Climate-resilient water safety plans:

Managing health risks associated with climate variability and change

World Health Organization

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Contents

Annexes

Abbreviations

CMIP	Coupled Model Intercomparison Project
CO_2	carbon dioxide
CORDEX	Coordinated Regional Downscaling Experiment
DFID	Department for International Development (United Kingdom)
DRR	disaster risk reduction
EPA	Environmental Protection Agency, United States
HACCP	hazard analysis and critical control point
IPCC	Intergovernmental Panel on Climate Change
IWA	International Water Association
IWRM	integrated water resources management
KNMI	Royal Netherlands Meteorological Society
NGO	nongovernmental organization
NTU	nephelometric turbidity unit
SWAT	Soil and Water Assessment Tool
UF	Ultrafiltration
UNEP	United Nations Environment Programme
UNISDR	United Nations Office for Disaster Risk Reduction
UV	Ultraviolet
WASH	water, sanitation and hygiene
WCI	Water Cycle Integrator
WEAP	Water Evaluation and Planning
WEDC	Water Engineering Development Centre
WHO	World Health Organization
WISE	Water Information System for Europe
WQP	World Health Organization Water Quality Partnership for Health
WSP	water safety plan

Executive summary

Long-term planning for an adequate and safe supply of drinking-water should be set in the context of growing external uncertainties arising from changes in the climate and environment. The water safety plan (WSP) process offers a systematic framework to manage these risks by considering the implications of climate variability and change.

This document is intended to help water suppliers and WSP teams who have already committed to using the WSP approach and are developing and implementing WSPs to gain greater understanding of climate change and how it can be considered and addressed in the WSP process. This document will also be useful to other stakeholders, particularly health and environment agencies who are supporting WSP implementation. It discusses how to take into consideration the broader issues of climate change, regional climate vulnerability assessments, disaster risk reduction and integrated water resources management within the WSP process. The details of how this is done for any particular WSP depend upon local circumstances.

The document identifies opportunities to enhance the WSP process and outcomes by considering the provision of safe water in sufficient quantity under changed future conditions and extreme weather events that may become more frequent and severe as the climate changes.

This guidance is aligned with the WSP modules as described in the World Health Organization/International Water Association *Water safety plan manual*. Therefore, this document is intended to be used in conjunction with the *Water safety plan manual* to ensure that climate change is considered as part of the WSP comprehensive risk assessment, management and continual improvement process.

The document presents the current state of knowledge on the impacts of climate change on the water cycle, drawing on information in the scientific literature, particularly the Intergovernmental Panel on Climate Change Fifth Assessment Report.

The document describes those modules of the *Water safety plan manual* where climate variability and change should be explicitly considered to ensure effective management of these risks through the WSP process. These modules are 1 ("Assemble the WSP team"), 2 ("Describe the water supply system"), 3–5 ("Identify hazards and hazardous events and assess the risks", "Determine and validate control measures, reassess and prioritize the risks", and "Develop, implement and maintain an improvement/upgrade plan"), 8 ("Prepare management procedures") and 9 ("Develop supporting programmes"). Key activities to be undertaken to support inclusion of climate change-related risks are described below.

The WSP team should consider past climate-related events that negatively affected the water supply system and learn about climate projections that could impact hazards and risks for the water supply system in the future. As described in modules 1 and 2 (sections 5.1 and 5.2 of this document), WSP teams may need to draw on expertise and information from other parties, such as specialists in hydrology and climatology, to understand potential climate change impacts in the context of their water supply.

When identifying hazards, assessing risks and planning improvements, as described in modules 3–5 (sections 5.3 and 5.4 of this document), WSP teams need to take a broad view of the potential risks. Changes in the climate feed into changes in environmental and social systems, which can impact the nature of the hazards and exposures ordinarily considered and introduce new hazards. Both the likelihood and severity of the consequences arising from the hazard or hazardous event are likely to change due to climate variability and change.

Modules 8 and 9 (section 5.6 of this document) of the *Water safety plan manual* cover the development of management procedures and supporting programmes. At a broad level these modules include developing programmes to build the institutional and individual capacity of water suppliers to manage risks associated with water scarcity and reliability in addition to water quality risks. These programmes include management procedures, for example emergency response plans (such as flood or drought management plans). The programmes can be used to bring together stakeholders from different disciplines to support a more catchment-based and holistic approach to managing water resources, for more resilient water supplies.

When considering climate change, and seeking to adapt to the change and improve resilience to increased climatic variability, the WSP team may identify opportunities and practices to work in partnership with others and influence their plans and programmes where these relate to the scope and implementation of the WSP.

Additional sources of information, detailed case studies and examples are provided throughout the document and as annexes at the end.

Introduction

1

1.1 Rationale for the document

The sustainable availability of safe drinking-water will be at risk unless water supply systems are resilient to both current levels of climatic variability and future change. Climate change is expected to alter the spatial distribution, timing and intensity of weather-related events. With the projection of more frequent and severe extreme weather events, climate change will create stress on freshwater resources and water quality and, therefore, the safety and security of drinking-water. These events, including higher incidence of flooding or drought, will result in adverse impacts on water supply services and pose a danger to development and human health. Population growth, urbanization and expanded industrial activities will also result in increases in water demand and exacerbate the impacts of climate change.

In the face of such anticipated climate change impacts, there is a need to improve the climate resilience of water supply services to cater for extreme weather conditions, increasing resource stresses and ensuing water quality and quantity issues. Water safety plans (WSPs), which constitute a proactive and comprehensive risk assessment and risk management approach to ensure the safety and security of drinking-water supplies, provide a valuable framework to address these issues. The World Health Organization (WHO) *Guidelines for drinking-water quality (1)* recommends water safety planning, and the WHO/International Water Association (IWA) *Water safety plan manual (2)* notes:

> *There can be a tendency for the identification of hazards to be limited to thinking about those direct inputs to the water supply system impacting microbial and chemical parameters, as these are important in terms of compliance with water quality standards. However, the approach to ensure safe water must go much wider, with consideration of aspects such as potential for flood damage, sufficiency of source water and alternative supplies, availability and reliability of power supplies, the quality of treatment chemicals and materials, training programmes, the availability of trained staff, service reservoir cleaning, knowledge of the distribution system, security, emergency procedures, reliability of communication systems and availability of laboratory facilities all requiring risk assessment.*

The principles and practice of water safety planning, and its implicit requirement that risks to drinking-water safety and security are identified, prioritized and managed before problems occur, makes it a valuable entry point to address the impacts of climate change.

1.2 Scope of the document

This document focuses on applying the WSP approach as described in the WHO/IWA *Water safety plan manual (2)* to identify and manage the risks that climate change poses to water security (quality and quantity). The document builds on previous work, including the *Vision 2030* report on the climate resilience of different water, sanitation and hygiene (WASH) technologies *(3)*, here focusing on strengthening and adapting WSPs as a highly relevant management approach to addressing climate risks. It is intended to help water suppliers that have made a commitment to use the WSP approach, or that are already developing and implementing WSPs, to gain a greater understanding of climate change issues and to support their integration within the WSP process.

The document will assist sector professionals, particularly water suppliers and WSP teams, to identify and incorporate the broader issues of climate change, disaster risk reduction (DRR) and integrated water resources management (IWRM) as important contributory approaches to the WSP process. How this is done for any WSP will depend upon local circumstances. This document also describes how water suppliers and WSP teams can best make use of information provided by other actors, such as climate vulnerability assessments at the level of the climatic or ecological zone, as inputs to their work on individual water supplies.

This document is intended to be used in conjunction with the WHO/IWA *Water safety plan manual (2)* to ensure that climate change is considered as part of the WSP comprehensive risk management and continual improvement process.

Outline of climate change impacts on water supply

2

2.1 Key messages from IPCC Fifth Assessment Report

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) *(4)* provides a global perspective on climate change impacts on water. Most of the discussion on water in the IPCC documents relates to water supply security rather than drinking-water safety. Although drinking-water safety is the focus of this document, some overview of the water supply security context is important due to the relationship between water supply security and water quality. For instance, loss of secure, safe water sources leads to the need to source drinking-water from less safe alternatives. In addition, reduced water volumes can lead to increased contaminant concentrations due to reduced dilution.

A key first point emphasized in the IPCC documents is that freshwater resources are limited. Approximately 80% of the world's population suffers threats to water supply security, as measured by indicators including water availability, water demand and pollution. Climate change will alter the availability of water and so threaten water supply security and, therefore, water quality and safety.

Climate change is increasing ambient temperatures, which affects the hydrological cycle. Mean and extreme values of most weather variables are shifting and are impacting health. This is because temperature and precipitation influence many communicable and noncommunicable diseases that are related to the quality and quantity of water. Diseases affected by climate change via water include food-, water- and vector-borne diseases, and the health consequences of undernutrition if crops fail (see section 2.4 for more on health impacts).

Those responsible for drinking-water safety need to understand how climate change is affecting water resources and the ways in which this could affect drinking-water supply systems to inform adjustments to policies, programmes and infrastructure to prepare for and cope with changing freshwater quantity and quality.

2.2 Predicted impacts of climate change on the hydrological cycle

The IPCC Fifth Assessment Report *(4)* projects:

- Increases in surface temperature, affecting the vapour-carrying capacity of the atmosphere. The magnitude and pattern of the global mean surface temperature increases vary depending on assumptions about greenhouse gas emissions.

- Less precipitation to fall as snow, resulting in snow cover decreasing in extent and duration. However, in the coldest regions, increased winter snowfall is expected to outweigh increased summer snowmelt.
- Reductions in snow and ice volumes and increases in the evaporation rate from lakes, reservoirs and aquifers due to higher ambient temperature. These changes decrease natural storage and availability of water unless precipitation increases.
- Shifts in the timing of river flows and possibly more frequent or intense droughts, increasing the need for artificial water storage.
- Global mean precipitation increases in a warmer world, with substantial variations across regions (including decreases in some locations). Precipitation is projected to decrease in subtropical latitudes, particularly in the Mediterranean, Mexico, Central America and parts of Australia, and to increase elsewhere, notably at high northern latitudes, in India and in parts of Central Asia.
- Wet regions and seasons generally to become wetter, while dry regions and seasons become drier.
- Changes in evaporation patterns similar to changes in precipitation, with moderate increases almost everywhere, especially at higher northern latitudes. Scenario-dependent decreases in soil moisture are predicted to be widespread, particularly in Central and Southern Europe, south-western North America, Amazonia and Southern Africa.

Climate change is already affecting the hydrological cycle. Examples of these effects and their causes are summarized in Table 1.

In addition to the impacts of climate change, the future of freshwater systems will be determined by demographic, socioeconomic and technological changes, including lifestyle changes. These affect exposures to weather-related hazards and requirements for water resources.

Changing land use is expected to strongly affect freshwater systems by, for example, increasing urbanization in ways that increase flood hazards. Of importance for freshwater systems is future agricultural land use, especially irrigation, which accounts for most global water consumption and severely affects freshwater availability.

Because the state of the science is continually being updated, it is important for water managers to seek out and utilize the most current information.

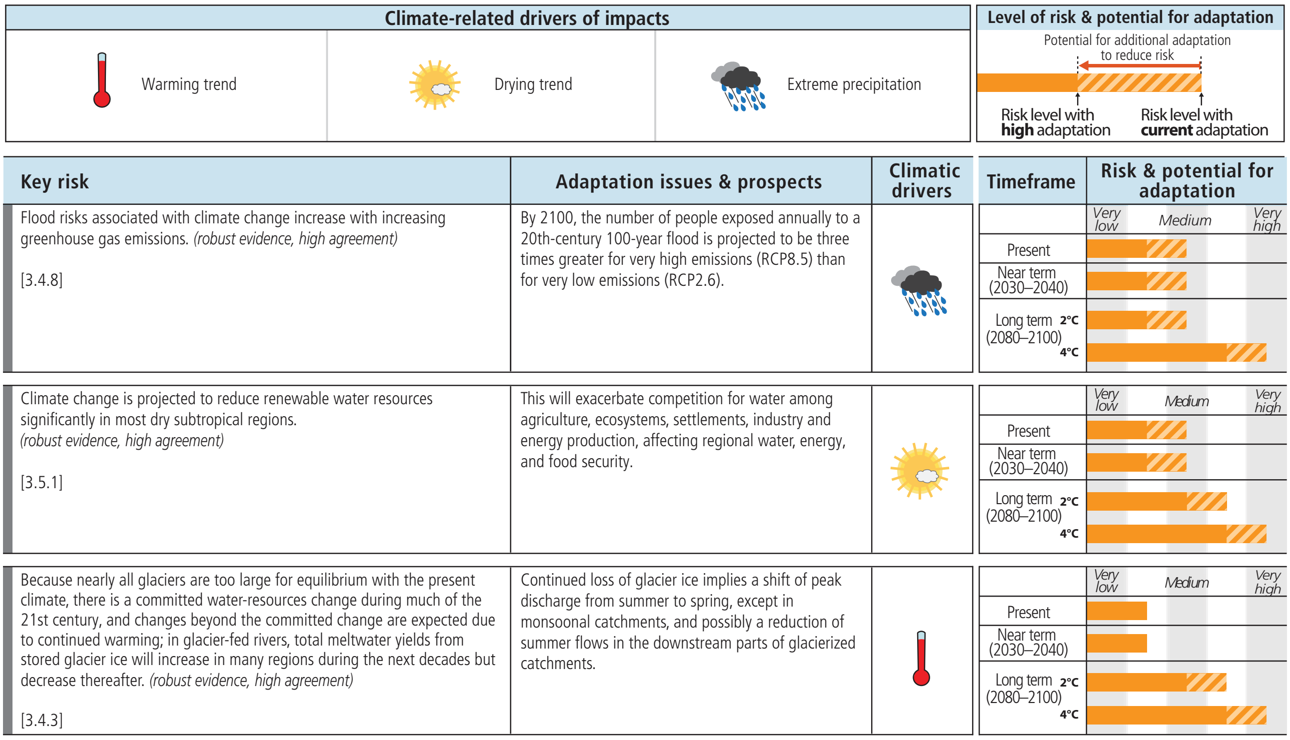
Figure 1 shows a summary of key risks from climate change for freshwater resources and the potential for reducing risk through mitigation and adaptation. Risks are presented in three time frames: the present, near term (2030–2040), and longer term (2080–2100).

Table 1. Observed impacts of climate change on the hydrological cycle

Observed change	Attributed to
Changed run-off (global, 1960–1994)	Mainly climatic change, and to a lesser degree carbon dioxide (CO_2) increase and non-climate factors such as land use change
Reduced run-off (Yellow River, China)	Increased temperature; only 35% of reduction attributable to human withdrawals
Earlier annual peak discharge (Russian Arctic, 1960–2001)	Increased temperature and earlier spring thaw
Earlier annual peak discharge (Columbia River, western United States of America, 1950–1999)	Anthropogenic warming
Glacier meltwater yield greater in 1910–1940 than in 1980–2000 (European Alps)	Glacier shrinkage forced by comparable warming rates in the two periods
Decreased dry season discharge (Peru, 1950s–1990s)	Decreased glacier extent in the absence of a clear trend in precipitation
Disappearance of Chacaltaya glacier, Bolivia (2009)	Ascent of freezing isotherm at 50 metres per decade, 1980s–2000s
More intense extremes of precipitation (northern tropics and mid-latitudes, 1951–1999)	Anthropogenic climate change
Flooding events (England and Wales, autumn 2000)	Extreme precipitation attributable to anthropogenic climate change
Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, and possibly increased temperature; multiple confounding factors
Decreased groundwater recharge (Kashmir, 1985–2005)	Decreased winter precipitation
Increased dissolved organic carbon in upland lakes (United Kingdom, 1988–2003)	Increased temperature and precipitation; multiple confounding factors
Oxygen depletion in a reservoir, moderated during El Niño Southern Oscillation episodes (Spain, 1964–1991 and 1994–2007)	Decreased run-off due to decreased precipitation and increased evaporative demand
Variable faecal pollution in a saltwater wetland (California, 1969–2000)	Variable storm run-off; 70% of coliform variability attributable to variable precipitation
Nutrient flushing from swamps, reservoirs (North Carolina, 1978–2003)	Hurricanes
Increased lake nutrient content (Victoria, Australia, 1984–2000)	Increased air and water temperature

Source: IPCC *(4)*.

Figure 1. Key risks from climate change for freshwater resources and the potential for reducing risk through adaptation



Source: IPCC *(4)*.

2.3 Climate impacts on water resources

It is difficult to accurately predict the extent and nature of changes to the hydrological cycle and the associated impacts on water resources at fine spatial scales. There will be high variability in impacts across spatial and temporal scales. Overall, climate models predict decreases of renewable water resources in some regions and increases in others, with large uncertainty in many places *(4)*. Broadly, water resources are predicted to decrease in many mid-latitude and dry subtropical regions and to increase at high latitudes and in many humid mid-latitude regions. Even where increases are predicted, there can be short-term shortages due to more variable stream flow (because of greater variability of precipitation) and seasonal reductions of water supply due to reduced snow and ice storage.

Climate change affects the quality of water through a complex set of natural and anthropogenic mechanisms working concurrently in parallel and in series *(4)*. Projections under climate change scenarios are difficult to perform and interpret because they require not only integration of the climate models with models used to analyse the transportation and transformation of pollutants in water, soil and air, but also the establishment of a proper baseline. Therefore, there are few projections of the impacts of climate change on water quality and, where available, their uncertainty is high. It is evident, however, that water quality projections depend strongly on (a) local conditions; (b) climatic and environmental assumptions; and (c) the current or reference pollution state.

The IPCC Fifth Assessment Report concluded that climate change is confronting water suppliers with a range of challenges, including those described below *(4)*. While the challenges presented below focus on the direct impacts on water quality, it is important to bear in mind indirect impacts on water quality as well, such as frequent and severe forest wildfires degrading water quality for cities that rely on water from forested catchments. Many drinking-water treatment plants, particularly small ones, are not designed to handle the more extreme influent variations expected with climate change. These demand additional or different infrastructure, which renders water treatment very costly, particularly in rural areas.

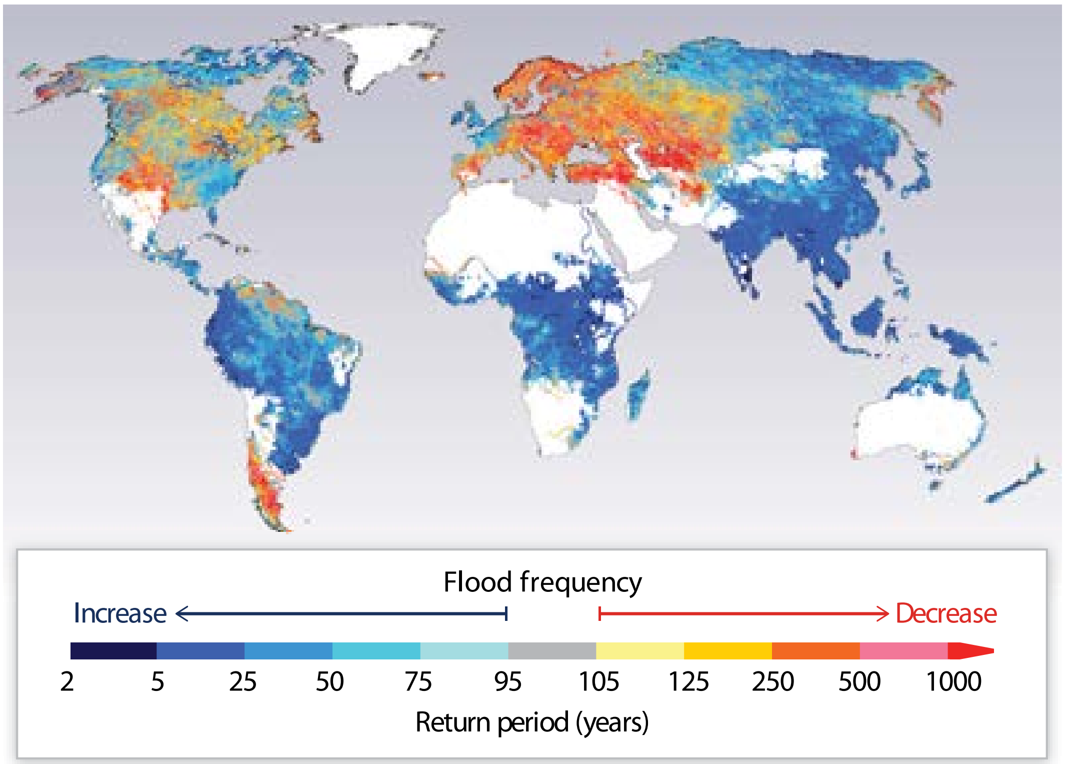
2.3.1 More intense precipitation and flooding

The IPCC predicts that changes in the water cycle over the next few decades will show similar large-scale patterns to those recently observed, namely substantial increases in heavy precipitation events in more regions than will experience decreases, but there are strong regional and subregional variations in the trends. Regarding the magnitude or frequency of flooding, there is lack of evidence in relation to the sign of the trend at global scale *(5)*. Changes in the near term and at the regional scale will be strongly influenced by natural internal variability and may be affected by anthropogenic aerosol emissions.

Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will probably become more intense and more frequent by the end of this century. From a drinking-water safety perspective, more intense precipitation events are often associated with reduced short-term water quality. Turbid, contaminated water can arise due to upstream soil erosion. Floods can also overwhelm storm water and wastewater containment systems and potentially overwhelm water treatment and distribution systems. In principle, pathogens, nutrients and hazardous chemicals may be diluted by higher flows. In practice, however, overwhelming of containment systems (both engineered and natural attenuation mechanisms) usually means that higher concentrations of pathogens and hazardous chemicals are present in water during higher flow periods – particularly the first flush. Widespread flooding events may become more intense and more common due to more intense rainfall.

Figure 2 shows examples of changes in the predicted return periods for floods. There is high variability in the emission scenarios affecting the magnitude of change in return periods. Nevertheless, a potentially large number of people could be exposed, particularly under high emission scenarios.

Figure 2. Change in the multimodel median return period in years in the 2080s for a flood that would have occurred on average once every 100 years during the 20th century



Source: IPCC *(4)*.

2.3.2 Increased drought

It is predicted that droughts will intensify in the 21st century in some seasons and areas due to reduced precipitation or increased evapotranspiration *(6)*. This applies to regions including Southern Europe and the Mediterranean region, Central Europe, central North America, Central America and Mexico, north-east Brazil, and Southern Africa.

From a drinking-water safety perspective, increased drought is often associated with longer-term poorer water quality. Whereas more intense precipitation events tend to mobilize contaminants into water, once present within water, low flows and reduced water levels tend to increase the concentration of pollutants and nutrients. Pollutant concentrations increase when conditions are drier. This is of concern for groundwater sources that are already of low quality, such as in certain locations in India and Bangladesh, North and Latin America, and Africa, where concentrations of arsenic, iron, manganese and fluorides are often problems *(4)*. Within large water reservoirs, higher temperatures and reduced flows can reduce dissolved oxygen levels. This less oxygenated water can release increasing benthic nutrients (for example phosphorus), in turn promoting elevated phytoplankton activity and the release of metals (for example iron and manganese) from lake sediments into the water body. In areas with less freshwater, there will be increased competition for those resources, and water suppliers will increasingly need to compete with other users for access to water allocations. Further, drought often leads to increased dependence on potentially less safe alternative water sources that might otherwise be avoided.

2.3.3 Increased temperature

From a drinking-water safety perspective, higher temperatures can result in increased cyanobacterial blooms and, accordingly, increased risks from cyanotoxins and natural organic matter in water sources. Warmer, less oxygenated water may also result in higher levels of certain metals, phosphorus and phytoplankton (see 2.3.2). These impacts may require additional treatment of drinking-water.

Within distribution and storage infrastructure, increased temperatures, possibly combined with reduced flows from restricting water use, provide more favourable conditions for some mesophilic opportunistic pathogens, for example *Naegleria fowleri*. Increased temperatures reduce the stability of chlorine residuals, further exacerbating problems in controlling opportunistic pathogens. At the same time, disinfection by-products will increase.

2.3.4 Sea level rise

Coastal groundwater will be affected not only through changes in groundwater recharge but also through sea level rise. Sea level rise combined with the rate of groundwater pumping determines the location of the saltwater–freshwater interface. Although most confined aquifers are expected to be unaffected by sea level rise, unconfined aquifers could suffer from saltwater intrusion *(4)*. The volume available for freshwater storage is reduced if the water table cannot rise freely as the sea level rises. This happens where land surfaces are low lying, for example on many coral islands and in deltas, but also where groundwater discharges to streams.

From a drinking-water safety perspective, any saltwater intrusion into drinking-water can increase water treatment costs for salt removal (*7*).

2.4 Potential impacts on health

As outlined in section 2.1, diseases affected by climate change via water are primarily food-, water- and vector-borne. Health impacts can also occur due to increased exposure to pathogens or chemicals in drinking-water and because of undernutrition if crops fail. Table 2 summarizes the main causal pathways by which exposures related to climate variability and change determine health impacts, primarily via drinking-water quality and quantity, and for which climate-resilient WSPs have the potential to contribute to reduced disease rates.[1]

[1] There are other pathways through which climate change may affect water availability and hence health, such as droughts elevating airborne dust levels and increasing risks of meningococcal meningitis in Africa. These are excluded from the table, as they are not strongly mediated by water supply systems, and therefore not clearly manageable through WSPs.

Table 2. Health impacts of climate variability and change exposures: causal pathways

Exposures affected by climate change	Potential impacts on water resources	Potential health and other impacts
Increased average temperatures	Accelerated growth, survival, persistence, transmission and virulence of waterborne pathogens, compounded by reduced stability of chlorine residuals Increased formation of disinfection by-products	Increased risks of foodborne and waterborne diseases from pathogens Possible increased risk of cancer with long-term exposure to disinfection by-products
Increased drought	Lower water availability for washing, cooking and hygiene, increasing exposure to waterborne contamination Increased concentration of pollutants when conditions are drier. This is of concern for groundwater sources that are already of low quality, for example in certain locations in India and Bangladesh, North and Latin America, and Africa, where concentrations of arsenic, iron, manganese, and fluoride are often problems Reduced groundwater tables and surface water flows may cause wells to dry up, increasing the distances to be travelled to collect (potentially unsafe) water, and increasing water source pollution Low rainfall may increase vector breeding sites by slowing river flow Decreased food security Lower food production in tropics; lower access to food due to reduced supply and higher prices	Increased burden of foodborne and waterborne disease Fluoride: dental and skeletal fluorosis Arsenic: skin changes (pigmentation changes, (hyperkeratosis), cancer (skin, bladder, lung), etc. Iron and manganese: discoloured water, unpleasant taste Increased risk of health impacts associated with malnutrition resulting from interaction of diminished food production and intake in poor regions, and higher rates of infectious disease Combined effects of undernutrition and infectious diseases; chronic effects of stunting and wasting in children
More extreme precipitation events	Lack of water for hygiene, flood damage to water and sanitation infrastructure, and contamination of water sources through overflow Heavier rainfall events and storm run-off, causing increased loading of pathogens, chemicals, and suspended sediment in surface waters Flooding causing overflow and contamination from sewerage systems, particularly where infrastructure is poor Long-term rainfall increases causing rising groundwater levels, which may decrease the efficiency of natural purification processes Increased surface water may expand breeding sites for vectors and increased rain may favour vegetation growth and allow expansion in population of vertebrate hosts. Flooding may also force vertebrate hosts into closer contact with humans Very high rainfall can reduce populations of insect vectors and intermediate hosts of infectious diseases (e.g. schistosomiasis) by flushing larvae from their habitat in pooled water	Increased risks of foodborne and waterborne diseases and of exposure to potentially toxic chemicals Increased or decreased risk of vector-borne diseases, depending on local ecology

Exposures affected by climate change	Potential impacts on water resources	Potential health and other impacts
Higher freshwater temperatures (with increased concentration of nutrients, such as phosphorus, and other factors)	Shifting geographical and seasonal distributions of e.g. *Vibrio cholerae* and *Schistosoma* spp. Increased formation of cyanobacterial blooms in freshwater Warmer, less oxygenated water can release increasing benthic nutrients (e.g. phosphorus), in turn promoting elevated phytoplankton activity, and release metals (e.g. iron and manganese) from lake sediments into the water body	Increased risks of foodborne, waterborne and water-based diseases such as cholera and schistosomiasis Liver damage, tumour promoter, neurotoxicity (longer-term effects depending on toxin exposed to)
Sea level rise	Coastal areas experiencing sea level rise may become uninhabitable and influence population displacement or force currently secure water sources out of use because of saline intrusion Sea level rise that increases the salinity of coastal aquifers, where groundwater recharge is also expected to decrease	Increased risk of waterborne diseases, health impacts of high salt consumption on noncommunicable diseases

Note: Exposures affected by climate change are based on IPCC *(4)*; potential health risks and impacts are based on WHO *(2)*, Hunter *(8)* and Bouzid, Hooper and Hunter *(9)*.

3 Regional climate vulnerability assessments for WSPs

Why this is important

To strengthen climate resilience through the WSP process, it is important to understand current and future risks posed by climate variability and change, which are often similar across a climatic or ecological zone. WSPs at the local scale could therefore benefit from the assessment of the vulnerability of water resources at a regional scale. This regional climate vulnerability assessment will provide important inputs into the WSP process.

Section 2 described some of the potential risks posed by climate to a safe and adequate water supply. To effectively address climate risks through the WSP process, WSP teams must understand which of the potential risks described are relevant to their own systems. For instance, a WSP team needs to understand the potential for temperatures in their area to increase in order to assess and manage an increased risk of cyanobacterial blooms. This sort of information can be derived from a climate vulnerability assessment, which involves an assessment of historical data and is ideally based on an analysis of future scenarios. As changes in climate are likely to be similar across a region that shares certain characteristics (that is, a climatic or ecological zone), it is recommended that regional climate vulnerability assessments are undertaken at a scale ranging from sub-basin level to continental level.

For example, meltwater from glaciers in the Himalayas contributes significantly to river systems and water resources in much of South Asia. For a water utility preparing a WSP, it is important to understand how this source of water may be affected by climate change on a regional scale. A regional climate vulnerability assessment may address such questions as: Will the seasonal pattern of river flows be affected? If glacial melt increases, will the availability of water increase in the short term? If glaciers continue to melt and retreat, will this reduce water resources in the longer term?

Understanding how climate variability and change are already affecting and are expected to impact water resources and water supply is a demanding task that could require expertise in climatology, hydrology, hydrogeology, statistics and environmental health. Regional assessments may be developed by regional or national governments, international organizations, NGOs and academic institutions. They may range from very sophisticated and comprehensive assessments to coarser simplified approaches.

This section will describe the following:

- the scope and purpose of a regional climate vulnerability assessment;
- the inputs and components of a regional climate vulnerability assessment;
- the relevant outputs of a regional climate vulnerability assessment;
- where a regional climate vulnerability assessment may be obtained;
- tools available for a regional climate vulnerability assessment.

3.1 Scope and objective of the assessment

The literature on vulnerability to climate change is extensive and many frameworks for assessing vulnerability have been proposed. The IPCC adopts an approach that defines vulnerability to climate change as "the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate variability and change" *(10)*. Vulnerability is described as a function of the exposure to certain climate risks, the sensitivity of the system, and the capacity of the system to adapt.

The focus of this section is on the exposure component of vulnerability. The objective of a regional climate vulnerability assessment, in the context of a WSP, is to provide WSP teams and other relevant stakeholders in a geographical area with information on the key climate impacts to inform the WSP process. This typically means assessing the current and future variability of factors such as rainfall, temperature and evapotranspiration, and how they might affect water supply. A simple example is the magnitude and likelihood of extreme flooding, and how this may change under future climate scenarios. Guidance on the more extensive vulnerability and adaptation assessments, which incorporate how societies can respond or adapt, has been developed by the United Nations Framework Convention on Climate Change *(11)*. WHO has produced similar guidance for conducting vulnerability and adaptation assessments, specifically tailored for the health sector *(12)*.

Climate vulnerability assessments can cover a range of scales. At the global scale, assessments have been made of the effect of climate change on water scarcity *(13)* and flood risk *(14)*. The IPCC Fifth Assessment Report on the impacts of climate change reported on nine separate regions, including each continent as well as polar regions and small islands *(15)*. At the continental scale, Eisenreich et al. *(16)* reported on the knowledge of climate change impacts across Europe for the European Environment Agency. The 2014 National Climate Assessment conducted by the United States Government divided the United States into 10 regions. Commonly, water resources assessments are undertaken from the river basin scale, such as for the Rhine *(17)*, to much smaller basin or sub-basin scale. Finally, it is possible to assess climate change vulnerability over regions that contain similar climatic or biophysical characteristics (for example Padgham et al. *(18)*, studying semi-arid regions in West Africa).

Guidance on how to incorporate the results of a climate vulnerability assessment into a WSP is described in section 5.

3.2 Inputs and components of the assessment

The complexity of regional climate vulnerability assessments can vary significantly. At its most simple, a regional climate vulnerability assessment can be based upon the collection and review of historical information on events such as floods and droughts. Records can be found in sources such as newspapers and official records. Historical data on climate- and hydrology-related parameters such as precipitation, temperature, sea levels and river flows can be used to assess their variability, including the likelihood and magnitude of extremes, and to identify any trends.

While a review of historical data is useful, there are limitations, and to assess future risks in a changing climate, modelling of climate and other processes may be required. This can result in a chain of models. At the highest level, general circulation models represent the interaction between the atmosphere, oceans, ice caps (cryosphere) and the land over the planet to produce estimates of climate variables such as temperature and precipitation, and how they are affected by different atmospheric concentrations of greenhouse gases. These global models operate at a resolution that can range from 100 to 500 km. The models require scenarios of greenhouse gas emissions that are typically derived from the IPCC, based on assumptions about factors such as population and economic growth, the adoption of less carbon-intensive technologies and the structure of the global economy.

Many general circulation models have been developed by different scientific groups around the world, and their outputs can be obtained from the World Climate Programme's Coupled Model Intercomparison Project (CMIP). To make the outputs of these models useful for regional analysis, they must be refined to a finer scale (or "downscaled") using a variety of techniques, such as regional climate models.

The outputs of these models can then be used in hydrological or water resources models at the regional scale. These models vary in their complexity and scale, ranging from those that "lump" or aggregate the characteristics of a catchment into a single unit, to those that divide the catchment into drainage basins or even finer-resolution grids that represent how variables such as land cover and soil type vary across the catchment. These models use input data that can classified as biophysical (soils, topography and vegetation), hydrometeorological (precipitation, temperature), socioeconomic (population, land cover) and water use (water demand per person). Data on infrastructure such as reservoirs and their operating rules can be required. Given the significant effect of land cover on key hydrological processes, scenarios of land use change based on trends such as urbanization may also be required. Although a multitude of modelling tools exist, two are briefly described in section 6.1.1.

As well as hydrological or water resources system models, other models may be used, such as:

- hydraulic models that can be used to estimate the extent of flooding from rivers;
- oceanographic models to estimate sea level rise, which can affect the risk of coastal flooding and saltwater intrusion;
- groundwater models that can be used to model the behaviour of aquifers and their recharge.

Given the complex chain of modelling, and the assessment of historical data, a regional climate vulnerability assessment could require the expertise of climate modellers, data analysts, hydrologists, and engineers, as well as economists and social scientists.

3.3 Relevant outputs

A regional climate vulnerability assessment could produce the following information that is useful for the WSP.

- A detailed understanding of the climate risks, such as flooding, increased sea level rise, and saltwater intrusion, that could impact water supply and safety.
- Projections of changes to key parameters, such as precipitation, temperature and river flows, under climate change scenarios. Average values are useful as well as information on the extremes. These could include the number of hot days or intense precipitation.
- Information on the likelihood and magnitude of extreme weather events, such as storms, floods and droughts, in both the current and future scenarios.
- Implications for water resources in the region, such as the threats to existing sources and the need to identify new water sources.

There may be significant uncertainty in the outputs of regional climate vulnerability assessments because of the uncertainties associated with input data and the model structure. A relatively common approach is to apply a safety factor to a model output, such as the estimated peak river flow, which involves increasing that value by a fixed amount (for example 20%). The United Kingdom Environment Agency, for instance, recommends using medium, high and upper bound values for increases to peak river flow across 11 regions *(19)*. Upper bound values might be applied in the case of critical infrastructure, such as water supply and treatment plants.

3.4 Sources of regional climate vulnerability assessments

There are various sources of regional climate vulnerability assessments.

- International organizations: The IPCC reported on potential impacts of climate change on key parameters for nine regions (including by continent as well as polar regions and small islands) in its Fifth Assessment Report. Other organizations holding information on regional climate vulnerability include the United Nations Environment Programme (UNEP) and World Meteorological Organization (see section 6.2 – CMIP and CORDEX). In Europe, many data and much information on water and climate can be accessed through the Water Information System for Europe.
- National and regional governments: An example is the United States National Climate Assessment *(20)*. National meteorological services and water ministries often hold information on climate variability and vulnerability to climate change.
- Academic institutions: There is much information in the scientific literature on vulnerability to climate change, through research projects. However, this information may be highly technical and access to the literature may be limited because of the cost of journal subscriptions.
- NGOs working nationally or internationally may have access to studies and data. A case study on the lower Mekong is cited in section 3.5.2.

Several online tools exist that provide information and data on climate risk (see section 6.2.1 for a few brief examples), and there are ongoing projects to develop further tools.

A significant challenge with the use of regional climate vulnerability assessments is that they focus on individual aspects that may affect the water supply system, such as changes in precipitation, flooding or groundwater, but do not take a comprehensive view. Therefore, the WSP team may need to use and review multiple sources of information.

3.5 Case studies

Annexes to this document present five case studies on the importance of integrating climate risks into WSPs. Two brief case studies on regional climate vulnerability assessments and how they can inform a WSP are presented below.

3.5.1 East Bay, California, United States

The United States Environmental Protection Agency (EPA) reported on an assessment made by the East Bay Municipal Utility District of its vulnerability to climate change *(21)*. Two separate statewide climate vulnerability assessments were reviewed; one by the California Energy Commission's Public Interest Energy Research and the California Climate Change Center, and one by the California Department of Water Resources. These two studies made several relevant conclusions – for example, snow will melt earlier in the season. Changes in total annual precipitation and impacts on droughts were inconclusive, but some scenarios predicted increased frequency and duration of droughts. It was reported that climate variability would generally increase. All this information could be used directly by the East Bay Municipal Utility District to develop plans to tackle the impacts of flooding, sea level rise, temperature increases, and droughts through reduced precipitation on water supply, demand and quality as part of its Water Supply Management Program.

3.5.2 Lower Mekong, Thailand and Lao People's Democratic Republic

A study was undertaken by the NGO START International to assess the impacts of climate change over the lower Mekong River valley, focusing on the tributaries in Thailand and Lao People's Democratic Republic *(22)*. The study used climate scenarios and a climate model developed by the Commonwealth Scientific and Industrial Research Organisation in Australia, joined with several hydrological models of each sub-basin. The study showed that the number of hot days (defined as greater than 33°C) could increase by as much as two to three weeks per year. The study also projected possible precipitation increases of between 10% and 30%, especially in the eastern and lower regions of Lao People's Democratic Republic. The study also showed that most sub-basins would have higher river discharges, although in dry years discharges could be lower. This information has implications for the availability of water, the likelihood of flooding and the demand for water.

Resilience and adaptation

4

Resilience and adaptation are common themes throughout this document. Box 1 shows the IPCC definitions for these two concepts.

Box 1. IPCC definitions of resilience and adaptation

Resilience: "The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation."

Adaptation: "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects."

Source: IPCC glossary *(23)*.

Although both terms are sometimes used interchangeably, they are different. In relation to health systems, WHO considers that "resilience relates to the capacity of the system itself to cope with and manage health risks in a way that the essential functions, identity and structure of health systems are maintained. While health adaptation seeks to moderate harm or exploit beneficial opportunities, the preservation of a certain level of quality and sustainable performance of the system itself is not ensured" *(24)*. The incorporation of a climate-resilient approach to health and water systems contributes to ensuring the performance of the system and therefore to sustainability and maximization of value for money of health and water investments. However, when the magnitude of climate-induced changes or shocks is significant, maintaining system resilience may not always be possible, and the system may collapse or fail. Within this guidance, adaptation (or control) measures that strengthen the resilience of the water system itself are promoted.

Increasing the adaptation and resilience of water supply systems to climate change risks requires long-term planning for continuing access to freshwater sources; managing water demand among competing needs; reviewing the resilience of the supply system itself; addressing policy needs, such as for water storage and flood control; implementation of control measures to ensure water quality (and quantity); and improving operation and maintenance to ensure continued effectiveness of control measures. The WSP process provides an effective framework to systematically address many of these requirements to improve adaptation and resilience.

As climate risks to water supply systems manifest through both increased frequency of extreme events and long-term stresses on water resources availability and quality, two complementary approaches are relevant and should be considered through the WSP process. Disaster risk reduction (DRR) focuses on mitigating exceptional events, principally through improving resilience; and integrated water resources management (IWRM) provides a framework for adaptation to the long-term changes associated with climate change.

4.1 DRR in the water safety planning context

The United Nations Office for Disaster Risk Reduction (UNISDR)[2] defines a disaster as "a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources".

Disaster risk aggregates the likelihood of the occurrence of disasters with their consequences through "the losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period". Disasters disrupt the normal function of a system and are usually caused by some external influence. For water supply systems, a disaster could disrupt the infrastructure itself (for example the integrity of the distribution network), the operation of the system or the safety of the water source. Floods and droughts are the natural hazardous events linked most closely to climate change that can affect water supply systems.

The related concept of DRR is the "practice of reducing disaster risks through systematic efforts to analyse and manage the causal factors of disasters, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events". Box 2 describes frameworks for DRR.

A national strategy for DRR would cover the whole range of potential extreme weather events and associated hazards that threaten an area and so should consider the continuity of safe water supplies, as by their nature and function public water supply systems may be designated as critical national infrastructure. Extreme weather events may directly impact the components of the water supply system (for example fracturing of pipelines, exceptional loading of pollutants and pathogens, or the potential failure of reservoirs). They may also lead to failure of external infrastructure that indirectly impacts water safety and security of supply, such as loss of power or transport disruption. By considering relevant types of disasters and their potential consequences through the WSP process, the WSP can contribute to DRR through better preparedness and contingency planning to facilitate water safety in an emergency as well as faster recovery of normal functions after an event.

Section 5.6.1 explains the links between DRR and the preparedness for incidents, disasters and extreme events that are part of every WSP.

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[2] http://www.unisdr.org/we/inform/terminology.

Box 2. DRR frameworks

In 2005, governments around the world committed to take action on DRR and adopted the Hyogo Framework for Action, which covered the decade to 2015.

Five principles of the Hyogo Framework for Action are:

- make DRR a priority: ensure that DRR is a national and a local priority with a strong institutional basis for implementation;
- know the risks and take action: identify, assess, and monitor disaster risks, and enhance early warning;
- build understanding and awareness: use knowledge, innovation, and education to build a culture of safety and resilience at all levels;
- reduce risk: reduce the underlying risk factors;
- be prepared and ready to act: strengthen disaster preparedness for effective response at all levels.

A post-2015 framework for DRR was agreed in Sendai, Japan, in March 2015. The Sendai Framework for Disaster Risk Reduction 2015–2030 *(25)* aims to achieve "the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries", and includes the following priority areas:

- understanding disaster risk;
- strengthening disaster risk governance to manage disaster risk;
- investing in disaster risk reduction for resilience;
- enhancing disaster preparedness for effective response, and to "build back better" in recovery, rehabilitation and reconstruction.

4.2 IWRM in the water safety planning context

Integrated water resources management (IWRM) is defined[3] as "the process which promotes the coordinated development and management of water, land, and related resources in order to maximize economic and social welfare without compromising the sustainability of vital environmental systems". The basis of IWRM is that water resources are finite and many different uses are interdependent. Water policy and management need to reflect the fundamentally interconnected nature of hydrological resources, and IWRM is the accepted alternative to the former sector-by-sector, top-down style of water management that dominated in the past. IWRM helps to protect the global environment, fosters economic growth and sustainable agricultural development, promotes democratic participation in governance, and improves human health.

The water resources used for drinking-water are subject to a wide range of quality, reliability and scarcity risks outside the control of the water sector. Climate change can exacerbate risks to water supplies, reinforcing the need for IWRM as a tool to support continued resilience of water supplies in a changing climate. Good water resources management will be critical in building resilience and in supporting adaptation to inevitable changes *(26)*. Box 3 sets

3 http://www.gwp.org/The-Challenge/What-is-IWRM/.

out the case for using IWRM approaches to support resilient water supplies as articulated in WHO Vision 2030 *(3)*.

Box 3. IWRM and climate-resilient water supply

Drinking-water accounts for only 15% of overall water use globally and often less in low-income countries *(27)*. At least 70% (considerably more in some countries) is used for agriculture. The temperature increase that is driving climate change will increase evapotranspiration and, consequently, agricultural water demand in many regions. Water for drinking and other domestic purposes must also compete with industry, power, recreation and the environment, each of which can 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 IWRM, it is critical that drinking-water supplies are protected to ensure both the quality and sufficient quantity of water.

Climate change will increase the urgency for better uptake and implementation of IWRM, to improve water efficiency, build resilience and support adaptation *(26)*. 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 other water-using sectors such as 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.

IWRM tools offer a range of adaptation options that can directly or indirectly help to reduce levels of risk to water supply systems. Many IWRM tools relate to the institutional and governance arrangements for water management rather than direct control measures. For example, developing environmental water quality and pollution regulations and enforcing these will help reduce the risks of source water contamination. Stakeholder engagement, including with catchment stakeholders and environmental regulators, is encouraged within the WSP process. While not all catchment management issues can be feasibly considered within the scope of a WSP, the protection of drinking-water resources requires a collaborative and strategic effort between a range of stakeholders, including the water supplier and WSP team.

Water suppliers should be aware of the broader water resources systems within which they operate, looking beyond the sources and into the catchment processes that sustain water supplies to assess risks and explore opportunities. For example, pressure on scarce source water can be reduced by safely using wastewater for agricultural irrigation. In well managed systems, the use of wastewater provides benefits not only to the drinking-water supplier but also to farmers by providing a reliable, affordable and nutrient-rich irrigation water source

(Box 4). Engaging with a range of catchment stakeholders will be critical to identify risks and opportunities outside the direct sphere of influence of the water supplier itself.

Section 5.6.2 provides guidance on how WSPs can incorporate IWRM to increase the resilience of water supply systems.

Box 4. Safe use of wastewater in agriculture

Water for agricultural irrigation consumes up to 70% of freshwater resources, placing pressure on water availability for drinking-water supplies, especially in water-scarce areas. Wastewater can be used as an alternative for irrigation purposes in order to mitigate climate change risks to water suppliers facing increased water scarcity.

Wastewater is a year-round source of irrigation water that contains valuable nutrients. It is therefore an attractive alternative water supply for farmers, as it offers a steady affordable supply of water and nutrients and reduces the need to buy chemical fertilizers.

However, use of wastewater poses health risks that need to be managed in order to protect farm workers and consumers of farm produce, and to address negative public perceptions of this practice. Moreover, national standards and regulations for wastewater treatment disposal and use are often fragmented across ministries and require a coordinated effort among responsible agencies to amend.

The WHO *Guidelines for the safe use of wastewater, excreta and greywater (28)* provide policy and regulatory guidance and a risk assessment and management framework using the same hazard analysis and critical control point (HACCP) principles as water safety planning. The WHO manual on *Sanitation safety planning (29)* provides practical guidance on risk assessment, monitoring and control measures for wastewater use that can be used to complement the WSP process.

5 Integration of climate change into the WSP process

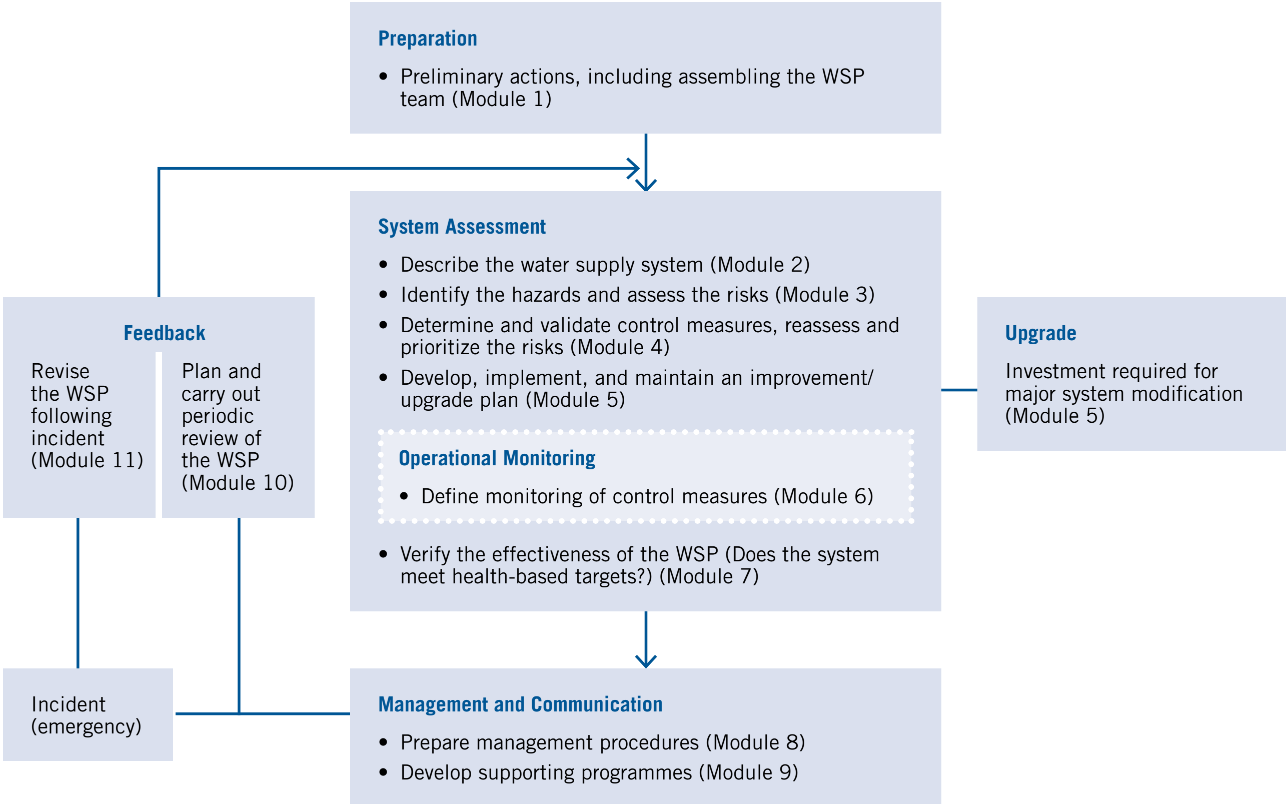
Why this is important

Planning for safe water supply in sufficient quantity in the long term is set in the context of growing external uncertainties arising from changes in the climate and environment. The WSP offers a framework to manage these risks by considering the implications of climate variability and change at various points in the WSP process. This section sets out the key considerations aligned with the WSP approach.

The WHO/IWA *Water safety plan manual (2)* provides practical guidance to support WSP development and implementation for water supplies managed by a water utility or a similar entity. The manual is broken down into 11 modules, as shown in Figure 3. This section identifies specific considerations for identifying and managing risks posed by climate change in a number of the modules and should be used to supplement the *Water safety plan manual* to strengthen the climate resilience of water supply systems.

The *Water safety plan manual* modules addressed in this document (modules 1–5, 8 and 9) are those that should explicitly consider climate change to ensure sufficient management of climate-related risks through the WSP process. For those modules not covered in this document, it is expected that appropriate consideration of climate-related issues will follow from explicit consideration of climate issues in the modules addressed in this document, with no additional guidance necessary for these modules. For example, additional control measures required to manage climate-related risks are explicitly addressed in this document (part of module 5). When WSP teams go on to define control measure monitoring plans in module 6, it is expected that climate-related controls will be considered alongside all other controls without any additional guidance required.

Figure 3. Overview of the WSP



Source: WHO *(2)*.

5.1 Module 1 – Assemble the WSP team

5.1.1 Seeking additional expertise

Why this is important

The WSP team normally consists of water supply system operators, managers and technical specialists, and often representatives from the health and environmental sectors. However, to consider and address the effects of climate change, WSP teams may require additional support in obtaining and interpreting climate-related information.

WSP teams should consult experts as needed to provide the evidence and information necessary to inform climate-related system description, hazard identification, risk assessment and improvement planning. These experts can help the WSP team gather and interpret information to support the integration of climate considerations into the WSP process, such as the results of any regional climate vulnerability assessments undertaken (see section 3).

Individuals whose expertise could add value when developing or revising the WSP to consider risks associated with climate change may include:

- a climatologist specializing in impacts and adaptation planning;

- a hydrologist or hydrometeorologist to advise on the possible climate impacts for the region of interest on water resources;
- a public health or water quality specialist who can advise on the health impacts of projected climate-related water quality changes;
- an emergency planning or civil protection expert to advise on DRR;
- a water planner with operational experience in a region where the current climate is similar to that likely to be faced in future in the WSP area;
- a water resources specialist with experience in water resources development across sectors and strategic water supply planning;
- other specialists, as required, to assist with the risk assessment for any new sources or water management arrangements that are under consideration.

5.2 Module 2 – Describe the water supply system

5.2.1 Describing current and future conditions that impact climate-related hazardous events

Why this is important

A detailed description of the water supply system is essential to support the hazard identification and risk assessment that are central to a WSP (see modules 3 and 4). To build climate resilience through the WSP process, the WSP team must gather sufficient information to understand and address vulnerability to climate-related risks.

When describing the water supply system, the WSP team should consider current and future (projected) conditions that have the potential for climate-related impact on water resources or the water supply system infrastructure. To gather the required information, WSP teams should draw on the experience and knowledge of core WSP team members and, where possible, on the expertise and guidance of additional advisers as described in 5.1.1.

Examples of system information that will support climate-related hazard identification and risk assessment include:

- reliability of source yields (considering seasonal variability and variability between years, for example due to droughts);
- historical water quality data and relationship with source yields;
- history and trends of extreme weather events (for example floods and droughts);
- future climate projections that could impact the water supply;
- water quantity and quality implications of current and projected climatic conditions;
- potential new or alternative sources;
- trends in land use and population growth impacting water resources supply or demand;
- other water abstracters in the catchment and their patterns of abstraction under normal and drought conditions.

WSP teams and expert advisers can obtain some of this information by reviewing the outputs of existing studies. For example, existing water resources assessments or basin management plans can provide valuable information on population growth or urban development that may increase water demand. The outputs of a regional climate vulnerability assessment will be particularly useful to WSP teams and should be consulted wherever available, as these assessments focus on current and projected climate scenarios and the associated impacts on water resources. Box 5 provides more information on the value of reviewing regional climate vulnerability assessments during the system description step of the WSP process.

Box 5. Regional climate vulnerability assessments to inform the system description

Regional climate vulnerability assessments can help WSP teams to understand which potential climate-related risks are relevant for their own water supply systems. As changes in climate are likely to be similar across a region – that is, a climatic or ecological zone – the assessments do not need to be undertaken at a water supply system level. Rather, the assessments can be undertaken at a broader level, for example the basin or continental level, by experts from regional or national governments, international organizations, NGOs and academic institutions. WSP teams should review the outputs of these assessments to gain an understanding of projected climate changes in their region and how the changes could impact their water supply systems and their WSPs.

WSP teams and expert advisers should refer to section 3 for more detailed information on regional climate vulnerability assessments, including scope and purpose, inputs and outputs, and where to obtain assessment results and supporting tools.

5.3 Modules 3 and 4 – Identify the hazards and assess risks

Why this is important

Modules 3 and 4 are core components of the WSP and consider potential hazards and hazardous events and the associated risks. Climate variability and change, as well as environmental and social systems (independent or as a consequence of climate change), will result in (a) potentially new hazards being experienced; and (b) changes in the risks associated with hazards and hazardous events.

The risk associated with a hazard or hazardous event is a combination of the likelihood of the hazard or hazardous event occurring (over some time frame) and the severity of the consequences of the hazard or hazardous event if and when it occurs. Both the likelihood and the severity of the consequences arising from the hazard or hazardous event, as well as the effectiveness of existing control measures, are likely to change due to climate variability and change.

5.3.1 Assess climate-related hazards and hazardous events

With climate change in mind, the WSP team should consider the types of hazards that might become more problematic within the local context with reference to general checklists of hazards, hazardous events and control measures. Table 2 provides a set of examples of climate-related water quality and quantity hazards and hazardous events and related control measures to manage associated risks. The WSP team should use its expertise, and bring in broader expertise if required, to help work through the risk scenarios in developing or updating its WSP.

The major climate-related hazardous events that affect water supply systems can be grouped under four broad scenarios:

- Increasing likelihood of flooding or increased run-off in some areas, which potentially overwhelms current sanitary protection measures, leading to damage or destruction of infrastructure and cross-contamination. Increased flooding is likely to derive from more intense rainfall events, from increased average rainfall, or from a combination of both.
- Increasing rainfall in some areas, potentially leading to long-term increases in groundwater levels, reducing the potential for pathogen and chemical attenuation or removal, and causing flooding of subsurface infrastructure and potentially rapid shallow groundwater flow.
- Decreasing rainfall or longer periods of low rainfall in some areas, potentially resulting in declining surface and renewable groundwater availability or longer droughts. This is expected to increase challenges to meet demands for water for domestic use, which may lead to consumers finding alternative (and potentially unsafe) sources of water. Decreasing total rainfall in some areas will reduce the capacity of surface water to dilute, attenuate and remove pollution and, together with rising temperatures, will change the patterns of microbial growth in both source and treated waters. Higher temperatures and evaporation will potentially lead to higher concentrations of biological and chemical contamination.

Climate-related hazards and hazardous events affecting water availability and reliability (quantity)

The *Water safety plan manual* describes the process for identifying hazards and hazardous events and assessing the levels of risk associated with each hazardous event. WSPs tend to focus on the hazardous events that impact water quality. In a broader water resources context, drought-related hazardous events, exacerbated by future climate change, can lead to scarcity and reliability risks. WSPs should consider the strategic risks posed by source water scarcity and the competing users of water in a catchment.

Climate-related hazards and hazardous events affecting water supply infrastructure

Water supply systems are exposed to a range of climate-related hazardous events that can impact the effective operation and overall structural integrity of water supply system assets. This can range from flooding of treatment works and auxiliary systems such as power supplies, damage of pipework due to flooding, scour and erosion damage at rivers and coastal areas, and sediment and silt build-up causing dirty water and reduced capacity of reservoirs, water inlets and other structures.

The impacts of climate change on water supply system infrastructure should be considered, including consideration of the resilience of technologies, such as storage, treatment and distribution systems that are able to cope with the future water resources implications and extreme weather events. The Vision 2030 report *(3)* includes a high-level review of the vulnerability of different WASH technologies to climate risks, which can be taken as a starting point for more detailed consideration in the local context.

Damage to infrastructure will often occur as part of wider disaster events, and can cause widespread disruption to power and transport networks that are largely outside the control of the water supplier. In these cases, the assessment of related hazardous events beyond the water system itself will be required in order to gain a full picture of the risks to which water supplies are exposed.

From a DRR perspective, it is essential to consider a range of potential hazardous events that the area might experience. In order to explore the hazardous events and their potential impacts on water safety, civil contingency planners may assist in developing credible hazardous event scenarios for the specific location.

Climate-related hazards and hazardous events affecting water quality

In general, the types of water quality hazards that are more likely to occur with increasing severity within existing water supplies as a result of climate change are those that are exacerbated by warmer, drier conditions or more intense precipitation events. Historically, these types of hazards and hazardous events have included factors such as:

- pathogens, for example oocysts of *Cryptosporidium* spp., along with particles (including topsoil in run-off), being driven into source waters in higher concentrations due to increased precipitation intensities, which can be further exacerbated following prolonged dry periods or in the event of fire-damaged forests, with reduced dilution due to lower storage levels;
- phytoplankton, for example toxigenic cyanobacteria, proliferating to higher levels in the slower-flowing, lower-turnover, warmer conditions within uncovered source water reservoirs;
- opportunistic pathogens, such as *Naegleria fowleri*, proliferating to higher levels in the slower-flowing, warmer water, which in turn would have less stable disinfectant residuals, within closed water storages and distribution systems;
- chemicals found in many groundwater systems (for example arsenic and fluoride), as well as chemicals in wastewater discharges, increasing in concentration due to less dilution and reaching levels of concern.

One of the predicted consequences of climate change is increased periods of water shortage in many parts of the world, and new water supplies are being tapped in many areas. (In other contexts, water flows might be higher, more variable or subject to more intense precipitation events.) Traditional water sources that have been used for many years are likely to be well understood, with the main hazards, hazardous events and control measures recognized and managed. However, there may often be no local experience with new water supplies, and issues relating to new supplies will be context specific. Water management agencies may be unfamiliar with the very different water qualities and challenges involved with new sources. For instance:

- Water suppliers familiar with surface water may be forced to bring on groundwater, or vice versa. Surface water supplies rarely contain metals at problem concentrations, but groundwater often does. Additionally, groundwater typically has fairly stable water quality, whereas surface water quality can be highly variable.
- Water suppliers familiar with sourcing water from large reservoirs may be forced to bring on river water sources, or vice versa. River water supplies rarely contain cyanotoxins at problem concentrations, but reservoir waters often do. Additionally, reservoir waters typically have fairly stable water quality, whereas river water quality can be highly variable.
- Water suppliers familiar with relatively clean water may be forced to use more contaminated water sources. Water from undeveloped catchments rarely contains hazards at problem concentrations, whereas water sourced from developed catchments often contain higher concentrations of hazards.
- Innovative water management arrangements may be implemented that introduce new types of hazards and hazardous events. For instance, there may be an increased reliance on recycled water in agricultural and urban settings, which might present increased risks of water-related disease if cross-connected into drinking-water supplies.

5.3.2 Consider climate-related impacts on the risk assessment

Risk is not simply an assessment of what has occurred in the past. Risk assessment in the context of a WSP is in fact primarily about envisioning what might occur in the future. The past can be a good guide to the future, but it is not a perfect one, particularly when new trends may emerge (known as the loss of stationarity).

Climate change itself will not change the basic nature of these threats to water services but it will change their likelihood and severity, and potentially the geographical range of some threats *(3)*.

A simple approach to incorporate climate change in the risk assessment is to assess, on the basis of climate change scenarios, the likely change in the risk over time. This may simply be an indication of direction, such as whether the risk is likely to increase or decrease over time. In some circumstances, climate change evidence is too uncertain to assign even a direction of change. In these cases, it is worth considering the level of risk that is deemed acceptable and identifying control measures that will reduce risks under all potential future climate change scenarios. Such a risk assessment should usually be informed by a regional climate vulnerability assessment (described in section 3) outlining the effects of climate change and other drivers on water resources and associated risks at the broad regional level. WSP teams can use this to consider how these larger-scale patterns are likely to impact the specific water supply systems that are under their direct control as a basis for strengthening and adapting risk management strategies within the WSP.

Impact of climate change on estimates of likelihood

The likelihood of future conditions, or frequency of occurrence, is typically assigned by the WSP team based on their local experience of the frequency of historical incidence. Events that have occurred only rarely in the past in the local context may be assumed to be rare in future, but that requires there to be no fundamental change in the nature of the drivers of the hazardous event.

However, in undertaking risk assessments, the WSP team needs to consider the likelihood of future events, and not be limited to basing likelihood predictions on the past. Some hazardous events will be more likely in the future than they were in the past, whilst others might be less likely. For instance, in an area likely to become warmer and wetter due to climate change:

- Contamination of source waters due to high intensity rainfall may have been rare in the past and unlikely in a specific context, but might become more frequent in the future.
- Failure of water conduits due to freezing may become less common in the future due to increased temperatures.

It will be difficult to place firm values on the likelihood for some scenarios, but hazardous events could simply be classified as to whether their probability is low but their impact is high (low probability/high impact events).

If the WSP team does not consider future likelihoods in its risk assessment, the WSP might underestimate or overestimate the likelihood and therefore the risk of certain hazardous events, resulting in a suboptimal allocation of resources.

Impact of climate change on estimates of consequence

In undertaking risk assessments, the WSP team should also consider the consequence of future events, and not base their estimates solely on past observations. Some consequences are likely to be more significant in the future, whilst others might be less significant. For instance, in an area likely to become drier due to climate change:

- The consequence of cyanotoxins in source waters might have been insignificant in the past due to regular turnover of the sources, limiting their carrying capacity for cyanobacteria to low densities in a specific context. Elevated and more consequential densities may occur in the future under lower flow conditions.
- The consequence of arsenic from groundwater sources might have been insignificant where that groundwater made up a small contribution to the total quantity of water supplied in the past. The consequence may increase to being more significant in the future if the groundwater begins to make up a greater proportion of the source.

As with likelihood, if the WSP team does not consider future consequence in its risk assessment, the WSP might underestimate certain risks or overestimate other risks.

Impact of climate change on control measure effectiveness

In the WSP process, the risk assessment outlined in module 4 involves considering existing control measures that are already in place to manage each hazardous event and validating the effectiveness of those control measures. WSP teams should bear in mind that the effectiveness of existing control measures may change with changing climatic conditions, impacting the risk assessment. Where existing controls are found to be insufficient to adequately manage current or future risk, additional control measures will be needed (see module 5 as well as section 5.4 within this document for additional information).

5.4 Module 5 – Improvement planning

5.4.1 Identify additional control measures to manage climate-related risk

Why this is important

Additional control measures are required to reduce significant climate-related risks identified and assessed in modules 3 and 4 to acceptable levels. Identifying control measures that improve management of current climate risks will be required, as well as control measures that take a strategic approach to managing long-term future risks. The control measures that help protect water supplies may be specific to drinking-water systems or may build upon broader improvements in water resources management aimed at reducing more widespread risks related to natural disasters. Some of these broader potential control measures will be the primary responsibility of other stakeholders rather than the water supply agency and so need to be developed in partnership with others.

Control measures that reduce risks under all future scenarios of climate and development can be considered "no regret" or "low regret". This means they deliver benefits under a wide range of possible futures. For instance, protecting sources from contamination by animals will be beneficial in reducing risks whether climate change results in wetter or drier conditions.

Control measures supporting water quality

The identification, implementation and monitoring of control measures to manage water quality is a critical component of water safety planning. Table 3 below provides examples of control measures alongside the related hazards and hazardous events that may be exacerbated by climate change. The Vision 2030 report *(3)* also includes a set of fact sheets with detailed information on adaptation options for different technologies.

Control measures and improvements supporting water availability and reliability

Where water availability and reliability are identified as significant risks, control measures are required to reduce levels of risk. In terms of managing scarcity and reliability risks, options can be classified as demand-side or supply-side options. Demand-side options aim to manage consumption and increase efficiency, thereby reducing the demand placed on water sources. Supply-side options, in contrast, aim to increase source yields and develop new sources to increase the water available for supply. When considering new sources of drinking-water, an assessment of both quantity and quality perspectives should be taken. Baseline monitoring, along with an assessment of catchment activities, should be conducted to establish source water conditions and quality.

In regions where water is scarce and competition for resources is high, especially during drought events, demand-side options are attractive because they do not increase the overall burden on catchment resources. Increasing efficiency in water supply systems also brings the co-benefit of reducing energy consumption, lowering the costs of treating and pumping water and reducing greenhouse gas emissions.

In addition, demand-side control measures will deliver these benefits under all future climate scenarios, whereas development of new water sources may be undermined by future changes in climate, which may reduce source yields compared to anticipated levels. The selection of a portfolio of demand- and supply-side options that is robust across a diverse range of potential future scenarios is a useful strategy to manage future uncertainty.

5.4.2 Consider the impacts of climate change on long-term plans

Why this is important

Some control measures in the improvement plan will manage existing risks over short timescales and can be periodically reviewed and adjusted when WSPs are reviewed. Other measures, such as capital infrastructure upgrades and new supply sources, may be much longer lived. Considering climate change and other risks associated with rising demand and pollution loadings will be important in these long-term aspects of improvement and upgrade plans.

Old infrastructure assets may require substantial capital investment for maintenance or upgrade and will probably be operated for many decades. As a general approach, adaptation strategies for water system infrastructure may require actions such as:

- **Designing adaptable infrastructure.** Water infrastructure often has a long lifespan and will be used in climate and societal conditions that could be very different to the present day. Infrastructure that can be upsized or adjusted with minimum cost and disruption is better placed to cope with future uncertainty. This might include designing water treatment works that can be upsized in the future if demand increases more than is expected.
- **Building in safety factors to infrastructure to accommodate uncertainty in future climate.** For example, increasing the capacity of a proposed storage may be used to offset the uncertainty in future rainfall patterns. The cost of doing this during the construction phase may be much lower than attempting to add capacity at a later date or construct additional sources. However, this is only applicable where the additional upfront costs are low relative to the risk offset.
- **Utilizing a range of options to achieve an outcome.** In the context of water this could include the diversified or conjunctive use of water sources such as groundwater, surface

water, desalination, rainwater harvesting, water recycling and water efficiency measures. This spreads the risk of climate change impacts across a range of measures rather than relying on a single solution. It should be noted that climate change is only one of many considerations in developing such options. For example, desalination is resilient to drought but is energy intensive, which may increase costs and be contrary to climate mitigation policies.

- **Supporting infrastructure with non-structural measures.** Non-structural measures are inherently more adaptable than fixed infrastructure assets. For example, water tariffs can be reformed on a periodic basis and used to influence consumer demand behaviour. Investments in information, planning and policy can provide greater confidence in the planning and design of infrastructure assets.

There is a wide range of background information available on adaptive decision-making; a concise introduction is provided by Ranger *(30)*.

5.5 Examples of climate change impacts that may influence hazards and hazardous events and associated control measures

Table 3 is intended to support due consideration of climate considerations into modules 3, 4 and 5 of the WSP process. The table provides examples of hazards and hazardous events that may be influenced by the impacts of climate change alongside potential control measures.

Note that this table provides illustrative examples only. The table is not intended to be exhaustive in that many important impacts, hazards, hazardous events and control measures may be missing. Similarly, the table is not universal in that its contents will not be relevant in all circumstances.

Note that most of the impacts, hazards, hazardous events and control measures are not uniquely associated with water safety planning in the context of climate change. Most are relevant to WSPs regardless of climate change. The effect of climate change is merely to change risk levels and, therefore, make particular control measures more or less necessary.

Table 3. Examples of hazards and hazardous events that may be exacerbated by climate change and accompanying potential control measures to reduce level of risk

Examples of climate change impacts	Examples of hazards	Examples of hazardous events potentially exacerbated by climate variability and change	Examples of control measures that may become more important to manage risks posed by climate variability and change
Enteric pathogens			
Increased temperatures Reduced run-off volumes Increased precipitation intensity Reduced reservoir turnover and depths	Pathogenic viruses, protozoa and bacteria, e.g. norovirus, *Cryptosporidium parvum* and *Campylobacter jejuni*	Occurring at higher concentrations in treated water due to: • Increased release of pathogens due to more intense precipitation causing wastewater containment breaches, treatment and management systems to become less effective • Increased release of pathogens due to more intense precipitation causing greater transport of manure from grazing animals • Decreased dilution, sedimentation and attenuation in source waters due to increased precipitation intensity and increased stratification in storages • Increased transfer of pathogens through treatment systems due to more intense precipitation and reduced storage volumes causing drinking-water treatment systems to become less effective • Selection of less safe alternative sources due to limited water resources availability in safer normal sources • Increased use of source waters for polluting activities due to reduced availability of alternative waters • Cross-contamination from damaged sewerage systems or flooding of sewer pump stations • Surface water ingress into septic tanks after flooding events leading to overflow of effluent into streams and rivers • Contaminated surface water entering well heads after large run-off events • Increased lateral flow in soils after large rainfall events may increase transport of contaminants, particularly in shallow aquifers	Source controls: • Minimize sewage and manure run-off from catchment, particularly from human and intensive juvenile stock animal sources • Increase riparian area integrity and vegetation cover • Introduce or enhance wet weather event storage and management capacity of wastewater management systems • Increase setback distance and improve buffering from watercourse to points of faecal matter deposition or storage of effluent • Develop a long-term drought management plan, e.g. increase consumption/use, find alternative water sources • Keep storage as full as possible to maximize detention times • Protect storage and catchment from activities that could introduce pathogens, e.g. recreation, grazing in direct proximity to water sources • Reduce impervious surface areas in water catchments to reduce run-off/inflow extremes • Cap unused bores and ensure current wells are appropriately sealed from surface run-off • For deep wells ensure casing extends well below the level of shallow aquifers Treatment controls: • Enhance or introduce additional treatment to handle increased pathogen challenge during peak events • Maintain or improve turbidity levels during treatment, particularly during peak events

Continues…

Examples of climate change impacts	Examples of hazards	Examples of hazardous events potentially exacerbated by climate variability and change	Examples of control measures that may become more important to manage risks posed by climate variability and change
Microorganisms proliferating within water storage and distribution systems			
Increased temperatures Reduced water availability	Opportunistic pathogens, e.g. *Legionella* spp. Total coliforms and associated compliance issues Biofilms and heterotrophic plate count bacteria and associated management issues Ammonia oxidizing bacteria and associated difficulty maintaining chloramine residual Actinomycetes and associated taste and odour compounds, e.g. geosmin	Occurring at higher densities more often within distribution system due to: • Increased water temperature due to environmental warming • Greater difficulty maintaining disinfectant residual due to increase in water temperature • Greater difficulty maintaining disinfectant residual due to reduced water turnover if water use restrictions are in place to respond to reduced water availability • Greater difficulty maintaining disinfectant residual due to decrease in source, and therefore treated water quality	Source controls: • Reduce disinfectant demand through optimizing source selection to minimize organic matter in water • Abstract source water from cooler depths • Increase riparian shade plantings around storages Treatment controls: • Reduce disinfectant demand through enhancing coagulation • Increase disinfectant residual concentrations at point of primary disinfection • Introduce or increase secondary booster disinfection • Change to disinfectant with reduced residual decay (e.g. to chloramine from chlorine, but noting the greater difficulty in managing chloramine residuals in many contexts) Distribution system controls: • Reduce treated water service reservoir operating levels to reduce hydraulic residence times • Design or modify system to reduce residence times within pipes • Design or modify system to minimize length of shallow or surface pipes (if practical) • Coat exposed pipes and tank roofs with white paint or make from reflective materials and avoid dark colours Point-of-use controls: • Avoid storing water in containers in direct sunlight • Coat exposed pipes and tank roofs with white paint or make from reflective materials and avoid dark colours • Refrigerate stored water

Examples of climate change impacts	Examples of hazards	Examples of hazardous events potentially exacerbated by climate variability and change	Examples of control measures that may become more important to manage risks posed by climate variability and change
Problematic source water algae and bacteria			
Increased temperatures Reduced run-off volumes Increased precipitation intensity Reduced reservoir turnover and depths	Cyanobacteria and associated cyanotoxins, e.g. microcystin, and taste and odour compounds, e.g. geosmin Diatoms and associated taste and odour compounds, e.g. *Asterionella* spp., compounds and filter blocking diatoms, e.g. *Synedra* spp. Benthic cyanobacteria and associated cyanotoxins, e.g. saxitoxins, and taste and odour compounds, e.g. geosmin Benthic actinomycetes and associated taste and odour compounds, e.g. geosmin	Occurring at higher densities more often within source water reservoir due to: • Increased water temperature • Increased hydraulic residence time due to more prolonged periods of drought • Increased nutrient loads due to increased precipitation intensity • Increased nutrient concentrations due to reduced dilution, particularly from point sources • Stronger stratification due to reduced flows • Changed biological niche leading to changes in the dominant species present to types not previously considered or experienced within the context	Source controls: • Reduce nutrient loads into storages. • Establish wetlands and riparian buffer zones to retain nutrients from run-off and minimize soil erosion • Where possible, use selective depth abstraction to source water from reservoir depths that minimize concentrations of hazards • Increase riparian shade plantings around storages • Operate storages and flows to maximize turnover if low turnover is a key underlying problem • Keep storages above levels that could lead to significant benthic influence on upper depths if problem arises at lower strata • Introduce artificial mixing to reduce stratification and oxidize nutrients • Dose algaecides pre-emptively to keep concentrations below problem levels • Protect storage from activities that could damage macrophytes, e.g. recreation, thereby helping to prevent a shift from aquatic macrophytes to planktonic dominance • Reduce impervious surface areas in water catchments to reduce inflow rates • Cover small storages where the risk is significant Treatment controls: • Cease pre-oxidation before filtration to avoid killing cells and releasing toxins and taste and odour compounds • Increase primary disinfection after filtration to inactivate toxins • Optimize coagulation and filtration to remove algal cells • Change to disinfectant with capability of removing toxins and taste and odour compounds, e.g. ozonation • Introduce ability to remove toxins and taste and odour compounds, e.g. powdered activated carbon or granular activated carbon Point of use controls: • Store water in darkness

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Examples of climate change impacts	Examples of hazards	Examples of hazardous events potentially exacerbated by climate variability and change	Examples of control measures that may become more important to manage risks posed by climate variability and change
Problematic plants			
Increased temperatures Reduced run-off volumes Increased precipitation intensity Reduced reservoir turnover and depths	Aquatic weeds and associated loss of utility of reservoir, e.g. *Cabomba*	Occurring at higher densities more often within source water reservoir due to: • Increased light penetration due to decreased turbidity, resulting from less run-off • Increased water temperature • Increased hydraulic residence time due to more prolonged periods of drought • Increased nutrient loads due to increased precipitation intensity • Increased nutrient concentrations due to reduced dilution, particularly from point sources • Stronger stratification due to reduced flows • Changed biological niche leading to changes in the dominant species present to types not previously considered or experienced within the context	Source controls: • Minimize nutrient run-off, particularly phosphorus, from the catchment • Establish wetlands in key catchment locations to retain nutrients • Mechanically harvest weeds from water • Kill weeds using herbicides safe for use in drinking-water • Increase riparian shade plantings around storages • Dose herbicides to keep concentrations below problem levels • Protect storage from activities that could introduce problem water weeds, e.g. water-based recreation
Chemical toxicants			
Increased temperatures Reduced run-off volumes Increased precipitation intensities Reduced reservoir turnover and depths	Agricultural chemicals, e.g. nitrate	Occurring at higher concentrations in treated water due to: • Decreased dilution in source waters due to reduced run-off • Increased intensity of agriculture in areas that are still viable due to drought-related reductions in total land area available for agriculture • Change to potentially more contaminated water due to increased abstraction and less inflow leading to change of contributing water sources • Selection of less safe alternative sources due to limited water resources availability in safer normal sources • Increased nutrient loads in source waters after large run-off events • Contamination of groundwater due to infiltration of pollutants with large rainfall events • Increased lateral flow in soils after large rainfall events may increase transport of contaminants, particularly in shallow aquifers	Source controls: • Minimize agrochemical run-off from catchment or recharge area • Minimize use of high-risk agrochemicals in recharge areas • Limit high-intensity agricultural activities in key catchment and recharge areas • Abstract water from deeper or better confined aquifers • Cap unused bores and ensure current wells are appropriately sealed from surface run-off • For deep wells, ensure casing extends well below the level of shallow aquifers Treatment controls: • Introduce reverse osmosis treatment

Examples of climate change impacts	Examples of hazards	Examples of hazardous events potentially exacerbated by climate variability and change	Examples of control measures that may become more important to manage risks posed by climate variability and change
	Chemicals from geology in groundwater, e.g. arsenic and fluoride	Occurring at higher concentrations in treated water due to: • Decreased dilution in source waters due to reduced inflows or recharge during more prolonged periods of drought • Change to potentially more contaminated water due to increased abstraction or overabstraction and less inflow leading to change of contributing water sources • Selection of less safe alternative sources due to limited water resources availability in safer normal sources	Source controls: • Abstract water from less contaminated sources • Avoid overabstraction that may change contributing source waters to more contaminated ones • Use multiple sources to dilute specific pollutants Treatment controls: • Optimize existing treatment to remove chemicals, e.g. coagulation optimization • Introduce enhanced treatment, e.g. pre-oxidation, ion exchange, chemical adsorption or reverse osmosis
	Disinfection by-products, e.g. haloacetic acids	Occurring at higher concentrations in treated water due to: • Decreased dilution of organic precursors in source waters due to reduced inflows or recharge during more prolonged periods of drought • Increased concentration of organic precursors in source waters due to increased run-off with increased precipitation intensity • Increased organic matter from phytoplankton due to reduced river flow and increased nutrient concentrations • Increased disinfectant concentrations to maintain residuals under hotter, lower-flow conditions • Increased residence times in the distribution network if water use restrictions are in place to respond to reduced water availability	Source controls: • Minimize nutrient run-off, particularly phosphorus, from the catchment • Establish wetlands in key catchment locations to retain nutrients • Replace vegetation that contributes high levels of organic run-off with less problematic vegetation • Introduce artificial mixing to reduce stratification and oxidize nutrients • Protect storage from activities that could introduce organic matter, e.g. water-based recreation Treatment controls: • Optimize existing treatment to remove precursors, e.g. coagulation optimization • Avoid pre-oxidation with chorine to limit chlorinated disinfection by-product formation • Introduce enhanced treatment, e.g. pre-oxidation, ion exchange, chemical adsorption or reverse osmosis • Introduce better optimized disinfection strategies, such as using booster disinfection rather than excessive primary disinfection • Move to using primary disinfectants with reduced disinfection by-product formation potential, e.g. ultraviolet (UV) or ozone

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Examples of climate change impacts	Examples of hazards	Examples of hazardous events potentially exacerbated by climate variability and change	Examples of control measures that may become more important to manage risks posed by climate variability and change
			Distribution system controls: • Reduce treated water service reservoir operating levels to reduce hydraulic residence times • Move to using residual disinfectants with lower disinfection by-product formation potential, such as using chloramines rather than free chlorine for maintaining residual • Design or modify system to reduce residence times within pipes
	Metals released from sediments, e.g. manganese	Occurring at higher concentrations more often within source water reservoir due to: • Reduced dilution from reduced overall rainfall quantity • Stronger stratification and reduced dissolved oxygen penetration due to increased temperature • Formation of acid sulphate soils, due to the exposure and rewetting of sediments	Source controls: • Manage river and wetland flow regimes to minimize the formation of acid sulphate soils • Abstract source water from depths that minimize concentrations of hazards • Operate storages and flows to maximize turnover • Keep storages above levels that could lead to significant benthic influence on upper depths • Introduce artificial mixing to reduce stratification and oxidize metals Treatment controls: • Optimize existing treatment to remove metals, e.g. coagulation optimization • Introduce enhanced treatment, e.g. aeration, pre-oxidation, ion exchange, chemical adsorption or reverse osmosis
Physical hazards			
Sea level rise due to increased temperatures Reduced run-off volumes Increased precipitation intensity	Salinity	Saline ingress into coastal estuaries and groundwater due to increased sea levels or overabstraction of freshwater influenced by saline groundwater Decreasing recharge may increase the salinity of some groundwater resources Decreased run-off in the headwaters of catchments leading to reduced dilution downstream, where saline inputs are more significant	• Maintain critical dilution flows in river and streams • Minimize high saline loads from specific sources entering rivers and streams (e.g. irrigation drainage or wetland discharge) • In controlled river systems, manage flows to minimize the concentration of highly saline water • Maintain or improve landscape vegetation to reduce shallow groundwater salinization • Control abstraction rates to prevent saline ingress • Recharge aquifers with wastewater to keep back saline ingress

Examples of climate change impacts	Examples of hazards	Examples of hazardous events potentially exacerbated by climate variability and change	Examples of control measures that may become more important to manage risks posed by climate variability and change
	Turbidity	Occurring at higher concentrations in treated water due to: • Increased intensity of agriculture in areas that are still viable due to drought-related reductions in total land area available for agriculture • Increased turbidity due to more intense precipitation events causing greater erosion of agricultural lands, stream banks and loads from urban stormwater	• Minimize sediment loads from agricultural and urban stormwater • Stabilize stream bed and banks to minimize erosion • Establish wetlands in key catchment locations to retain nutrients • Increase riparian area integrity and vegetation cover
General			
Increased temperatures Reduced run-off volumes Increased precipitation intensity Reduced reservoir turnover and depths Increased wind intensity	Water quality hazards that are present in new water sources	A hazard becomes problematic due to a new water source being used to augment a drinking-water supply or a new water source being used in place of an existing water source (refer above for examples of hazards for which this is a potential hazardous event)	• Carefully consider all hazards that might be relevant to the new water source • Undertake baseline water quality testing of the new water source • Review capability of existing treatment systems against the treatment requirements of the new water source and augment the treatment if required • Operate the water source assuming the worst case for its quality in the absence of knowledge about that quality until new knowledge has been amassed
	Water quality hazards that cause unforeseen incidents	A hazard becomes problematic when it was not foreseen and is only revealed after adverse consequences have occurred or are about to occur	• Place emphasis on assessing emerging or future risks • Maintain a water quality incident and emergency management plan • Prepare specific contingency plans for foreseeable hazardous scenarios • Identify available-to-use alternative sources • Increase treated water storage capacity to allow avoidance of problem periods • Set up systems to enable rapid community alerts, e.g. boil water alerts and water consumption avoidance advisories and orders

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Examples of climate change impacts	Examples of hazards	Examples of hazardous events potentially exacerbated by climate variability and change	Examples of control measures that may become more important to manage risks posed by climate variability and change
	Water quality hazards that are present due to new water management arrangements	A hazard becomes problematic due to a new water management arrangement that can lead to new water-related exposures or cross-connections, e.g. managing demand for potable water by supplying non-potable water for certain uses (outdoor use, toilet flushing)	• Carefully consider all hazards that might be relevant to the alternative water management arrangements • Ensure treatment systems adequately reduce hazard concentrations in the alternative water to allow for both the intended and inadvertent but inevitable uses of, and exposures too, that water • Implement rigorous systems to prevent excessive exposures beyond those intended to the alternative non-potable water supply • Implement rigorous systems to prevent cross-connections or inadvertent tap-ins that could cause the potable water supply to become contaminated by the alternative non-potable water supply • Operate the alternative water source assuming the worst case for its quality in the absence of knowledge about that quality until new knowledge has been amassed
	Water quality hazards that arise due to effects on infrastructure	A hazard becomes problematic due to a failure of water supply systems resulting from, for instance: • Heat-related power failures and loss of pumping and treatment systems • Wind-related power failures and loss of pumping and treatment systems • Direct damage to infrastructure from high winds, e.g. storage tanks • Floods overwhelming treatment systems and assets in general • Heat-related asset failures such as increased rate of pipe bursts due to heat and drought-related ground movement • Heat-related impacts on water treatment chemicals such as loss of potency of sodium hypochlorite solution • Drying landscape leads to cracking of riverbanks and degradation of bores	• Install backup systems for critical infrastructure and develop backup water supply options where possible to help in the event of system failure • Develop systems to provide safe water in the event of system failure • Store critical chemicals and materials away from excessive heat • Select materials and chemicals that can withstand increased temperatures • Install robust assets and use installation procedures that protect assets from heat-related stresses, ground movements and flood events

5.6 Modules 8 and 9 – Management procedures and supporting programmes

Why this is important

The consideration and integration of relevant aspects of climate change, together with IWRM and DRR, will broaden the stakeholder group whose responsibilities overlap with those preparing the WSP. WSP teams need to develop a degree of familiarity with the language and concepts of the other professions involved. The teams need to identify opportunities and practices to work in partnership with others and influence the plans of others where these impinge on the scope and delivery of the WSP. In many nations, there are national or regional actions and processes already established covering IWRM and DRR issues and these provide means to address some of the broader impacts of climate change on WSPs.

5.6.1 Consider climate- and weather-related emergencies when developing management procedures

A WSP should include preparedness for incidents, disasters and extreme events as part of module 8. Flood and drought response plans, for instance, are commonly addressed by WSP teams and may receive priority attention where climate variability and change is considered through the WSP process. Extreme weather events may either lead to failure of external infrastructure, affecting water safety and security of supply (for example through loss of power or transport disruption), or impact directly the components of the water supply system itself (for example through limiting the availability of supply, fracture of pipelines, increasing pollutants). By integrating relevant types of disasters and their potential consequences into a WSP, the WSP can contribute to DRR through better preparedness and contingency planning to facilitate water safety in an emergency as well as faster recovery of normal functions after an event.

Thorough emergency response planning often involves identifying alternative water supplies to be used during the emergency. During a disaster, it is probable that the civil protection services will seek advice from the water supply organization on providing safe supplies if normal supplies are disrupted. In many cases, new water supplies or novel water management arrangements are implemented in an emergency without sufficient time allowed to properly understand and manage the risks that may arise. For instance, existing treatment plants designed for water with certain characteristics may be faced with treating a very different type of water, and may not do so adequately. Early preparedness through development of emergency management procedures will greatly assist with the management of drinking-water quality risks that might arise due to climate change. Years of preparation may be required to examine the quality of alternative source waters and establish and implement the source water management and treatment requirements for the new sources. For all water supplies in areas that are likely to be affected by climate change, good forward planning is essential. Forward planning should involve assessing water supply options from a quantity and a quality perspective. This may include undertaking baseline monitoring and an assessment of activities taking place in the catchment to establish source water conditions and quality.

It is good practice to stress-test emergency response plans, as through role play and "sunny day" exercises. The WSP team could additionally identify opportunities to contribute water safety inputs to emergency exercises organized by others (for example a major flood incident exercise).

WHO and the Water Engineering Development Centre (WEDC) have prepared a series of technical notes relating to the provision of safe water and sanitation in emergencies *(31)* that may inform emergency response planning. These notes provide practical, evidence-based recommendations in responding to immediate and medium-term water, sanitation and hygiene needs of populations affected by emergencies. The notes are relevant to a wide range or emergency situations, including both natural and conflict-induced disasters. They are suitable for field technicians, engineers and hygiene promoters, as well as staff from agency headquarters. The notes cover:

1. Cleaning and disinfecting wells.
2. Cleaning and disinfecting boreholes.
3. Cleaning and disinfecting water storage tanks and tankers.
4. Rehabilitating small-scale piped water distribution systems.
5. Emergency treatment of drinking-water at the point of use.
6. Rehabilitating water treatment works after an emergency.
7. Solid waste management in emergencies.
8. Disposal of dead bodies in emergency conditions.
9. How much water is needed in emergencies.
10. Hygiene promotion in emergencies.
11. Measuring chlorine levels in water supplies.
12. Delivering safe water by tanker.
13. Planning for excreta disposal in emergencies.
14. Technical options for excreta disposal in emergencies.
15. Cleaning wells after seawater flooding.

5.6.2 Include climate risk management in supporting programmes

Supporting programmes, which are addressed in module 9 of the WSP process, provide a valuable opportunity to build the institutional and individual capacity of water suppliers to manage risks associated with water scarcity and reliability in addition to water quality risks. These programmes can bring together stakeholders from different disciplines to support a more catchment-based and holistic approach to managing water resources for more resilient water supplies. Research programmes can be used to fill existing knowledge gaps and provide the evidence base to support improved decision-making and future WSP iterations. A broad range of potential supporting programmes have been identified and are grouped below according to capacity development, stakeholder engagement and research.

Capacity development can cover a range of themes, including:

- understanding the principles of IWRM and the institutional arrangements for water resources management and use;
- strategic water resources and water supply planning, including the use of supply and demand predictions and climate change scenarios to explore future uncertainties;
- climate variability and change and hydrology to support the understanding of the processes governing source yields and the impacts of climate change on hydrology;
- demand management, including leakage control, changing consumer behaviour and techniques to enhance operational efficiency;
- flood or drought event management and planning, including development of control rules and triggers and management procedures to manage risks to water supplies.

Stakeholder engagement and outreach programmes can cover:

- building partnerships with other stakeholders, such as other abstractors (agriculture, industry, energy, etc.) and ministries and agencies responsible for water resources management and the environment, to foster improved coordination of water management and preservation of water quality and quantity.

Programmes of research can build the evidence base in areas such as:

- water supply system modelling to support increased operational efficiency and targeted capital investments;
- catchment hydrology and source modelling to improve estimates of yield and allow climate change impact assessment studies to be carried out;
- data collection and monitoring of water quality and quantity issues, such as source water volumes and system leakage volumes and other losses from the system;
- pilot projects to investigate feasibility of new technologies to improve the efficiency and effectiveness of planning and operational activities.

With respect to climate change, the science and local and regional understanding of climate change and its impacts is developing. Thus, the climate change aspects of the WSP should be reviewed regularly. This is already implied by the inclusion of "Research and development" within tool 5.1 of the *Water safety plan manual*. The organization responsible for the WSP may already finance or contribute to research and development on climate change for its own resource planning and management. In addition, further research and development may be taking place, financed by others. The WSP team may consider appointing a champion to consider and advise on developments in climate science, impact assessment and adaptation, which are relevant for the WSP team. Adapting to climate change will be an important part of IWRM, and the WSP team champion for climate change should liaise with the organization(s) responsible for IWRM in the WSP area.

To support emergency response planning and DRR (module 8), the WSP team should review lessons and understanding that can be integrated into the WSP from post-event reviews in other areas of the country or further afield, as well as following any event experienced by the water supplier themselves.

6 Supporting information and guidance

6.1 Introduction

Some tools, models and data resources have been developed that can help with contingency planning and prediction of climate change impacts. This section provides further references for WSP teams considering climate change issues as part of the WSP process. The references are intended to introduce WSP teams to the key concepts in climate risk management and to broaden teams' understanding of climate change issues and the potential opportunities that water resources management and DRR may offer to support climate resilience in the WSP process. The resources are by no means exhaustive, but are intended to give a cross-section of background material. The following web portals provide access to a wealth of additional resources:

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- PreventionWeb disaster risk portal: http://www.preventionweb.net/
- Global Water Partnership: http://www.gwp.org/

6.2 Further resources on climate change and water supplies

6.2.1 Tools and data sources

Title	Coupled Model Intercomparison Project (CMIP)
Description	The CMIP is an ongoing programme by the World Climate Research Programme to develop common standards for general circulation models, using input from many different models and teams. The project offers access to data sets on climate projections for different scenarios.
Reference	World Climate Research Programme's Working Group on Coupled Modelling
Link	http://cmip-pcmdi.llnl.gov/index.html?submenuheader=0

Title	CORDEX project
Description	CORDEX is an international project hosted in Sweden that aims to evaluate and improve regional climate models, to produce coordinated data sets of downscaled projections, and to improve the use of regional climate data.
Reference	World Climate Research Programme's CORDEX project
Link	http://cordex.org

Title	**Water Information System for Europe (WISE)**
Description	WISE is the gateway to information for the European Union on water. WISE offers access to data through the European Environment Agency, EUROSTAT, and the Joint Research Centre on topics ranging from flood risk to water quality.
Reference	Water Information System for Europe, European Commission/European Environment Agency
Link	http://water.europa.eu/

Title	**Soil and Water Assessment Tool (SWAT)**
Description	SWAT is a public domain hydrological modelling tool that can be used to assess the impacts of climate change on water quality and quantity. SWAT also provides tools for analysing climate and weather data. SWAT is just one of many models that can be used to assess climate impacts on hydrological processes, and these models vary in their licence requirements.
Reference	Soil and Water Assessment Tool, Agricultural Research Service of United States Department of Agriculture/Texas A&M AgriLife Research
Link	http://swat.tamu.edu/

Title	**Aqueduct Global Flood Analyser**
Description	Developed by the World Resources Institute, the Aqueduct Global Flood Analyser is a web-based platform to gives information on flood risk at a global scale. The user can assess the annual risk of flooding at riverine and coastal locations and estimate the potential economic damage.
Reference	Aqueduct Global Flood Analyser, World Resources Institute
Link	http://www.wri.org/resources/maps/aqueduct-global-flood-analyzer

Title	**Water Evaluation and Planning (WEAP)**
Description	WEAP is a modelling tool for integrated water resources planning. The model incorporates the na tural environment with the engineered environment, and allows the user to assess the impacts of different policy options and water allocations.
Reference	Water Evaluation and Planning tool, Stockholm Environment Institute
Link	http://weap21.org/index.asp?NewLang=EN

Title	**eartH2Observe Water Cycle Integrator (WCI)**
Description	Tool developed as part of European Union-funded project to collect global data sources on water resources management. The user can build user-defined maps with layers such as precipitation, temperature, streamflow and ground and surface water indicators.
Reference	eartH2Observe Water Cycle Integrator (WCI), eartH2Observe project
Link	https://wci.earth2observe.eu/

6.2.2 Guidance and documents

Title	**Vision 2030: The resilience of water supply and sanitation in the face of climate change**
Description	The Vision 2030 study of DFID and WHO sets out to increase our understanding of how anticipated climate change may affect drinking-water and sanitation services and what can be done to optimize the resilience of technologies, infrastructure and services. A summary for policy-makers is supported by several technical publications that provide useful background material for WSP teams.
Reference	World Health Organization and Department for International Development. Vision 2030: the resilience of water supply and sanitation in the face of climate change. Technical report. Geneva: World Health Organization; 2010.
Link	http://www.who.int/water_sanitation_health/publications/9789241598422/en/

Title	**Guidance on water supply and sanitation in extreme weather events**
Description	This publication summarizes how basic disaster preparedness and early warning procedures can be implemented in the water and wastewater sector in the European context, and identifies the specific challenges of extreme weather events to vulnerable areas. It provides advice on the implementation of WSPs with specific attention to small water supply and sanitation systems; and on multisectoral cooperation, including communication. It also includes a review of experience and good practice in the European Region, summarizing proven adaptation measures for water utilities, drainage and sewerage, and wastewater treatment systems during extreme weather events.
Reference	World Health Organization and United Nations Economic Commission For Europe. Guidance on water supply and sanitation in extreme weather events. Geneva: World Health Organization; 2011.
Link	http://www.euro.who.int/en/health-topics/environment-and-health/water-and-sanitation/publications/2011/guidance-on-water-supply-and-sanitation-in-extreme-weather-events

Title	**Creating Resilient Water Utilities (CRWU)**
Description	The United States EPA Creating Resilient Water Utilities (CRWU) initiative assists the water sector, which includes drinking-water, wastewater, and stormwater utilities, in addressing climate change impacts. Through the development of practical and easy-to-use tools, EPA promotes a clear understanding of climate science and adaptation options by translating complex climate projections into accessible formats. This information helps utility owners and operators better prepare their systems for the impacts of climate change.
Reference	United States Environmental Protection Agency (US EPA): Creating Resilient Water Utilities (CRWU).
Link	http://water.epa.gov/infrastructure/watersecurity/climate/

Title	**Managing climate extremes and disasters in the water sector: lessons from the IPCC SREX report**
Description	The special report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX) was commissioned by the Intergovernmental Panel on Climate Change (IPCC) in response to a recognized need to provide specific advice on climate change, extreme weather and climate events ("climate extremes"). This brief seeks to highlight key thematic findings and learning from SREX. It makes suggestions for immediate action to avoid further damage from climate extremes and to build a more resilient future with benefits that go beyond water management. For water sector policy-makers and planners, or indeed anyone whose work contributes to the management of water, this brief should prompt discussion and understanding of several questions: Why are extreme events a critical issue for water management? How is the water sector affected by the risk and impact of extreme events? What actions can be taken to manage these risks?
Reference	Managing climate extremes and disasters in the water sector: lessons from the IPCC SREX report. Climate and Development Knowledge Network; 2012.
Link	www.cdkn.org/srex

Title	**Hydro-climatic disasters in water resources management: training manual**
Description	The main objective of this training material is to build the capacity of water managers and others to develop strategies for coping with hydro-climatic disasters such as floods and drought within the context of water resources management. An added expectation is improving the resilience of vulnerable communities and reducing the impact of extreme events. The document provides valuable background material for WSP teams seeking to manage the hazards associated with current and future climate change.
Reference	Hydro-climatic disasters in water resources management: training manual. United Nations Office for the Coordination of Humanitarian Affairs – Headquarters (OCHA), United Nations Office for Disaster Risk Reduction – Regional Office for Africa (UNISDR AF), International Network for Capacity Building in Integrated Water Resources Management (Cap-Net), Nile IWRM Capacity Building Network (Nile IWRM Net); 2009.
Link	http://www.unisdr.org/we/inform/publications/10358

Title	**Adapting urban water systems to climate change**
Description	The handbook provides local governments and utilities with up-to-date information as well as access to resources and good practice examples. This will enable them to increase their awareness of how the potential impacts of climate change will affect their urban water systems and to build their capacity to develop a long-term strategy for adaptation in the water sector. The handbook does not aim to cover all aspects relating to adaptation or to present a complete picture of the origins and consequences of climate change, but rather aims to distil the most relevant aspects for urban water management.
Reference	Adapting urban water systems to climate change. ICLEI European Secretariat; 2011. Prepared within the framework of the European research project SWITCH (2006 to 2011).
Links	http://www.switchtraining.eu/home/ *and* http://www.switchtraining.eu/fileadmin/template/projects/switch_training/files/Modules/SWITCH_Adaption-Handbook_final_small.pdf

Title	**Updated WHO/WEDC technical notes on WASH in emergencies**
Description	These four-page illustrated notes, originally prepared in 2011 and updated in 2013, provide practical, evidence-based recommendations in responding to immediate and medium-term water, sanitation and hygiene needs of populations affected by emergencies. The notes are relevant to a wide range of emergency situations, including both natural and conflict-induced disasters. They are suitable for field technicians, engineers and hygiene promoters, as well as staff from agency headquarters. The notes could help to inform the identification of emergency response control measures to support resilience of water supply systems during climate-related natural disasters.
Reference	Updated WHO/WEDC technical notes on WASH in emergencies. World Health Organization and Water Engineering Development Centre; 2013.
Link	http://www.who.int/water_sanitation_health/publications/technotes/en/

Title	**Global Water Partnership (GWP) Integrated Water Resources Management ToolBox**
Description	The IWRM ToolBox is a free and open database with a library of background papers, policy briefs, technical briefs and perspective papers as well as large sections of case studies and references. The ToolBox also contains a wealth of tools for water management that support climate change adaptation and is a useful resource for those involved in the WSP process when seeking to gain a broader understanding of water resources management and climate change adaptation.
Reference	Global Water Partnership (GWP) Integrated Water Resources Management ToolBox
Link	http://www.gwp.org/en/learn/iwrm-toolbox/About_IWRM_ToolBox/

Title	**Intergovernmental Panel on Climate Change, Fifth Assessment Report. Working Group II – Chapter 8, Urban areas**
Description	This chapter focuses on what we know about the potential impact of climate change on urban centres and their populations and enterprises, what measures are being taken to adapt to these changes (and protect vulnerable groups), and what institutional and governance changes can underpin adaptation. Water supply is included in this assessment and is usefully placed in the context of the broader issues of climate change impacts in the urban context.
Reference	Revi A, Satterthwaite DE, Aragón-Durand F, Corfee-Morlot J, Kiunsi RBR, Pelling M et al. Urban areas. In: Climate change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE et al., editors). Cambridge, United Kingdom, and New York, United States of America: Cambridge University Press; 2014:535–612.
Link	http://www.ipcc.ch/report/ar5/wg2/

Title	**Intergovernmental Panel on Climate Change, Fifth Assessment Report. Working Group II – Chapter 10, Key economic sectors and services**
Description	This chapter assesses the implications of climate change for economic activity in key economic sectors and services, economic welfare, and economic development. This includes water supply systems as well as linking into a wide range of water-related and water-dependent economic activities.
Reference	Arent DJ, Tol RSJ, Faust E, Hella JP, Kumar S, Strzepek KM et al. Key economic sectors and services. In: Climate change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE et al., editors). Cambridge, United Kingdom, and New York, United States of America: Cambridge University Press; 2014:659–708.
Link	http://www.ipcc.ch/report/ar5/wg2/

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Annex 1. Netherlands case study: potential climate change impacts on the drinking-water function of the Rhine and Meuse rivers

Context

The rivers Rhine and Meuse are an important source of drinking-water in the Netherlands, contributing to approximately 40% of the total drinking-water supply, with the remaining 60% coming from groundwater *(1)*. Most intake stations along the Rhine and the Meuse are situated in the central part of the country (Figure A1.1). After intake, the water is pretreated and then pumped to the dunes, where the water is artificially infiltrated and purified. After a residence time of two months, the water is pumped up again for final treatment to drinking-water. Direct purification of river water to drinking-water takes place at one intake station on the Meuse River (with large storage basins) and one intake station along Lake IJssel (Figure A1.1).

In 2014, the Royal Netherlands Meteorological Society (KNMI) published four climate change scenarios for the Netherlands *(2)*. Generally, warmer summers are projected, but summer precipitation may increase or decrease, depending on the scenario. The most critical scenario with respect to water availability is W_H, with a projected increase of mean summer (JJA) temperature of 2.3°C, an average decrease in summer precipitation of 13%, and an increase in potential evapotranspiration of 11% during summer in the year 2050 (all changes relative to current climate, i.e. the period 1981–2010). This scenario would result in more frequent occurrence of severe droughts and heatwaves in the Netherlands, with important consequences for water quantity and water quality.

Figure A1.1. Drinking-water in the Netherlands: sources and customers

Note: Intake stations of river water for drinking-water production in the Netherlands are shown by green circles; blue circles indicate the coastal dunes where river water is infiltrated, pumped up and post-treated.

Zwolsman and Van Bokhoven *(3)* and Van Vliet and Zwolsman *(4)* investigated the impact of low river flows and heatwaves on the water quality of the Rhine and the Meuse rivers in the Netherlands, and the consequences for drinking-water production. Impacts of heatwaves and low river flows were investigated by systematically comparing water quality during years with heatwaves and hydrological droughts (i.e., 1976 and 2003) to that in reference years with greater average river flows and temperature distribution (Table A1.1). Water quality data were taken from a large database on surface water quality in the Netherlands (http://live.waterbase.nl), coming from the National Water Quality Monitoring Programme.

Table A1.1. Mean monthly discharges of the Rhine and Meuse rivers recorded at the border with Germany and Belgium, 2002–2004 (showing hydrological drought July–December 2003)

	Rhine (border station Lobith): Q (m^3/s)			Meuse (Borgharen, 15 km to border): Q (m^3/s)		
	2002	2003	2004	2002	2003	2004
April	2152	1540	1774	198	93	132
May	2712	1764	2064	172	133	136
June	2195	1658	2052	70	62	39
July	1963	1251	1696	51	27	38
August	2113	1013	1536	69	17	86
September	1787	936	1495	36	13	62
October	2415	1266	1537	97	17	53
November	4845	1160	1978	560	26	125
December	3301	1425	1685	389	110	191

In addition, Sjerps, Zwolsman and ter Laak *(5)* studied the effect of climate change on pharmaceutical concentrations in the Rhine and Meuse rivers, based on monitoring data and discharge during the years 2010 and 2011 and the KNMI climate scenarios. By comparing the water quality during dry years to that of more average years, several impacts of droughts and heatwaves on river water quality could be identified:

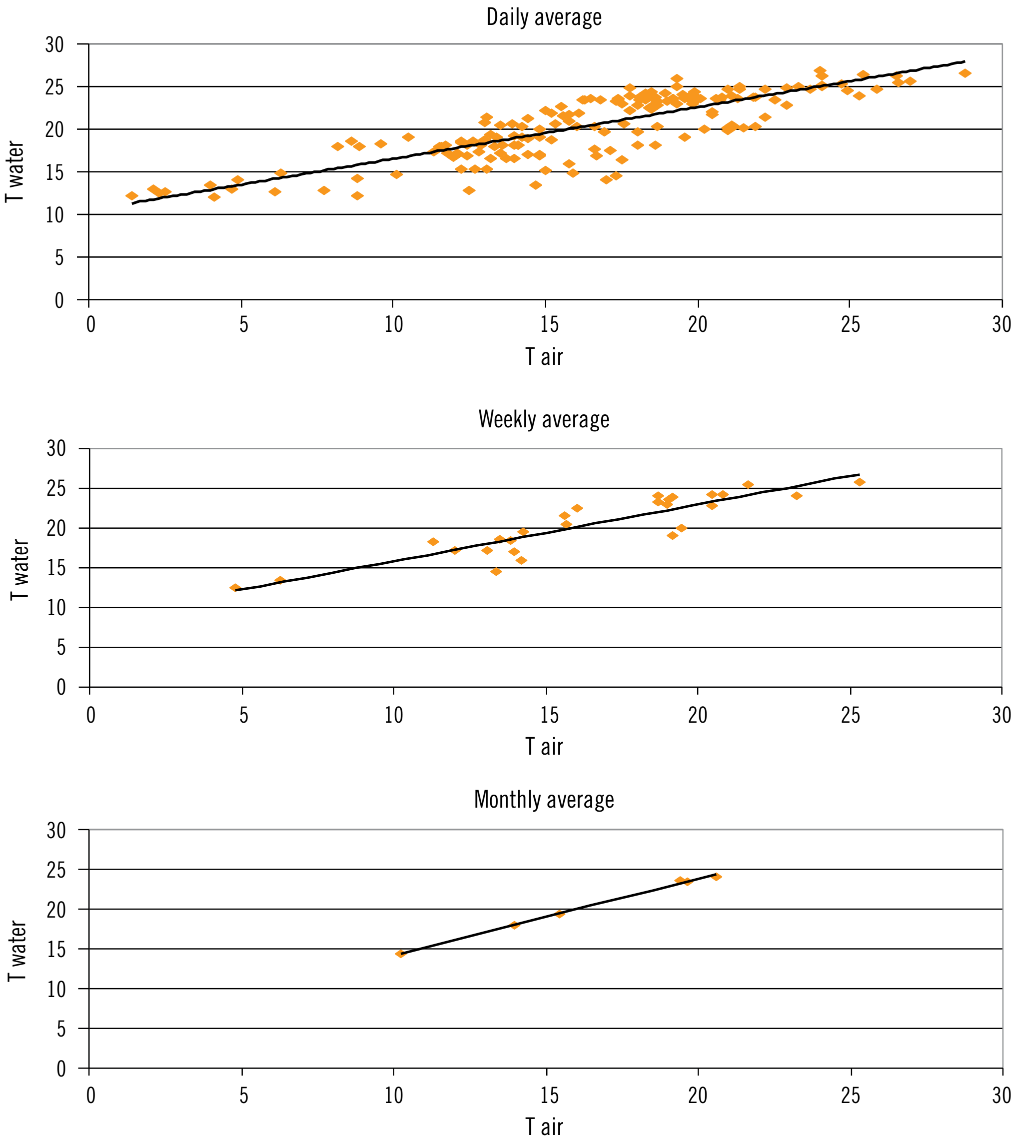
- increase in water temperature
- increase in eutrophication potential
- less dilution of point source emissions
- salinization of (tidal) river stretches.

These impacts are described in more detail below.

Impact of climate change on river water temperature

Surface water temperature closely follows air temperature, for both short-term (daily) and long-term (monthly) timescales. As an example, Figure A1.2 shows the relation between the temperature of the Meuse River and air temperature; similar results have been obtained for the Rhine River (not shown). This means that future water temperatures in the Netherlands will be seriously and predictably impacted by climate change.

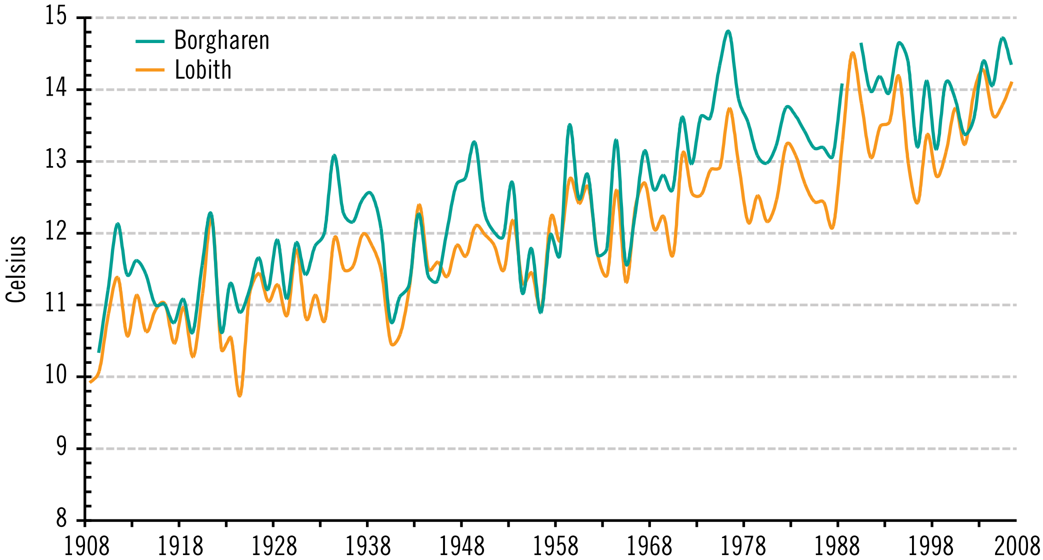
Figure A1.2. Correlation of river water temperature and air temperature in the Meuse River at the Dutch-Belgian border, based on daily, weekly and monthly averages (data from April to September 2003)



The water temperature of the Rhine River during the dry and hot summers of 1976 and 2003 is clearly higher than in the reference summers 1975/1977 and 2002/2004, respectively. Temperature increase compared to the reference summers amounted to 1.4–1.8°C in summer 1976 (JJA) and 1.4–1.6°C in summer 2003 *(3)*. In the Meuse River, Van Vliet and Zwolsman *(4)* found that the water temperature during the dry and hot summer of 2003 (JJA) was on average 2°C higher compared to the reference summer temperature of 2002 and 2004.

On top of this interannual variability, a distinct long-term trend of increasing river water temperature is apparent over the past 100 years. Over the past century, an increase in average annual water temperature by 4°C (!) has been observed, both in the Rhine River and the Meuse River (Figure A1.3). Some two thirds of this trend is due to an increase in discharges of cooling water (power plants and large chemical plants), while one third can be ascribed to an increase in average air temperature over the past century (that is, due to climate change).

Figure A1.3. Increase of average annual water temperature in the Rhine River over the 20th century



Note: Station Lobith = Rhine River at Dutch-German border; station Borgharen = Meuse River, 15 km down-stream from Dutch-Belgian border.

The long-term increase in water temperature is of major importance as it affects the capacity of the river to cope with the impacts of climate change. For instance, during the heatwave of August 2003, water temperatures often exceeded the ecological and drinking-water production threshold of 25°C, whilst during the (stronger) heatwave of 1976 this was seldom the case *(3)*. During the heatwave of July 2006, an all-time high water temperature of 28.0°C was recorded, both in the Meuse and in the Rhine. Such high water temperatures pose a direct threat to the aquatic ecology of the river and give rise to associated problems for drinking-water production (see next section). It can be concluded that the increasing use of both rivers for cooling purposes has seriously affected their capacity to cope with the growing impacts of climate change.

Impact of heatwaves on eutrophication

Low river flows combined with high water temperatures create ideal conditions for eutrophication. A typical example of algae blooms and their impact on general water quality is shown in Figures A1.4 and A1.5, representing the heatwave of July 2006 in the Netherlands (the strongest heatwave recorded in the past 300 years). Chlorophyll-a concentrations peak during the heatwave, but more importantly, the algae blooms have a strong impact on water quality, in terms of dissolved oxygen and pH, and hence on the ecological status of the river. Dissolved oxygen and pH show day–night oscillations, due to the dynamics of primary production during the day (consumption of CO_2, production of oxygen) and the opposite process (respiration) overnight. This leads to a dramatic fluctuation of dissolved oxygen, decreasing to 2 mg/L during the night, and increasing up to 16 mg/L during the day. Obviously, such strong variation in dissolved oxygen poses severe stress to the aquatic ecology, especially sessile organisms (benthos), which cannot evade the stressful conditions.

Besides the impact on aquatic ecology, algae blooms pose a challenge to drinking-water production. The algae have to be removed by flocculation and sand filtration, whilst supplementary treatment with activated carbon may be required to remove associated taste and odours from the water (for example geosmin, 2-methyl isoborneol). To reduce the impacts of heatwaves and low river flows on the eutrophication potential of river systems, nutrient reduction programmes in the catchment area may be required.

Figure A1.4. Chlorophyll-a concentration (µg/L) in the Rhine River (border station Lobith) and Meuse River (border station Eijsden) from June to August 2006

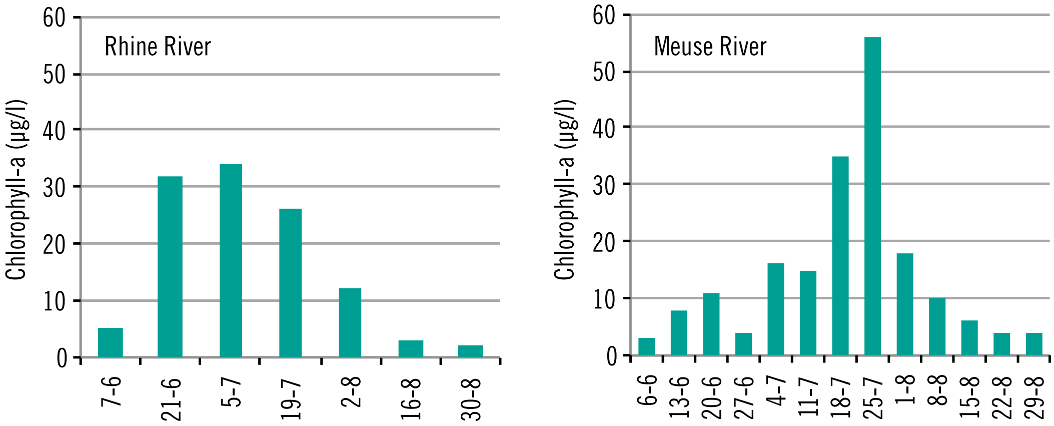
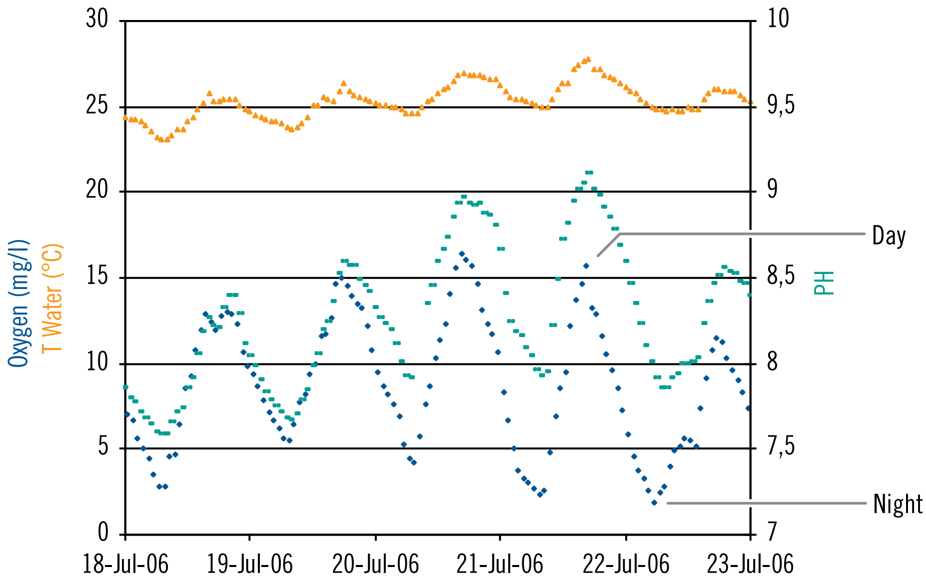


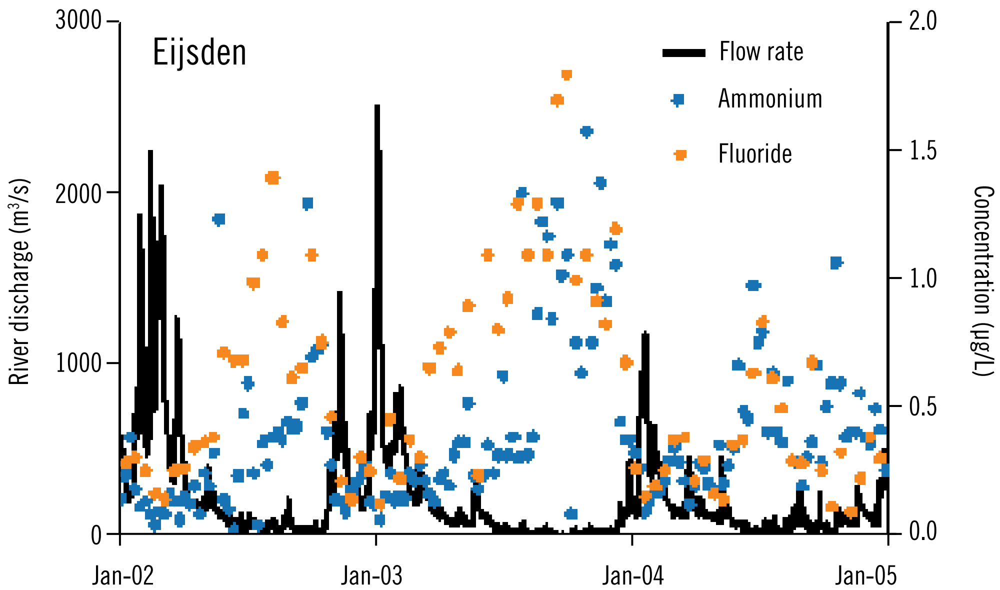
Figure A1.5. Day–night cycle of water temperature (orange), dissolved oxygen (blue) and pH (green) in the Meuse River (border station Eijsden) during the heatwave of July 2006



Impact of droughts on river water quality

The impact of hydrological droughts on the dilution capacity and the water quality of the Rhine and Meuse rivers has been studied extensively by KWR *(1, 3–5)*. Basically, these studies are based on real water quality data (as opposed to model projections) obtained during dry summers and compared to water quality of reference summers with average hydrological conditions. Generally, it is found that water quality is negatively influenced by droughts for parameters such as major ions (for example, chloride, sodium, calcium), nutrients, trace metals and organic micropollutants. An example is shown for ammonium and fluoride in the Meuse River (Figure A1.6).

Figure A1.6. River discharge, ammonium and fluoride concentration in the Meuse River (station Eijsden = border Netherlands-Belgium) during 2002–2004 (note influence of low river flows on river water quality)



The decline in water quality during droughts is related to limited dilution of point source emissions, such as communal and industrial wastewater treatment plants. It is noteworthy that if pollutant sources are mainly of diffuse origin, then chemical loading depends on the amount and intensity of rainfall in the catchment area; hence the chemical loading from non-point sources may decrease during droughts, as discussed and referenced in Zwolsman and Van Bokhoven *(3)*. This is the case for nitrate in the Rhine River, where the source of pollution is dominated by diffuse sources (soil leaching) rather than point source activities. Consequently, nitrate concentrations in the river water are quite invariant over a wide range of river discharges, as chemical loading and dilution capacity behave oppositely with respect to river flow, balancing their impacts.

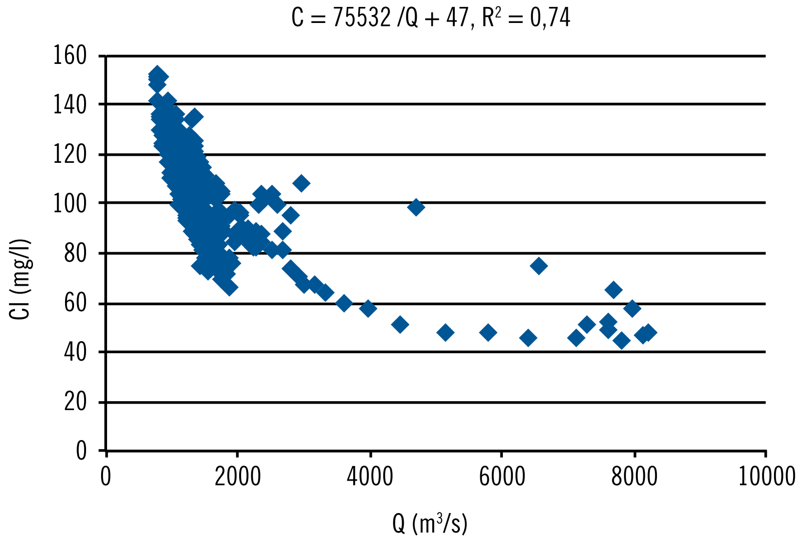
From a drinking-water perspective, the concentration of chloride and bromide in the Rhine is relevant, especially during low river flows. The impact of river flow on chloride concentration in the Rhine is shown in Figure A1.7. The data set, based on daily measurements in the year 2011, can be described by a simple dilution equation:

$$C = a/Q + b$$

where C = chloride concentration (mg/L), a = chloride load (g/s), Q = river flow (m^3/s) and b = chloride background concentration (mg/L).

The current chloride load (estimated from Figure A1.7) is 75 kg/s and the background concentration is 47 mg/L. From this C-Q relation, it can be calculated that if the river flow drops below 730 m^3/s, chloride will exceed the Dutch drinking-water standard of 150 mg/L (assuming a constant chloride load to the system). Such low river flows are projected indeed in the future under the W_H climate scenario *(6)*.

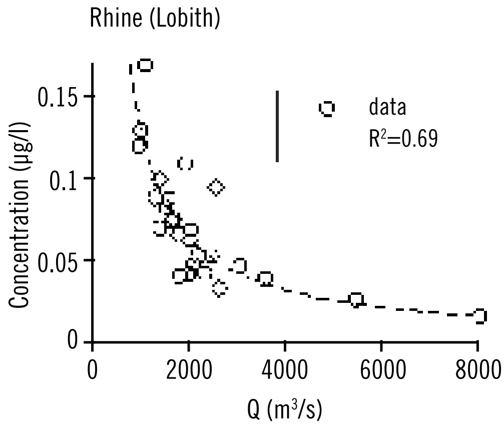
Figure A1.7. Impact of river flow on chloride concentration in the Rhine River, station Lobith (note that the Dutch drinking-water standard (150 mg/L) is reached during low river flows); data set from 2011



Typically, the bromide concentration of the Rhine River increases from 100 µg/L during average river flows to 300 µg/L during low river flows *(3)*. The increasing concentration of bromide during low river flows is relevant if ozone is used in the water treatment process, because this will increase the formation of (carcinogenic) bromate during ozonation. If only a small fraction of bromide is converted to bromate during ozonation, the Dutch drinking-water standard for bromate (5 µg/L) will already be exceeded.

Pharmaceuticals are emitted to surface water by wastewater treatment plants at a more or less constant load. Thus, an inverse relation between the concentration of many pharmaceuticals and river flow is anticipated. Sjerps, Zwolsman and ter Laak *(5)* used recent monitoring data to project future concentrations of pharmaceuticals in the Rhine and Meuse rivers under different climate scenarios. Data were selected for the year 2011, characterized by a prolonged low flow period, with the year 2010 as the reference period. For various substances, the concentration could be described by the dilution equation $c = \frac{a}{Q} + b$, similar to chloride. A typical example is shown in Figure A1.8 for carbamazepine in the Rhine and the Meuse.

Figure A1.8. Relation between river flow and concentration of carbamazepine in Rhine River (station Lobith) and Meuse River (station Eijsden) during 2010/2011



Source: Sjerps, Zwolsman and ter Laak *(5).*

Sjerps, Zwolsman and ter Laak *(5)* used these Q-C relationships to study the effect of hydrological variability (that is, dry years and wet years) and climate change on water quality of the Rhine and Meuse rivers in the year 2050. Both factors appear to have a significant influence on water quality. The impact of a very dry hydrological year (1976) on chemical concentrations can vary by a factor of 1.5 in the Rhine up to a factor of 2 in the Meuse (as compared to an average hydrological year, such as 1967). The impact of climate change on water quality is of the same order of magnitude. When these two impacts are combined, concentrations of pharmaceuticals in the Meuse are projected to increase by a factor of 3 to 4 in a very dry year under the fast climate change scenario (W_H), compared to a normal hydrological year under current climate. In the Rhine, the concentrations may increase by a factor of 2 to 3.

Because the Meuse is a typical rain river and its catchment area is relatively small (10 times smaller than that of the Rhine), the combined effect of a dry year and climate change has greater impact on the water quality of the Meuse compared to the Rhine. For example, the projected concentrations of AMPA (metabolite of the herbicide glyphosate) in the Meuse increase up to 10 µg/L in the W_H scenario; while the AMPA concentrations in the Rhine remain below the drinking-water intake standard of 1 µg/L. As long as the Rhine is fed with meltwater from the Alps during dry spells *(7)* the discharge will not drop so steeply compared to the Meuse, which is solely fed by rainwater.

The potential decline in future river water quality due to climate change poses a risk to drinking-water production in the Netherlands. However, measures are in progress to improve the efficiency of wastewater treatment with respect to pharmaceuticals. Efficient post-treatment (ozonation and activated carbon) has already been installed on large wastewater treatment plants in Germany and Switzerland. It is likely that the Netherlands will follow this example in the coming years.

Salinization

Zwolsman *(1)* noted that salinization was expected to increase within the Netherlands for two reasons. First, rising sea levels may lead to upconing of seawater in coastal aquifers, threatening the use of those aquifers for drinking-water supplies. Second, low flows of the Rhine allow seawater to intrude further inland, particularly during periods of north-westerly winds or spring tides, which lead to high seawater levels near the coast. Under normal hydrological conditions, seawater penetrates via the Rhine estuary (the so-called Nieuwe Waterweg) up to the city of Rotterdam (Figure A1.9). However, under unfavourable conditions – that is, low river flows and high seawater levels – seawater can intrude further upstream into river branches used for irrigation (Hollandsche IJssel) or drinking-water production (Lek).

Salinization of the freshwater tidal branches of the Rhine River typically occurs when low river flows coincide with high seawater levels at the mouth of the estuary. Given the likelihood of north-westerly winds and low river flows coinciding, the highest risk of salinization is in the fourth quarter of the year. An example of salinization of the mouth of the Lek during the drought of July–November 2003 is shown in Figure A1.10.

Figure A1.9. Rhine estuary (Nieuwe Waterweg + Nieuwe Maas), including the tidal freshwater branches Hollandsche IJssel and Lek (blue circle)

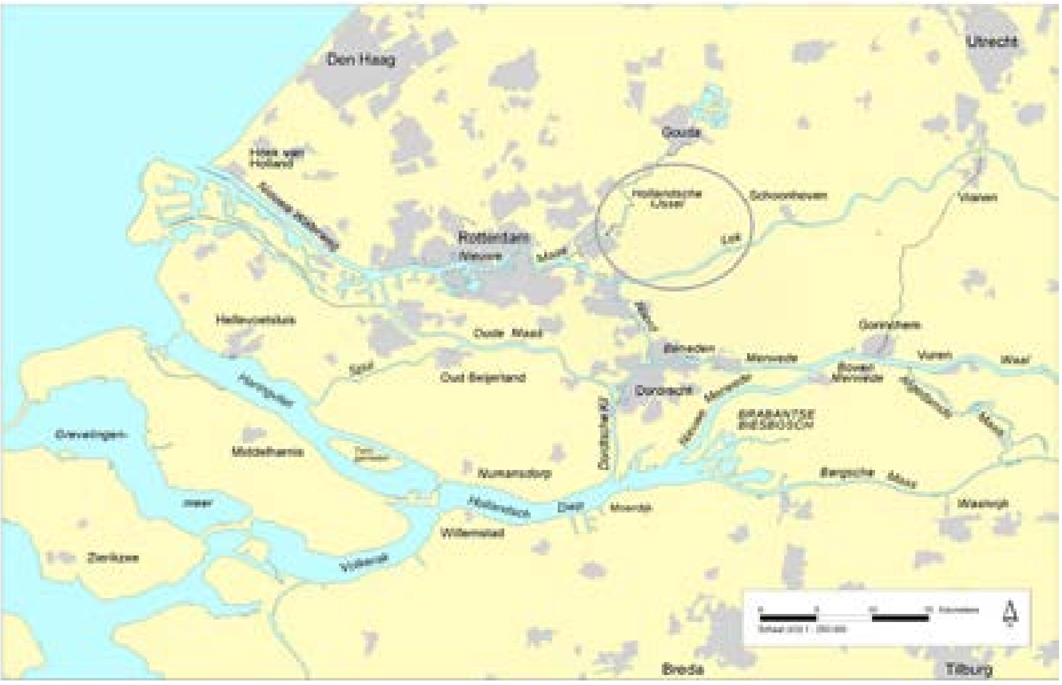
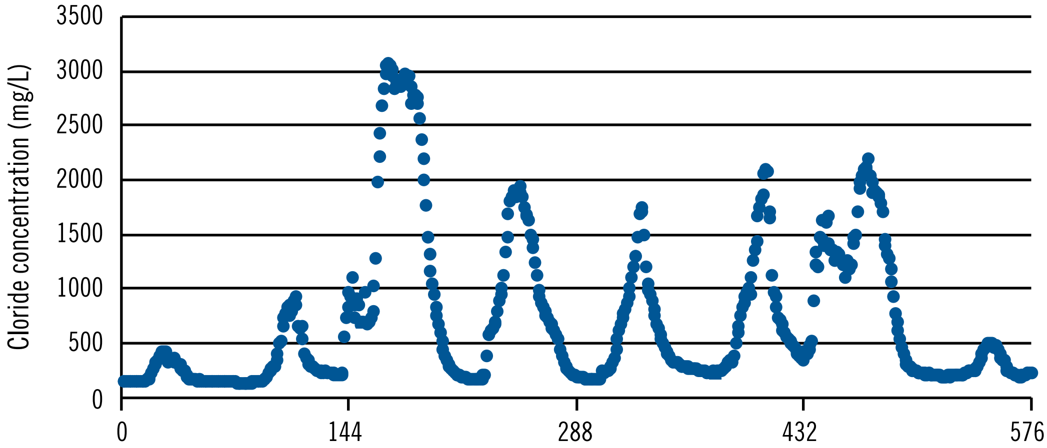


Figure A1.10. Salinization of the Rhine estuary (branches Nieuwe Maas and Lek) during the 2003 drought



Salinization increasingly affects the drinking-water function of the Lek River. Near the mouth of the Lek, river water is abstracted through riverbank filtration. It was found that the salinity of the pumped groundwater along the Lek is gradually increasing, due to past seawater intrusion events. Since more of these events are anticipated in the future because of climate change, the local water company has decided to expand current water treatment at the three most downstream production locations with a desalination step. Consequently, treatment costs will increase in the future.

System resilience to change

From the studies conducted in the Netherlands it appears that general trajectories can be established for rivers under the impact of climate change. Water quality of rivers with commonly low summer discharges and with a predominant pollutant input by point sources, like the Meuse *(4)*, is likely to be most sensitive to drought conditions due to limited stream dilution and high water temperatures. In contrast, rivers with a relatively high summer discharge (for example rivers fed by snowmelt) are unlikely to experience the same degree of impact. For instance, water quality effects of droughts on the Rhine were far less compared to the effects observed in the Meuse *(3, 5)*. In fact, water quality of rivers with a high relative contribution of diffuse pollution sources might be stable or even become better during droughts, as a result of less supply of pollutants by soil leaching and overland flow.

The ability of a river system to cope with changes associated with climate change will be a function of ecosystem resilience. Studies of the Rhine and Meuse have shown that the impact of droughts on water quality will be greater when the water quality is already poor. Thus, reductions in pollution discharges into the Rhine and Meuse will increase the resilience of these rivers to future climate change. Without addressing climate change, historical water quality issues could again become significant in the future.

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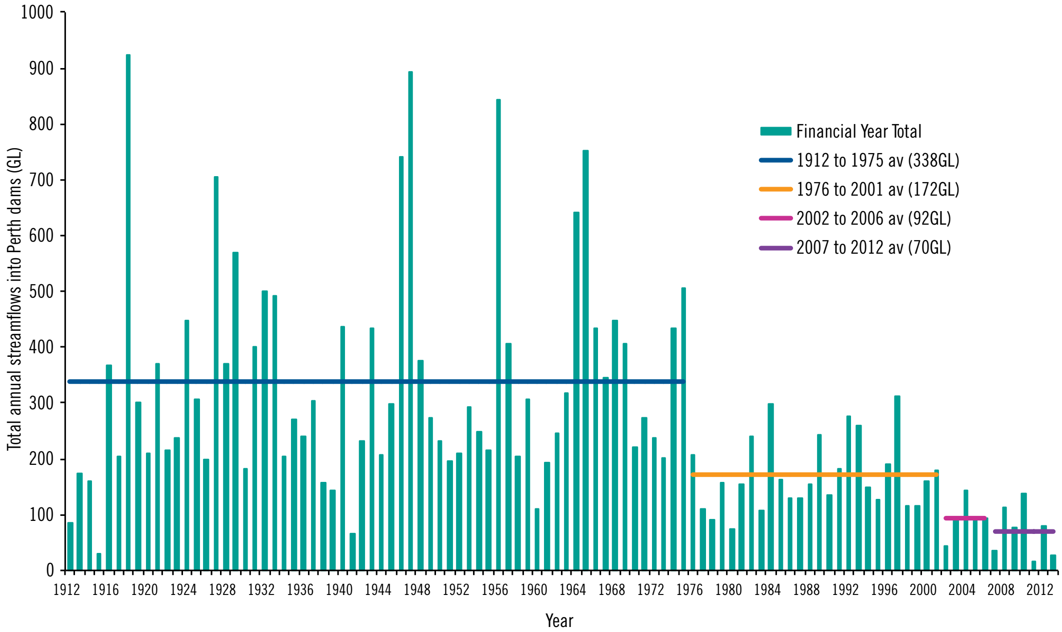
Annex 2. Australia case study: water safety plans to manage risks from a supplemental water source in Western Australia

Context

The Water Corporation is the main supplier of water in Western Australia. It has been studying the effects of climate change on water quality for many years and is renowned for its excellent water planning and response to these changes. This case study describes the experience of the Water Corporation with drinking-water quality and safety and highlights the useful lessons for other suppliers that may face similar problems in future.

In Western Australia, reduced rainfall has had a significant negative impact on many of the state's surface water and groundwater sources. This is clearly demonstrated in Figure A2.1, where 12% decreases in rainfall have resulted in a 50% reduction in streamflow into Water Corporation surface water sources. The south-west of Western Australia is one region that has been severely impacted by climate change and reduced rainfall, significantly so over the past 10 years.

Figure A2.1. Declining inflows to storage dams for Perth, Western Australia



Note: Periods are financial year July to June, and are labelled as financial year ending. Inflows are simulated for periods prior to construction of some of the dams.

Source: Water Corporation, 2013.

Risk assessments have been completed at various points in time as knowledge, understanding and awareness of water quality hazards and catchments have increased. Following the development of the WHO water safety plan concept *(1)* and the development of the Australian Framework for Management of Drinking Water Quality, the water safety planning process at the Water Corporation commenced in 2004, with Margaret River being one of the first schemes assessed.

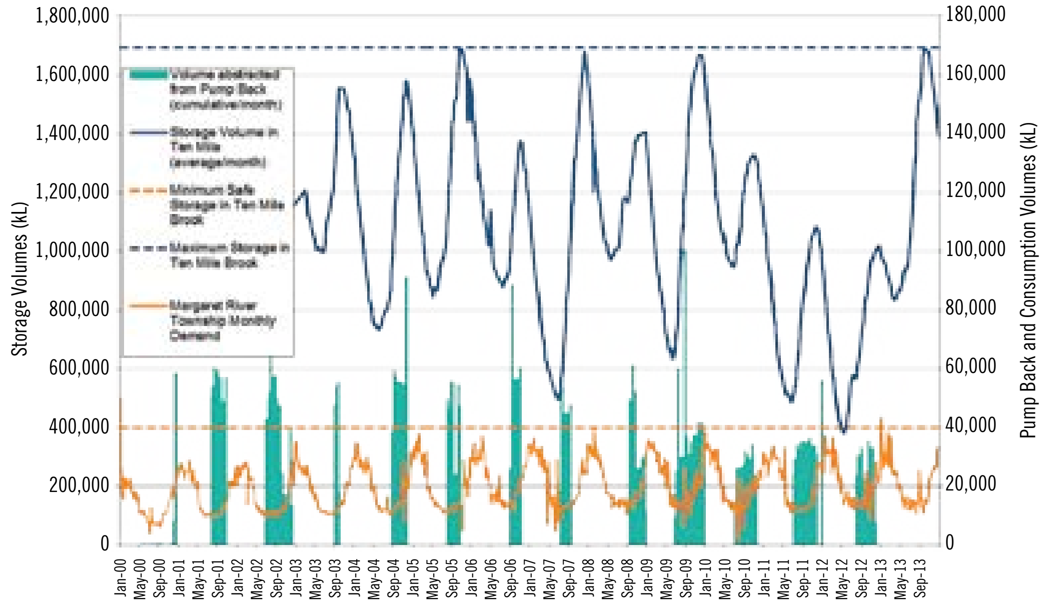
Margaret River scheme

Located approximately 280 km south of Perth, Margaret River has a permanent population of over 10 000 local residents, with around 500 000 visitors annually. The region experiences a Mediterranean type of climate, with warm dry summers and cool wet winters. Annual rainfall varies between 900 mm and 1100 mm in the catchment areas. This temperate climate has enabled Margaret River to become one of the major wine-producing regions in Australia. With a growing residential population and expanding tourism, the Water Corporation has invested significant resources into ensuring a safe, reliable drinking-water supply to the town.

The main source for Margaret River is Ten Mile Brook Dam, constructed on a tributary of the main Margaret River. When Ten Mile Brook Dam was commissioned in 1994, it was expected that this 1700-million-litre surface water source would be able to supply Margaret River for more than 20 years. With the impact of low run-off conditions the yield of Ten Mile Brook catchment is estimated at around 650 million litres per year, depending on rainfall. Thus, while Ten Mile Brook Dam is considered to have good source water quality, the change in inflows lead to this water supply being considered highly vulnerable.

Supply to Margaret River town became problematic in the early 2000s following consecutive low rainfall winters. It was therefore decided to supplement the Ten Mile Brook Dam by using a pump back from Margaret River Dam, which had a high source pathogen risk classification. Figure A2.2 shows the Margaret River demand, storage levels and the pump back operation since 2000.

Figure A2.2. Margaret River pump back, demand and storage levels 2000–2013



Development of water safety plans

In 2004, the Water Corporation began developing water safety plans for its 245 supply localities. With this huge number of supplies, priority was given to schemes considered "high risk" for water quality. The Margaret River scheme was one of the first localities to be reviewed because of the high rate of pump back from Margaret River Dam and the high source risk level.

As part of the water safety planning process, sources are reviewed and placed into one of five surface water risk categories, with level 1 sources requiring minimal treatment (disinfection only), and level 4 sources requiring extensive treatment; anything above level 4 is considered "unsuitable" for use. The basis for this risk classification is from a pathogen perspective, using historical *Escherichia coli* results and a perceived bacterial and viral risk, as well as *Cryptosporidium* and *Giardia* spp. risk based on observed land use activities.

The catchment for Ten Mile Brook had some private land, with some cattle grazing occurring, and based on these observations this source was considered moderate risk (level 3 – requiring some additional treatment barriers such as filtration or ultraviolet (UV) disinfection). However, the Margaret River pump back source was considered as unsuitable based on previously high *E. coli* numbers and the large number of cattle directly grazing within feeder streams leading to the pump back. There were also very few source protection measures that could have been taken to reduce the risk. In addition, turbidity and *E. coli* spikes were observed on the outlet of Ten Mile Brook Dam when the pump back was operating.

As a result of the water safety planning process, an action plan was developed. In the medium term a number of steps have been taken to mitigate the pathogen risks associated with using the Margaret River pump back as a source. These steps are summarized below and discussed in more detail in the following sections (Figure A2.3):

- Installation of turbidity analysers at the outlets of Margaret River pump back and Ten Mile Brook with auto shut-off of the pump station should turbidity be measured at greater than 5 nephelometric turbidity units (NTU). Turbidities greater than 5 NTU have been associated with high rainfall, increased pathogen loads and decreased disinfection effectiveness.
- Upgrading UV disinfection at the outlet of Ten Mile Brook.
- Relocating the pump back of Margaret River to the back of Ten Mile Brook.
- Membrane filtration at the outlet of Margaret River pump back.
- Abandoning Margaret River pump back as a source and developing a new source from a confined aquifer source.

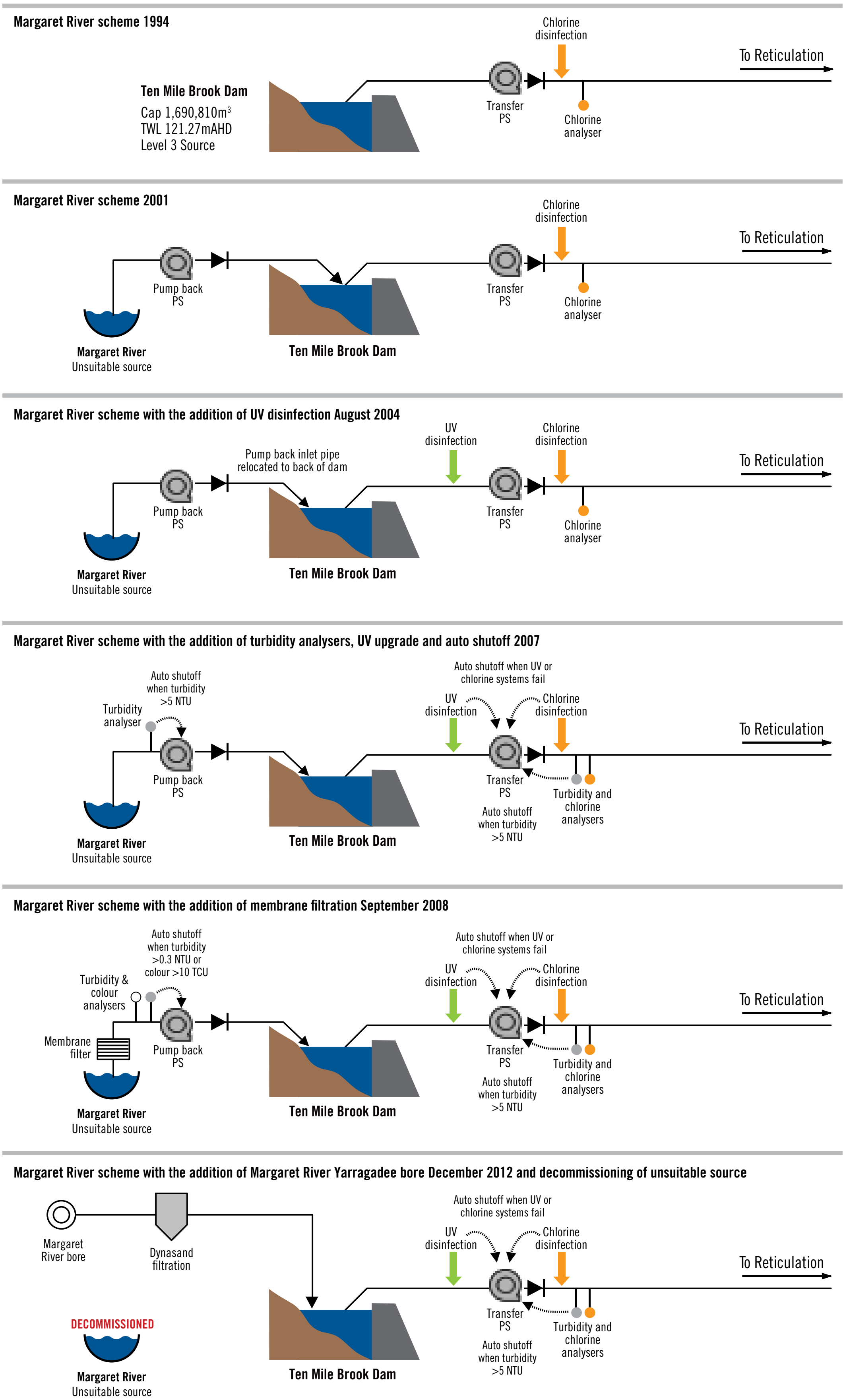
The long-term strategy was to install a water treatment plant at Ten Mile Brook.

Water safety plan operating strategy and action plan

With additional treatment taking months to commission, the water safety plan provided an effective tool to immediately develop and agree on appropriate operating strategies for the source based on the water quality from the pump back and Ten Mile Brook supply dam. It was decided to place turbidity limits on the use of the pump back, limiting use to periods when turbidity was below 5 NTU, as high readings of *E. coli* usually coincided with elevated levels of turbidity. This operational limit (process control point) was employed as a surrogate indicator of the pathogen load coming from the pump back and was used to restrict operation to times of likely lower pathogen risk. Other immediate actions included the relocation of the pump back inlet to the back of Ten Mile Brook to limit short-circuiting and allow maximum natural die-off and dilution in Ten Mile Brook dam before disinfection, and commissioning of a UV disinfection unit.

In August 2004 a UV disinfection unit was commissioned on the outlet of Ten Mile Brook Dam. While this additional barrier alone was not sufficient to meet the requirements set by the Water Corporation it was still seen as an effective interim risk reduction measure. The UV disinfection unit became a critical control point, targeting > 40 mJ/cm^2. Subsequently, as the Water Corporation became more familiar with the limitations of UV disinfection, the WSP was revised in 2006 and process control point limits were applied to water quality on the outlet of Ten Mile Brook Dam for colour (10 hazen units) and turbidity (< 2 NTU) to assure the effective operation of the UV barrier.

Figure A2.3. Margaret River scheme, showing the changes in water supply arrangements over time in response to the changing climate



Water quality incident, winter 2007

During the winter of 2007, Ten Mile Brook Dam experienced very low run-off from the catchment. This resulted in the supply to the locality becoming even more reliant on the pump back from the Margaret River. It was estimated that by the end of the 2007 winter over 50% of the water stored in Ten Mile Brook Dam was sourced from the pump back. The higher proportion of pump back water in Ten Mile Brook Dam resulted in operational limits for colour and turbidity being breached on the outlet of the main dam. This prompted response actions to be invoked, as set out in the water safety plan, based on the possibility that the single protozoan barrier on the outlet of Ten Mile Brook Dam (UV disinfection) may be compromised.

The immediate response was to cease pump back operation until the water in Ten Mile Brook Dam met the operational limits for colour and turbidity.

Thinking ahead to the 2008 winter, another dry winter would see the 2007 scenario repeated but with more severe consequences for water quality and water supply continuity.

Accelerating the plan for augmentation by groundwater was considered but was deemed impractical.

As the only remaining option was to use even more pump back water from the Margaret River it was therefore considered necessary to install a second barrier to protozoan pathogens on the pump back from Margaret River. The action plan included:

- a microfiltration water treatment plant on the pump back from Margaret River;
- increased capacity and redundancy for the UV plant on the outlet of Ten Mile Brook Dam;
- purchase of private land in the catchment that was considered a possible source of *Cryptosporidium* and *Giardia.*

All waters entering the Ten Mile Brook Dam were now considered "low risk" with respect to *Cryptosporidium* and *Giardia*. Hence, the Ten Mile Brook Dam risk level was changed to a level 2 source. The UV on the outlet of Ten Mile Brook Dam is a robust second line of defence for the treated water supply. The microfiltration and UV plants are both designed to "fail safe", which means failure to achieve associated operational limits result in the supply shutting down automatically.

Alternative source development, 2012

While the actions following the winter 2007 incident considerably reduced the water quality risks at Margaret River, there was still a need to develop an alternative source solution.

The use of the high-risk Margaret River pump back with ultrafiltration (UF) and reliance on a single UV barrier on the outlet of Ten Mile Brook was a catalyst to commence planning to stabilize the water supply to Margaret River and to establish the criteria for the selection of new sources.

This resulted in the Water Corporation establishing a preference order for new sources based on pathogen risk, as set out below:

1. confined groundwater
2. unconfined groundwater
3. surface water (large dam)
4. surface water (small dam)
5. pump back only acceptable if dam not operated for a minimum of 30 days after pump back ceases.

The planning for Margaret River subsequently recommended using a confined aquifer source. This source was developed in 2012, along with an associated water treatment plant for iron removal. This enabled the Margaret River pump back source to be decommissioned, thus further reducing the water quality risks at Margaret River.

Long-term plan

A further planning review in 2014 of the Margaret River scheme supported the construction of a water treatment plant at the outlet of Ten Mile Brook Dam. This would address the gap in the treatment for pathogen removal. Although the source risk is relatively low, adequate treatment should be in place that is appropriate for this level of risk (that is, level 2 treatment for a level 2 source). The current treatment of UV and chlorination disinfection provides an acceptable pathogen risk reduction; however, this is considered to be a temporary arrangement. Typically, a level 2 source requires a physical removal barrier, such as granular media filtration.

The long-term planning recommendation is to install a level 2 treatment plant at Ten Mile Brook Dam.

Conclusion

Climate change has seriously undermined the yield of many schemes operated by the Water Corporation across Western Australia. New source development is expensive and in most cases can take many years to commission. In the interim, there is increasing pressure to use high-risk sources to augment supply. Development and implementation of water safety plans is an effective mechanism to identify and then minimize risk to customers when operating those sources. By paying careful attention to risk assessments, mitigation strategies, control points and response plans, utilities can demonstrate due diligence while accommodating climatic and water quality variations.

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Annex 3. Nepal case study: water safety plans to manage risks in Nepal

Introduction

Ensuring that water safety plans (WSPs) systematically consider and address potential water quality and quantity impacts related to climate change helps to create more effective WSPs and more resilient water supply systems. The United Kingdom Department for International Development (DFID) and World Health Organization Water Quality Partnership for Health (WQP) have therefore collaborated to develop the draft guidance document *Climate-resilient water safety plans: managing health risks associated with climate variability and change*.

Piloting of the guidance document has been carried out in Nepal with technical support from WQP and financial support from DFID. DFID is supporting the development of climate-resilient WSPs as part of a US$ 10 million project seeking to build adaptation to climate change in health in Bangladesh, Ethiopia, Nepal and the United Republic of Tanzania through resilient water, sanitation and hygiene. In Nepal, DFID-funded development of climate-resilient WSPs builds directly on the WSP programme established through WQP, drawing on existing WSP awareness and support, capacity, tools and regulatory drivers. In turn, the DFID project contributes to the WQP goals by providing additional resources to support national partners in continued WSP strengthening, implementation and monitoring.

Climate-resilient WSPs have been piloted in five water supply systems in Nepal. Key findings are summarized below, which demonstrate the value of considering climate impacts through the WSP process.

Climate-resilient WSP pilot findings and responses: climate change hazards, risks and control measures

Climate change-related hazardous events in Nepal are generally described as coming from increased precipitation intensity and variability, decreased water flows, and increased temperature variability, all of which have an impact on availability and quality of water supply and can lead to water safety problems.

Global warming is impacting both surface water and groundwater sources. More intense precipitation is leading to an increase in pathogen release, turbidity, chemicals and nutrient loads from catchment areas, and floods are causing short-term contamination in surface water sources that is often beyond the capacity of water treatment plants. Increased rainfall intensity and longer drought periods are also causing increased or decreased groundwater levels and contamination of groundwater due to infiltration of pollutants. Increased run-off is causing surface water to enter wellheads and inundate pit latrines, especially in the lowland areas such as the Terai. The intense rainfall also causes cross-contamination and surface pollution due to damaged sewerage systems, surface drains and floods. Other hazardous events include landslides; floods damaging intakes, pipelines and other structures; and wildfires in drought periods, which damage plastic pipes lying on the surface in the jungle areas.

The major control measures considered in the design of climate-resilient water supply systems need to account for these hazardous events. These include catchment protection with measures to control soil erosion and landslides and divert flood water during rainfall events; improved wellhead protection; installation of deep-set tubewells; design of water treatment plants to accommodate a range of pollution events expected during extreme situations (or introduction of additional treatment and storage capacity to account for interruption of production time, quality and quantity); use of appropriate pipe materials; and water conservation and protection of local or alternative sources, including awareness of the 3R principles (reduce, reuse and recycle) in the water and sanitation sector.

Figure A3.1. Examples of climate-related issues from a pilot site (Jomsom, Mustang)

Increased sediments mean relative height of pipe crossing is lower

River intake prone to damage from landslide and flooding

Pipe damage on steep slopes

Due to groundwater depletion spring and associated intake structure is lower

Modification of the WSP process to address climate issues

In order to increase the climate resilience of WSPs, some modification to the WSP process has been introduced, whereby a climate change expert (or person with knowledge of climate change) is included in WSP teams. The hazard identification and risk assessment now includes consideration of climatic hazards, including extreme weather events such as heavy rain, floods and drought, and control measures that are sensitive to climate change and extreme weather events are included in the WSP. The WSP teams are encouraged to draw lessons from past climate-related events that impacted the water supply system and learn how climate-related changes could impact the water supply system in future. WSP teams are encouraged to tap into the opportunities available in their local areas for engagement with other stakeholders, including health officers and local experts.

Consideration of climate-induced hazards and more resilient control measures is being introduced into many existing WSPs, supported by WQP. For example, the WSP in Barchour Ranipani (Tanahu) initially had the usual control measure of a diversion channel above the intake to protect against contamination of the source water through the upstream irrigation channel during the rainy season. However, considering the risks of landslides and floods related to extreme weather conditions, the critical part of the open channel has now been replaced by a pipeline and has therefore been made more climate resilient.

Conclusions and outcomes

The climate-resilient WSP pilots in Nepal demonstrate that the WSP process provides an effective framework for considering and addressing risks to water supply systems brought about by climate change. The existing national WSP implementation guidelines and associated training manuals for both urban and rural systems, which were developed under WQP, have been revised to accommodate climate change issues. The previous WSP approach has therefore been replaced by a revised WSP approach that promotes consideration of climate impacts, with the concept of climate resilience implicit and fully integrated, such that the term "climate-resilient WSP" may become redundant in the future.

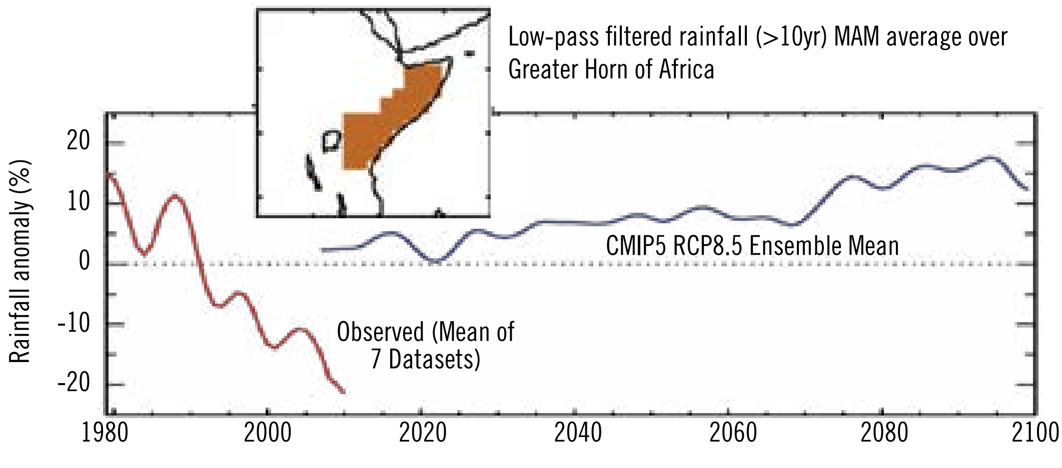
This case study shows how support from other donors is being used to build almost seamlessly on the work done by WQP. The effects of climate change shown here are not unique to Nepal and there is increasing interest from other countries (for example Lao People's Democratic Republic and Viet Nam) on this approach and the lessons to be drawn from it.

Annex 4. United Republic of Tanzania case study: how can WSPs help adapt to an uncertain climate?

Water safety plans are designed to provide a proactive approach to managing water supply risks. But what happens when the risks are uncertain? In East Africa, the climate is projected to be wetter by the end of the 21st century, with more intense wet seasons and less severe droughts during October to December and March to May *(1)*. However, the current observed trend shows a decrease over the last three decades in the March–May seasonal rainfall *(1)*. As illustrated in Figure A4.1, these conflicting reports of decreasing and increasing rainfall create the "East Africa paradox". There are a number of theories for this paradox that are being investigated *(2)*, but without resolution yet. For water managers, this paradox creates significant uncertainty about future water availability and how they should be adapting to climate change.

However, there are aspects of the forecasts in which there is a higher degree of confidence and that can be used by water managers to influence their climate adaptation planning; for this we will focus on two areas, the implications for quantity and quality.

Figure A4.1. The "East Africa paradox": current drying trend and projections for increased rainfall for March–May "long rains" over Greater Horn of Africa



Note: The image shows the lowpass-filtered time series (50% amplitude cutoff at 10 yr) of observed (left-hand line) and projected (right-hand line) March-May rainfall anomalies averaged over the greater Horn of Africa (area shown by inset). Observed data are averaged over seven gridded datasets and projected data are averaged over 39 Coupled Model Intercomparison Project Phase 5 (CMIP5) models forced by the scenario with the largest projected greenhouse gas emissions and associated climate change. Units are percentage of the 1901–2000 climatology, calculated using gridded observed datasets available for each year or corresponding CMIP5 historical runs *(3)*.

While there is overall uncertainty about the projections for total precipitation, and therefore the quantity available from rainfall, there is good evidence that the rainfall will be more intense. For the United Republic of Tanzania, this will be associated with a shorter "long rains" (March–May), longer dry periods, and more extreme wet days. The implications are that there will be greater variations in water availability throughout the year, with water storage and management of demand increasingly important. A study of historical data in the United Republic of Tanzania highlighted how the majority of groundwater recharge for the Makutapora Wellfield, which provides Dodoma's drinking-water supply, is associated with extreme rainfall events, with 75% of recharge associated with just 11 seasons over a 55-year period *(4)*. As the authors recommended, with the projected shift to more intense rainfall there is likely to be increases in the groundwater recharge, making groundwater an important water storage and adaptation option. Groundwater would not just be a solution for drinking-water supply, but an important resource for agriculture, so WSPs should consider other abstracters and whether regulation is sufficient to protect abstractions for drinking-water.

More intense rainfall and more extreme wet days will be associated with water quality impacts. Heavier rainfall is associated with increased run-off, entraining increased sediment loads, and flooding. Rainfall events are associated with a decline in water quality as animal faeces and sewage get washed into surface water. Floods and extreme rainfall events can cause damage to infrastructure, and heavy sediment and pollution loads can make treatment ineffective *(5)*. Where groundwater recharge is associated with these extreme events, as in the United Republic of Tanzania, it will be important for WSPs to understand the quality changes in groundwater during the rapid recharge periods and appropriate management solutions.

At present, there has been limited documented uptake of WSPs in the United Republic of Tanzania. Other forms of management systems are being implemented, such as to improve the reliability of water points, which will support adaptation and build resilience as the potential for longer dry periods with a lack of alternative water sources will put increased pressure on water points. However, WSPs will support a more holistic approach to analysis of potential water supply and water services impacts associated with climate change.

In summary, in areas where there may be high uncertainty in some aspects of the climate change projections, as in the United Republic of Tanzania, WSPs should focus adaptation on the aspects in which there is more confidence, and ensure that the team stays up to date with the latest projections for the region. In the United Republic of Tanzania, a focus on adapting to greater variability of and more intense rainfall will help to build resilience, whether a wetter or a drier climate eventuates.

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Annex 5. Ethiopia case studies: responding to climate change in Ethiopian water supplies

Small community-managed water supply scheme, Meskan district, Southern Nations, Nationalities and People's Region, Ethiopia

Ellie kebele of Meskan district in Southern Nations, Nationalities and People's Region was one of the pilot community-managed water supply schemes implementing climate-resilient water safety plans (WSPs).

For most of the water sources in the pilot areas, consideration was not given during development and construction to the impact of floods. Therefore, there are water sources and public fountains that do not function during the rainy season when they are flooded. But after the initiation of climate-resilient water safety planning, the team mobilizes their respective communities and resources to dig diversion ditches to safeguard their water sources from the intensive flood hazards that occur in every rainy season and prevent the provision of safe and adequate water supply to community members at Ellie kebele.

During the rainy season, flooding is a great challenge, contaminating and inundating the water source and stopping the supply of clean water. Hence, the community members have been obliged to look for alternative water sources, mostly unimproved water sources such as ponds and river waters. Moreover, the climate-resilient WSP team identified that the source was not fenced and farming activities were performed in close proximity to the water source.

Following training in climate-resilient water safety planning, the team agreed with the Ellie kebele administration that the farming activity was a significant hazard to the water supply.

Efforts are now under way to relocate farming activities that are close to the water source. Once farming activities have been relocated, plans are in place to plant indigenous trees to protect and maintain the water table.

Policy formation for climate-resilient water safety planning, Ethiopia

Climate change and variability impacts nearly all social and economic sectors, including the water sector, with significant consequences. Ethiopia has a complex and varied climate due its diverse geography. Climate change is likely to have a significant impact on the availability and safety of water resources in Ethiopia. Some of the impacts of climate change and variability are manifested in the increasing number of extreme weather events, including floods and drought, and the increasing incidence of waterborne diseases, reduced water quality and increasing energy demand.

Figure A5.1. The community in Ellie kebele mobilized its own resources to dig a 250-metre diversion ditch to protect the only water source, which benefits more than 6000 people

Figure A5.2. Shafi, staff of district water office, showing the farming activities near the water source in Ellie kebele

In Ethiopia, systematic and comprehensive water quality monitoring and assessment is lacking, except ad hoc water quality testing, which often follows the outbreak of diseases or reported health problems related to water, sanitation and hygiene. Hence, continuous and comprehensive water quality monitoring and surveillance activities are not in place in most institutions and organizations. As the result of the project "Building adaptation to climate change in health in least developed countries through resilient WASH", the Government of Ethiopia has developed and endorsed policy and guideline documents on climate-resilient WSPs to ensure water safety from source to the point of use through the consideration, assessment and management of climate-related risks. Associated measures are being implemented as part of a national WASH programme in Ethiopia. The policy and guideline documents have been circulated for wider use by different sectors and WASH development partners in the country.

Figure A5.3. National policy and guideline documents on climate-resilient WSPs, Ethiopia

South Achefer district, Amhara region, Ethiopia

Lalibela kebele is located in South Achefer district of Amhara state. The Lalibela community-managed water supply scheme was a pilot climate-resilient WSP implementation site in Ethiopia. The water source in this kebele was exposed to the risk of damage and contamination due to flooding, especially in the rainy season. Following training, the climate-resilient WSP team identified flood risks and mobilized the community to dig a diversion ditch to protect the water scheme from potential damage and contamination risks. Currently planning is under way for the construction of a standard diversion ditch to protect the water source from flood risks (from the Zabzi River) in the longer term. Indigenous vegetation was also planted around water sources to provide protection from heavy flooding and improve water recharge. Appropriate fencing was constructed to protect the well water source. The climate-resilient WSP team also identified that an old, rusty and damaged water tank may represent a public health hazard in addition to causing significant water wastage. Therefore, the water supply, sanitation and hygiene committees, in conjunction with the climate-resilient WSP team, engaged with the community to encourage them to raise money for a replacement, with support from the Regional Water Bureau.

Figure A5.4. The community dug a diversion ditch and planted indigenous vegetation to protect the water scheme from potential flood damage and contamination. Proper fencing was also constructed

Figure A5.5. This water tanker was leaking and has been rusting for many years in Lalibela kebele, Amhara regional state. The one on the ground is a new tanker that will replace the old one

Annex 6. Bangladesh case study: Impacts of salinity on drinking-water sources

Impacts of salinity on drinking-water sources in Bangladesh

Bangladesh is, according to the Global Climate Risk Index, the most vulnerable nation to extreme weather events. The vulnerability of Bangladesh is due to its vast coastal area, high population density and dependence on natural resources. The IPCC 2007 report predicted that the rise in sea level due to global warming would flood 17% of Bangladesh and create 20 million refugees by 2050.

The vulnerability of the coastal area has been increasing due to the rising impact of extreme events in recent decades, including cyclones, higher tidal levels, storms, floods and saline intrusion. These extreme events have been impacting the quality and quantity of both groundwater and surface water resources. In the last 30 years, saline-affected areas have increased by 26% (*1*).

Although national statistics in 2011 indicate that about 88% of the people are using safe groundwater through tubewells for drinking and household purposes, a recent field assessment on climate vulnerability and adaptation revealed that availability of safe drinking-water in the area has been decreasing, with 50% of the coastal people having no choice but to collect drinking-water and household water directly form unsafe sources such as ponds, canals and rivers. These sources are becoming contaminated by surface run-off and intrusion of saline waters. The saline concentration of many shallow tubewells is increasing to a level whereby they become unusable and are abandoned. The water table has also been declining, making it necessary to sink deeper, more expensive wells. In some areas even this deep tubewell option has not been successful due to a lack of aquifer availability. The normal tidal height has increased in both low and high tide events, causing erratic waterlogging problems in some areas. The metal parts of tubewells have been affected by corrosion. Coastal communities are experiencing increased health problems, including pneumonia, diarrhoea, dysentery and fever among children, and diarrhoea, typhoid and stomach pain among the adult population.

The coastal areas are low lying and flat, with an average height of 3 metres above mean sea level. During cyclones Sidr in 2007 and Aila in 2008, ocean water breached embankments, resulting in the long-term destruction of surface sweet water resources such as ponds, canals and rivers through intrusion of saline water into more inland areas.

Bangladesh has 54 transboundary rivers with India. In past decades, these rivers carried torrents of water through the major rivers to the Bay of Bengal, restricting the ocean saline water from moving inland. But in recent years, control of these rivers by India has reduced throughflow, affecting the natural balance of sweet and saline water and causing the gradual inland movement of saline waters. When the surface water bodies become saline, the upper shallow aquifer becomes susceptible to saline contamination from the surface water due to the natural phenomenon of aquifer recharge. The reduced river flows also result in a rise of riverbed levels through sedimentation.

Aiming to tackle the risks posed by climate variability and change, Bangladesh is one of the four pilot countries implementing a project supported by the United Kingdom's Department for International Development (DFID) on "Building adaptation to climate change in health in least developed countries through resilient WASH", which includes the implementation of climate-resilient WSPs. The coastal communities are making efforts to adapt to the adverse situation in many ways, including mixing rainwater with salty tubewell water for better taste through dilution; use of aluminium sulphate (alum) and chlorine tablets to purify dirty surface water; building safe water storage for drinking purposes in households to cover emergency periods; and use of home-made filters, made from layers of cloth, to clean pond water. For domestic usage other than drinking, coastal populations use surface water such as pond or river water, assisting water rationing.

Annex 6 references

1. Mahmuduzzaman M, Ahmed ZU, Nuruzzaman AKM, Ahmed FRS. Causes of salinity intrusion in coastal belt of Bangladesh. International Journal of Plant Research. 2014;4(4A):8–13.

PUBLIC HEALTH AND ENVIRONMENT

The guidance presents the current state of knowledge on the impacts of climate change on the water cycle as well as the associated health impacts and is intended to help water suppliers committed to or already using the water safety plan (WSP) approach, to gain a greater understanding of climate change issues and to support the identification and management of climate change risks within the WSP process.

The document will assist sector professionals, particularly water suppliers and WSP teams, to identify and incorporate the broader issues of climate change, disaster risk reduction (DRR) and integrated water resources management (IWRM) as important contributory approaches to the WSP process.

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