience, which was primarily driven by the technology. Thus, household-provided sanitation systems using resilient technologies is likely to be more resilient than more complex sewerage systems despite the more comprehensive management available for the latter.

Current estimates of global coverage with water supply and sanitation do not take climate resilience into account. If they did, it would be clear that the world is badly off-track to meet both the water supply and sanitation targets. A reduction in coverage can be expected unless action is taken, because communities will find that their water and sanitation services are not resilient to climate changes in the short and medium term. While there are uncertainties in climate prediction, the signals are clear enough in critical regions. Enough is already known about the resilience of technologies to act now.

There is a strong rationale for monitoring, and targets set for years after 2015 should be more graduated, with greater emphasis on technologies and approaches considered appropriate at a regional level, rather than applying universal categorizations of technology adequacy.

Significant changes in policy and programming for water supply and sanitation provision are required. Decentralization of water supply infrastructure will be important to hedge drought and flood risks, but should be placed within a context of greater centralization of management, or at least much stronger ongoing central support. International targets after 2015 should also focus on increasing access for low-income groups to an at-house water supply. It is unlikely that this can be achieved solely through piped water supplies, so the potential of achieving this through providing household tubewells warrants further investigation. For sanitation, decentralization of technology and management appears likely to be more resilient, although some central supporting functions will be needed.

The decadal climate forecasts for 2020 show large-scale, spatially coherent changes, which continue to 2030. The changes predicted for 2030 are generally consistent with the trends identified by the Intergovernmental Panel on Climate Change (IPCC) for 2050 and beyond. Regions identified as hotspots of concern with regard to the implications of climate change for water and sanitation are southern Africa, the Mediterranean basin and north-eastern South America, which are all likely to get drier, and south and east Asia, which are likely to have increased risks of flooding. Although large parts of the world are unlikely to see major changes in precipitation by 2030, there is still a need to carry out local climate risk assessments in these areas to ensure that appropriate technologies are identified and used.

It is expected that coverage with water supply and sanitation will significantly increase by 2020, with most regions having over 75% coverage with water supply, but lower rates of sanitation coverage. Water supply coverage is likely to be dominated by piped supplies and tubewells. Pit latrines tend to dominate the sanitation increase. Of particular concern are those areas which are drying and also projected to have high rates of coverage with piped water and sewerage systems. Improvements in management will be urgently required in these regions.

Research is required to improve those technologies currently considered to have only medium resilience, to increase their potential for application. Research is also required into non-piped alternatives to deliver at-house water supplies, and to assess whether water usage would be at the same level as for piped supplies. The development and use of climate risk assessment tools for the sector is a priority. There is an urgent need to improve the knowledge and monitoring of water resources if future demands are to be met within a changing climate. This is particularly important for groundwater, where knowledge is most lacking. Further development of climate models is needed to improve capabilities for decadal prediction on regional scales.

Organizations involved in the delivery of water supply and sanitation services need to develop and pilot approaches to adapting to climate change, and to document those that effectively build resilience. This includes documenting autonomous community-level adaptations that occur and prove successful.

1. Introduction

This report presents the findings of an assessment of the resilience to climate change, by 2030, of water and sanitation technologies and management approaches. It is focused on drinking-water supply and sanitation. While wider water management issues in the light of climate change are of critical importance, these are the focus of other substantial pieces of work (for example, Arnell, 2004; Bates et al., 2008; Sadoff & Muller, 2009). To date, there has been relatively little focus specifically on the impact of climate change on services.

This report has global relevance but is focused on low- and middle-income countries, as these are those most at risk both from climate change and where progress on providing water and sanitation services is most limited. This combination of factors represents both a risk and an opportunity to develop climate resilient services. A number of key terms are used within the report and these are defined in Box 1.

Box 1: Definition of key terms used in this report

A number of terms used in this report have precise technical meanings. The following six key terms are used with the definitions employed by the Intergovernmental Panel on Climate Change (IPCC) Working Group II.

Adaptation: adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation.

Adaptive capacity: the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Ensemble: a group of parallel model simulations used for climate projections. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions only characterize the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model difference.

Mitigation: an anthropogenic intervention to reduce the anthropogenic forcing of the climate system. It includes strategies to reduce greenhouse gas sources and emissions, and enhancing greenhouse gas sinks.

Resilience: the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change.

Vulnerability: the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Source: IPCC (2007)

Water and sanitation provision in the future, in common with investments in other aspects of water management, must be resilient to climate change. Failure to ensure that services are resilient will have significant public health consequences as water quality deteriorates, water quantity becomes less certain and sanitation systems cause environmental contamination. Without taking climate change into account, the limited progress made towards increasing access to drinking-water supplies and sanitation is likely to suffer reversals in the near future.

Decisions on management approaches and technologies for water and sanitation services need to be tested against their vulnerability and adaptive capability to climate changes to determine their resilience. Water supplies and sanitation systems are vulnerable to present-day climate variability. Extended dry periods may cause water sources to dry up or become intermittent and reduce the performance of sewers. Heavy rainfall events may cause damage to infrastructure, flooding and contamination of water supplies, with consequent public health risks. Such variability in precipitation is likely to increase with climate change (Arnell, 2004; Bates et al., 2008; IPCC, 2007) and will pose new challenges to water and sanitation technologies and management approaches.

Climate change will also have impacts on natural water stores, such as mountain glaciers and groundwater. Some of these impacts will have serious consequences for water supplies, for instance in parts of the Andes where cities and towns are reliant on glaciers for their water supply. In the Himalayas, research into glacier recession makes it increasingly clear that there will be problems for high mountain communities, but the impact is likely to be lower on large rivers, particularly in their downstream stretches where rainfall is more important in driving the hydrological system (Rees & Collins, 2004). There is significant variation in the response of glaciers to climate change, for instance there is some evidence that glaciers in the eastern part of the Himalayan mountain chain may be accreting rather than receding (Fowler & Archer, 2005). Climate change impacts on groundwater are poorly understood and relatively little is known about available groundwater resources in many regions. This hinders the development of sustainable and resilient water supplies.

Technologies and management approaches capable of adapting to the full range of climate scenarios need to be identified and their use prioritized in future investments. Those only able to adapt to a limited range of climate change scenarios should become lower priorities. Deployment of more resilient technologies will need to be supported by stronger and more effective governance to ensure that climate change concerns do not result in continued or increased inequity in access to services.

There is significant uncertainty in most climate predictions. For more distant time periods, the climate (and so prediction) depends to a large extent on what actions are taken to stabilize the global temperature. Many of the predictions made for climate changes work on time horizons that are relevant for the construction of large infrastructure, such as major urban water supply and sanitation systems, but the uncertainty attached increases the complexity of future planning. This will make more adaptive and flexible management essential in securing services that are climate resilient in the long term. For many water and sanitation systems, and particularly those commonly used in rural areas and by lower-income communities, the lifespan of technology is shorter, potentially increasing the flexibility in response. However, as many of these technologies are vulnerable to existing climate threats, there is an urgent need to understand shorter-term climate changes that may compromise sustainability. Climate predictions on decadal timeframes are therefore potentially highly useful in meeting the demands of policy-makers, planners and operators to support better planned services.

The major climate-related threats that affect water and sanitation technologies can be grouped under three broad scenarios:

(a) Increasing likelihood of *flooding or increased run-off* that overwhelms currently used sanitary protection measures, leading to damage or destruction of infrastructure and gross contamination. Increased flooding is likely to derive from more intense rainfall events, from increased average rainfall, or a combination of both.

(b) Decreasing rainfall resulting in *declining surface and renewable groundwater availability*, leading to increased challenges to meet demands for water for domestic use or for supporting water-borne sanitation. Decreasing rainfall will also reduce the capacity of surface water to dilute, attenuate and remove pollution.

(c) Increasing rainfall leading to long-term *increases in groundwater levels*, reducing the potential for pathogen and chemical attenuation or removal, and causing flooding of sub-surface infrastructure and potentially rapid shallow groundwater flow.

Climate change itself will not change the basic nature of these threats to water and sanitation services, but it will change their severity and frequency, and potentially the geographical range of some threats. It will increase the need and demand for new ways of planning water and sanitation programmes, of predicting threats and of developing or refining technologies.

1.1 The wider context of water management

There is a significant literature available on the wider relationships between water and climate, and much of this has been synthesized in the IPCC technical paper on water (Bates et al., 2008). Climate change will have wide-ranging impacts on water, and indeed many of the impacts of climate change will be felt through changes in water availability, floods and droughts (Stern, 2006; IPCC, 2007). Good water resources management will therefore be critical in building resilience in countries and communities, and in supporting adaptation to unavoidable changes (Sadoff & Muller, 2009).

The drinking-water sector accounts for only 15% of overall water use globally, and often less in low-income countries (Gleick, 2008). The vast majority of water use – 70% and considerably more in some countries – is for agriculture. The increasing temperature that is driving climate change will increase evapo-transpiration, and therefore the agricultural water demand in many regions. Water for drinking and other domestic purposes also must compete with other sectors – industry, power, recreation and the environment – which either consume more water or place restrictions on availability of water at particular times of the year.

Given the multiple demands for water across many sectors, water needs to be managed in an integrated manner with transparent approaches for its allocation and necessary trade-offs between different uses. Systems to share the benefits that come from water – food, energy, ecosystem services – are crucial to maximize the overall contribution of water. This is even more important where waters are shared by two or more countries. Water also needs to be used efficiently to ensure that sufficient water is available to meet priority demands. Within the paradigm of integrated water resources management, it is critical that drinking-water supplies are protected to ensure the quality of water and to ensure sufficient quantities of water. Integrated management also needs to take into account the capacity of the water environment to absorb wastes from sanitation systems – whether discharged below ground or into surface waters.

Climate change will increase the urgency for better uptake and implementation of integrated water resources management, to improve water efficiency, build resilience and support adaptation (Sadoff & Muller, 2009). Drinking-water and sanitation require adequate volumes of water to be allocated to each and every community, in order to satisfy their domestic water needs. The water and sanitation sector differs in this way from water-using sectors such agriculture and energy, where flows of water required to produce food and power in any one location to some extent can be substituted by imports of goods and services from other regions or countries.

1.2 Impact of climate change on water quality

Changes in water quality caused by increasing temperatures and changing flows will be a key impact of climate change. Increased flooding is commonly associated with: deterioration of water quality, with increased pathogen loads from flooding of, or damage to, sanitation systems; increased suspended solids concentration leading to increasing challenges for water treatment; and chemical pollution from agriculture, industry and transport. Flooding typically affects the effectiveness of sanitation systems and may lead to widespread contamination of water sources.

Decreasing rainfall, particularly when combined with increasing temperatures, is likely to result in increasing risks of blooms of cyanobacteria (blue-green algae) 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 may lead to mobilization of natural chemicals, such as arsenic and fluoride, although there is a lack of evidence on which to base firm conclusions. In some circumstances, increasing rainfall may also lead to increased loads of suspended solids.

Saline intrusion into aquifers and surface waters represents another significant threat to water and sanitation technologies. A quarter of the world’s population lives in coastal areas, many of which are already water stressed and experiencing rapid population growth. Rising 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 suggest 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.

Where saline intrusion is expected to be a problem, a number of alternative technologies could be considered. In some countries, such as Bangladesh, deeper confined aquifers exist that offer a safe source of water, but in other countries rainwater harvesting (where climate changes suggest this will deliver sufficient water), desalination or blending with low salinity waters may all need to be considered. Even where alternative sources of water are available, experience shows that use for drinking-water must be prioritized and strictly regulated to avoid over-use by other sectors.

1.3 Other factors that will affect water supplies

The problems caused by climate change must be set within a wider context of other factors that will affect water demand and quality. Population growth will cause massive increases in demand that will have major implications in Africa and Asia, particularly because of the economic water scarcity caused by the limited infrastructure in place to deliver water services (IWMI, 2007). Population growth is also expected to have negative impacts on water quality as increasing rates of pollution occur, particularly in areas with low sanitation coverage.

Economic growth will increase water demands for all uses and for higher levels of service for water supply and water-using devices, as well as fuelling demand for more convenient and, potentially, water-based sanitation. Urbanization will place greater stress on water resources to secure adequate supplies of water within an economically viable distance of settlements, and by increasing demands resulting from higher levels of service through piped water. It is also likely to result in increased pollution.

Climate change will interact with these factors and in many cases magnify their impact but in other cases may counteract negative impacts. To provide resilient water and sanitation services, technologies and planning are needed that are capable of building adaptive capacity to cope with multiple threats, and not only those of climate change.

1.4 Water and sanitation as a source of greenhouse gas emissions

Although much of the focus on water and sanitation services is on adaptation to climate change, they can also make a contribution to mitigation. Technologies that employ significant pumping are likely to emit greenhouse gases. Thus reducing energy consumption and switching to low-carbon power is important and there may be opportunities to modify technology design to reduce energy requirements. For instance, although conventional sewers operate on gravity, virtually all require some periodic uplift pumping to ensure that sewers do not lie below the level of treatment works. Switching to technologies that have a lower requirement for pumping, for instance modified sewerage, can make a positive contribution to reduction in greenhouse gas emissions.

A study in South Africa concluded that use of on-site sanitation systems where possible was likely to produce less greenhouse gas than sewerage and wastewater treatment, mainly because of lower energy requirements (Freidrich, Pillay & Buckley, 2009). This study also found that options that recycled water to meet increasing demand had a lower carbon footprint when using a life-cycle assessment approach than the base condition or construction of new infrastructure.

Human waste, like other forms of organic material, is a potential source of greenhouse gas emissions, although waste (solid and wastewater combined) accounts for less than 5% of global emissions (Bogner et al., 2007). The IPCC Working Group III estimated wastewater to contribute 590 $MtCO_2$ equivalent of methane and a further 100 $MtCO_2$ equivalent of nitrogen dioxide based on assessments of conventional sewerage and sewage treatment. Where wastewater treatment is used, Cakir & Stenstrom (2005) concluded 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 IPCC noted that the greenhouse gas emissions from septic tanks, latrines and open-air defecation remain largely unquantified and a global systematic assessment is needed (Bogner et al., 2007; Bates et al 2008).

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 solely related to human waste and how much from 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 coverage with sanitation, these levels of emissions may decrease (El-Fadel & Massoud, 2001; Prendez & Lara-Gonzalez, 2008). 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.

2. Methods

This project assessed technology resilience in the face of likely climate change focused around two key short to medium points in time: 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 was selected to represent the minimum expected lifespan of technologies that have been installed to date, including ongoing efforts to meet the MDG drinking-water and sanitation target in 2015. It provides an indication of the potential for climate change to undermine short-term sustainability and reflects current and historical programming, policy decisions and current climatic variability. The principal consequences of changes by 2020 relate to management of infrastructure already, or soon to be, in operation.

The year 2030 represents a period of time in which significant policy changes can be expected to have influenced technology selection and progress within the water supply and sanitation sector. This includes investment decisions and technology choices that have yet to occur and are therefore open to optimization. Decisions made to improve access to water and sanitation by 2030 need to be based on several factors. Access to higher service levels (such as a drinking-water source at home) is likely to be increased, and is desirable from a health perspective (Howard & Bartram, 2003). Policy choices for 2030 also provide opportunities to plan for likely climate changes expected later in the 21st century.

2.1 Data collection

The research project comprised three main areas of activity. Detailed descriptions of the methods employed in each study are provided in the corresponding reports on the enclosed CD-Rom and are only summarized here.

First, the vulnerability and potential adaptation of technologies and management approaches were assessed, based on existing information in relation to current climatic challenges and variability. The potential vulnerability and adaptive capacity of each technology and management approach were used to define resilience. Data were collected through a review of published and unpublished literature on the climatic challenges to technologies and management approaches to service delivery, and the evidence for the success of responses implemented to date. A series of semi-structured interviews were held with 11 key water and sanitation specialists (out of 30 contacted) using a pre-tested topic guide. Finally an on-line questionnaire targeting water and sanitation professionals was run for three months. Data analysis was both qualitative (for the semi-structured interviews) and quantitative (for the questionnaire survey).

Second, forecasts were prepared on the likely average precipitation changes at a global scale, centred on 2020 and 2030. In addition, estimates were made of the likely changes in frequency of 5-day heavy rainfall events. These were prepared using the Met Office Hadley Centre decadal prediction system (DePreSys). DePreSys is the first decadal forecasting system and uses a well-validated climate model, HadCM3, which is one of those used in the IPCC Fourth Assessment Report (IPCC, 2007). DePreSys has the potential to forecast climate changes resulting from both natural variability and man-made factors. Forecasts were based on average changes over 9-year periods centred on 2020 (2016–2024) and 2030 (2026–2034). The forecast used a 10-member ensemble and started from conditions observed on ten consecutive days in March 2007. Model climatology was provided by the mean of four simulations for 1979–2001 including anthropogenic and natural forcings.

Third, the forecasts of drinking-water and sanitation coverage were based on the WHO/UNICEF Joint Monitoring Programme on Water Supply and Sanitation (JMP) methodology (WHO/UNICEF, 2004) using linear regression. The long-term forecast for the world population in 2020 was 7.7 billion, including all countries irrespective of information on water and sanitation access. This is a slightly higher estimate than the United Nations prediction of 7.6 billion (United Nations, 2005). The JMP pooled data sets for improved water supply and sanitation facilities for each country were disaggregated to provide the data for the proportion of the population with access to each of the facilities within this category. The disaggregation was carried out for the total population of each country, and for the rural and urban population. Then the proportion of the population using improved water supply or sanitation facilities was forecast. The values were constrained to a minimum of 0% and a maximum of 100%. Lastly, the proportion of the population using a particular type of improved water supply or sanitation facility was forecast. These forecasts were scaled so that the sum of the individual facility usages was equal to the total coverage.

3. Technologies and their resilience

The following sections describe the technologies and management approaches considered, and review their vulnerability, adaptive capacity and resilience. A general finding from the review is that resilience did not depend on the number of adaptations possible, but the impact of each adaptation in reducing vulnerability.

A set of fact sheets has been developed to provide detailed information on the adaptation options for different technologies. These notes cover particular vulnerabilities, different adaptations for planning, maintenance, monitoring and education. Extracts to illustrate the guidance provided are shown in Table 1.

Table 1
Extracts of vulnerability and adaptation options

Vulnerability	**Impacts**	**Adaptation methods**			
		Capital expenditure	**Operational expenditure**	**Monitoring**	**Socioeconomic tools**
Utility piped water supplies – flooding increases					
Water intakes may be left exposed as water levels fall. Highly turbulent water flows in rivers after heavy rain may damage intakes.		Design overflows for source reservoirs to prevent failure Develop, implement and update water safety plans. Design water intake to accommodate varying water levels (for example floating booms). River intakes strengthened to withstand more turbulent flows. Develop groundwater sources where feasible.	Maintain spillways and channels in good order.	Early warning system installed.	Disseminate early warnings. Update and disseminate evacuation procedures. Increase frequency with which emergency procedures are practised.

Vulnerability	Impacts	Adaptation methods			
		Capital expenditure	Operational expenditure	Monitoring	Socioeconomic tools
Pit latrines – increased rainfall causes groundwater levels to rise					
Inundation of the pit from below.	Contamination of groundwater and soil, potentially reaching drinking-water resources.	Provide protected water supply. Consider options: shallower pits and more frequent emptying; dry composting latrines; sewerage.	Regular pumping or emptying of pit latrine (particularly in urban setting) – link to smaller pit sizing.	Monitor drinking-water quality.	Education to increase marketing and use of alternatives.

3.1 Water supplies

Water supplies may be either piped or point sources, and may be managed by dedicated utilities (public or private), local governments or communities. Where piped water is supplied this may be delivered through multiple taps within houses, through a single tap at the house or yard, or through public taps. Point water sources are often managed by the community, but in some cases (in particular roof rainwater catchment and tubewells) may be owned and operated by individual households.

3.1.1 Piped water supplies

The resilience of a piped water supply is a function of the resilience of its components – the source, treatment and distribution through primary, secondary and tertiary pipes, and in-system storage infrastructure. This complexity increases the vulnerability of piped supplies, but also provides some adaptive capacity within the system as a whole.

Securing and protecting the water source (or sources) is the first critical step in enhancing the resilience of piped water supplies. Piped water supplies in many countries already face significant problems in ensuring a sufficient quantity of water to meet demands, or have sources with significant water quality problems that increase treatment costs. Source water quantity problems may result from inadequate storage of surface water, or underdevelopment of available groundwater resources. They may also arise because of excessive leakage in the distribution system, leading to excess demand on the water source. Building resilience of piped water supplies requires action to secure sufficient volumes of water from water sources, to reduce losses and ensure that demands are realistic.

For coastal areas, water sources may already be vulnerable to increased salinity, and this is likely to become an increasing risk as sea levels rise. Adapting to these problems could involve either the use of desalination, although this remains expensive and energy-intensive, or the development of more remote water sources unaffected by salinity.

In environments that are getting warmer and prone to more frequent heavy rain events, cyanobacteria are likely to represent an increasing threat in surface water sources. Cyanobacteria produce toxins that have an adverse effect on human and animal health, and are of particular importance where water is used to prepare solutions for dialysis. In seasonal environments with high temperatures and significant nutrient inflows, algal bloom development will be promoted. The greatest risk comes from the sudden displacement of the bloom, which commonly occurs when there are heavy rainfall events after a prolonged dry period (Chorus & Bartram, 1999). In most circumstances, source protection is the preferred method of control of cyanobacteria, as removal through water treatment is expensive and difficult.

Current designs for treatment processes will be increasingly challenged by changing source water qualities, caused by an increasing frequency of heavy rainfall events. Processes will require significant upgrading (additional pre-treatment steps, increased chemical doses) in order to enable drinking-water quality standards to be met. Particular challenges are likely to include: increased suspended solids, requiring greater coagulant dosing, optimizing of settler design or additional pre-filtration steps; increased microbial loads, leading to greater chlorine demands; and anthropogenic chemical pollution. Small water supplies, with commonly no or very limited treatment (simple filtration or disinfection or both) are likely to be under greatest threat from quality changes in water sources. For these supplies, protecting sources and reducing the potential sources of contaminants (hazards) within catchment areas for surface and groundwater will be vital if water supplies are to remain safe. Where treatment is used, it is important that assessments are made of the likely changes in water quality that may be encountered, and of whether the currently deployed treatment processes will be able to cope with expected or potential changes in quality.

Larger piped water supplies commonly employ treatment of water before distribution. Most conventional forms of treatment – aeration, filtration, sedimentation (both natural and enhanced) and disinfection – are designed to reduce suspended solids, remove pathogenic microorganisms and reduce the presence of objectionable or harmful chemicals. In some areas, additional pre-treatment (pre-chlorination or aeration and so on) may be applied to deal with particular water quality problems. Some contaminants, such as organic pesticides and their metabolites, require more sophisticated forms of treatment (such as granulated activated carbon) not commonly encountered outside of developed countries. Some natural chemicals, such as arsenic and fluoride in groundwater, can be removed by a variety of processes. These processes have proved successful, particularly when part of utility-managed water supply. Treatment systems should employ a multiple barrier principle, with several treatment steps in place to ensure that treated water is produced even if one of the processes malfunctions.

The piped network of all systems is vulnerable because of the large spatial spread of pipes crossing a variety of environments, and because of in-system storage. Pipes have to cross environments, for instance low-lying areas, where there is increased vulnerability to floods and other risk events. The vulnerability of piped systems also arises from the large numbers of pipe joints, which are often the points of greatest weakness both for breaks and for ingress of contaminated water. Factors such as leakage and intermittent supply regimes will also increase the potential for contamination. In-system storage may also be vulnerable to damage or water quality degradation where this is not protected against flood risks.

Delivering resilient piped water supplies therefore requires action at source, during treatment and through distribution. Using the water safety plan approach to look at vulnerabilities at each stage of the system to climate-induced risks may be an effective approach to understanding climate impacts and adaptation options (Bartram et al., 2009), but it is likely that new risk assessment tools that are better able to assess uncertainty may be needed.

3.1.2 Non-piped water supplies

The non-piped water supplies considered in this assessment are: tubewells (also known as boreholes in some countries) fitted with a single outlet, usually in the form of a handpump; dug wells; protected springs; and household rainwater catchment.

Tubewells are a resilient technology. They can usually be located so as to reduce the impact of local sources of pollution, although this flexibility may be restricted where fracture basement aquifers are used. The resilience of tubewells arises not only from their relatively low vulnerability, particularly against microbial contamination, but also from their adaptive capacity.

Tubewells are vulnerable to falling water tables in relation to both quantity and potentially quality of water, as pollution may become more concentrated. In some parts of the world, tubewells are contaminated by natural contamination from arsenic and fluoride (WHO, 2004). These sources can still be used but will require treatment to reduce levels to safe limits. For both arsenic and fluoride, relatively simple treatment processes are available that can be attached to community wells or designed for household use. Experience to date in the use of such technologies, however, remains mixed and sustaining either household or community level treatment appears problematic.

Flooding is a significant threat to tubewells, but raising wellheads has been shown to be effective in minimizing the impact of particular flood events (Luby et al., 2008). Where there is widespread contamination, the screen can be set at significant depth and impermeable casing used through shallower aquifers to prevent ingress (Macdonald et al., 1999). In some cases, contamination can still occur in the wet season through the use of contaminated priming water (Howard et al., 2007).

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 by other sectors, particularly agriculture. This is a problem found in many parts of the world where use of water in irrigation has led to dramatic declines in water tables. It may be possible to sink deeper tubewells, which may mean shifting from handpumps to motorized pumping for domestic supply. Addressing falling water tables will almost always require action to reduce abstraction by other sectors in order to maintain water tables at levels suitable for withdrawal for domestic use. Declining water tables may also lead to water quality problems, as deeper and more contaminated aquifers are exploited. This may require additional treatment being applied, for instance aeration to remove iron or manganese.

Household roof catchment to harvest rainwater, and protected shallow springs are less resilient to climate changes. Both are vulnerable to decreasing and more variable

recharge (with the exception of relatively rare artesian springs that tap confined aquifers) and are thus dependent on water resources that are likely to vary rapidly in response to rainfall changes, with limited reserve capacity.
Most household rainwater catchment systems do not provide year-round water supply and often do not last a full dry season. Many protected springs also commonly show declining yields 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 (Gould & Nissen-Petersen, 1999; Howard et al,. 2003; Howard et al., 2006). Both have limited adaptability because they are inflexible as regards location, that is they can only be constructed where the spring emerges or next to the roof catchment. Although adaptations do 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.

Larger-scale collection from ground catchments may be an effective response, and in dry countries 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 increasing 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.

Dug wells are considered to have limited resilience because of high vulnerability both to a decreasing quantity of water and to high risks of microbial contamination during periods of high rainfall (Gelinas et al., 1996; Howard et al., 2006; Godfrey et al., 2006). 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, which is increasingly recommended (Hira-Smith et al., 2007; Howard et al., 2007). However, although chlorination has been shown to be effective where there is regular external oversight, as in relief situations (Godfrey et al., 2003), sustaining such approaches by communities has been called into question (Mahmud et al., 2007).

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, but research in southern Africa has shown that collector wells can be successful in such environments (Macdonald & Davies, 2000). Application of this technology remains largely limited to particular countries and has not been widely used. Without such interventions, maintaining the yield of dug wells in drying environments is likely to be problematic.

3.1.3 Resilience of water supply management approaches

This study found that, for most technologies, the management approach appears to be more important than the technology itself in determining the resilience of drinking-water supplies. In particular, the management model for piped water supplies is critical to their resilience. Despite the relatively low resilience of this technology, the evidence suggests that with the right management model the inherent vulnerability can be overcome. Where there is a centralized utility management body (private or public) that is responsible for operation, adaptive capacity and resilience increases. This is because such entities typically have access to a sufficient body of staff, with a wide skill mix, who are in general properly trained to undertake the tasks for which they are responsible. Larger utilities also usually have easier access to finance – derived from tariffs, but also taxes and transfers from large donors in some countries – to allow for the construction, upgrading or rehabilitation of infrastructure. Such utilities have the potential to develop new sources of water, improve treatment processes and replace broken or worn pipes and fittings.

This does not mean that all utilities are actually resilient in practice – because of poor management, corruption, and poor staff training and retention, many utilities do not actually have the right numbers and type of staff, and often cannot easily access finance. Evans et al. (2009) for instance noted that in eastern Europe and Central Asia, utilities were not well-placed currently to adapt to changing water availability and quality, although there were some positive trends. But with reform, experience suggests that larger utilities are able to attract financing and undertake significant improvements in supply, indicating an adaptive capacity.

By contrast, community-managed rural piped schemes and, to some extent, small town water supplies lack the natural advantages of large utility organizations. Small town water supplies tend to be in a better position than community-managed supplies because governments and donors are paying increasing attention to the needs of small towns, and as a consequence more finance is available for capital works. Nonetheless, the amount of 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, however, 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 not be currently feasible.

For community-managed supplies, capital finance (usually external to the community) is typically restricted to initial construction and is only rarely available for subsequent upgrading or rehabilitation. Finance raised through tariffs is typically low and rarely even covers the basic costs of operation and maintenance. Available labour is generally unskilled or at most only equipped with short, basic training in supply operation. More often than not, operation and maintenance are undertaken by community volunteers who receive little or no remuneration. 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 (WHO, 2004).

Where groundwater sources are used, protection measures have proved effective in ensuring the quality of water entering community-managed piped systems. However, where surface water is used and treatment is required, experience indicates that performance is typically weak, resulting in systematic ongoing contamination or high vulnerability to contamination events. Management of the piped network also tends to be weak, and good quality source water frequently becomes grossly contaminated during distribution. Where pumping is required then vulnerability tends to increase as supplies are more likely to be intermittent. Piped supplies that rely on surface water (and the small number of non-piped supplies such as pond sand filters) may face increasing problems of water quality in source waters, which will increase costs of supply and increase potential risks to health.

Community management of non-piped sources is also commonly weak unless external support is provided, with large numbers of installed water supplies non-functional at any one time (Harvey & Reed, 2006; Kabir & Howard, 2007). The lack of supporting functions through surveillance programmes, which have been shown to improve the sustainability of community-managed supplies (Lloyd & Bartram, 1991; Howard & Bartram, 2005), increases the adverse impact of poor management on water supply resilience.

Increasing rainfall and, in particular, more frequent heavy rain events will make the use of point water sources in urban areas increasingly difficult if on-site sanitation is used. Only tubewells are likely to have the adaptive capacity to cope with increased threats through deepening intakes and casing off contaminated shallow aquifers (Macdonald et al., 1999). Protected springs and dug wells in such urban environments have been identified as highly contaminated and at high ongoing risk of contamination (Howard et al., 2003; Cronin et al., 2007). Such technologies should be replaced either by more robust technologies such as a tubewell or by piped water systems. It is unlikely that climate change will represent a significant risk of increased cross-contamination in rural areas, provided appropriate measures to prevent groundwater contamination are put in place.

3.2 Sanitation

Sanitation, here defined as the collection, containment or treatment, and disposal of excreta, can be delivered through on-site or off-site means. On-site sanitation includes a range of options, from very simple non-water using pit latrines to septic tanks connected to flush toilets and which take household greywater. Off-site systems are forms of sewerage where part or all of the excreta are transported away from the household for treatment or disposal at a central point. Sewerage may be conventional (typically, connected to flush toilets and household greywater, and in many cases stormwater) or modified – where only liquid matter is piped away (small-bore sewerage) or where sewerage works on a non-constant flow principle (shallow sewers) and does not take stormwater.

3.2.1 Pit latrines

The available evidence suggests that dry and low-flush pit latrines have a high climate resilience because there is significant adaptive capacity through changes in design. 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. Where pits are regularly emptied, for instance in high density periurban areas, pit stability could be affected and in such situations more permanent linings may be warranted to avoid pit collapse.

In environments where flooding may be an increasing risk, pit latrines may be more vulnerable. In the past, flooding of pit latrines has been responsible for widespread environmental contamination and public health risks (see, for example, Cairncross & Alvarinho, 2006). Research has shown that, in areas affected by short-term flooding, water source contamination is typically greater where there is no sanitation than where there is on-site sanitation (Howard et al., 2003; Cronin et al., 2007).

It is possible to adapt pit latrine designs, for instance by using raised latrines or constructing smaller pits that require more frequent emptying (Kazi & Rahman, 1999; Parry-Jones & Scott, 2005). 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, for instance as done in the Chars Livelihoods programme in Bangladesh (B. Evans, personal communication, 2008). The risks from flooding may be exacerbated by owners using floodwater to flush out the latrine pits (Chaggu et al., 2002). This can only be overcome by providing pit-emptying services that are affordable and reliable.

Where increased rainfall (even seasonally) leads to rising groundwater levels, this can lead to flooding of the pit and contamination of shallow groundwater. This has often been given as a justification for not installing latrines where groundwater is used as a drinking-water source. The risks might increase in an environment that is getting wetter, but changes in design (for example, to vault latrines) and the implementation of simple risk-based approaches to defining separation distances and the selection of appropriate groundwater technology may all reduce these risks (MacDonald et al., 1999; ARGOSS, 2001; Chave et al., 2006).

Pour–flush latrines have a slightly lower resilience than dry pit latrines, although their level of resilience is similar. 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 (Pedley et al., 2006). This risk may be compounded in situations where groundwater levels are also rising. 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. Extreme rainfall events would not be likely to have any greater impact on pit latrines that use low volumes of water, for instance pour–flush latrines, than on dry pit latrines.

3.2.2 Septic tanks

Septic tanks, which tend to be linked to toilets that use large volumes of water, are likely to be less resilient than latrines. In drying environments, the volumes of water required to keep a septic tank functioning may be difficult to sustain. In environments where groundwater level rises or extreme events increase, managing drain field operation and preventing tank flotation present particular problems. There is evidence that flooding of septic tanks and drain fields can represent a very significant source of environmental contamination as a consequence of flooding (Cairncross & Alvarinho, 2006). 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, fitting non-return valves to pipes to prevent back flows, and ensuring that any vents on the sewer are above the expected flood line (Reed, 2008). Floods can also cause structural damage to septic tanks, which will lead to widespread environmental contamination. By allowing water into the tank if it is not full, the internal and external pressures can be balanced, which may prevent the tank from collapsing.

3.2.3 Conventional and modified sewerage and wastewater treatment

Sewers have more limited climate resilience and in particular face threats from significantly decreasing rainfall and water flows, and from heavy rainfall events, which can result in widespread environmental contamination and public health risks. Combined sewers, which carry both sewage and stormwater, are particularly vulnerable to storms and extreme rainfall events. Once the input exceeds a certain value, the excess wastewater is discharged untreated into the environment from the combined sewer overflow, contributing to increased contamination of surface water. This can be very significant; for instance in Ontario, Canada, 81% of the 1544 reported releases of sewage were caused by wet weather (Podolsky & MacDonald, 2008).

Combined sewers are typically designed to manage a certain flow of wastewater, based on a range of environmental, social and economic factors, and with additional reserve capacity to deal with particular extreme events, for example a one in five- or a one in ten-year storm event. However, the magnitude and frequency of these extreme events are identified from historical records, which may not be reliable in the face of climate change (Bates et al., 2008). Heavy rain events may also cause back-flooding of raw sewage into houses, with consequent significant risks to public health. Flood events can also cause physical damage to sewer infrastructure, resulting in leakage of sewage into the environment (CSIRO, 2007), as can differential ground settlement that can occur post-floods or after prolonged drought (Fehnel, Dorward & Mansour, 2005).

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 inspection covers in roads and the toilets and washbasins of homes and buildings (Caribbean Environmental Health Institute, 2003). Shut-off valves can prevent such back-flow, but in many cases in developing countries these have not been installed (Few et al., 2004).

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 already may cause greater blockages.

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 (Schulz & Murphy, 2008). 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 (Hrudey et al., 2003).

Small-bore and shallow sewers may be more resilient in drying environments, as they typically use less water than conventional sewerage. As a consequence they are less vulnerable to decreasing water availability. Because small-bore sewers only carry effluent they should not be significantly affected by blockages resulting from solids deposition unless the pipework is damaged and soil enters the system. Shallow sewers may be at greater risk because they carry solids and work on the principle of intermittent suspension. Thus some deposition occurs as part of the functioning of the system. Significant reductions in inflow or significant non-faecal solids may increase the risk of blockages. Modified sewers will still be at risk from damage from floods and other extreme events, and in some cases may be at greater risk because their shallower depth makes them more vulnerable to flood damage. There may also be slightly greater risk from damage resulting from ground settlement.

The infrastructure and the operational components of a wastewater treatment works can be damaged or taken out of service by flood waters, resulting in the discharge of untreated sewage and sewerage overflows. The impact of these events can be long-lasting, and may continue during reconstruction or repair of damaged infrastructure. Wastewater treatment plants also face other significant threats from climate change. Where hydraulic designs are poor, heavy rainfall events may cause short-circuiting of technologies such as waste stabilization ponds. As most treatment plants are located close to rivers or the sea, floods can cause significant damage to infrastructure, leading to widespread environmental contamination. In drying environments, the carrying capacity of receiving waters is likely to decrease. This will increase the treatment requirements, and hence the cost and potentially the carbon footprint of wastewater treatment.

3.2.4 Resilience of sanitation management systems

This study found that the resilience of sanitation is not as management-driven as the resilience of drinking-water supply. The majority of sanitation facilities that have been built and are used are maintained by individual households. Only in urban areas is there reliance on external operations for maintenance, through the provision of emptying services for pit latrines and septic tanks, and sewerage and sewage treatment services. There is increasing evidence that even very low-income households are able to adapt designs of latrines within short time horizons, often in response to particular events. This indicates that the adaptability of the technology is such that the impact of management weaknesses can be overcome.

In urban areas, sewerage utilities should, in principle, benefit from the same advantages as utility-run drinking-water supply. Commonly, a combined service is provided. However, in practice, unit costs for sewerage services are often higher than for drinking-water supply and it is often difficult to raise sufficient finance to operate systems, including from user tariffs. As a consequence, there is often a cross-subsidy from water tariffs, which may in turn make piped water unaffordable for low-income users with no prospect of being connected to a sewer system. In many developing countries, costrecovery of basic operation and maintenance costs for sewerage have proved even more problematic than for water supplies, with consequent impacts on service quality.

3.3 Resilience assessment

The evidence reviewed shows that all technologies in current use have some adaptive capacity, but that this varies significantly between technologies. The technologies also have varying vulnerability to different climate scenarios. The technologies considered in this assessment can be plotted in a matrix of adaptive capacity and vulnerability for different future climate conditions, as shown in Figures 1–3. This grouping can guide thinking through priorities for technology selection for the future.

Figure 1
Resilience matrix: vulnerabilities and adaptability of improved water supply and sanitation facilities under conditions of increased rainfall

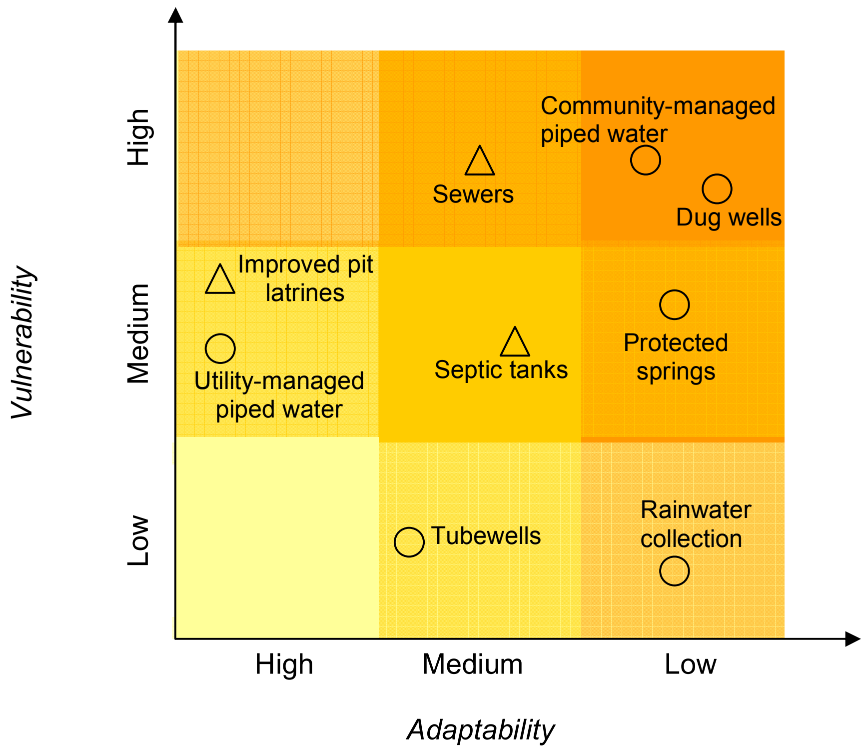


Figure 2

Resilience matrix: vulnerabilities and adaptability of improved water supply and sanitation facilities under conditions of decreased rainfall

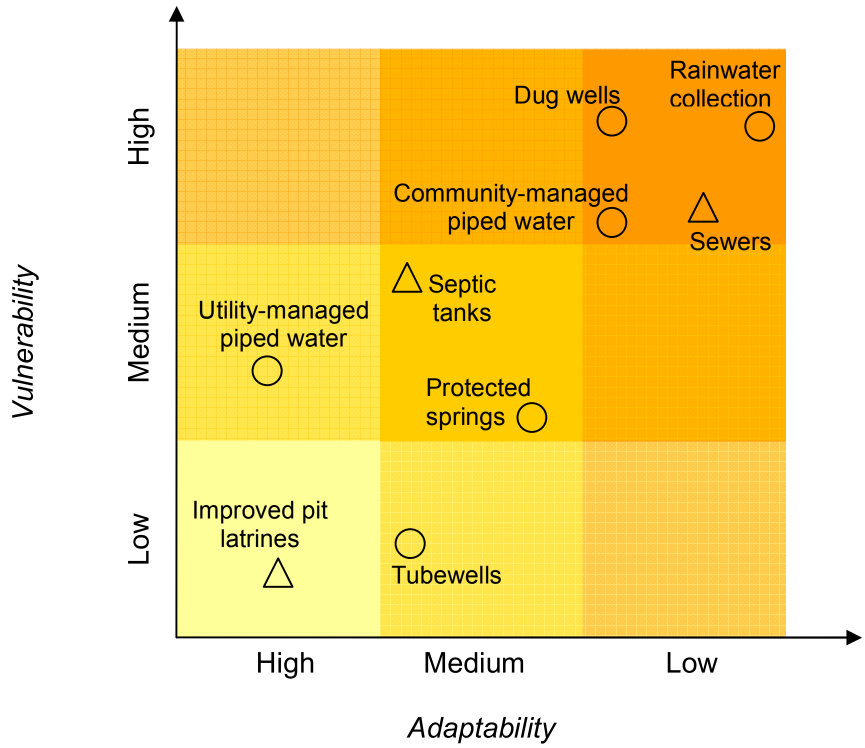
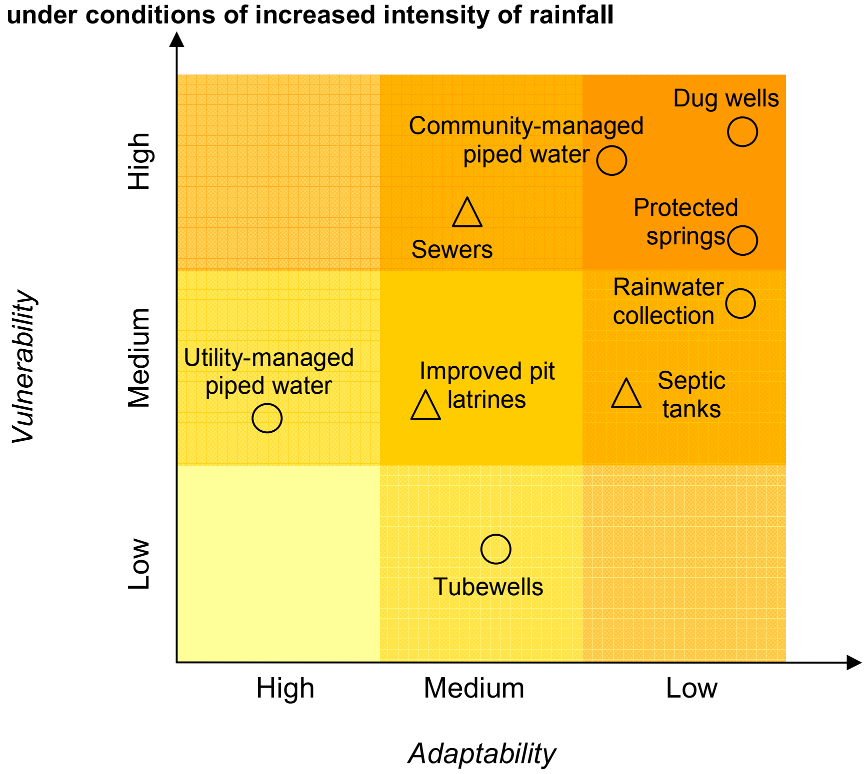


Figure 3

Resilience matrix: vulnerabilities and adaptability of improved water supply and sanitation facilities under conditions of increased intensity of rainfall



It is essential that 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.

4. Policy implications

This study has flagged a set of key policy issues that the water and sanitation sector will need to address if services that are resilient to climate change are to be provided.

4.1 Centralize or decentralize for greater resilience?

One of the key policy questions arising from a changing climate is how services will be best delivered in the future. This question covers both centralization of infrastructure to deliver services, and institutional centralization of management irrespective of whether infrastructure is centralized or decentralized (see Box 2).

Box 2: Centralize or decentralize?

Decentralized infrastructure offers benefits because it spreads the risks from drought and extreme events and so is often more climate resilient. The problems associated with decentralized infrastructure are increasing costs of maintenance (whether this is by a centralized utility or not) because there is more infrastructure.

Decentralized management may offer some benefits in terms of greater end-user involvement in operation and maintenance, but often suffers from very limited access to skilled professionals. As a result, infrastructure deteriorates quickly and is at risk from extreme events.

Centralized management of decentralized infrastructure offers potential advantages in terms of access to skills, but may increase costs. In the past, it has failed to meet user demands and resulted in unsustained water supplies.

Making policy choices about centralization needs to take into account the need to adapt to climate change and to other factors related to management skills, availability of staff, equity, trends in service demand and global targets. In programming terms, three key approaches can be identified:

- decentralized infrastructure, with multiple discrete water supplies serving and managed by individual communities;

- centralized infrastructure, ranging from single to multiple water sources serving a set of larger communities in a physically connected system;

- decentralized infrastructure, using multiple sources integrated into a centralized management system serving a larger set of communities.

Centralization of infrastructure and associated management may offer benefits in ensuring that system operators have staff with high technical competence. However, the need for long pipe and sewer runs makes operation, maintenance and response to events time consuming and expensive. In most cases, increased automation of alerts and shut-down functions are required, and the operator needs greater capacity to undertake relatively sophisticated prediction of events and their impacts. Centralized infrastructure is a feature of most developed countries, although most have at least some small decentralized water supplies.

Decentralization of infrastructure also depends on the distribution and yield of available water sources. Climate change is therefore likely to influence whether decentralized infrastructure becomes more or less attractive in the medium term. In a climate that is drying, decentralization is likely to become more attractive because it will spread the risks associated with the drying up of individual water sources, although this advantage will depend on the degree of drying and the size and locations of communities affected. Decentralization will also help to avoid the construction of poorly adapted and vulnerable large infrastructure. In a climate that is getting wetter, decentralization will offer some benefits by diffusing risks of local flooding, thereby reducing the potential for widespread contamination and increased public health risks from water supplies.
In climates with more frequent heavy rainfall events, decentralization of infrastructure is probably desirable. Operating a centralized system under such a climate will create more critical points whose vulnerability effectively controls the entire system. For instance, in the 2007 floods in Gloucester, England, the flooding of the Mythe pumping station resulted in the supply to 350,000 people being interrupted (Pitt, 2007).

Decentralization of management, typically associated with decentralization of infrastructure, is common in rural areas of low- and middle-income countries, and to a lesser extent developed countries. Decentralization increases both the number and proximity of staff or volunteers for operation and maintenance, but there is usually only very limited access, at short notice, to staff with greater technical skills. This increases the risk of failures during extreme events, a problem for both developed and developing countries (see, for example, Hrudey et al., 2003). The often crucial support to community managers through surveillance or monitoring functions has rarely been offered, despite evidence of success from developed and developing countries (Lloyd & Bartram, 1991; WHO, 1997; Howard & Bartram, 2005).

Decentralization does not automatically result in better governance and service delivery. Low-income groups may be disadvantaged by the capture of services by elites able to manipulate local systems. The degree to which decentralization is possible also depends on demographic changes – for instance, increasing urbanization will challenge the degree of decentralization that is practical.

The integration of a decentralized infrastructure within a more centralized management structure is a model that has been out of vogue for many years, as community management became the predominant paradigm for water supply provision. In part this is well-founded on past experience. However, the community management model itself has often failed to deliver sustained improvements. Efforts to ensure that technologies and the management of services are sufficiently robust in the light of climate changes suggest that the centralization of management – or at the very least the implementation of support functions such as surveillance – will be key to ensuring resilience. With the likely widespread increases in unpredictability of rainfall and water availability, reliance on unpaid and poorly trained local volunteers to manage services will greatly increase the risk of failure in services and of increases in public health hazards.

Most of the above discussion primarily refers to water supplies. For sanitation there seems a much weaker case for infrastructure centralization under most conditions. The majority of people worldwide with access to sanitation manage this at a household level. There is a strong case, however, for greater access to centralized support functions to ensure that the enabling environment for sanitation acquisition – trained and skilled providers, social marketing and promotion – remain in place to persuade households to continue to build and use latrines. Where pit latrines and septic tanks require periodic emptying, such services (whether provided by the private or public services) will also be required and are likely to come from outside particular communities.

4.2 Levels of service

There has been a trend of increasing numbers of people with access to a household tap. By 2006, over half the global population had such access (WHO/UNICEF, 2008). In some regions, rates of household connection are increasing more quickly than other forms of improved supply. This is particularly important in urban areas, but even in rural areas large parts of the developing world are increasing access at higher service levels. This is desirable given the evidence that this level of service is associated with greater health and socioeconomic benefits (see Box 3).

Box 3: The benefits of an at-house water supply

The evidence from a number of studies and reviews has indicated that much greater health benefits are accrued if people have a water supply at their plot rather than having to walk to a shared water supply. This is often simply a single tap in a yard. The health benefits derive from improved hygiene facilitated by much greater water use, and more time to devote to child care and productive purposes.

In general, an at-house water supply will mean that each person will use about 50 litres per day, compared to no more than 20 litres per day for a water supply within 30 minutes total collection time, and frequently less in communities lacking even this level of service.

Source: Howard & Bartram (2003).

Given the health, social and economic benefits, there is a strong rationale for international and national targets – after the deadline for achieving the Millennium Development Goals has expired in 2015 – to focus on increasing access to an at-house level of service, particularly for low-income groups. Delivering this level of service will demand better management of water resources and making more effective allocations between competing sectors to ensure that abstraction is sustainable. Increasing access to an at-house water supply provides an opportunity, in countries where there has been limited progress in providing communal water supplies, to move directly to delivering better quality services for disadvantaged people.

Achieving access with this level of service in a climate resilient way raises the issue of whether a household level of service can only be delivered via piped water systems or whether alternative supplies, such as tubewells, offer an equally viable approach. For instance, in parts of south Asia there are relatively high rates of household tubewell coverage, and such approaches may be viable in Africa. Household-owned water supplies tend to be better maintained than community-managed supplies, provided a supply chain for parts and spares is in place, presumably because it is considered to be an essential household asset.

Much of sub-Saharan Africa is underlain by basement fracture aquifers capable of supplying only relatively low volumes of water. Because of their low permeability such aquifers are naturally self-limiting in the abstraction rate they can support, unlike higher permeability aquifers which can more easily be depleted through unsustainable rates of abstraction. Delivering at-house levels of water supply through developing multiple small aquifers from relatively low-yielding household tubewells may be more climate resilient than relying on piped systems dependent on a small number of high-yielding groundwater sources. However, where sufficient water resources exist, it may be cheaper to deliver at-house water supplies through piped systems

This suggests a policy direction to meet household levels of service through the increased provision of tubewells at household level, although in practical terms there may need to be a combination of approaches to deliver higher levels of service in any one community. In contrast to piped supplies, however, there is a lack of evidence on how much water is used when there is a household tubewell fitted with a handpump. This is a key research issue. If households use roughly 50 litres per capita per day – the same as estimated for most piped systems (Howard & Bartram, 2003) – then household tubewells are viable from a public health perspective.

Moving forward with a household tubewell approach will require avoiding the development of very small aquifers not capable of providing a year-round supply and taking steps to prevent contamination of water as a result of poorly maintained tubewells. It will also require careful planning to ensure that pumping rates do not cause excessive reduction of groundwater. This approach raises important research questions about the availability of sustainable groundwater sources and reducing the currently very high cost of borehole drilling in most African countries.

For urban areas, the use of piped systems to provide household connections is likely to remain the focus of work to achieve higher service levels. Efforts will need to be made to improve the reliability of systems to provide continuous supplies. In drying environments, however, this means considering how services are structured. Rather than relying on single sources of water, piped supplies are likely to benefit from the development of multiple sources, potentially supporting discrete areas of the piped network with the potential for cross-supply. This approach is already used in many larger urban utility systems, but may also benefit smaller urban supplies with an emphasis on lower abstractions from any single source. Within existing urban supplies, the potential for having multiple discrete networks is also worth considering.

There will be an increasing need to account for climate changes in hydrological, demand, urban development and economic models for urban piped water supplies, to identify how much water will be required and where. For utilities to become climate resilient, there will be a need to address operational performance, particularly in those countries where water may become less available. Climate resilience will require utilities to put in place management measures to be able to meet objectives of equity by extending services to those lacking access, while ensuring that existing users continue to receive adequate services. This will require reducing unaccounted-for water, in particular leakage, and measures to manage demand.

4.3 Monitoring of water and sanitation coverage

The water and sanitation sector currently monitors progress towards meeting the Millennium Development Goal targets for water and sanitation through the WHO/UNICEF Joint Monitoring Programme on Water Supply and Sanitation (JMP). This monitoring is based on data derived from user questionnaires (as opposed to supplier estimates of infrastructure) and household surveys undertaken at national level. The JMP has estimated progress by assessing the number of people who use "improved" technologies (see Box 4), although the JMP is increasingly using the concept of water and sanitation ladders, and a more disaggregated approach to monitoring (WHO/UNICEF, 2008).

Box 4: JMP definitions of improved and unimproved water and sanitation technologies

Water supply		**Sanitation**	
Improved	*Unimproved*	*Improved*	*Unimproved*
Piped water into dwelling, plot or yard Public tap/stand pipe Tube well/borehole Protected dug well Protected spring Rainwater collection	Unprotected dug well Unprotected spring Cart with small tank/drum Tanker truck Surface water (river, dam, lake, pond, stream, canal, irrigation channel) Bottled water	Flush or pour–flush to: - piped sewer system - septic tank - pit latrine Ventilated improved pit latrine Pit latrine with slab Composting toilet	Flush or pour–flush to elsewhere Pit latrine without slab or open pit Bucket Hanging toilet or hanging latrine No facilities or bush or field (open defecation)

Source: WHO & UNICEF (2000).

The JMP categorization did not take climate change (or indeed other measures of sustainability) into account. In considering the evidence collected during this study, it is clear that such an approach is not adequate for future monitoring. As shown in Tables 2 and 3, many of the technologies currently considered as "improved" and therefore providing access will in fact only have restricted application. In Tables 2 and 3, high resilience is taken to mean resilient in most climate scenarios and therefore of global applicability. Medium resilience indicates resilient in a significant number of climate scenarios. Low resilience means resilient only in a restricted number of scenarios.

Table 2
Water supply technology resilience

Technology	Resilience	Key issues
Tubewells	High	Motorized pumping may pose challenge in drying environments
Dug wells	Low	Problems with water quality; securing year-round supply already problematic in some areas
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

Table 3
Sanitation technology resilience

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; treatment requirements may increase as carrying capacity is reduced

As noted above, the management of drinking-water supplies can overcome inherent technological weaknesses. Thus the low and medium resilience of piped and treatment systems can be overcome provided a sound utility is responsible for management. The greatest effort should therefore be placed on improving management systems to improve sustainability.

In settings where utility management is not possible, greater attention should be placed on delivering those technologies with high resilience. Technologies with medium resilience should be deployed only after a rigorous local assessment to ensure their appropriateness for the particular setting. Research to improve the resilience of these technologies would appear to be warranted. Technologies considered to have low resilience are best viewed as supplementary sources or as interim solutions within a plan for progressive improvement in access. In all cases, effective supporting surveillance functions are required to improve sustainability.

Current predictions are that the Millennium Development Goal target for drinking-water supply will be met, while that for sanitation will be missed by a long way (WHO/UNICEF, 2008). These predictions are based on monitoring that does not take account of climate change resilience. The implication of the findings of the present study is that, if climate resilience is taken into account, predicted progress will be much more limited than currently estimated, and the world will be badly off-track to meet both the drinking-water and sanitation targets. The findings of the present study also imply that there is a risk that rates of coverage will decline in the near future, as the effects of climate change in the short to medium term result in access being lost by communities who find that they have a non-resilient and non-functional water supply or sanitation system.

Monitoring and assessment of progress in the sector in the future must take climate resilience into account when estimating access to sustainable water and sanitation services. There is a strong rationale for insisting that targets set after 2015 should take account of sustainability and employ a graduated approach, rather than applying universal categorizations of technology adequacy. More attention should be placed on identifying regionally acceptable technologies, using peer review mechanisms operating at the regional level. In other fields, notably governance, the feasibility of such mechanisms for these purposes has been demonstrated.

5. Climate and coverage predictions: regional hotspots

Changes in climate will not be uniform across the globe, and there are wide variations in the coverage attained and the technologies used between different regions. This suggests a need to identify key hotspots where attention is most urgently needed. It is important both to understand the likely trends in water and sanitation coverage and to take account of climate predictions.

5.1 Water and sanitation coverage forecasts

Coverage with access to water supply is projected to be over 75% for most countries by 2020 (see Table 4), with Africa the only continent with significant numbers of countries not reaching this level. These estimates are based on current trends and thus do not capture more recent policies or programmes that might accelerate progress.

Table 4
Forecast water supply coverage (%) by 2020

Region	**Water supply**					
	Piped at home	**Public taps**	**Wells**	**Protected springs**	**Rainwater**	**Total**
Western Asia	79	3	10	1	0	93
Sub-Saharan Africa	18	16	28	5	2	70
South-east Asia	42	6	34	4	8	94
South Asia	23	20	53	0	0	96
Oceania	18	0	4	11	8	41
Northern Africa	86	3	4	0	0	93
Latin America and Caribbean	89	2	5	1	1	98
Eurasia	66	7	19	1	0	92
Eastern Asia	83	0	17	0	0	100
Total developing countries	50	10	30	2	1	93
Developed countries	95	1	2	1	0	100
Total	51	10	29	2	1	93

Water supply coverage in 2020 is predicted to be dominated by household connections and wells. Piped water coverage is projected to be over 75% in about three-quarters of countries in Latin America and the eastern Mediterranean. Such coverage is predicted to be much lower in Africa and south Asia, with a mixed picture in east and south-east Asia. Coverage with protected wells is high in south Asia and parts of south-east Asia and Africa. It is generally low in Latin America. Protected springs and household rainwater harvesting both typically account for less than 10% of improved water supplies in all regions.

Rates of access to sanitation are projected to be lower than those for drinking-water, and by 2020 the majority of countries in Africa, the Indian sub-continent and south-east Asia will have less than 75% coverage (see Table 5). Latin America is forecast to have over 75% coverage. Public sewer connections are predicted to be low in Africa, south Asia and south-east Asia, but higher in part of east Asia and Latin America. Pit latrines make up over 50% of sanitation coverage in four fifths of the countries in Africa, but are less common elsewhere. Septic systems, including low-volume flush technologies, form the majority of coverage in south, east and most of south-east Asia.

Table 5
Forecast sanitation coverage (%) by 2020

Region	Sanitation			
	Sewerage	Septic systems	Pit latrines	Total
Western Asia	54	33	4	91
Sub-Saharan Africa	8	10	36	54
South-east Asia	5	56	20	81
South Asia	7	36	11	54
Oceania	5	5	36	47
Northern Africa	71	5	17	93
Latin America and Caribbean	62	22	7	91
Eurasia	47	8	40	95
Eastern Asia	35	31	23	88
Total developing countries	24	29	19	72
Developed countries	78	18	2	98
Total	28	28	18	74

Coverage with both water supply and sanitation is predicted to be higher in urban than rural areas, particularly for piped water, sewer connections and the use of septic tanks. The combined effect of increasing rates of at-house connections and of sanitation systems that use water will demand better management of services, to ensure that services are efficient, and improved management of water resources, particularly in countries and regions likely to become drier.

5.2 Climate forecasts

Over the next few decades the magnitudes of changes resulting from natural variability may in some regions be comparable with those caused by man-made factors. Changes resulting from natural variability may be of equal or opposite sign to anthropogenic changes, so may temporarily alleviate or exacerbate the impacts of the latter. Decadal prediction science is at an early stage, and thus the forecasts presented below are best estimate predictions. For more detail, please see the climate change projection study. Predictions in this study were derived from an ensemble of DePreSys simulations designed to indicate both most likely (best estimate) changes and ranges of variability.

The best estimates shown are 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 4) 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.

Figure 4
Changes in precipitation (as percentage of 1979–2001 climate) predicted for the 2030s

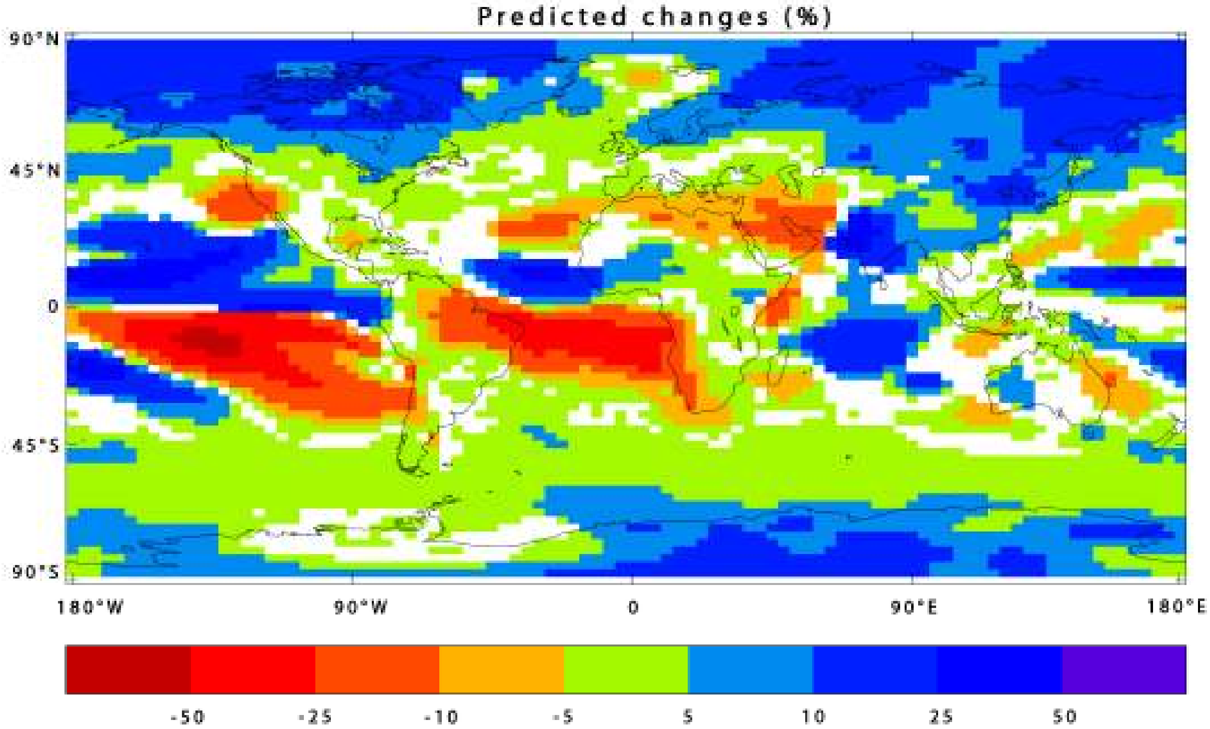


Figure 4 shows changes in annual mean precipitation predicted for 2030. These predictions were assessed for consistency with corresponding predictions from two other ensemble prediction systems. The clearest signals are: decreases in annual mean precipitation in southern Africa, the Mediterranean basin 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.

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.

As shown in Figure 4, 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.

5.3 Regional climate hotspots

A number of key regional hotspots of concern have been identified where predicted changes in climate by 2030 are clearest and are most likely to have significant implications for water supply and sanitation. These are areas where research efforts in building adaptive capability in technology and planning are urgently required. Examples of such hotspots include:

- environments predicted to become drier – southern Africa, the Mediterranean basin, Central America and north-eastern South America;

- environments predicted to experience increased risk of flooding – south and east Asia.

Taking the regional climate changes identified above, an indicative list of appropriate technologies by region can be identified. These are shown in Table 6, which is designed to promote discussion within the sector, and to encourage more detailed local and regional assessments.

Table 6
Indicative list of technologies suitable by region

Region	High resilience	Medium resilience	Low resilience
South-western Africa – getting drier	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	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	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug well not appropriate

Region	**High resilience**	**Medium resilience**	**Low resilience**
Rest of sub-Saharan Africa	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate	Rainwater and dug wells appropriate provided local conditions permit
Northern Africa – getting drier	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	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	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug wells not appropriate because of microbial contamination threat
South-east Asia – likely to experience more flooding	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug wells not appropriate because of microbial contamination threat
Central Asia	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate with reasonable safeguards	Rainwater and dug wells appropriate with reasonable safeguards
East Asia – likely to experience more flooding	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug wells not appropriate because of microbial contamination threat
Central America	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate, but additional safeguards against flooding required	Rainwater appropriate Dug wells not appropriate
North-east South America, likely to get drier	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped and unconventional sewers appropriate Conventional sewers and septic tanks not appropriate	Rainwater and dug wells may be appropriate, but will face challenges from long-term drying trends

Region	High resilience	Medium resilience	Low resilience
Rest of South America	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate with reasonable safeguards	Rainwater and dug wells appropriate with reasonable safeguards
Eastern Mediterranean and west Asia	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Water supplies and unconventional sewers appropriate Conventional sewers and septic tanks not appropriate	Dug wells appropriate Rainwater not appropriate
Pacific Islands	Tubewells, utility-managed piped water and pit latrines could be used with reasonable safeguards	Protected springs, community-managed piped supplies, septic tanks and sewerage appropriate depending on local conditions, but sewerage and septic tanks unlikely to be appropriate	Rainwater and dug wells appropriate depending on local conditions

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 (for example, around the Gulf of Guinea) 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. For Africa, Calow et al. (in press) concluded that the regions at most risk would be those that receive between 200 mm and 500 mm of rainfall; this encompasses the areas in north and southern Africa identified in this study as being at significant risk of drying. These areas were considered to be at particular risk because they would include communities likely to experience increased water stress but without traditional methods of adaptation.

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 is combined with predicted increasing piped water coverage, which is already over 75%. In Central America, this is likely to be combined with risks to infrastructure from damage by extreme rainfall events. 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.

6. Conclusions and future research needs

A number of conclusions can be drawn from this study and a number of areas have been identified where further research is required in order to support the water and sanitation sector to become more resilient to climate change.

6.1 The urgent need to improve climate resilience

The currently used set of technologies for drinking-water and sanitation show relatively limited climate resilience. For water supply, tubewells are found to be a highly resilient technology, and for piped water, utility management has the potential to overcome low technological resilience to enable the technology to become highly resilient. Protected springs have medium resilience, but technologies such as dug wells and household rainwater collection, which have low resilience, should be considered only as interim or supplementary solutions. For sanitation, pit latrines (both dry and low-flush) are the only form considered to be highly resilient. All other technologies are considered to have lower resilience and thus more restricted application. Management of sanitation has a much lower impact on resilience than management of water supply.

If climate resilience were taken into account, the current estimates of coverage with access to drinking-water supply and sanitation would be significantly reduced. As a consequence, the world would be badly off-track to meet both the water supply and sanitation targets. Given the limited resilience of available technologies and weaknesses in management, it is likely that – without action – there will be a loss of coverage, as communities find that their water supplies and sanitation services are not resilient to changes in climate.

Action is required now to improve resilience of services and to ensure that all new water and sanitation services take climate risks into account. Despite the significant uncertainties in climate predictions, there are clear enough signals and sufficient evidence of the weakness of technologies to justify immediate action.

6.2 Technology improvement and domestic water quantity

For those technologies identified as having medium resilience, further research would be warranted to improve their resilience and thus their scope for application. For all technologies and management approaches, it is important to document adaptations that prove successful and in particular to capture autonomous adaptations by communities, as these will provide insights beyond those of professionals. This will be of particular relevance to sanitation systems, which are largely provided and managed by households. In urban areas, a critical technology gap concerns acceptable alternatives to conventional sewerage for sanitation in dense urban settlements, to provide the same level of service, with lower requirements for water and inflexible infrastructure.

The public health benefits from an at-house water supply indicate that this should be the focus for future investments, but it is far from clear whether such supplies can be delivered through piped networks, particularly in rural areas. The development of alternative approaches using self-supply of water from tubewells or micro-systems able to serve a small number of households from a single source needs further investigation. Whether such supplies can be supported by the available water resources base and whether supply chains can be established that would enhance sustainability needs to be assessed.

The policy shift implied in switching to an approach advocating a non-piped water source for at-house water supplies is significant. In order to justify such a switch, there needs to be solid evidence that households would use the same amount of water as from a household tap and thus accrue similar health, social and economic benefits. There is therefore an urgent need for high-quality studies to quantify household water use with such forms of supply.

6.3 The need to understand the water resource base

This work has highlighted the need to improve information and understanding of available water resources. There is a lack of hydrological and hydrogeological information in developing countries, making forward planning of new water supplies extremely uncertain. This critical gap urgently needs to be filled because without a clearer understanding of available resources it will be impossible to make the significant policy shifts and undertake the programming to meet targets for higher service levels.

There is great uncertainty about the impact of climate change on groundwater, which in turn reflects the current limited knowledge on available groundwater resources, recharge and sustainable yields. It is unlikely that global truths can be identified as yet for groundwater recharge. Research to understand the impacts of climate change on groundwater at regional levels is urgently needed to help inform future decision-making.

The ongoing research efforts on glacier recession and its impacts on mountain hydrology are important. But more work needs to focus on the impacts at local levels, for instance the impact of glacier recession on springs providing the sources of water for community water supplies in mountain communities. More also needs to be understood about the increasing risks of flooding from increasing rain (as opposed to snow), and threats from hazards such as glacial lake outburst floods, and their potential impacts on water and sanitation facilities.

6.4 Climate planning

Current decadal climate prediction capability exists, and regular updates to decadal forecasts are available. However, these are at an early stage of development. More research is needed to better understand sources of decadal regional prediction skill and further development of climate models is needed to improve decadal predictions on regional scales.

It is important that all water and sanitation utilities and programmes to deliver water and sanitation undertake climate risk assessments. This is particularly important for large infrastructures with long expected lifespans. There is a need to develop and test tools for climate risk assessment that are capable of properly addressing the uncertainty associated with future climate changes. To some extent the water safety plan approach provides a framework for assessing climate risks and planning adaptation, but additional tools will be required.

Developing adaptive management of water supplies in the light of climate change, with an emphasis on building resilience, is an urgent research need. A key element will be to develop more scenario-based planning approaches, which will afford greater flexibility in developing and adapting management approaches. Such scenario planning should include plausible climate projections, as well incorporating the more predictable changes from social, economic and demographic drivers. Scenarios need to capture the likely nature of changes, for instance progressively increasing periods of drought, decreasing groundwater levels and increasing demands.

To support decision-making in selecting options, it is critical that planners ask themselves some key questions to help develop a range of climate scenarios and responses. The kind of questions that need to be asked include:

- What projected changes are likely to occur in the area?
- What are the implications for drought and floods?
- Will risks of contamination be likely to increase because of heavy rainfall events or rising groundwater levels?
- What are the emerging trends and challenges being identified from climate-related changes to water resources and supplies?
- How can these best be addressed?
- What climate, hydrological and hydrogeological data are available and where can they be obtained?
- What are the likely projections in demand (urban, rural)?
- Can projected future demands be met under the climate scenarios suggested for the area?
- What options exist for expanding services, and are there multiple sources of water available?
- Are alternative sources seriously affected by natural or man-made contamination?

The technology-by-technology fact sheets on the CD-ROM provide guidance to help planners and operators deliver more effective adaptation programmes. It is strongly recommended that significant resources are focused on supporting the water and sanitation sector to develop the tools for adapting and building resilience to change at a variety of levels, including community level. This requires funding from local, national and international sources.

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