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Climate Resilient Water Safety Plans (CR-WSP)

Compilation of potential hazardous events and their causes

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i. Introduction

Climate-resilient water safety plans (CR-WSPs) extend the established WSP framework by also identifying and managing climate-related impacts on water supply systems to strengthen resilience. An effective WSP considers all potential threats within the water supply system (i.e. both climate and non-climate related) and prioritizes remedial actions based on the most significant risks identified. The Ministry of Water, Irrigation and Electricity of the Federal Democratic Republic of Ethiopia provided a strategic framework on climate resilient water safety as well as guidelines for implementation of CR-WSPs in urban water utilities. The World Health Organisation has also published guidance on Climate-resilient water safety plans in 2017 (WHO 2017).

CR-WSPs were piloted in 2014-2018 in the water supplies of Adama and Addis Ababa, Ethiopia under the project Source to Tap and Back (S2TAB). The project addressed water resources management, development and service delivery, and thus provided a framework in which WSP implementation could be linked to other water activities, such as improving the situation in the catchment. Vitens Evides International led this project in which the German Environment Agency (Umweltbundesamt, UBA, WHO Collaborating Centre for Research on Drinking-Water Hygiene) and the Dutch National Institute for Public Health and The Environment (RIVM, WHO Collaborating Centre for Research on Drinking-Water Hygiene) led the implementation of the CR-WSPs.

The following information presents a compilation of information on hazardous events from the references given below. It was piloted under S2TAB and adapted based on the experiences gathered within the project, and aims to support practitioners, particularly water suppliers, health agencies and consultants, in implementing CR-WSPs. It was piloted in large (urban), professionally managed water supplies in limited resource settings, however, may also be applied and adapted for water supplies in other settings.

This is not intended to be an exhaustive list, and may need to be adapted for application in the local context. It is intended to complement existing comprehensive guidance for implementation by providing a tool for practical application.

ii. How to use this guidance

A **hazard** is a microbial (e.g. pathogens), chemical (e.g. arsenic), physical (e.g. turbidity) or radiological agent or insufficient available quantity that can cause harm to public health. Depending on the local context, hazard classifications may be expanded to address other hazards relevant to a water supply, including those related to climate impacts (e.g. quantity, reliability, consumer acceptance).

A hazardous event is an incident (or situation) that introduces (or amplifies) a hazard (or several hazards) to the water supply, or fails to remove them. The hazardous event can occur from source (catchment) to consumer (household). Hazardous events should clearly describe the impact on water safety and the cause, i.e. "X happens (to the water supply) because of Y"

Example:

> Source water is contaminated by agricultural fertilizers (X) due to poor application practices in the immediate vicinity of the extraction point (Y).

The hazard assessment is an essential part of every WSP. Within this step, each microbial, chemical, physical and radiological hazard, quantity, reliability and consumer acceptance, as well as each event through which it could be introduced to the water supply system should be assessed. This is an important basis for assessing the resulting risk for each of these combinations of hazards and hazardous events in the subsequent step of WSP implementation.

The structure of this document follows the water supply steps from catchment / source via treatment, distribution to the consumers' premises, with a strong focus on potential impacts of climate change on water safety.

The following list gives examples of possible hazardous events, including those which may be caused or accelerated by climate change, and threats that may need to be rephrased and further details added to specify the resulting hazardous events in any given water supply where relevant. One of the most relevant considerations of including climate change aspects into the development of WSPs is to consider

- the occurrence of new hazardous events which may introduce contamination of the drinking-water supply (e.g. lower-quality groundwater with high salinity levels reaches abstraction point due to drought periods that cause lowered groundwater tables), and
- potential increases in occurrence frequencies and changes to their intensity and severity of their effects which may result in a need to consider events in the future which have a perceived low severity or frequency in the current conditions (e.g. increased frequencies of introduction of hazards along with

particles to source water due to increased frequencies of heavy rainfall events and subsequent surface runoff),

- intensification of the occurrence of climatic events (e.g. intensification of rainy / dry seasons, increased frequency of heavy rainfall events, or increased number of hot days).

As socio-economic factors may also influence the quantity of drinking water required and available, respective hazardous events are also included. As many hazardous events may introduce a number of different hazards (or fail to reduce or remove them), the list refers to hazards in general, which will then need to be specified by the teams conducting the hazard assessment. Only in cases where really only one hazard is concerned, this is specified in the hazardous events.

For the implementation of CR-WSPs, this document needs to be used in combination with further guidance on CR-WSP for assisting implementation as it only focuses on the step of hazard assessment, which should be implemented as part of the comprehensive CR-WSP approach. For example, World Health Organisation published guidance on Climate-resilient water safety plans in 2017 (WHO 2017) which contains such support, including on appropriate control measures to manage identified risks.

NOTE: A water supplier should use these examples and tips for guidance only! The hazard assessment must be specific for each system, and may include events and hazards not included within this generic list. For each hazardous event presented in the list, water suppliers should check whether it is relevant for their system and therefore should be included in the hazard assessment, included in an adapted form, or not be included.

For each hazardous event, identify the underlying causes to better define and refine the event. The better the hazardous event is defined, the better the risk can be assessed and the risk management approach can be tailored to what is happening.

Potential hazardous events to be considered in water supply steps

1 Catchments

Following the steps of the water supply chain, the catchment area is the first step where hazards may enter the system. The following list contains examples of hazardous events that may happen in the catchment, and further information on hazardous events relevant for catchments may be found in the publications Protecting Surface Water for Health (Rickert et al (eds), 2016) and Protecting Groundwater for Health. (WHO/IWA 2006).

A lack of knowledge about e.g. raw water quality and existing hazards / hazardous events can lead to inadequate protection of water in the catchment, poor assessment of risks, and inadequate control.

It should be considered that changed catchment conditions (e.g. climatic changes, reduced vegetation cover, increased surface sealing, and landscaping activities) may create new hazardous events or change the risk profile of existing hazardous events in the future, which then need to be considered in the review and revision process.

General distinction how hazards can reach the abstraction point: o direct introduction of hazards into the groundwater body, o direct introduction of hazards into surface water body, or o via surface runoff and / or groundwater feeding the surface water body

1.1 Examples of general hazardous events related to catchment

1.1.1 Urbanisation / population growth

- Reduced water availability per capita due to increased demand driven by e.g. economic development (higher water usage per capita).
- Reduced water availability per capita due to increased demand driven by population growth
- Wastewater is polluting the water source (through direct discharge, disposal of wastewater or waste into the water body) due to absent or inadequate sewage infrastructure matching urbanisation
- Wastewater is polluting the water source (through direct discharge, disposal of wastewater or waste into the water body) due to absent or inadequate sewage infrastructure matching population growth

1.1.2 Increased temperature

- Reduced source water quantity due the presence of a greater number of water-intensive plants in the catchment (e.g. arising from increased water temperature and/or nutrient loading)
- Freshwater-saltwater interface along river estuary reaches the point where raw water is abstracted and leads to increased salt concentrations, caused by sea level rise
- Increased introduction of hazards (e.g. in areas with already nitrate polluted groundwater) caused by more intense farming activities which become possible with higher temperatures and resulting longer growing seasons

1.1.3 Reduced rainfall / drought

- Increased hydraulic residence time of pathogens in source water due to decreased flow during extended drought seasons
- Influenced hazard transport and / or quantity available, caused by variations in the occurrence of dry periods or droughts and increase of the relative flow contributions of e.g. wastewater or mining discharges
- Reduced quantity available for drinking-water purposes due to increased competition between different water uses for water quantity available in times of reduced rainfall
- Lower-quality groundwater containing hazards intrudes abstraction point during drought periods
- Freshwater-saltwater interface along river estuary reaches the point where raw water is abstracted and leads to increased salt concentrations, caused by reduced river discharge due to reduced rainfall

1.1.4 Increased rainfall / run off / flooding / snowmelt

- Mobilisation of accumulated sediment and nutrients and sudden influx into raw water source caused by rainfall after drought / dry periods
- Topsoil is washed into surface water body with rainfall after drought / dry season, increases turbidity and introduces hazards caused by enhanced run-off due to reduced absorption capacity of the soil
- Introduction of hazards to the source water is enhanced due to melting of glaciers, leading to increased surface runoff
- Increased frequencies of introduction of hazards along with particles to source water due to increased frequencies of heavy rainfall events and subsequent surface runoff
- Influenced hazard transport caused by climatic variations in the amount of precipitation, snowmelt or melting of glaciers which lead to increased water flow in the water body

- Introduction of hazards to the water source due to flooding during rainy season caused by increased run-off during rainy seasons
- Large amounts of hazards are introduced into the water source more quickly, and leaching from upper soil layers is increased due to heavy rainfall, particularly after drought / dry periods, causing changes in water pathways and introduction of new rapid pathways
- Source water contamination caused by major run-off from sealed surfaces close to intake zone / extraction point
- Introduction of hazards to the source water due to erosion of the area caused by increased run-off during rainy seasons
- Hazards are introduced to the source water in times of snowmelt, leading to increased surface runoff

1.1.5 Fires / volcanic eruptions / erosion

- Increased introduction of hazards to source water and possibly influence on water quantity due to reduced vegetation / forest cover and a resulting accelerated accumulation of dust and erosion
- Increased introduction of hazards to source water and possibly influence on water quantity due to land uses such as agriculture and urban development which accelerate accumulation of dust and erosion
- Increased introduction of hazards to surface water body caused by landslides which accelerate erosion
- Increased introduction of hazards to source water and possible influence on water quantity caused by fires and volcanic eruptions which may lead to changed vegetation cover, accelerating accumulation of dust, and erosion
- Increased deposition of dust and increased turbidity caused by fires and volcanic eruptions

1.1.6 Other

- Increased competition for water quantity available caused by more intense farming activities which become possible with higher temperatures and resulting longer growing seasons
- Freshwater-saltwater interface along river estuary reaches the point where raw water is abstracted and leads to increased salt concentrations
- Raw water from poor water quality cannot be blended with higher-quality water from other sources to manage drinking water quality in times of reduced raw water availability
- Lower water buffering capacity and more intermittent inflows to the source water caused by deforestation and heavier land use leading to effects on the hydrology in the catchments

- Changed climatic conditions lead to introduction of new hazards (e.g. opportunistic invader species) in raw water
- Challenges to providing sufficient water quantity under different climatic conditions due to insufficient available storage capacity for raw water
- Deterioration of water quality caused by increased biological activity in shallow, warm open channels

1.2 Examples of hazardous events related to specific activities

1.2.1 Domestic wastewater

- Increased concentration of pollutants in wastewater discharges reach the source water due to reduced dilution occurring when conditions become drier
- Pathogens and nutrients are introduced into the source water when flooding causes overflow from latrines or sewerage systems, particularly combined sewers
- Pathogens and nutrients are introduced into the source water when flooding overwhelms sewerage treatment plants and causes effluents of lesser quality
- Pathogens and nutrients from discharges from open defecation reach source water directly, through infiltration or indirectly via surface run off
- Pathogens and nutrients from discharges from untreated or poorly treated domestic wastewater / faecal matter from on-site systems (e.g. overflowing of effluents caused by poor maintenance of the systems or by not removing retained solids on time) reach source water directly, through infiltration or indirectly via surface run off
- Source water becomes contaminated due to leachate from solid waste site
- Pathogens and nutrients are introduced into the catchment and subsequently source water due to unsafe re-use of human or animal faeces / wastewater

1.2.2 Farming and agriculture

- Contamination of the raw water and reduction of its quantity due to increased use of raw water source for agriculture in case of reduced availability of alternative waters
- Contamination of the raw water due to greater reliance on recycled water or wastewater for irrigation in case of reduced availability of alternative waters
- Quantity is reduced and contamination caused by farming activities like irrigation or drinking-water for cattle

- Quantity is reduced and contamination caused by increasing temperatures and / or lack of precipitation, increases the effect of farming activities like irrigation or drinking-water for cattle
- Hazards are introduced to the source water by animals' direct access to water body, livestock and other animals, contaminating the source water
- Agricultural chemicals (e.g. fertilizers and agricultural pesticides/ algaecides) used reach source water directly or through surface runoff
- Stored agricultural chemicals (e.g. fertilizers and agricultural pesticides/ algaecides) reach source water in case of leakages
- Manure or faecal material from application or storage, particularly from intensive animal practices, reach source water through infiltration or via surface runoff
- Increased introduction of hazards is caused by accelerated accumulation of dust and erosion due to agricultural activities that cause deforestation
- Contamination of the raw water caused by lack of best management practices for pesticide control, irrigation / drainage / to match irrigation to crop needs, and for nutrient management
- Algal blooms are caused by nutrients from agricultural activities reaching the surface water directly or through surface runoff

1.2.3 Industries

- Introduction of hazards to source water from untreated or poorly treated industrial wastewater discharges
- Enhanced concentrations of hazards in source water from untreated or poorly treated industrial wastewater discharges in case of less mixing due to reduced surface water flows
- Contamination of the raw water and reduction of its quantity due to increased use of raw water source for industries in case of reduced availability of alternative waters
- Contamination due to lack of best management practices for design and operation of industrial activities
- Hazards reach source water from discharges / leachate from hazardous waste sites / contaminated sites

1.2.4 Mining activities

- Discharges / leachate from extractive mining reaches source water
- Contamination of the raw water and reduction of its quantity due to increased use of raw water source for mining in case of reduced availability of alternative waters
- Enhanced concentrations of hazards in source water from mining activities in case of less mixing due to reduced surface water flows

- Salinization of river source water as a consequence of mining activities, especially of salt mining
- Increased introduction of hazards due to mining activities causing deforestation and accelerating accumulation of dust and erosion
- Acidic water with low pH reaches the source water from mining activities
- Reduced water quantity caused by mining, energy generation or other impoundments that cause changes in the hydraulic regime

1.2.5 Other direct uses of the water body or human activities

- Spills or leakages from major spills or continuous small spills, both accidental and deliberate, reach source water (directly or indirectly via surface runoff)
- Traffic, including waterway transportation and vehicle maintenance activities, contaminates waterbody directly or via surface runoff
- Application of de-icing salts in traffic contaminates waterbody directly or via surface runoff
- Human pathogens reach surface water body through recreational activities (e.g. swimming)
- Hazards are introduced to the source water by human activities with direct water contact, such as clothes washing
- Hazards are introduced to the source water by human activities with direct water contact, such as using oil pumps for water extraction for irrigation purposes and car washing
- Water quantity is reduced by human activities with direct water contact, such as water extraction for irrigation purposes

1.3 Examples of hazardous events related to surface water sources and raw water storage reservoirs

- Higher levels of hazards are present because of decreased sedimentation and attenuation of pollutants in source water as a result of increased precipitation intensity
- Human pathogens are directly discharged through flow of fishpond water into the surface water body from aquacultural systems using wastewater and from fish excreta
- Direct discharge of human pathogens through flow of fishpond water into the surface water body from aquacultural systems using wastewater and from fish excreta is enhanced by flooding
- Cyanobacterial (“algal”) blooms are enhanced and presence of pathogens and toxigenic cyanobacteria increased by seasonally reduced water flow and resulting water stagnation

- Hazards are moved closer to the abstraction point by extreme heat that reduces vertical mixing of surface water bodies, modifying the dynamics of the raw water source
- Increased concentration of pollutants is caused by droughts due to evaporation
- Presence of higher levels of opportunistic pathogens (e.g. Naegleria fowleri) is caused by seasonally reduced water flow and resulting water stagnation
- Presence of higher levels of opportunistic pathogens (e.g. Naegleria fowleri) is caused by increased water temperature
- Presence of indigenous bacteria such as cyanobacteria in source water is increased by higher water temperature causing enhanced stratification
- Growth of indigenous bacteria such as cyanobacteria in raw water is stimulated by an increase in CO_2 levels
- Hazards are introduced from hydraulic connections between trenches, creeks, ponds, lakes, and moors to the surface water body
- Non bio-degradable wastes enter the river e.g. by wind and may increase turbidity through dust attached to its surfaces
- Hazards are introduced from surrounding soil / groundwater (e.g. humic material, arsenic, fluoride, manganese, iron, sulphate, radiological agents) to the surface water body

1.4 Examples of hazardous events related to groundwater

- Increased concentration of pollutants when conditions become drier and there is less recharge, particularly in groundwater sources that are already of low quality
- Increased concentration of pollutants in case of increased abstraction / overabstraction with less inflow, particularly in groundwater sources that are already of low quality
- Reduced quantity available if increased winter precipitation is compensated with higher evaporation due to higher summer temperatures
- Higher levels of hazards as long-term rainfall increases, causing rising groundwater levels which decrease the efficiency of natural purification processes
- Transport of contaminants is increased , particularly in shallow aquifers, with increased lateral flow in soils after large rainfall events
- Contamination sources are mobilised or lower quality water intrudes due to increased pumping in times of drought
- Hazards are introduced from surrounding soil to groundwater (e.g. humic material, arsenic, fluoride, manganese, iron, sulphate, radiological agents)

2 Abstraction

The next step in the water supply chain is abstraction of the water. The following list contains examples of hazardous events that may happen for abstraction from surface water sources or from groundwater sources, focusing on events that take place at the physical abstraction infrastructure.

2.1 Typical potential hazardous events to consider for abstraction from surface water sources

- Introduction of hazards is enabled through damages to pipes between abstraction and treatment, e.g. from roots or animals
- Hazards are introduced during repair and maintenance by untrained staff e.g. with contaminated tools
- Quantity is reduced by breakdown of pumps (defect, power failure, lack of standby pumps, spare parts, back-up generator)
- Ingress of hazards is caused by damaged inspection covers
- Raw water quantity available is reduced by damages to dam structure over time leading to losses
- Raw water quantity available is reduced by colder winters leading to increased rates of blocking of abstraction infrastructure through ice
- Raw water quantity available is reduced by heavy rainfall or floods introducing debris to the river flow that damages the raw water intake infrastructure
- Raw water quantity available is reduced by falling water levels leaving water intake exposed
- Pathway for concentrated hazard entry is allowed by falling water levels even in times of no water abstraction
- Abstraction of raw water containing hazards cannot be avoided in settings with a fixed offtake that does not allow to selectively harvest higher quality water from the water column (e.g. in case of algal blooms etc.)

2.2 Typical hazardous events to consider for abstraction from groundwater sources (dug wells, boreholes, spring sources)

- Reduced quantity due to drying up of wells caused by to reduced groundwater tables
- Reduced quantity is available due to failure (e.g. due to flood, slips or earthquake-related damage) causing infrastructure to become dysfunctional
- Hazards reach the source water with contaminated water from the surface entering well heads after intense run-off / flooding events (e.g. after heavy rainfall)

- Hazards reach the source water with ingress of surface water in case of flooding of area around well
- Quantity is reduced by break down of pumps (defect, power failure, lack of standby pumps, spare parts, back-up generator)
- Contamination enters dug well, borehole or spring source during construction due to contaminated equipment
- Contamination enters borehole during construction due to residual substances used in drilling
- Contamination of the borehole due to poor quality of the bore casing (joints, cracks or corrosion) in the bore casing
- Contamination enters borehole through well head or casing which is damaged due to inappropriate wellhead design or construction
- Contamination of the groundwater due to cracked lining representing a pathway for introducing hazards
- Contamination of the groundwater due to lack of seal on rising main representing a pathway for introducing hazards
- Contamination of the groundwater due to lack of or damaged cover on well representing a pathway for introducing hazards
- Contamination of the groundwater due to cracked or damaged apron or pump-house floor representing a pathway for introducing hazards
- Contamination of the groundwater due to faulty masonry on spring protection representing a pathway for introducing hazards
- Contamination of the groundwater due to eroded backfill on spring source representing a pathway for introducing hazards
- Contamination of the groundwater due to ropes and buckets used to withdraw water from dug well or spring source representing a pathway for introducing hazards
- Hazards are introduced due to vandalism as access to unfenced dug well, borehole or spring source makes it a target
- Contamination is introduced through stagnant water uphill or in the direct vicinity of the dug well, borehole or spring source and absence of drainage channel / diversion ditch
- Available quantity is reduced when sediments, iron or manganese cause the well to clog
- Hazards are introduced during repair and maintenance by untrained staff e.g. with contaminated tools
- Available quantity is reduced by too high velocity due to poor design causing premature breakages of channels or pipes of the borehole
- Available quantity is reduced in case of breakdown of well pump (defect, power failure)
- Contamination may be introduced through lack or damage to cover of wells in the vicinity of the abstraction point

3 Treatment process

Treatment processes may follow abstraction of the water from surface water or groundwater sources. The goal of the treatment processes is to reduce hazards in the water to an acceptable level for consumption. Nevertheless, hazardous events may occur during the treatment processes, which might introduce hazards into the drinking water.

This list of hazardous events in the treatment process has a focus on the types of treatment present in the water supplies where it was first piloted, and may need to be adapted for application in the local context.

It should be considered that changed conditions in the treatment (e.g. climatic changes, changes in the quality of the raw water to be treated) may create new hazardous events or change the risk profile of existing hazardous events in the future, which then need to be considered in the review and revision process.

General distinction how hazards can be introduced or insufficiently removed during treatment:

- treatment inappropriate or insufficient for the raw water quality
- direct introduction of hazards into the water through treatment chemicals,
- introduction of hazards into the water through the reaction (other than the intended one) of treatment chemicals with constituents of the raw water, or
- failure of the treatment process to remove the hazard or reduce it to an acceptable level for consumption

3.1 General hazardous events related to treatment processes

- Inadequate back-up (infrastructure, human resources) leads to poor performance of the whole process in case of failure of the initial resources
- Interruption to the treatment process or poor water quality due to damage to treatment infrastructure in case of e.g. flooding, fire or other severe weather events
- Interruption to the treatment process or poor water quality due to failure of alarms and monitoring equipment which hinder quick response in case of treatment failure
- Interruption to the treatment process or poor water quality during accidents and recurring disasters, due to a lack of preparedness
- Introduction of hazards to incoming or treated water through cross-connection to contaminated water/wastewater, internal short circuiting
- Increased turbidity and affected treatment process caused by dust accumulation around the treatment area

- Hazards are insufficiently removed / reduced if the treatment is not well adapted to prevailing raw water quality and flow variations
- Hazards are insufficiently removed / reduced due to poor dose control, leading to poor functioning of treatment step

3.2 Typical hazardous events to consider for coagulation / flocculation / sedimentation

- Insufficient hazard removal due to increase in raw water volume which leads to increased flow rate, and subsequently insufficient settling time for flocs
- Insufficient hazard removal due to waters with little turbidity, changing pH, poor alkalinity or of variable quality as well as certain composition of organic matter make coagulation difficult
- Insufficient hazard removal due to insufficient dosing to waters with suddenly increased suspended solids /higher turbidity which require greater coagulant dosing
- Introduction of hazards or compromised treatment from contaminated chemicals and materials
- Insufficient hazard removal due to reagents of poor quality leading to insufficient coagulation/flocculation
- Insufficient hazard removal due to insufficient availability of reagents and compromised treatment (including for example blocked supply chains arising from flooding, natural disasters etc.)
- Insufficiently removed organic matter caused by too low pH (ideal range from 6 - 10) due to poor alkalinity control, leading to dissolving of flocs in flocculation with iron
- Insufficiently removed organic matter caused by too low or too high pH (ideal range from 6 - 8) due to poor alkalinity control, leading to dissolving of flocs in flocculation with aluminium
- Poor functioning of treatment step because of dose malfunction of reagents in other treatment steps
- Insufficient removal of hazards due to clogging of chemical lines, leading to insufficient chemical dosing and subsequently treatment
- Insufficient removal of hazards due to lack of skilled and trained staff, leading to improper dosage of chemicals and poor performance of treatment process
- Insufficient hazard removal due to power cuts and lack of backup power system which lead to failure of dosage pumps and insufficient chemical dosing
- Insufficient hazard removal due to breakdown of power supply and lack of backup power system which leads to failure of dosage pumps and insufficient chemical dosing

- Insufficient hazard removal due to insufficient mixing- and contact times between chemicals and water, leading to compromised formation of flocs and breaking up of flocs
- Insufficient hazard removal and compromised treatment due to floc removal (e.g. scrapers) mechanism malfunctions
- Ineffective removal of flocs due to insufficient capacity in sludge disposal for peak loads
- Insufficient hazard removal and compromised treatment due to power cuts and lack of backup power system which lead to failure of mixing facilities
- Insufficient hazard removal due to breakdown of power supply and lack of backup power system which leads to failure of failure of mixing facilities

3.3 Typical hazardous events to consider for sand filtration

- Compromised hazard removal due to poor source water quality or water of variable quality which compromises filter operation
- Compromised hazard removal if treatment steps (e.g. clarifiers) before the sand filter are not working well, and less particles can be removed before the filter
- Compromised hazard removal and water quality if design of the filter and the operational requirements of the treatment plant do not match the raw water quality, leading to insufficient water treatment
- Compromised hazard removal due to sudden increases in the rate in which water passes through the filter which will shake loose particles that have already been trapped in the sand, causing “spikes” in the turbidity
- Reduced quantity in case of algal blooms with algae blocking the filters
- Insufficient hazard removal if filter design does not match operation flow rates
- Compromised removal of hazards if depth of the filter is insufficient
- Compromised functioning of treatment step due to inappropriate operation of the filter (i.e. how and how often the filter is backwashed, if the backwash water is returned to the head of the plant, how the filter is restarted, the management of the filter ripening and the procedures used in cleaning the filter sand, lack of proper valve lubrication and maintenance, media not inspected and/or cleaned, poor operator training and support)
- Compromised removal of hazards due to frequent filter backwashing which mixes filter layers, and affects particle size of filter particles, leading to reduced filtration capacity
- Compromised removal of particles if the filter bed is not completely fluidized during filter backwashing

- Insufficient backwashing water available to maintain removal of hazards in case of increased temperature, and higher frequency / flow rates may be needed to reach necessary flushing velocity
- Insufficient backwashing water available to maintain removal of hazards in times of higher turbidity, and higher frequency / flow rates may be needed to maintain removal of hazards

3.4 Typical hazardous events to consider for chlorination

- Insufficient removal / reduction of microbial hazards if chlorine dose is too low to leave enough free available chlorine to disinfect the water effectively
- Insufficient removal / reduction of microbial hazards if natural organic matter is not removed and reacts with the disinfectant and disinfection by-products (not normally of high concern) can be formed
- Insufficient removal / reduction of microbial hazards due to high ammonium concentration in the raw water which also reduces disinfectant
- Increased disinfection by-products caused by increased organic matter making an increase in chlorine dosage necessary
- Increased levels of more toxic brominated disinfection by-products in case of seawater intrusion into raw water which increases bromide levels
- Insufficient removal / reduction of microbial hazards in case of insufficient availability of chlorine compromising treatment (including for example blocked supply chains arising from flooding, natural disasters etc.)
- Insufficient removal / reduction of microbial hazards if available chlorine is of poor quality, compromising treatment
- Insufficient removal / reduction of microbial hazards if old chlorine solution or poorly stored chlorine (e.g. exposed to sunlight or uncovered) is used, compromising treatment
- Compromised treatment due to unapproved or contaminated chemicals and materials
- Compromised treatment due to poor dose control / dosing equipment (including calibration of dose controller’s sensor, dose calculation)
- Insufficient chlorine reaching dosing point may lead to poor functioning of chlorination
- Insufficient chlorine dosing and resulting microbial hazard removal due to wrong monitoring (e.g. incorrect sampling, incorrect recording of readings, incorrect method for measurement, incorrect calibration) of free available chlorine
- Insufficient removal / reduction of microbial hazards due to power cuts and lack of backup power system which lead to failure of dosage pumps and insufficient chlorine dosing

- Insufficient hazard removal due to breakdown of power supply and lack of backup power system which leads to failure of dosage pumps and insufficient chlorine dosing
- Insufficient removal / reduction of microbial hazards due to power cuts and lack of backup power system which lead to failure of mixing facilities
- Insufficient hazard removal due to breakdown of power supply and lack of backup power system which leads to failure of mixing facilities
- Insufficient removal / reduction of microbial hazards as chlorine dosage is not in accordance with the amount of water to be treated in case of increased water flow
- Insufficient removal / reduction of microbial hazards if water temperature is too low to allow for efficient chlorination
- Insufficient removal / reduction of microbial hazards if pH of the water is outside effective range (typically pH is rather too high (ideal range pH < 7,5), resulting in a lower percentage of the free available chlorine existing in its more powerful disinfecting form), compromising disinfection
- Insufficient removal / reduction of microbial hazards if turbidity of the water is too high (should be < 0,2 NTU) or changes rapidly (e.g. in case of heavy rainfall after dry period) when the chlorine is added to it, which can hinder the access of chlorine to hazards
- Insufficient removal / reduction of microbial hazards (e.g. protozoa, viruses) which do not sufficiently react to disinfection
- Insufficient removal / reduction of microbial hazards if free available chlorine is in contact with the water for an insufficient time (typical recommendation: 30 minutes) to efficiently reduce microbial hazards

4 Distribution system

After treatment, the drinking water is distributed to the consumers. During distribution, hazardous events may occur which could introduce hazards into the drinking water.

The list of hazardous events in this section focuses on piped distribution systems and storage. Further information on hazardous events in distribution systems can be found in the publication Water Safety in Distribution Systems (WHO 2014). When post-treatment is applied to the drinking water, this may also introduce new hazards due to occurrence of hazardous events during this step.

It should be considered that changed conditions in the distribution system (e.g. climatic changes, changes in pressure and consumption) may create new hazardous events or change the risk profile of existing hazardous events in the future, which then need to be considered in the review and revision process.

General distinction how hazards can reach the distribution system:

- direct introduction of hazards into the distribution system through damages and / or surrounding contamination sources,
- direct introduction of hazards through materials used in the distribution system, or
- re-contamination through re-suspension or regrowth of hazards

4.1 Typical hazardous events to consider for piped networks

- Ingress of contamination is enabled and quantity reduced through lower temperatures, including resulting freezing of soil, which may damage distribution pipes’ infrastructure
- Increased microbial hazards due to higher temperature of the drinking water (pipelines) especially when the pipes are located above the ground
- Ingress of contamination is enabled and quantity reduced through increased rate of pipe bursts due to heat and drought-related ground movement and drying soil
- Ingress of contamination is enabled and quantity reduced through distribution infrastructure damages due to floods
- Ingress of contamination is enabled by negative, or fluctuating, pressure conditions (e.g. intermittent operation, low pressure events, power cuts or the effect of a pressure wave within the system)
- Ingress of contamination is enabled by loose joints, pin-holes, loose connections, cracks, holes in the pipeline coupled with low internal pressures

- Contaminated backflow enters the distribution system from residential / industrial / commercial customers in case of a lack of backflow prevention device or failure of device
- Ingress of contamination is enabled by accidental cross-connection (or illegal / unauthorized connections) between drinking-water and non-drinking-water assets or wastewater during construction or maintenance (e.g. opening of usually shut valves)
- Ingress of contamination from surrounding soil / surfaces is enabled by pipes located above ground which are prone to damages (e.g. accidental breakage, UV exposure for plastic pipes)
- Microbial contamination enters the distribution system due to insufficient performance of valves that lead to compromised isolation, flushing and/or disinfection of potentially contaminated areas, and water leakages from valves may flood areas around above ground pipes
- Microbial hazards are insufficiently disinfected if increased water temperatures makes it more difficult to maintain sufficient disinfectant residual
- Increased disinfection by-products due to increased water temperatures which make it more difficult to maintain applicable disinfectant residual, leading to application of increased disinfectant concentrations
- Increased disinfection by-products due to reduced upstream water quality from water treatment plant (e.g. higher turbidity, colour, organic materials) which make it more difficult to maintain applicable disinfectant residual, leading to application of increased disinfectant concentrations
- Microbial hazards are insufficiently disinfected due to reduced water turnover if water use restrictions are introduced due to water shortage which make it more difficult to maintain sufficient disinfectant residual
- Microbial hazards are insufficiently disinfected due to reduced water turnover in concrete tanks which increases pH and reduces effectiveness of chlorine
- Increased disinfection by-products due to reduced water turnover if water use restrictions are introduced due to water shortage which makes it more difficult to maintain applicable disinfectant residual, possibly leading to application of increased disinfectant concentrations
- Introduction of contamination through unhygienic construction, repair and maintenance methods
- Introduction of hazards through unsuitable construction materials
- Reduced quantity, introduction of water colour and other hazards through inappropriate materials which are incompatible with the water quality and / or other materials in the system may cause corrosion and resulting loss of structural integrity and introducing contamination

- Pipe slimes, sediment and deposited minerals such as silicates or oxidised manganese and iron are re-suspended in the distribution system during high-flow events or flow reversals
- Survival and growth of microbiological hazards caused by biofilms in piped networks
- Increased deposition and biofilm growth in tanks, pumps and fittings in dry periods
- Regrowth of microbial hazards in the distribution system due to increased temperatures and higher assimilable organic carbon
- Accumulation of particles (e.g. floc after the treatment plant, sediments, manganese deposits), particularly at dead ends, due to long stagnation
- Hazard introduction from aged and rusted steel- and galvanised pipes in distribution system when damaged
- Introduction of contamination due to improper construction, repair and maintenance of sewer lines, drainage lines, water distribution lines and storage reservoirs, particularly in case of leaking sewers and insufficiently repaired drinking-water lines, and unhygienic work practices and recommissioning
- Introduction of contamination due to lack of integrated infrastructural development, particularly in case of leaking sewers, damaged or insufficiently repaired drinking-water lines, and unhygienic work practices and recommissioning
- Introduction of contamination and reduced quantity due to damaged, rusting or lacking covers of manholes allowing ingress of animals, vermin, faeces or roof drainage, and dust covering the pumps compromising their functioning
- Introduction of contamination and reduced quantity due to unprotected manholes, or covers that are left open allowing ingress of animals / vermin, faeces, roof drainage, and dust covering the pumps compromising their functioning
- Re-contamination of the distribution system with hazards from private pipes (house connections) outside the responsibility of the water utility
- Entry of hazards from pipes located on private premises that may be contaminated from septic tanks and pit latrines located on the same premises
- Ingress of contamination due to ongoing compromised conditions of pipes located under buildings which are difficult to access in case of damages, leading to undetected leakages and lack of repair,
- Reduced quantity and contamination through backflow in case of consumers as well as industries illegally connecting to distribution system
- Contamination of and damage to the distribution system by people e.g. through damaging distribution pipes (vandalism)

- Contamination of and damage to the distribution system by people e.g. through open defecation and waste disposal in the open (especially in case of uncovered manholes / damaged valves)
- Reduced quantity in case of flooding damage to critical assets from e.g. sea level rise/storm surge
- Saline intrusion into aging/damaged pipes or during low pressure events (bursts etc.)
- Erosion from heavy precipitation/flooding exposing underground pipes leading to an increased risk of damage, illegal connection, UV exposure etc.
- Sediments may be resuspended and biofilms sloughed off in case of abnormal flow events (e.g. increased velocity from burst; change in flow direction due to maintenance issues)

4.2 Typical hazardous events to consider for post treatment storage

- Introduction of hazards through damaged or lacking vent screens allowing ingress of animals / vermin / faeces
- Introduction of hazards through damaged, rusting, or lacking tank covers allowing ingress of animals, vermin, faeces or roof drainage
- Introduction of hazards through covers that are left open allowing ingress of animals / vermin /faeces / roof drainage
- Introduction of hazards and reduced quantity through cracks in storage reservoirs
- Introduction of hazards through insufficient cleaning of reservoirs, e.g. build-up of sediment or living organisms, including algal or biofilm growth
- Introduction of contaminated water containing hazards (including potentially animal faeces if access is not restricted)due to lack of surface sealing which slopes away from storage running towards storage and entering it through damages
- Introduction of hazards due to roots of plants or trees in vicinity damaging reservoir
- Introduction of hazards through dissolving or corroding tank materials
- Introduction of hazards through unhygienic sampling procedures
- Introduction of hazards due to unauthorised access to storage reservoirs by humans (e.g. through breaking of fencing or unfenced reservoirs) leading to vandalism and sabotage
- Insufficient removal of microbial hazards due to insufficient residence time of water after chlorination at the storage reservoir not allowing for sufficient contact time

- Ingress of hazards and reduced quantity through unsealed joints and cracks of underground storage reservoirs leading to ingress of contamination from groundwater and to water loss
- Insufficient quantity supplied to consumers' demand due to inadequate capacity of storage reservoirs
- Reduced quantity due to power cuts and lack of backup power systems leading to failure of booster stations
- Reduced quantity due to different capacities of inlet and outlet pumps leading to reservoir overflow
- Increased microbial hazards due to higher temperature of the drinking water (reservoirs) especially when the storage is located above the ground

5 Typical potential hazardous events to consider for customers' water collection, private storage and household transfer systems

In many settings, drinking-water is directly available at the premises to consumers. However, in some settings the drinking water may also need to be collected at public taps, transported to the premises (e.g. in jars), and / or temporarily stored at the household level. At this step, further hazardous events may occur during collection, transport and storage which might introduce hazards into the drinking water.

General distinction how hazards can reach the water at the collection and household level:

- o direct introduction of hazards into the water in collection containers,
- o direct introduction of hazards into the water in storage containers, or
- o through inappropriate hygiene practices

5.1 Typical hazardous events to consider in customers' private collection, storage (including jars) and household transfer systems

- Introduction of hazards due to collection and storage of water from different sources and with different qualities in the same containers
- Introduction of hazards if collection- and storage containers are used for storing different liquids or materials
- Introduction of hazards and reduced quantity due to cracked, leaking or insanitary collection- and storage containers
- Introduction of hazards through animals / insects entering the container if lid of collection- and storage containers is absent or damaged
- Introduction of hazards due to storage containers / jars kept at ground level allowing for contamination to enter through e.g. animals or poor sanitation practices or ingress of contamination from water pooling or flooding during rainy season
- Introduction of hazards from faeces, garbage and other wastes in an insanitary area around the storage container / jar
- Introduction of hazards due to pump from ground level tank to roof tank drawing groundwater because storage is leaky
- Accumulation of hazards / sedimentation due to insufficient cleaning of collection- or storage container
- Introduction of hazards due to use of an inappropriate or insanitary tap or utensil to draw water from the storage

- Introduction of hazards due to poor hygiene practices (e.g. dirty hands) to draw water from the collection- or storage container
- Introduction of hazards from low quality of materials or use of unapproved materials used for pipelines and storages at household level
- Increased chlorine level (chemical and odour levels) caused by excessive chlorination at the household level
- Ingress of contamination through animals / vermin /faeces through damaged or lacking vent screens at household storage tanks
- Introduction of hazards from insanitary tanker trucks (if used)
- Ingress of contamination from improperly installed consumer-owned sewer lines and drinking-water lines (e.g. use of inappropriate materials, cross-connection) in case of poor workmanship and / or conditions
- Ingress of contamination from low quality of materials or use of unapproved materials used for pipelines and storages at household level
- Ingress of contamination during flooding or heavy rainfall from contaminated water entering underground water storage tanks (flood)
- Increased microbial hazards due to increased temperatures in water stored at the household level (temperature)
- In settings with predicted increase in annual rainfall, consumers may switch to less safe rain water harvesting to save water tariffs
- In settings with intermittency or other supply interruptions, consumers may switch to less safe rain water harvesting
- In settings where there is too much free available chlorine or if the water shows colour, consumers may switch to less safe rain water harvesting

5.2 Typical hazardous events to consider for public taps

- Drinking-water is chemically and faecally contaminated due to ingress of contamination into pipes from leaking public taps through unsealed surfaces and / or cracks, especially if distribution system is operating intermittently
- Reduced drinking-water quantity due to water losses from leaking public fountains
- Drinking-water is faecally contaminated due to unhygienic practices during collection (i.e. ingress of contamination to the water collected as well as to the distribution system through insanitary taps or attachments (e.g. hoses))
- Collection containers are contaminated by spilt water that becomes contaminated through runoff when placed on the ground to collect water
- Hazards from animal faeces, garbage etc. in the collection area contaminates collection containers when placed on the ground to collect water

- Damages to infrastructure and reduced quantity if the collection area is not fenced, and animals (including those used for collecting the water) can access the fountain area
- Damages to infrastructure and reduced quantity from unauthorized entry and vandalism to the collection area
- Contaminated water backflow into the distribution system from hose connection to tap
- During floods, droughts or other times where the supply is impacted, consumers cannot access public taps, and may switch to less safe but accessible sources

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7 Main references and bibliography

Elala D (2011): Vulnerability assessment of surface water supply systems due to climate change and other impacts in Addis Ababa, Ethiopia. Examination paper. Accessed at http://files.webb.uu.se/uploader/858/MFS-164elala-daniel.pdf on 06 July 2018

Khan SJ, Deere D, Leusch FDL, Humpage A, Jenkins M, Cunliffe D (20165) Extreme weather events: Should drinking water quality management systems adapt to changing risk profiles? Water Research 85 (2015) 124-136

Ministry of Water, Irrigation and Energy of the Federal Democratic Republic of Ethiopia (2015) *Climate Resilient Water Safety Strategic Framework*. Addis Ababa, Ethiopia

Ministry of Water, Irrigation and Energy of the Federal Democratic Republic of Ethiopia (2015) *Climate Resilient Water Safety Plan Implementation. Guidelines for Urban Utility Managed Piped Drinking Water Supplies*. Addis Ababa, Ethiopia

Rickert, B., Schmoll, O., Rinehold, A., and Barrenberg, E. (2014) *Water safety plan: a field guide to improving drinking-water safety in small communities* World Health Organization Copenhagen, Denmark. Accessed at http://www.euro.who.int/__data/assets/pdf_file/0004/243787/Water-safety-plan-Eng.pdf?ua=1 on 04 January 2018

Rickert B, Chorus I, Schmoll O. (eds) (2016) *Protecting Surface Water for Health* World Health Organization Geneva, Switzerland. Accessed at http://www.who.int/water_sanitation_health/publications/pswh/en/ on 18 December 2017

WHO/IWA (2006) *Protecting Groundwater for Health. Managing the Quality of Drinking-water Sources*. Editors: Schmoll, O. Howard, G., Chilton, J. & Chorus, I. World Health Organisation and International Water Association London, UK. Accessed at http://www.who.int/water_sanitation_health/publications/protecting_groundwater/en/ on 04 January 2018

WHO (2008) *Training workbook on water safety plans for urban systems*. World Health organization Western Pacific Region

WHO/IWA (2009) *Water Safety Plan Manual: Step-by-step risk management for drinking-water suppliers* World Health Organisation and International Water Association

WHO (2014) *Water Safety in Distribution Systems*. World Health Organization Geneva, Switzerland. Accessed at http://www.who.int/water_sanitation_health/publications/water-safety-in-distribution-system/en/ on 04 January 2018

WHO (2016) *Protecting surface water for health. Identifying, assessing and managing drinking-water quality risks in surface-water catchments*. Editors: Rickert B, Chorus I, Schmoll O. World Health Organization Geneva, Switzerland. Accessed at http://www.who.int/water_sanitation_health/publications/pswh/en/ on 04 January 2018

WHO (2017) *Climate-resilient water safety plans: Managing health risks associated with climate variability and change*. World Health Organization Geneva, Switzerland. Accessed at http://www.who.int/water_sanitation_health/publications/climate-resilient-water-safety-plans/en/ on 04 January 2018

WHO SEARO (2016) *Capacity training on urban water safety planning. Participant's handbook*. World Health Organization New Delhi, India. Accessed at http://www.searo.who.int/entity/water_sanitation/documents/WSP_Training_Modules/en/ on 04 January 2018