Guidelines for improved operation of drinking water treatment plants and maintenance of water supply and sanitation networks

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Foreword

Project PREPARED addresses the adaptation of the water sector to climate change effects. It has been anticipated that some of the impacts of climate change, such as rises in average temperature and sea level, will only become apparent after many years. However, climate change-driven events are already happening with increasing frequency and intensity. This is the case of extreme storm and rain events and heat, drought and cold periods, which may impact water and wastewater systems. Therefore, in addition to structural adaptations of infrastructures that may be implemented on a medium- to long-term basis, many urban water utilities also need to adapt rapidly to on-going climate change effects.

Diverse scenarios are available for each country and region. In addition, the same climate effects may impact the various sectors and utilities differently. On the other hand, certain climate change effects may impact the infrastructures of all urban water cycle sectors.

The adaptation of water utilities to climate changes has been tackled in PREPARED through sectorial and integrative approaches. The former, which comprised adaptation measures for drinking water supply, wastewater and stormwater systems, were addressed in several work packages. The outputs produced include corrective and preventive measures for drinking water treatment plants, and drinking water and sanitation networks. With this respect, state-of-the-art knowledge and outputs from various PREPARED tasks were integrated and developed in PREPARED deliverable D5.5.5 in the form of guidelines, whose objectives are to support the design and implementation of adaptation measures. Accordingly, the D5.5.5 guidelines herein summarized comprise four chapters:

Chapter 1 – Improved operation of drinking water treatment plants

Chapter 2 – Maintenance of water supply networks

Chapter 3 – Maintenance of wastewater networks

Chapter 4 – Operation and maintenance of stormwater systems

For the sake of practical usefulness, adaptation measures, as well as their supporting technologies, methods and tools, are schematically and concisely presented in the guidelines. These also specify supplementary sources of more detailed and comprehensive information, which, in addition to pertinent PREPARED deliverables, include outputs from projects CARE-W, DayWater, TECHNEAU, CARE-S and AWARE-P.

Acronyms and abbreviations

AOC: assimilable organic carbon

AOP: advanced oxidation process

ARPS: acoustic resonance pipe scanner

BAC: biological activated carbon

BDOC: biodegradable dissolved organic compounds

CCTV: closed circuit TV

C/F/S: coagulation/flocculation/sedimentation

CSO: combined sewer overflow

DAF: dissolved air flotation

DBPs: disinfection by-products

DOC: dissolved organic carbon

DMA: district metered area

EDCs: endocrine disrupting compounds

GAC: granular activated carbon

GHGs: greenhouse gases

HAA: haloacetic acids

IAM: infrastructure asset management

MF: microfiltration

MIB: 2-methylisoborneol

MW: molecular weight

NF: nanofiltration

NOM: natural organic matter

OBPFP: oxidation by-products formation potential

O&M: operation and maintenance

PAC: powdered activated carbon

RO: reverse osmosis

RWH: rainwater harvesting systems

SUDS: sustainable urban drainage systems

SUVA: specific UV_{254nm} absorbance, defined as UV_{254nm}/DOC

T&O: taste and odour

TOC: total organic carbon

THMs: trihalomethanes

TSS: total suspended solids

UF: ultrafiltration

VOCs: volatile organic compounds

WSN: water supply networks

WTP: water treatment plant

WWTP: wastewater treatment plant

Contents

1 Improved operation of drinking water treatment plants

Maria João Rosa (LNEC)

1.1 Introduction

Drinking water treatment plants are being or will inevitably be challenged by short- and long-term impacts driven by climate changes. The major challenges and the corresponding adaptation options were tackled in different Working Areas of PREPARED and are part of the following deliverables:

- D5.2.4 and D5.2.5 – Assessment of current treatment works to handle climate change related pollutants and options to make current multi-barrier systems climate change proof (Raspati *et al.*, 2013)
- D5.2.7, Chapter §4 – Adapting water treatment to severe droughts and intense rainfall events in the Algarve, Portugal (Rosa *et al.*, 2014)
- D5.5.2 - Adapted operation of drinking water systems to cope with climate change, in particular, Chapters §4 (Kardinaal, 2013), §5 (Eikebrokk, 2013), §6 (Menaia and Mesquita, 2013) and §7 (Rosa and Mesquita, 2013).

Major outputs of the above-mentioned deliverables are herein integrated aiming at providing guidelines for improved operation of drinking water treatment plants in climate change scenarios.

1.2 Climate change impacts and challenges

1.2.1 Impacts and challenges identified

What are we facing or will we be facing driven by climate change and how do these changes may challenge the drinking water treatment plants are questions that need effective short-term answers and action to guarantee the continuity of a safe and resilient water supply.

Within the scope of D5.2.4, the following climate change impacts on raw water quality were identified (Raspati et al., 2013):

- faster and more severe raw water quality changes, particularly critical during climate extremes, i.e. droughts and intense rainfall events, and
- an overall increase in water:
  - temperature;
  - natural organic matter (NOM) concentration;
  - turbidity;
  - microbial load, including (micro)algae and/or cyanobacteria;
  - nutrients, taste and odour compounds and cyanotoxins, most often hepatotoxic microcystins; and

- anthropogenic organic micropollutants, including endocrine disrupting compounds (EDCs), e.g. pharmaceuticals and pesticides.

While these are current or emerging issues, most surface water treatment plants (WTPs), such as those analysed in D5.2.4 (Raspati *et al.*, 2013), were designed to remove (or inactivate) microorganisms, particles and colloidal matter using conventional surface water treatment by coagulation/ flocculation/ sedimentation, filtration and disinfection (AWWA 1999), in many cases assisted by pre-ozonation and powdered activated carbon (PAC) adsorption.

In order to handle the climate change challenges, utilities often rely on adjustments of chemicals' and PAC dosing, sludge wasting and filtration cycles (filtration rates, filtration time, backwashing). In addition to risks related with insufficient removal of macrocontaminants (NOM, TSS, particles, turbidity, microorganisms), these measures may particularly fail to control the undesired formation of the disinfection by-products (DBPs) and other micropollutants occurring in the raw water (Rosa *et al.*, 2009).

Table 1 summarizes the critical aspects of conventional water treatment related with climate change-driven challenges. Treatment adaption strategies are addressed in section 1.6.

Table 1 - Conventional surface water treatment and identification of critical aspects related with climate change-driven challenges (Rosa and Mesquita, 2013)

Treatment step	Critical aspects	
	Target contaminants	Interfering 'species'
1 Oxidation	Microorganisms, DBP control, T&O compounds, cyanotoxins, iron and manganese, EDCs and other micropollutants	Temperature, NOM, pH, bromide, alkalinity, hardness, ammonium, turbidity, micro(algae) and cyanobacteria, ...
2 Clarification (C/F/S)	Turbidity, micro(algae) & cyanobacteria, NOM (for enhanced coagulation)	Temperature, pH, alkalinity, hardness, NOM (for regular coagulation), ...
3 Filtration	Residual turbidity, micro(algae) & cyanobacteria, other microorganisms	Temperature, ...

1.2.2 *NOM and disinfection by-products*

As fully detailed by Eikebrokk (2013) (in D5.5.2), NOM has significant impact on water treatment as well as on distribution processes (Eikebrokk *et al.*, 2007):

- affects water colour, taste and odour levels;
- controls most treatment processes, and affects overall treatment performance, including barrier efficiency;
- challenges process control systems (increased seasonal variability in raw water quality, incl. NOM content and NOM nature);
- increases coagulant demand and sludge production rates;

- affects filter run lengths, filter backwash and energy use;
- affects disinfectant demand and/or disinfection efficiency;
- forms DBPs during chlorination, ozonation, *etc.*;
- affects stability and removal of inorganic particles and pathogens and increases mobility of micropollutants;
- adsorbs to metal precipitates, affects corrosion processes and biological stability of distribution systems water;
- increases soft deposits, biofilm formation and regrowth in distribution systems;
- fouls membranes, blocks the activated carbon pores and/or outcompetes with taste and odour compounds, micropollutants, *etc.* for adsorption sites; and
- increases the organic loads and affects design and operation of ozonation-biofiltration systems.

DBPs, such as trihalomethanes (THMs), haloacetic acids and haloacetonitriles, include species that are potentially carcinogenic and/or endocrine disruptors or have other undesirable health effects (WHO, 2011). Non-halogenated biodegradable DBPs (expressed as AOC – assimilable organic carbon or BDOC – biodegradable dissolved organic carbon) may promote bacterial regrowth in the distribution systems and sustain biofilm development on pipe walls, where pathogenic organisms (bacteria, protozoa, viruses, (oo)cysts, endospores) may grow and/or be entrapped (Menaia and Mesquita, 2013).

The type and concentration of DBPs formed depend on the oxidant type and dose (concentration x contact time) as well as on the raw water quality in terms of temperature, pH, alkalinity and DBP precursors, i.e. NOM (type and concentration) and bromide contents (the latter is particularly important when ozonation is used). Climate change will therefore impact the DBP formation due to temperature increments and changes in the water NOM and inorganic (alkalinity, conductivity, pH) matrices. Increased NOM contents, due to e.g. humic and fulvic acids and algal/cyanobacterial organic matter, may promote DBP formation (WHO, 2004). Special care must be taken to ensure a safe disinfection and (at least partial) removal of microcontaminants while minimizing DBP formation, particularly THMs and bromate, the DBPs regulated in the EU Drinking Water Quality Directive.

1.2.3 Organic microcontaminants

Organic microcontaminants of increasing environmental-health concern may have an anthropogenic origin (e.g. pharmaceuticals, pesticides, personal care products), may be naturally produced in water sources (e.g. taste and odour compounds, cyanotoxins) or be released (cyanotoxins and other metabolites) or produced (e.g. DBPs) during water treatment. They usually occur dissolved in the water and are thus not effectively removed by conventional water treatment (Rosa *et al.*, 2009; WHO, 2011). In turn, they may constitute a health issue in drinking water supply, when no additional barriers exist in the WTPs, e.g. physical operations (e.g. nanofiltration or reverse osmosis membranes), oxidative, biological (e.g. slow sand filtration, GAC biofiltration) or hybrid (fine-PAC adsorption/membrane (bio)reactor) processes.

1.2.4 Acute problems associated with severe droughts and intense rainfall events

Severe droughts and intense rainfall events usually amplify the impacts of the above-mentioned challenges and may catalyse acute problems in water treatment as follows.

Micropollutant control may be particularly challenging in drought scenarios and intense rainfall events. Associated with these climate extremes, increased concentrations of microcontaminants may occur. In addition, the raw water may become highly turbid, and NOM and microbiologically loaded, and these are characteristics which strongly hinder the performance of the oxidation, coagulation and adsorption processes due to the associated increases in demand of oxidant(s), coagulant(s) and adsorbent.

Water scarcity and rain events may also drive strong variations in water background inorganic matrices (pH, alkalinity, conductivity, salinity, bromide), which also challenge the treatment directly and indirectly. Ions are not (significantly) removed by conventional surface water treatment (unless ion exchange, chemical precipitation, nanofiltration or reverse osmosis are used) but they interfere with the oxidation, coagulation and adsorption phenomena and may therefore severely impact (enhancing or hindering) the treatment effectiveness and efficiency for removing particles, microorganisms, colloid matter, NOM and other organics.

Bromate formation may also become an issue in water scarcity scenarios, when the inlet bromide concentration increases due to saline intrusion in groundwater and surface waters used for drinking water production (USEPA, 2005, Rosa *et al.*, 2009, WHO, 2011).

1.3 Framing the strategy

The variety and complexity of the climate change-driven challenges call for a general framework strategy embracing the following vectors (Raspati *et al.*, 2013):

- Understanding of local conditions – knowledge of typical/historical behaviour of source water quality, adequate and early monitoring/warning systems, and contingency plans.
- Integration – integrated water resource management, water saving campaigns, raw water source protection, integration of all stakeholders including NGOs and customers.
- Flexibility – considering alternative raw water sources, availability of redundant modular treatment processes adjusting/upgrading treatment technology and capacity.

An overview of the treatment adaptation strategy and measures follows.

1.4 Detecting rapid changes that lead to risk

The ability to detect rapid changes that lead to risk is a key issue for deciding on and implementing the adequate preventive and corrective actions. As detailed in Rosa and Mesquita (2013), this requires:

1. Implementing pro-active measures to identify changes in quantity and quality of water resources.
   a. Anticipating the water source pollution – modelling intense rainfall events (frequency and intensity), runoffs and droughts.
   b. Characterizing the water source pollution – monitoring (volume and water quality parameters) of intense rainfall events and wastewater discharges in the watershed.
   c. Characterizing the source water availability and quality – modelling the water quality for different scenarios.
   d. Regular monitoring/inspection of the source water quality – visual inspection, e.g. of water scums, turbidity and colour, including as much as possible parameters of rapid determination for early warning of quality changes requiring treatment adaptation (e.g. cyanobacterial blooms, muddy and clay waters).
2. Implementing pro-active measures to identify the impact of raw water quality changes in the produced water quality.
   a. Monitoring the critical treatment steps' effectiveness and efficiency, using as much as possible reliable online measurements.
   b. Modelling WTP response to raw water quality changes.

WHO's Water Safety Plans (WHO 2009) and the ISO 22000 family of standards addressing food safety management are robust frameworks for mapping the critical water quality parameters and the critical treatment steps for each WTP. WTP modelling is a very useful tool for identifying and managing critical changes that lead to risk.

The effectiveness and cost-efficiency of the monitoring programs can be improved by a combination of raw water quality management and treatment control. Examples of relevant parameters may be found in Rosa and Mesquita (2013).

1.5 Preventive measures

Better than acting correctively is to prevent risks from occurring. This can be achieved by preventing hazards and or minimizing their consequences and frequency.

As far as climate change-driven risks to drinking water treatment are concerned, preventive measures encompass the implementation of (Rosa and Mesquita, 2013):

- Global policies for minimizing the climate change drivers (i.e. for reducing the GHG emissions and increasing their sequestration), which will reduce the challenges to drinking water quality.

- Management planning including:
  - Pro-active measures for improving the reliability of the source water quantity and quality, e.g.:
    - Efficient water use.
    - Watershed pollution control (agricultural, industrial, domestic, stormwater).
    - Proper water management, including the variation of the water abstraction depth to prevent/minimize scums and algal and cyanobacterial biomass from entering the WTP.
  - Alternative water sources, e.g. water reuse, water transfer between supply systems.
  - Pro-active measures for improving the detection of trigger factors of rapid changes that lead to risk.
  - Pro-active measures for improving WTP ability for timely adaptation of the treatment process to changes in raw water quality, e.g.:
    - Performance assessment and benchmarking treatment plants praxis.
    - Water Safety Plan implementation.
- Contingency plans for extreme events (e.g. drought, intense rainfall, and pollution peaks).

1.6 Adapting conventional water treatment

As summarized in Table 1, each treatment barrier has specific critical aspects in terms of target contaminant(s) and interfering 'species' (i.e. water quality parameters), which determine specific adaptive measures. Measures focusing on specific contaminants are more detailed in D5.5.2 (Kardinaal, 2013; Eikebrokk, 2013; Menaia and Mesquita, 2013). Herein, the focus is on adapting the water treatment for the integrated control of climate change-driven challenges, and the text is organized in terms of treatment barriers.

1.6.1 Pre-oxidation and final disinfection

Surface water treatment often starts and ends with chemical oxidation for pre-oxidation and final disinfection, respectively (AWWA 1999). Pre-oxidation is mainly used to control the biological growth in the WTP, to inactivate biological forms resistant to chlorine (the oxidant mostly used in the final disinfection step), to oxidise microcontaminants (e.g. taste and odour compounds, cyanotoxins, EDCs) into less harmful species, to oxidise soluble forms of iron and manganese and produce settleable forms, and to assist the subsequent coagulation. Final oxidation addresses water disinfection at the WTP outlet and throughout the water supply system (disinfectant residual).

Chlorine, chlorine dioxide, permanganate and ozone are the most popular oxidants. The relevant criteria and algorithms for pre-oxidant and final disinfectant selection are illustrated in Figure 1 and Figure 2, respectively. In these figures, TOC (total organic carbon) represents NOM and OBPFP (oxidation by-products formation potential), the formation potential of DBPs.

Oxidant demand is proportional to NOM content. Increasing NOM and increasing oxidant doses thus lead to increased DBP formation up to a limit when NOM is no longer the limiting reagent.

DBP formation (OBPFP in Figure 1 and Figure 2) depends on the oxidant type and dose (residual concentration x contact time) and on the water quality, e.g. NOM, pH, temperature, alkalinity, ammonium, bromide. DBPs are in general low MW, hydrophilic compounds, therefore difficult to remove in downstream barriers, i.e. C/F/S and filtration. So the focus should be on minimizing their formation rather than on removing them.

If the oxidant is chlorine and the bromide level in raw water is low, chlorinated forms of trihalomethanes (e.g. chloroform) and haloacetic acids (e.g. di- and trichloroacetic acid) will prevail. Otherwise, analogue forms of bromide will be also important, e.g. bromodichloromethane and bromodichloroacetic acid.

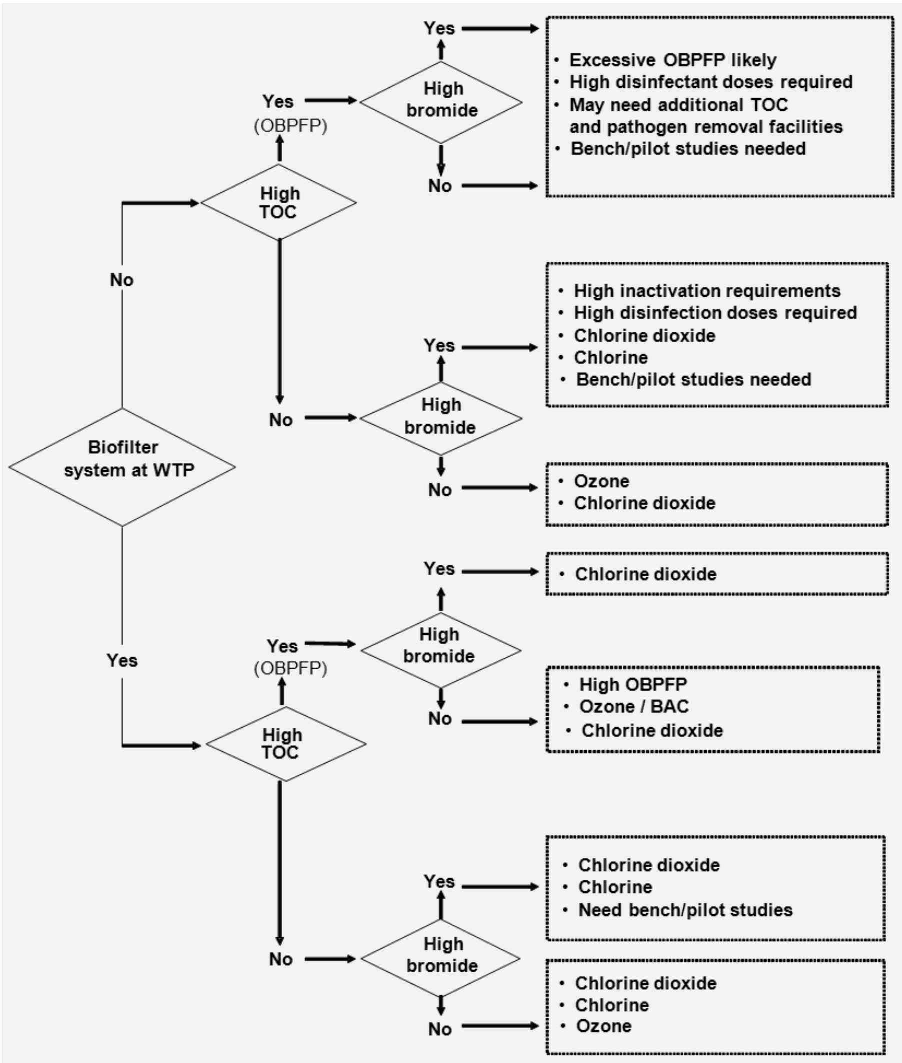

Figure 1. Algorithm for selecting the primary disinfectant (USEPA 1999a)

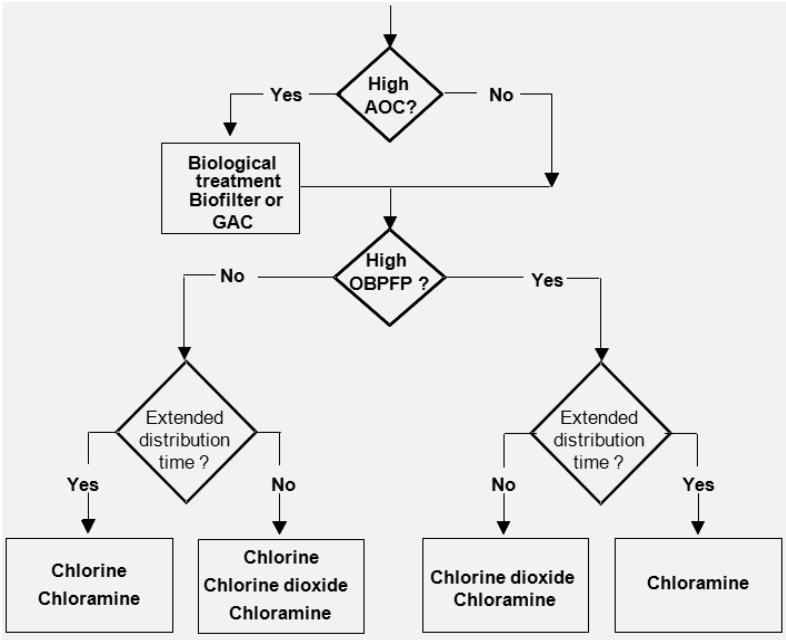

Figure 2. Algorithm for selecting the final disinfectant (USEPA 1999a)

Bromate, brominated organic compounds and AOC (or BDOC) are ozone's DBPs. Ozone should not be applied to raw water containing bromide levels higher than 100 µg/L, at which high levels of bromate (at pH > 8.7) or brominated organic compounds (at pH < 8.7) will be probably produced (Figure 2).

For NOM-rich waters, AOC (or BDOC) formation is an issue for chlorine and ozone oxidation, for it is resistant to conventional treatment and may compromise water stability during distribution. As such, if effective barriers against AOC, such as biofilter systems (section 1.7.3), do not exist, the use of oxidants is limited (Figure 1 and Figure 2).

Increased NOM contents (TOC concentration) in raw waters will certainly increase the DBP formation as well as the final disinfectant demand for controlling the microbial pathogens if no adequate measures are adopted. This will require preventive and/or corrective measures (USEPA, 1999a; Rosa *et al.*, 2009):

i) Decreasing NOM content in the raw water through an integrated water resource management, when alternative sources exist

ii) Adjusting the dose or even the pre-oxidant used (Figure 1)

iii) Improving NOM removal in C/F/S prior to the final chlorination (USEPA, 1999b) or using a final disinfectant of low NOM-reactivity, i.e. chlorine dioxide or chloramines (Figure 2).

Intense rainfall events may increase ferrous iron and manganese contents in raw water, which will increase oxidant demand. However, if the stoichiometric demand is exceeded, undesired soluble oxidised species are produced, e.g. Mn^{+7} (pink water). In this case, strong oxidant (e.g. ozone) dosing should be reduced and $KMnO_4$ should be used as auxiliary oxidant. Another typical practice for controlling manganese peaks is to allow the sand filters to be covered by a layer of manganese dioxide, which adsorbs and self-catalysis the Mn^{2+} oxidation by the $KMnO_4$ or chlorine applied to the filters – manganese greensand filtration (AWWA, 1999).

When toxic cyanobacterial blooms occur in the source water, the pre-oxidation processes should be well controlled since they can promote cyanobacterial cell rupture and subsequent release of cyanotoxin into water. The extracellular cyanotoxins are not easily controlled by conventional water treatment, and cyanobacteria cell lysis should thus be avoided before cell removal. Some dissolved cyanotoxins may be destroyed by ozone, however the process efficiency depends on the ozone dose and water quality, and impractical high doses would be required for the complete oxidation of the cyanotoxins. Removing the cyanobacteria prior to oxidation process is considered a safer practice.

1.6.2 Coagulation/flocculation/sedimentation

Coagulation/flocculation/sedimentation (C/F/S) is conventionally designed to clarify the water, i.e. for turbidity removal. For NOM-rich waters, it may however be operated for NOM removal, providing conditions for enhanced coagulation.

Turbidity removal is strongly affected by water turbidity and alkalinity binomial (AWWA, 1999) – high turbidity/low alkalinity waters are easily coagulated by adsorption/neutralization, high turbidity/high alkalinity waters demand higher coagulant doses, low turbidity/high alkalinity waters are sweep coagulated, whereas low turbidity/low alkalinity waters are resistant to coagulation and therefore require the previous addition of turbidity and/or alkalinity (often lime). In climate change scenarios, pre-hydrolysed metal salts (e.g. polyaluminium chlorides) may be preferable to simple metal salts (e.g. alum, ferric chloride), as these coagulants show high efficiencies for turbidity removal and are less affected by temperature, NOM concentration and alkalinity variations.

Coagulation can be effective for NOM removal if performed at low pH (5-6), i.e. enhanced coagulation, which can be achieved by simple salt coagulant (e.g. alum or ferric chloride) overdosing and/or pH adjustment. As detailed by Eikebrokk (2013), enhanced coagulation efficiency depends on the coagulant type and concentration, on the raw water inorganic matrix (pH, alkalinity, hardness) and on the mixing conditions (time and intensity). For instance, high alkalinity waters will require increased coagulant doses to lower the water pH (AWWA, 1999; USEPA, 1999b).

Enhanced coagulation may be used in conventional clarification (i.e. in coagulation/flocculation/sedimentation) or prior to other solid-liquid separation units, e.g. dissolved air flotation (C/F/DAF, section 1.7.1), contact filtration (section 1.6.4) or membrane separation (section 1.7.5). Recommended coagulation conditions depend on the separation process and should be adjusted e.g. to improve flock settleability, floatability, filterability or to minimize membrane fouling, as discussed in the next sections.

However, as concluded by Eikebrokk (2013), beyond a specific NOM concentration level, enhanced coagulation processes can no longer act as a stand-alone NOM removal process, mainly because of reduced treated water quality, high chemical demand, excessive sludge production, short filter runs, high backwash water consumption, short filter runs due to rapid head loss development and/or early filter breakthrough, reduced treatment production capacity, *etc.*

1.6.3 PAC adsorption

Microcontaminants, as well as DBP precursors (NOM), may be controlled in conventional WTPs if C/F/S is assisted by PAC adsorption. The PAC doses often required (10-40 mg/L) make this option a good solution for controlling episodes but limit its technical-economic and environmental feasibility on a continuous basis.

Tailoring PAC addition is crucial to achieve high removal efficiencies. The physicochemical characteristics of PAC (particle size, porosity and surface chemistry), target pollutants (molecular weight, polarity, hydrophobic/ hydrophilic nature, charge distribution) and water quality (pH, ionic strength, NOM content) are key variables, as they determine the competitive adsorption kinetics and capacity (AWWA, 1999; Chorus and Bartram, 1999; Campinas and Rosa, 2006; Campinas *et al.*, 2013) – NOM may severely compete for the adsorption sites or block the pores' entrance; the inorganic water matrix affects the intra- and intermolecular electrostatic forces, and therefore the adsorbate's molecular size and the adsorbate-adsorbate and adsorbate-carbon interactions.

Adsorption modelling is a powerful tool to assist PAC selection and optimization (e.g. Campinas *et al.*, 2013), but bench or pilot tests are often recommended to characterize the target compound(s) adsorption in the real water matrix.

1.6.4 Filtration

Increments of temperature and turbidity (suspended solids, including microalgae and cyanobacteria) may promote high filter head losses, thus requiring increased frequency of filter backwash. Filter shutdown and restart should be gradual to minimise particle breakthrough.

Increased NOM concentration impacts the operation of enhanced coagulation-contact filtration process, as above discussed (Eikebrokk *et al.*, 2004).

Sand filtration may also be operated to improve manganese removal. In this case, sand filters are allowed to be covered by a layer of manganese dioxide, which adsorbs and self-catalyses the Mn^{2+} oxidation by the $KMnO_4$ or chlorine applied to the filters – manganese greensand filtration (AWWA, 1999).

1.7 Upgrading water treatment with advanced or alternative treatments

When optimization of existing processes provides insufficient improvement of treatment, utilities need to consider advanced or alternative processes for upgrading the water treatment. In fact, in some regions such as in Northern

Europe, these options are already in place. Examples of advanced or alternative processes include dissolved air flotation, alternative oxidants and advanced oxidation processes, activated carbon (bio)filtration, membrane pressure-driven processes and hybrid processes of adsorption and low-pressure membranes.

1.7.1 *Dissolved air flotation*

Dissolved air flotation (DAF) is very efficient for removing low-density particles, like microalgae, cyanobacteria and protozoan (oo)cysts, and for treating NOM-rich waters. For these types of waters, it may thus be advantageous to replace C/F/S or flock blanket clarification by C/F/DAF, as found for cyanobacterial-rich waters (AWWA, 1999; Ribau Teixeira and Rosa, 2007; Ribau Teixeira *et al.*, 2010). As further detailed in D5.5.2 (Rosa and Mesquita, 2013), C/F/DAF was found to be less affected by NOM concentration and type and showed higher removal efficiencies of *Microcystis aeruginosa* cells (above 92% in terms of chlorophyll a) using more cost-effective operating conditions (mixing intensity and time, recirculation ratio) including lower coagulant dose (Ribau Teixeira and Rosa, 2007).

1.7.2 *Advanced oxidation processes*

Advanced oxidation processes (AOPs) comprise the formation of the hydroxyl radical, which is a strong oxidant (von Sonntag, 2007). O_3-based AOPs include ozone at pH 8-10, ozone with UV radiation and/or H_2O_2, ozone with TiO_2 and/or H_2O_2. According to von Gunten (2003), the addition of H_2O_2 to the existing ozone oxidation was, a few years ago, the most frequent and lowest cost option for upgrading a WTP with an AOP. Examples of other AOPs include UV with H_2O_2, an option that has gained in popularity (Meunier *et al.*, 2006; Mamane *et al.*, 2007; Hofman-Caris and Beerendonk, 2011), the Fenton process and catalytic oxidation.

AOPs have a high oxidation potential for microbial pathogens and micropollutants, but several side-aspects should be considered. In addition to increased chemicals and energy consumption, water pH and alkalinity play a key role in AOP performance, since bicarbonate and or carbonate ions compete for the hydroxyl radical, respectively in high alkalinity waters and at high pH values (USEPA, 1999a). Also, AOPs are less effective than ozone for oxidizing ferrous iron and manganese (USEPA, 1999a), do not ensure a disinfectant residual and may form DBPs, including bromate. Finally, NOM oxidation is not complete and yields low molecular weight biodegradable organic compounds (AOC) which support biological regrowth in distribution networks, besides being DBP precursors although less problematic than the hydrophobic fraction.

As for ozone oxidation, AOPs may be used for primary or secondary oxidation, i.e. before or after water clarification, the latter with lower THM potential formation due to previous partial removal of NOM.

1.7.3 *Activated carbon filters and biofilters*

As earlier discussed in sections 1.6.1 and 1.7.2, oxidation or advanced oxidation processes applied to NOM-rich waters increase water BDOC and

AOC, and should therefore be complemented with downstream biofiltration, such as biologically active carbon (BAC) filters (Figure 1 and Figure 2).

Accordingly, ozonation or AOP promotes the biological activity in GAC filters. Actually, as recently demonstrated by Mesquita (2012) under controlled conditions at lab scale, the biological activity inevitably develops in GAC filters fed with biodegradable organics, turning them into BAC systems.

While requiring proper management of biofilm development and activity, to avoid excessive head loss and microorganisms' release in the treated water, the adsorption-biodegradation synergy established in BAC filters provides a continuous bioregeneration of the activated carbon and improves process effectiveness, efficiency and reliability (Mesquita *et al.*, 2006; Mesquita, 2012).

In a climate change scenario, when ozone-resistant, non-biodegradable and non-adsorbable pollutants are an issue, secondary ozonation or AOP combined with downstream BAC filtration may constitute a permanent barrier against refractory pollutants, BDOC and AOC, cyanotoxins and other organic micropollutants (e.g. EDCs, pharmaceuticals). BAC/GAC filtration may also control inorganic pollutants by microbial/chemical reduction, e.g. bromate (Marhaba, 2000; Huang *et al.*, 2004; Rosa *et al.*, 2009).

Figure 3 illustrates the ozonation-biofiltration process applied in Skien, Norway, described by Eikebrokk (2013). In this process, between ozone oxidation and the biofilters, there is an alkaline (calcium carbonate) prefilter where metals in raw water precipitate, e.g. iron, manganese and aluminium. These precipitates, particularly the iron hydroxide, are very effective NOM adsorbents, and similar amounts of NOM are therefore removed in the alkaline prefilter and in the biofilter. Weak performance of this ozonation/ biofiltration process is related to inadequate ozone dose control and/or poor biofilter design and excessive NOM content in the raw water. All these factors may lead to biofilter overload, poor removal of AOC (or BDOC) and ultimately to increased risk of problems with biological regrowth and biofilm formation in the distribution system.

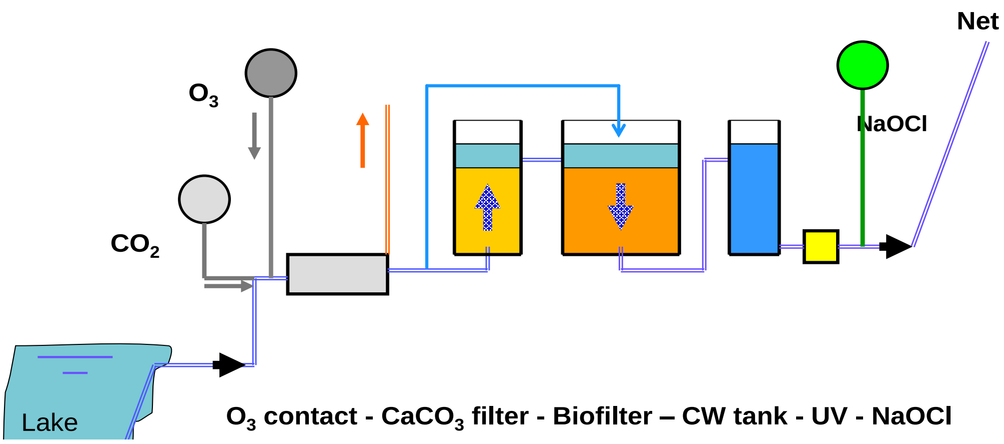

Figure 3. Ozonation-biofiltration, alkaline prefiltration and UV-disinfection treatment used in Skien, Norway (Eikebrokk 2013)

1.7.4 *UV radiation*

UV radiation is also gathering interest in water treatment since it can be effective for destroying/inactivating biological forms resistant to chemical oxidation, including *Cryptosporidium* oocysts and *Giardia* cysts (USEPA, 2006), while minimizing the DBP formation, and in particular the halogenated DBPs. However, the UV dose required for water disinfection depends on the nature of the microorganisms and on the water turbidity/transmittance. The most UV-resistant organisms are viruses, specifically Adenoviruses, and bacterial spores. The protozoon *Acanthamoeba* is also highly UV-resistant. Bacteria and (oo)cysts of *Cryptosporidium* and *Giardia* are more susceptible, having a fluence requirement of 20 mJ/cm^2 for an inactivation credit of 3 log (Hijnen *et al.*, 2006).

To enable accurate assessment of the effective fluence in continuous flow UV systems in water treatment practice, biodosimetry is still essential, although the use of computational fluid dynamics improves the description of reactor hydraulics and fluence distribution. For UV systems that are primarily dedicated to inactivate the more sensitive pathogens (*Cryptosporidium*, *Giardia*, viruses), additional model organisms are needed to serve as biodosimeter. For turbid waters (> 10 NTU) UV disinfection is limited and for certain microorganims the required doses are very high.

UV disinfection is particularly interesting in regions where chlorine-free distribution systems are very common, such as in Nordic or cold climate regions. For example, in the Skien (Norway) WTP (Figure 3), the chlorine dosing system used is mainly a backup to the installed UV-disinfection system. According to Eikebrokk (2013), chlorination is also used to help control heterotrophic plate counts (22 °C) at levels below 100/mL. The applied chlorine doses are however very low, typically 0.1-0.2 mg/L, thus leaving no free chlorine residuals in the distribution network.

UV radiation is also an option for refractory pollutant control, but the doses required are much higher (1-2 orders of magnitude) than those used for disinfection.

1.7.5 *Membrane technology and hybrid processes*

Membrane technology includes a broad range of solutions for adapting the treatment systems to deal with the climate change driven risks.

Membrane pressure-driven processes include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). While the low-pressure (0.1-1 bar) MF membranes (0.1-2 μm) safely ensure turbidity and pathogen removal, including *Cryptosporidium* oocysts and *Giardia* cysts, UF (2-200 nm or 50-100 kDa MW cut-off; 0.5-5 bar transmembrane pressure) can also remove viruses and coagulated NOM (Campinas and Rosa, 2010a).

NF membranes are more selective (0.5-5 nm or 150-300 Da MW cut-off; 5-20 bar). In addition to effective removal of turbidity and pathogens, they present high removals of dissolved organics – NOM, micropollutants and DBPs above 150-300 Da, e.g. cyanotoxins (Ribau Teixeira and Rosa, 2006, 2012), EDCs, pesticides, pharmaceuticals – and partial to high removal of inorganics (e.g. bromate, bromide, hardness ions, heavy metals, nitrate, salinity). Reverse osmosis is adequate for desalination and is widely used in water scarce regions, where brine disposal in the receiving waters (ocean) is not an issue.

Hybrid processes of adsorption and low-pressure membranes, e.g. PAC/MF or PAC/UF, are also promising options, for they integrate PAC ability for adsorbing coagulated and dissolved organics, with the high particles' retention of the low-pressure UF and MF membranes.

Hence, PAC/MF(UF) assure pathogen (protozoa, bacteria and viruses), cyanobacteria and turbidity removal, full retention of PAC particles and the control of coagulated and dissolved NOM (which is a major responsible for membrane fouling), DBPs and other adsorbable micropollutants (Campinas and Rosa, 2010b, 2010c, 2011). Major advantages of PAC/UF(MF) processes in a climate change context are related to: i) low unit energy consumption, due to the low transmembrane pressures applied and the PAC ability for assisting the membrane fouling control (Campinas and Rosa 2010b); ii) small PAC particle size, which improves adsorption kinetics and, compared to conventional PAC addition to C/F/S, allows superior water quality with lower PAC consumption and sludge production (Campinas and Rosa 2010d); iii) process flexibility, by easily adjusting PAC type and dose to the target contaminant(s) and feed water quality.

The successful application of membrane technology relies on an effective membrane fouling control, which otherwise may prohibitively decrease the membrane flux and deteriorate its selectivity. It may be ensured through adequate pre-treatment, e.g. by pH control (Ribau Teixeira and Rosa, 2003), membrane cleaning, and operating conditions, which should allow maximum water recovery rates with minimal unit energy and chemicals' consumption.

1.7.6 Summary

Table 2 summarizes the ability of alternative and advanced treatment options above discussed for adapting conventional WTPs to deal with climate change-driven challenges.

Table 2 - Effectiveness of alternative and advanced processes for macro and microcontaminant control in a climate change scenario (Rosa and Mesquita, 2013; Rosa et al., 2009)

Contaminants	C/F+DAF	UV	GAC	BAC	MF	UF	PAC/UF	NF [a]	RO
Protozoa (cysts, oocysts)	+/-	+	+/-		+	+	+	+	+
Bacteria (vegetative forms)	-/+	+	-		+	+	+	+	+
Bacteria (endospores)	-/+	-	-		+	+	+	+	+
Helminth eggs	+/-	-	+/-		+	+	+	+	+
Cyanobacteria	+	- [b]	+/-		+	+	+	+	+
Enteroviruses	-	-	+/-		+/-	+	+	+	+
NOM_SUVA < 3 L/(mgC·m)	-/+	+/-	-/+	+	-	-	+/-	+	+
NOM_SUVA > 4-5 L/(mgC·m)	+/-		+/-	+/-	-/+	+/-	+	+	+
AOC	-	+/-	-/+	+	-	-	-/+	+/-	+
THM	-		+		-	-	+	+/-	+
HAA	-		+		-	-	+	+/-	+
Bromate	-		+/-	+/-	-	-	-/+	+	+
Bromide	-				-	-	-	+/-	+
Chlorate	-				-	-	-	+	+
Chloride	-				-	-	-	+/-	+
Nitrate	-				-	-	-	+	+
Sodium	-				-	-	-	+/-	+
Sulphate	-				-	-	-	+	+
Microcystins	+ or -/+ [c]		+ or /- [d]		-	-	+ or +/- [d]	+	+
T&O (MIB, geosmin)	-/+		+		-	-	+	+	+
VOCs	+ [e]		+		-	-	+/-	-/+	+
EDCs and pharmaceuticals (hydrophobic and chemically resistant)	-/+		+		-	-	+	+	+
Pesticides (including chemically resistant)	-/+		+ or +/- [d]		-	-	+	+	+

Sources: AWWA (1999), USEPA (1999a-b, 2005, 2006), Marhaba (2000), Huang *et al.* (2004), WHO (2004, 2011), Ribau Teixeira and Rosa (2003, 2006, 2007, 2010, 2012), Campinas and Rosa (2006, 2010a-d, 2011), Mesquita *et al.* (2006, 2012), Mesquita (2012)

-	Not adequate
-/+	Limited effectiveness
+/-	Partial control if adequate operation conditions are guaranteed
+	Effective provided adequate operation conditions are guaranteed
	No information available

[a] Considering 200 Da MW cut-off

[b] UV should not be used to control cyanobacteria, since it leads to cell rupture and cyanotoxin release

[c] Effective removal of intracellular toxins; no significant removal of dissolved toxins

[d] Depends on chemical characteristics of the target compound

[e] There are volatilization conditions in C/F/DAF

1.8 Miscellaneous

Both conventional and advanced technologies, except those involving contaminant destruction, such as chemical or biological oxidation, produce solid and liquid wastes with high contaminant concentrations. Adequate treatment and disposal of those wastes should be guaranteed.

In some scenarios, e.g. during a cyanobacterial bloom, the recirculation of sludge supernatants must be thoroughly assessed, and in some situations avoided, as it may constitute a severe input of refractory contaminants (dissolved cyanotoxins or other metabolites from cell lysis) which may compromise the treated water quality.

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2 Maintenance of water supply networks

José Menaia and Ana Poças

2.1 Introduction

Water supply networks (WSN) inevitably have to deal with the effects of global and regional climate changes (Major *et al.*, 2011). These are already challenging many WSN. However, some challenges will intensify in the long term, as climate changes develop. Accordingly, WSN will have to adapt in order to respond to, mitigate or prevent the impacts of climate change effects.

Maintenance plays a crucial role in the adaptation of WSN, particularly because most of these are several decades old and many are deteriorated, having accumulated significant amounts of deferred maintenance and rehabilitation (USEPA, 2010; Le Gauffre *et al.*, 2013).

In PREPARED, climate changes and impacts on the water sector were tackled in different Working Areas, which outcomes include the following deliverables with relevance for WSN adaptation:

- D1.1.1- Catalogue of European adaptive initiatives of the water sector to face climate change (Staub and Moreau-Le Golvan, 2011)
- D5.0.1 - Planning for resilient water supply and sanitation systems: state-of-the-art (Hem *et al.*, 2010)
- D5.5.1 - Exploration of existing technologies for maintenance (Bruaset *et al.*, 2012)
- D5.5.2 - Adapted operation of drinking water systems to cope with climate change (Menaia and Mesquita, 2013)
- D5.5.4 - Impacts of climate change on maintenance activities: a case study on water pipe breaks (Le Gauffre *et al.*, 2013)
- D6.2.7 - Use of Scenarios in PREPARED (Ashley and Tait, 2012).

Herein, outputs from these deliverables and other state-of-the-art publications, including contributions from projects CARE-W, DayWater, TECHNEAU, CARE-S and AWARE-P are integrated to outline the pertinent climate change context and impacts, and draw corresponding maintenance guidelines for WSN adaptation.

2.2 Climate change

According to available scenarios and depending on their geographic location, WSN face or will be impacted by one or more of the following main climate changes (Ugarelli *et al.*, 2010; Major *et al.*, 2012):

- increase in air average-temperature;
- increase in variability of air temperature;
- extremely hot periods;
- more frequent, severe and prolonged drought periods;
- more frequent and intense rain and storm events.

While still under discussion (de Vries *et al.*, 2012, Petterson *et al.*, 2013) other changes were projected (Petoukhov and Semenov, 2010; Kodra *et al.*, 2011; Cohen *et al.*, 2012) including:

- increases in frequency and intensity of cold waves;
- increased severity and frequency of colder winter periods.

These are prudently considered herein, as evidences on their occurrence have been reported (Le Gauffre *et al.*, 2013).

2.2.1 *Impacts and challenges*

While differently among regions, WSN will be impacted by one or more of the above climate changes throughout the world. Hence, the capacity of WSN to supply good quality and safe water uninterruptedly and at the adequate pressure will be challenged, namely by impacts that threaten their structural condition and integrity, and functioning at present and in the medium- and long term.

2.2.2 *Changes in temperature*

The above-mentioned temperature changes will impact WSN directly (e.g. increases in water temperature will promote microbial regrowth) and indirectly (e.g. warmer and/or dryer weather will lead to increased water demands). Accordingly, foreseen temperature-related effects include those described below:

- Increases in WSN and surrounding soil waters temperature will lead to faster rates of both internal and external pipe corrosion (Menaia and Mesquita, 2013). Under these conditions, the occurrence of breakage, fissures, cracks or holes is likely to increase, particularly in aged metallic unlined pipes. Likewise, water losses may increase while intrusions may be promoted, including particles and chemical and microbial contaminants from the adjacent soils. In addition, corrosion derived particulates may be added to WSN deposits, thereby potentiating the occurrence of discolouration events.
- WSN pipe biofilm growth/detachment rates tend to increase with temperature, thus contributing to the presence of microorganisms and particles, which may compromise the microbiological quality of the water and potentiate the occurrence of discolouration (Menaia and Mesquita, 2013).
- Hot weather, particularly if combined with intensive water uses (e.g. irrigation, industry) or increases in population (e.g. summer tourism peaks in coastal areas in Southern Europe), may lead to excessive flow demand increases and peaks. In addition to challenging WSN hydraulic capacity, the associated higher head loss may need to be overcome at the operational level through higher pressure levels which may lead to increased wearing of pipes and fittings (Alegre and Covas, 2010) and cause bursts, losses and intrusions to take place with increased frequency (Ugarelli *et al.*, 2010).
- Increased air temperatures and, therefore, higher evapotranspiration rates during dry periods can lead to increments in pipe breakage rates

due to differential soil movement due to uneven shrinkage, particularly in expansive clay soils (Sægrov *et al.*, 1999; Wols and van Thienen, 2013).

- More frequent soil movements leading to increments in pipe breakage rates are also likely to occur due to more freeze/thaw cycles arriving with increased variability in temperature (Vevatne *et al.*, 2007).
- In cold climate regions, similar consequences may arise from the lengthening of soil freezing periods, as it is already occurring in some European and American cities (Le Gauffre *et al.*, 2013).
- In critical coastal zones, the rise in sea level due to ocean water warming and increased ice melting may impact WSN by rising water table levels (Ugarelli *et al.*, 2010). These may bring instability and differential settling of infrastructure bedding and foundations supporting soil, thus possibly causing pipe breakage and damages to equipment housing and storage tank facilities. In addition, increased water table levels may aggravate flooding of vulnerable equipment facilities like pumping, monitoring, valve control and booster stations. Saline intrusion into ground waters may also arise, then increasing soil corrosiveness and, thus, the incidence of pipe breaks (Case, 2008).

2.2.3 *Drought*

Summer droughts and a drier climate are expected for Continental and Mediterranean Europe, respectively. Such circumstances and the accompanying water scarcity will challenge WSN capacity, structural integrity and functionality in several ways (Ugarelli *et al.*, 2010). Associated impacts on WSN may then comprise:

- As drought will lead to the concentration of NOM, contaminant and particulates in source waters, particularly in those of surface origin, many WTP will be challenged with regard to their treatment effectiveness (Rosa and Mesquita, 2013). Therefore, it is likely that in many WSN water will undergo reductions in bio-stability and increases in particle loads. Consequently, microbiologically mediated in-pipe processes (i.e. biofilm growth and detachment, corrosion) may be intensified (Menaia and Mesquita, 2013). Then, in addition to degradation of the water´s microbiological quality, deposits accumulation and concomitant potential for discolouration events in WSN are likely to be intensified.
- Particularly when concurrent with temperature increases, drought periods are generally accompanied by rises in water demand. As discussed above, apart from challenging WSN hydraulic capacity, such circumstances may lead to the need for excessive pressure levels and, thus, to increased wearing of pipes and fittings (Alegre and Covas, 2010) which may lead to bursts, losses and intrusions taking place with increased frequency (Ugarelli *et al.*, 2010).
- During drought periods, water table levels may lower thus bringing changes in the geotechnical behaviour of soil. These changes may jeopardize the stability and damage the bedding and foundations of

pipelines and other WSN infrastructures (Ugarelli *et al.*, 2010), affecting their structural integrity.

2.2.4 *Intense rain events*

Increased frequency of intense rain events impacting drinking water systems is forecasted for many European regions (Ugarelli *et al.*, 2010). In addition to increased loads of NOM, contaminants and particles in source waters through runoff, challenges to WSN infrastructures and their operational conditions mainly include the effects of flooding, soil erosion and structural changes. These may be more critical in coastal areas when combined with the above-discussed effects of sea level rise. Accordingly, impacts on WSN include (Ugarelli *et al.*, 2010):

- Flooding, leading to soil erosion and movement around pipes bedding and infrastructure foundations. Resulting mud and landslides may add in damaging pipelines and infrastructures. These may be washed away or sunk as a result of differential ground settlement.
- Increased water infiltration during flooding may cause water table rises, which in turn may lead to differential ground settlement thus impairing WSN infrastructures as discussed above.
- At vulnerable locations, intense runoff may lead to flooding of WSN equipment housing facilities and cause failures in critical equipment (e.g. pumping, booster and monitoring stations, remote control valves). Such circumstances may be aggravated in certain critical locations, including those where flooding may also result from river or stream overflow after extreme rain events.

2.3 Adaptation measures

To adapt to the effects of ongoing and forecasted climate changes, urban water systems need to be as flexible and resilient as possible, owing to the uncertainty of predictions (Howe *et al.*, 2011). Some impacts of climate change will only become apparent after many years and drinking water systems are linked to other urban sectors. Hence, WSN flexibility and resiliency will be more sustainably and effectively achieved if approached within the framework of a long-run strategic planning process integrated in the overall urban planning process (Howe *et al.*, 2011).

Ideally, WSN adaptation would be more effectually implemented through the planning, design and construction of the systems from scratch. However, practically all needed WSN are already in place and their full renewal is impracticable. Hence, WSN adaptation to climate change will be primarily achieved through incremental modifications carried out through operation and maintenance (O&M) practice as well as rehabilitation and capital improvement of the existing systems, in the framework of a long-term plan aimed at the best balance of performance, risk and cost.

A great deal of adaptation measures can be taken at the WSN operation level. However, their feasibility and implementation, as well as WSN performance and serviceability, will largely depend on the systems integrity, condition and functionality status, which highly rely on the suitability and effectiveness of the systems' maintenance (Alegre *et al.*, 2006; Alegre and Covas, 2010).

2.3.1 *Maintenance of water supply networks*

As unpredictable failures and anomalies occur, corrective maintenance actions need to be taken to restore the system's integrity and functioning.

The frequency of such remedial actions, which is likely to increase with ongoing climate change effects, can be brought down by proactively lowering the systems' vulnerability to failures and malfunctioning. Along with improving WSN performance and serviceability, this aim can be achieved through the implementation of medium- (tactic) to long-term (strategic) programed maintenance interventions (Alegre and Covas, 2010).

Programed maintenance includes both the rehabilitation, renewal and replacement or redesign of WSN parts at rates and to extents that inevitably depend on funding availability (Alegre *et al.*, 2012). In addition, integrating WSN maintenance programming and capital replacement cycles renders by far more effective and economic results as compared to non-planned, piecemeal adaptations (Major *et al.*, 2012). Hence, incorporating proactive maintenance planning within the overall WSN infrastructure asset management (IAM) frameworks is strongly advisable, particularly in the context of adaptation to climate change (Alegre and Covas 2010; Alegre *et al.*, 2012).

Commonly, the following maintenance classes are considered (Alegre and Covas, 2010):

- Reactive
  - *Corrective or curative maintenance*: repair of the occurring failures (e.g. pipe burst) and anomalies (e.g., pump malfunction), and mitigation of their recurrence whenever possible.
- Proactive
  - *Preventive systematic maintenance*: tactically programed maintenance activities that are performed on a periodic basis. Essentially based on the identification of the likelihood of failures (e.g. a pump approaching the effective end of it service life). In addition to reducing failures and, thus corrective maintenance needs and costs, preventive maintenance allows for opportunities for improving WSN performance and reliability. However it may prescribe unnecessary activities, involving superfluous resource spending.
  - *Predictive systematic maintenance*: maintenance activities that are strategically programmed based on assessments of the probability of failures based on monitoring the condition and vulnerability of system components. In addition to reducing overall maintenance needs and costs, predictive maintenance is more suited to improving WSN performance and reliability, as well as their flexibility and resilience. Hence, predictive systematic maintenance is better fitted for climate change

adaptation, provided that planning takes into account the updated forecasts of pertinent regional changes and impacts.

Proactive maintenance planning needs to be supported by data on the structural and functional condition of system components, as well as on system performance. These data are produced through:

- Inspection of the structural and functional condition of the system components, on an occasional or scheduled basis
- Monitoring of WSN hydraulics and water quality parameters occasionally, systematically or continuously.

Hydraulic and quality models that simulate water pressure, flow and quality changes are useful tools for assessing WSN integrity and functionality. Likewise, those models are also useful to support the planning of inspection and monitoring activities. These will be more effectively done if carried out if delimited within District Metered Areas (DMA). In brief, these are subdivisions of WSN that are manageable as sub-systems with some common characteristics or features. The DMA concept is detailed below in 2.3.5.

2.3.2 Inspection

Above-ground components of WSN are more suitable for direct inspection of their security, integrity and vulnerability. The integrity and condition of buried pipes are much harder to check by direct observation, with opportunities mostly confined to repair or construction work. Assessments are frequently inferred from hydraulic observation (e.g. pressure, flow/capacity, leaks).However, some techniques and equipment are increasingly available for internal inspection of pipes. Below, available methods for inspection of WSN facilities, equipment and pipes are outlined.

Facilities

In order to assess the vulnerability of the facilities' foundations, it is important to carry out the inspection of soil consolidation and erosion status, and the geotechnical assessment of its propensity for settlement if impacted by foreseeable climate changes (e.g. floods, water table rise, temperature increases, drought). Tell tale signs, such as cracks in walls of facilities (e.g. service reservoirs, pumping stations) may be indicative of soil susceptibility to settlement.

In addition to signs of deterioration of tank walls and foundation (e.g. cracks) the inspection of service reservoirs should include checking for the condition of protections against the intrusion of small animals, insects and particulates, as well as conditions for runoff water entry.

Equipment

The inspection of equipment (e.g. pumps, valves) includes the checking of leaks and of proper functioning. In addition to abnormal heating, pumping rates or energy consumption, also unusual sounds or vibrations may be indicative of pump malfunctioning.

Pipes

Although with much more restricted applicability than for sewer networks, the inspection of buried pipes interior can be done through video inspection with close circuit television (CCTV). In recent years, the cost-effectiveness of acoustic resonance pipe scanners (ARPS) for measuring the wall thickness of metallic pipes has been demonstrated e.g., by Breivoll Inspection Technologies (BIT – Oslo, Norway).

2.3.3 *Monitoring*

The inspection of buried pipelines is a difficult task, given their limited accessibility and the complexity of pipe networks. Thus, data representing system hydraulic behaviour (e.g., capacity, losses) is often used to appraise pipe condition and integrity. Water quality monitoring data may provide additional information, as several quality-related symptoms (e.g., turbidity, excessive chlorine residual decay) are related to pipe condition.

Pipe integrity

A reduction in pipe hydraulic capacity may arise from the deterioration of pipe condition due to tuberculation and scale formation, such as that resulting from corrosion processes. Head loss tests may be used to assess such condition.

Breaches often are the more problematic failures in WSN pipes´ integrity. In addition to water losses, these may channel intrusions of contaminated water, soil, and/or mud that may promoted by zero or negative in-pipe pressures. Thus, in addition to negative environmental and economic impacts, pipe breaks have the potential to cause public health problems (Sægrov *et al.*, 2006).

Pipe leakage, as an indicator of loss of integrity, may be detected through various symptoms (USEPA 2010, Bruaset *et al.* 2013):

- the appearance of surface water (e.g. moist soil, standing or flowing water) on the ground, road surface, building basements *etc.*;
- reduced water pressure in the network, or complaints of insufficient pressure at the consumer's tap. However, pressure decreases due to pipe leakage are often indistinguishable from those resulting from increased water demands;
- abnormal flow levels evident in system monitoring telemetry or flow logging, including both sudden events (pipe breaks), high night flow levels (high background leakage), and increasing night flow levels (accumulation of smaller breaks and/or increase in diffuse leakage).

Proactive leak detection surveys are common forms of planned searching for hidden leaks in WSN (USEPA 2010). As discussed in Bruaset *et al.* (2013), a variety of techniques and equipment are used for this purpose, including:

- Acoustic, thermographic and electromagnetic techniques that identify the sound of water escaping a pipe or detect changes in the thermal or electromagnetic properties in wet soils, respectively. Details on these techniques are provided elsewhere (e.g. Alegre and Covas 2010; USEPA, 2010)

- Gases with low solubility in water (e.g., helium, hydrogen) may be used as tracers for leak detection (USEPA, 2010). The gas is injected into WSN water or dewatered pipeline under testing. Sensors detect gas released by soil above leaks. Alternatively, chemical conservative tracers (e.g. fluoride, approved fluorescent dyes) can be added to WSN water and be detected in the water appearing in the soil surface above the leakage point.

The overall integrity of buried pipelines can be indirectly assessed by evaluating water losses based on flow monitoring and consumption data. These data may be useful in supporting the planning of the above-described proactive leak detection surveys. Water losses management is an established field of knowledge with well tested practice, such as described e.g., in Lambert & Hirner (2000), Farley & Trow (2003), Loureiro (2010), USEPA (2010). Quoting the IWA Blue Pages on Water Losses (Lambert & Hirner, 2000):

"The best practice in management of water losses consists of a combination of continuous water balance calculations together with night flow measurements on a continuous or 'as required' basis. The water balance, usually taken over a 12- month period, should include a thorough accounting of all water into and out of a utility system, including inspection of system records; an ongoing meter testing and calibration program; and due allowance for the time lags between production meter reading and customer meter reading.

The water balance calculation quantifies volumes of total water into the system, authorised consumption (billed and unbilled, metered and unmetered) and water losses (apparent and real). Where continuous leak detection is not being practised, the process may also include a benefit cost analysis for recovering excess leakage, leading to a leak detection program.

Water quality parameters

As detailed in Menaia and Mesquita (2013), sudden changes in the quality parameters of the water travelling within WSN may indicate external contamination due to intrusions through holes or fissures. On the other hand, abnormal or changing levels of WSN water quality may reflect poor pipe condition as determined by in-pipe processes, either locally or upstream:

Disinfectant residual – except for weakly reactive monochloramine, sharp decreases in the concentration of disinfectant residual may indicate intense contamination of the water by intrusions, as chlorine or chlorine dioxide are rapidly spent in reactions with organic and reduced inorganic contaminants. On the other hand, abnormally high decay rates may be a sign of poor pipe condition, such as excessive deposit accumulation, intense corrosion or biofilm development.

Bacterial counts – in addition to intrusions and deposit accumulation, high and increasing numbers of microorganisms may indicate that, due to deficient WSN water bio-stability and temperature increases, biofilm is growing excessively. Methods for evaluating water bio-stability and quantify microorganisms are discussed in Menaia and Mesquita (2013).

- *Turbidity* – turbidity increases may equally denote the occurrence of intrusions. In addition, turbidity may be indicative of intensive corrosion or re-suspension of accumulated deposits. Besides nephelometric turbidity measurements, particle counters can be used for on-line monitoring of particles levels in WSN water. Turbidity-based methodologies to assess WSN deposit accumulation intensity and rates are detailed in Alegre *et al.* (2010).
- *Organoleptic parameters* – volatile organic compounds (VOC) or stained substances or particles that ingress WSN may impart taste, odour and/or colour to the water. These may reach threshold levels and be sensed by consumers. In addition to intrusion or infiltration, VOC contamination may reach the water by permeation through plastic pipes. Hydrocarbon mobilization from iron pipe coal tar lining during flushing may also impart taste and odour to WSN water (Alegre *et al.*, 2010).

2.3.4 *Hydraulic and quality models*

In addition to assisting sensor siting and off-line monitoring and sampling location and frequency, models help to simulate how the system should perform, both in terms of quantity (e.g. flow, pressure) and of quality (e.g. chlorine residual), thus allowing to find and track occurring abnormalities, including those arising from pipe breakage or poor hydraulic-capacity (Alegre *et al.*, 2010; USEPA, 2010).

2.3.5 *District Metered Areas (DMAs)*

For the sake of manageability, WSN inspection and monitoring are often methodologically developed at the DMA level.

A DMA is a watertight subdivision of WSN that can be isolated by closing valves so that water inputs and outputs can be monitored at the entrance of each of the defined subsystems. Such subdivisions have differentiated features (e.g. water origin, pressure and/or altimetry zones) and are usually defined for a number of service connections between 500 and 2000. Their size varies with network topology and population density, along other possible factors.

In addition to its usefulness in designing and implementing inspection, monitoring and maintenance plans, the DMA approach is important in assessing the effectiveness of O&M measures to correct abnormalities or improve WSN, performance, flexibility or resilience.

2.4 Adaptive maintenance

Preparing drinking water utilities to cope with climate change impacts cannot be unlinked from the governance and planning of the other urban management sectors, particularly those related with the overall urban water cycle (Howe *et al.*, 2011; Major *et al.*, 2011). In addition, some climate changes that affect WSN condition and performance are external and depend on the capacity of upstream installed treatment (e.g. to produce bio-stable, non-aggressive and low-turbidity water), as well as on changes in water demand, like those due to population or industry relocation. On the other hand, keeping WSN integrity and condition is not fully independent of network operation, for instance in what relates to pressure and flow velocities.

Even so, proper maintenance of WSN is essential for their performance in supplying water of good quality and safety, uninterruptedly and at adequate pressure. In this context, water losses due to pipe breakage are mostly stressed owing to their frequency, effects on supply and environmental and economic significance (i.e. losses in water source water availability, rises in energy consumption and thus increases in costs and CO_2 emissions).

Accordingly, WSN maintenance is of increasing importance given the present deterioration of most water supply systems infrastructure, whose degradation tends to accelerate with the on-going climate changes (USEPA, 2010).

However, as discussed above, foreseeable climate change impacts will not only lead to increases in buried pipelines breakage, but may also affect WSN integrity and condition by a number of diverse effects.

Accordingly, the inspection and monitoring tasks described in 2.3.2 and 2.3.3 need to be programmed and implemented appropriately as to assess the condition of WSN components in terms of their vulnerability to impacts of the predicted climatic change challenges.

Overall, the threats of climate change are those already known to the generality of the WSN. However, depending on its specificity and location, each WSN may now face threats that were previously inexistent or insignificant, or not predicted. In this context, the assessment of WSN features of particular attention with respect to their vulnerability relatively to locally pertinent forecasted challenges is highlighted below. Related inspection techniques may be found elsewhere (e.g., Sægrov *et al.*, 2006; Alegre *et al.*, 2010; Bruaset *et al.*, 2013).

Above-ground facilities

Above-ground infrastructures are more easily inspected, as they allow for direct observation and access. Degradation of their structural and functional condition may be accelerated by climate change effects. Observable structure damages (e.g. wall cracks) may indicate instabilities in the supporting soil. Assessment of soil susceptibility to settling or erosion under drought, wetting (e.g. water table rising) or flooding conditions as a possible cause for the damage of facilities, equipment (e.g. storage tanks, pumps and SCADA housing) and piping should be considered. If necessary, corrective measures may need to be taken (e.g. geotechnical stabilization of soil, French drains, cut-off walls, reinforcement of facilities foundations and/or structure, flood diversion, rehabilitation with flexible piping, *etc.*) and redundancy (re)assured or reinforced.

In addition to flooding and dislodging, the capacity and condition of pumps to respond to and sustain possibly predicted demand increases and peaks may need to be addressed. Flow and pressure metering equipment adequacy, condition and calibration are particularly important for evaluating and controlling WSN performance, especially in what concerns buried pipes break leakage losses survey and control (USEPA, 2010).

Buried infrastructure

Buried pipeline inspection and maintenance is not easy owing to the limited opportunities for direct observation, and well as to their complexity and extension. Hence, apart from major leakages that are made evident by the appearance of water in soil or on surface, data and information on pipes integrity and condition are mostly inferred from water loss assessments, as well as from water quality monitoring and complaints.

The assessment of water losses (2.3.3) provides data on pipelines with defective integrity, which become candidates for rehabilitation. With this purpose, data from water loss assessments may be complemented with proactive leak detection surveys (2.3.3), which then will allow to pinpoint pipes with leaks and poor condition.

The occurrence of lines in defective condition due to accelerated in-pipe processes (i.e. corrosion, excessive biofilm growth and loose deposits' build-up) may also be revealed by water quality data (2.3.3) and customer complaints (e.g., discoloured water). Complementary inspective and corrective maintenance measures may then be required. Other than pipe rehabilitation or replacement, these may include incrementing treated water bio-stability, corrosion control, diagnosing deposits accumulation and implementing or improving pipe cleaning. Details on criteria and methods for pipe cleaning, corrosion control, rehabilitation and replacement are provided in Alegre *et al.* (2010).

Owing to the deterioration state of many WSN infrastructures, extensive rehabilitation is needed to restore their required performance while adapting to climate changes. In other situations, existing drinking water systems have no capacity to respond to demand increases or peaks, like those arising from population and/or industry relocation, seasonal tourism, along with those driven by temperature increases and/or drought (Major *et al.*, 2011). In these circumstances, redesigning the system's overall masterplan may be needed for rehabilitation and adaptation. Then, it may be necessary to adjust, re-locate or redistribute storage and/or pipeline capacity, which may consequently impact pumping arrangements and energy consumption.

In any instance WSN rehabilitation entails substantial financial expenditures and thus needs to be programmed and integrated in the capital replacement cycles (Major *et al.*, 2012). Hence, WSN adaptive rehabilitation will be more effectively and sustainably attained in integrated in the overall system IAM strategic planning.

Criteria, methodologies and tools to support WSN rehabilitation strategic planning were developed in the CARE-W project and can be found in Saegrov (2005). These include modelling tools for assessing pipe failure probability and hydraulic reliability, models and tools for strategic planning, decision criteria and multicriteria procedures for annual rehabilitation plans.

More recently, inclusive and updated methodologies, and open-source software were developed for drinking water, wastewater and stormwater IAM as outcomes of the AWARE-P project (Alegre *et al.* 2013). The approach developed envisages the strategic, tactical and operational planning of urban water systems, including their rehabilitation and/or redesign needs and prioritization. The methodologies, criteria and software, available at www.aware-p.org, support the state-of-the art identification and quantifiable programming of actions towards IAM objectives, which comprehend WSN adaptation to climate change.

2.5 Overview of guidelines for adaptive maintenance

Maintenance has a crucial role in keeping WSN integrity and condition, in order that these can be operated so as to meet the required performance and serviceability. Such role is, however, hindered by the age and deterioration state of many WSN infrastructures, particularly buried pipelines, which generally constitute their largest and most critical part. In addition such circumstances tend to aggravate with time at rates that are increased by climate change effects. Therefore, WSN maintenance and long-term planning is of great and growing importance, particularly in the context of WSN adaption to on-going climate changes.

Available scenarios predict differences in climate change effects among regions. However, different effects may have similar impacts on WSN. That is the case of failures in WSN pipes and infrastructure integrity, which may arise or be intensified by a variety of climate change effects such as:

- Dislodgment of pipeline bedding and/or above ground infrastructure foundations due to soil settlement may result from low soil stability due to consolidation loss under drying during drought or because of water table lowering. Expansive soil differential settling may also arise with water infiltration due to flooding or water table elevation, which may be caused by the rise in sea level.
- Weakening of pipe wall and fitting strength, and pipe fissuring and breakage are enhanced by temperature driven increments in internal/external corrosion rates and/or by wear due to excessive pressure that may be induced operationally by limited capacity during peak demands, in hot and/or drought periods.
- Equipment malfunction, failure and deficient sealing are likely to increase in frequency as a direct consequence of warming or indirectly due to more intense and prolonged work periods.

As regards WSN water quality and safety as driven by in-pipe processes (i.e. microbial regrowth and deposit build-up), climate change effects will have mostly adverse impacts related to, although not exclusively:

- Microbial regrowth, potentially leading to degradation of water quality and safety, will mainly depend on the bio-stability of the water delivered by water treatment plants. However, as detailed in Menaia and Mesquita (2013), growth rates of biofilm and planktonic microorganisms will be enhanced by temperature increases along with lowered effectiveness of disinfectant residual, as its decay will be enhanced by temperature rises and, in many cases, by water NOM increments, as well as by corrosion and deposits accumulation (Monteiro and Menaia, 2013).

- Deposit accumulation may be a cause of degradation of the water's microbiological quality and, upon re-suspension, may impart turbidity, colour, taste and/or odour (e.g. discolouration). Deposit accumulation will be counteracted in WSN where high flow velocities (self-cleaning velocities) occur (Vreeburg and Boxall, 2007) more often due to demand increases during hot and dry weather periods. However, this will not be the rule, as in distribution sectors the pipe diameters are often oversized (by comparison to what would be required by human consumption) in order to respond to firefighting demands. Instead, higher accumulation of deposits may be expected for most of the cases, since increases in WSN water particle levels are foreseen due to enhanced biofilm growth and pipe corrosion and/or wearing (Poças *et al.*, 2013), as well as increases in treated water particle loads in many WSN.

In addition to water losses and the associated increments in treatment costs and environmental impacts that arise with the need to treat more water, pipe breakages are also potential points of entry for WSN water contamination, which may have public health significance. On the other hand, apart from lowering consumers' confidence and trust, whenever recurrent accumulation of deposits takes place, these can be continuous sources for the microbial contamination of WSN water.

Therefore, retaining the integrity and condition of WSN, as well as their equipment and hydraulic capacity, is important for WSN maintenance, particularly when referring to adaptation to climate changes. In this context, the adaptive role of maintenance also encompasses the creation of conditions for optimized WSN operation allowing for the minimization of pipe breakages, water losses and degradation of the water quality and safety. Adequate pressure management and the reduction of the occurrence of low, stagnant or tidal flows, along with decreasing water travelling times, are measures that contribute to achieving those objectives.

In addition to immediate needs for corrective maintenance to repair detected or reported failures or malfunctions, preventive and/or predictive maintenance planning, scheduling and implementation are essential to reduce the overall maintenance needs, at the same time that long-lasting WSN performance and economy are sustained. Such planning and scheduling rely on data and information through top-down and/or bottom-up approaches for the characterisation of WSN components condition and vulnerability.

For facilities and equipment above ground, such data and information can be easily obtained through direct inspection. While technologies (e.g. video inspection, resonance pipe scanners) are available to assess the condition of buried pipelines through proactive leak detection surveys, the direct inspection of whole WSN buried infrastructure is often hardly practicable given the dimension and complexity of most WSN.

Unless made evident by the surfacing of water or moisture, localisable pressure or flow drops, or water quality monitoring data (e.g. abnormal decay of disinfectant residual, microbial contents and/or turbidity increases) most pipe failures can remain undiscovered. The integrity of WSN pipelines – commonly at the DMA level - may be assessed though the implementation of water losses assessment and control programs (Alegre and Covas, 2010; USEPA 2010,), which may then be complemented with proactive leak detection surveys to localise pipe breakages, whose frequency is likely to increase with climate change.

Likewise, in-pipe processes are often difficult to track. So, dedicated monitoring of water quality and analysis of consumer complaints, particularly for the most critical WSN parts (e.g., low or no-flow zones, corroding iron pipes) are advisable. Abnormally high microbial numbers in WSN water may indicate intense biofilm (re)growth. Tap water discolouration events, which are one of the leading causes of consumer complaints, often are useful signs of deposit build up. Programmed surveys on deposit accumulation intensity and rates – for instance through re-suspension potential method (RPM) exercises – can provide data on WSN pipes deposit accumulation condition and susceptibility (Alegre et al., 2010).

Thorough, fundamental data and information to support the defining of maintenance needs and programming long-term WSN proactive maintenance can be obtained from:

- detected and/or reported failures and malfunctions;
- WSN hydraulic integrity analysis;
- implementation of programs for losses assessment and control;
- development of leak detection surveys;
- water quality monitoring;
- consumer complaints;
- inspections of above ground facilities and equipment;
- updated forecasts on local climate changes and impacts; and
- projected water demand trends as driven by population growth/decrease or relocation and climate change forcing.

While the corrective maintenance capacity, including the prompt response to emergency situations, is important to ensure WSN day-to-day operation and performance, the WSN's flexibility and resilience required for sustainable adaptation to climate change can only be properly achieved through long-term predictive systematic maintenance. In addition to reducing needs and costs for corrective and emergency maintenance, it allows for the identification of the most effective and economic options for WSN rehabilitation.

In locations where temperature changes and/or drought, as well as population and/or industry relocation have the potential to significantly alter water demands, redesigning the system's overall masterplan may be needed for adaptation. Then, it may be necessary to adjust, re-locate or redistribute storage and/or pipeline capacity, which may consequently impact pumping arrangements and energy consumption.

Accordingly and given the magnitude of involved efforts and costs, WSN adaptation to climate changes will be more effectively and sustainably attained if approached within the overall infrastructure IAM framework planning.

Useful criteria, methodologies and tools to support decisions on WSN rehabilitation strategic planning design and implementation were developed in the CARE-W project and can be found in Saegrov (2005).

More recently, the AWARE-P IAM planning methodology and open-source software were developed and made available (www.aware-p.org) for urban water utilities (Alegre *et al.*, 2013). These are of particular usefulness to the planning of proactive/predictive maintenance for WSN adaptation to climate changes.

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3 Maintenance of wastewater systems

Stian Bruaset

3.1 Climate change impact and challenges

Studies (e.g. Frei *et al.*, 2006) indicate an increase of extreme precipitation events for Europe due to climate change effects. Large parts of North-West Europe are expected to have increased intense precipitation events due to climate change associated with the A2 and B2 emission scenarios.

Increased rainfall intensity and unfavourable runoff conditions (large city impervious areas) will be the cause of more frequent and longer periods of operation of Combined Sewer Overflows (CSO) in combined systems. For CSO there is a strong non-linear relationship between increase of precipitation intensity and discharge quantities (Vevatne *et al.*, 2007). If no measures are taken against this, some studies indicate that discharges from CSO might double during the next 50 years (Madsen, 2007; Semadeni-Davies *et al.*, 2006).

Average temperature increase will also affect the wastewater systems, with the possible effects of increased odour and corrosion problems. Temperature increase together with changed precipitation patterns will lead to periods of drought, especially in southern Europe. After periods of drought, events of heavy rain will lead to large runoff and flooding, which can possibly increase due to dry grounds. A reduced ground water table can cause land subsidence, which will have structural effects in the wastewater pipes. Problems in wastewater pipes in hot climate areas might therefore be an effect of droughts and increased temperature (Ugarelli *et al.*, 2010).

Sea level rise is expected at different magnitudes throughout Europe. The expected magnitude of the sea level rise and the elevation of the existing wastewater systems and their CSOs will be determinant on how much the systems will be affected. Intrusion of sea water through CSOs is a major concern for many municipalities. This will lead to fuller wastewater systems, treatment of waters with increased salinity, acceleration of assets deterioration, backflow of wastewater into the networks, and increased flooding on public areas and in basements.

Frequent changes during the winter season between periods of frost and mild temperatures will lead to heavy rain falling on frozen ground when there is no possibility for surface water to infiltrate into the ground. In addition, melted snow will contribute to extended amounts of water on the ground. All the water will run off the ground and many times exceeds the capacity of the combined wastewater networks (Vevatne *et al.*, 2007). Most of the existing combined wastewater systems cannot handle these amounts of water which will result in surcharged systems, risk of flooding, increased frequency of CSO operation and large amounts of wastewater discharges to surrounding areas and water courses.

The combined effects of more extreme precipitation events and more frequent freeze/thaw cycles and general snow melting during winter will increase the hydraulic load on the wastewater systems, consequently causing higher load on the existing CSOs and wastewater treatment plants (WWTPs). If these effects are not counteracted they will cause more effluent discharge of untreated wastewater through CSOs. The hydraulic detention time of wastewater in WWTPs may also be reduced drastically during such incidents. Other problems in the wastewater networks include deterioration of the pipes and a possibility of more frequent sewer blockages due to a higher number of pipe breaks and generally more strain on the system caused by climate change (temperature and water quantity changes) and urbanisation (water quantity increase). All these problems generally result in a higher potential to increase untreated discharges through CSOs and from WWTPs.

Adaptation strategies and measures in order to mitigate the impact of the intensified and increased rainfall, increased snow melting and sea level rise must therefore be evaluated and implemented. Such measures and strategies should include existing and well-proven methods and technologies for operation and maintenance of the wastewater network and the CSOs in order to reduce discharge through CSO and the impact on WWTPs. The purpose of operation and maintenance (O&M) is to ensure the design functionality and to restore the system components to the suitable working condition after events like extreme weather episodes. The proper O&M practices depend greatly on site conditions and design of the system.

The following chapters will identify existing well-proven strategies, technologies and methods for maintenance, which can be implemented in wastewater systems for the purpose of reducing climate change impacts. Focus will be on maintenance. Outputs from other PREPARED deliverables were used as input (Bruaset *et al.*, 2012).

The main climate change threats for the wastewater (sanitary and combined) systems are (Howe *et al.*, 2005; Bates *et al.*, 2008; Howard and Bartram, 2010; Berggren *et al.*, 2008):

- Increased potential for corrosion and odours caused in the sewerage network as a result of increased sewage concentrations associated with flow reduction due to water efficient uses, increasing ambient and seasonal temperatures, and longer travel times within the sewer network.
- Increased number of incidents of sewer overflows due to increased rainfall intensity during storms.
- Uncontrolled surcharges may introduce microbial and chemical pollutants to water resources that are difficult to handle through the use of conventional drinking water treatment processes.
- Increased risk of pipe failure and collapse due to dry soil conditions.
- Rising groundwater may increase ingress of water into sewers, affecting treatment capacity, and may make any contamination that leaks out more mobile.

- Increased salinity levels in wastewater due to rising seawater levels resulting in increased infiltration and inflow (through CSOs) to sewerage network and at WWTPs.
- The combination of sanitary wastewater and stormwater makes the combined sewer systems particularly vulnerable to storms and extreme rainfall events, because once the input exceeds a certain value, the wastewater in excess is discharged untreated into the environment through the combined sewer overflows, contributing to increased contamination of surface water.
- In combined sewer systems storms and extreme rainfall events generate runoff volume inputs that may exceed the system capacity, either of the inlets or sewers. In these cases, stormwater runoff in excess may accumulate in the catchment surfaces originating high depths of flooding or high velocity runoff in case of high slopes, causing injuries to public, damages to property, disturbances in services and activities (Almeida *et al.*, 2013). This may be aggravated in coastal systems by sea level rise.
- Serious consequences also arise when sewers overflow into houses (basement flooding) and other built up areas, leading to major disruption of services, severe damage to buildings, and immediately threatening the health of the population exposed to the floods. After the floods have receded, the contamination of household furnishings and fabrics may continue to represent a health risk for the occupants for a considerable length of time.
- In addition to sewer overflows occurring during floods, sewer systems and surrounding infrastructure can suffer structural damage if the flood strength causes land movement or erosion around buried sewer pipes, or if sewer pipes above ground are washed away by the flood waters. Structural damage to the sewers may also occur as a result of differential ground settlement, which can occur after floods or heavy rainfall, or during periods of drought.
- In many coastal areas, sewer outfalls discharge into the sea, either as short or long sea outfalls. As it is expected that sea levels will rise in the future, water levels in the sewers may increase as a response. Sea water flows back into the wastewater network through existing CSOs and outfalls, causing backwater effects and thus flooding through manholes in roads, streets and in basement of homes and buildings. These effects will be aggravated in cases where the system is subject to the joint effect of rainfall and tide (Latona *et al.*, 2012).

As listed above, increased frequency of sewer overflows and flooding will be caused by intensified precipitation events and reduced capacity in the storm/sewer networks. These effects of climate change should determine the choice of rehabilitation methods for the storm/sewer pipes. Due to capacity problems in the systems, there will be a need to utilize all potential capacity already installed in the networks. Some rehabilitation methods introduce more capacity in the pipes than other methods after rehabilitation, for instance full replacement, e.g. using pipe bursting. These methods might therefore be used more often in the future.

3.2 Adaptation measures

In general, operation can be regarded as actions taken in the course of normal functioning of drain and sewer systems (CEN, 2008), while maintenance is routine work undertaken to ensure the continuing performance and serviceability of the wastewater systems.

Maintenance includes work both on a management level and on an operational/technical level, i.e. on-site work.

Following EN752, the maintenance plan details the maintenance policies and schedules for each component of the system and should include the following:

- *Type of maintenance strategy* to be used in each component of the system and the monitoring, requirements and frequencies. The strategies for maintaining drain and sewer systems are planned or reactive maintenance, or a combination of both:
  - *Planned maintenance* includes a programme of work to remedy the defects and problems identified during inspection. It is particularly required to reduce the incidence of failure where the consequences are severe
  - *Reactive (or crisis) maintenance* involves responding to failures and problems as they are identified. It is appropriate for those parts of the system that can function with little or no maintenance
- *Risk assessment,* taking into account the probability of failures and their consequences.

At the management level of adaptation measures, the planning, both on short- and long-term, is an important aspect. Within planning it is important to take climate change effects, both present and future, into account. At the same time, state-of-the-art methods must be applied so that utilities can optimise their maintenance planning and implementation.

3.2.1 Hydraulic models

Hydraulic models for sewer systems are currently not as much used for O&M purposes as hydraulic models are for drinking water systems. However, in utilities with enough resources to build and maintain wastewater hydraulic models, they do exist and are used to plan O&M activities. Many different commercial hydraulic models exist, both for purchase and as freeware. A long range of analytic tools for sewer networks do also exist, which are tools that can use data from GIS systems and hydraulic tools in order to provide, among other things, condition forecasting, calculate performance indicators, make a long term plan for the whole system, analyse infiltration and exfiltration of the sewer pipe network or calculate probability for blockages or corrosion of the pipes. Common to all of these analytical tools is the use as basis for decisions on operation and maintenance, since hydraulic models have great potential to simulate systems behaviour for different defined scenarios.

Hydraulic models for wastewater systems can be used for:

- Analysis of CSO operation. The analysis can show the frequency and duration different CSO's are in operation as well as pollutant emission from them.
- Analysis of probability of backflow of water in the sewer pipes causing flooding in basements or on the urban surfaces.
- Analysis of backwater effects caused by tide in the sewer pipes, namely in flooding in basements or on the urban surfaces.
- Analysis of the combined networks hydraulic capacity and performance for different rainfall return periods.

3.2.2 CARE-S and AWARE-P

The CARE-S project (Computer Aided Rehabilitation of Sewer Systems) (Saegrov, 2006; http://www.sintef.no/care-s) developed a comprehensive suite of tools as support to rehabilitation planning of wastewater networks. AWARE-P has further developed an infrastructure asset management planning method supported by a planning software (Coelho *et al.*, 2013; baseform.org) which makes available on an advanced technology platform the best tools for visualizing, diagnosing and evaluating any given water supply or wastewater system, through a portfolio of performance, risk and cost models, at global and detailed levels. It enables the assessment and comparison of any number of alternative intervention solutions, using standardized methods that facilitate informed decision-making (Alegre *et al.*, 2013).

Many tools from CARE-S can be used to rank candidate pipes for inspection and condition assessment (through inspection), prior to identifying and prioritizing rehabilitation candidates. Multi-criteria decision support and socio-economic consequences are used to rank pipes for rehabilitation. The tools of CARE-S include (Saegrov, 2006):

- *Performance Indicators tool*: supports the performance assessment of sewer systems, providing the calculation, storage, update, retrieval and analysis facilities of a control panel of 41 performance indicators for rehabilitation.
- *Blockage tool*: helps the user to assess the probability of sewer blockages and root penetration, thus identifying pipes prone to cause blockages. The tool analyses a set of blockage- and attribute data and calculates the factors used to determine blockage probability.
- *Load model*: is a program for gravity sewer pipes that calculates stress values in rigid non-reinforced concrete pipes based on external loads and pipe characteristics. A pipe will structurally collapse when its resistance gets lower than the stress inducing external and internal loads. The resistance is based on pipe material, diameter and wall thickness. The model will identify vulnerable pipes that can be used in planning maintenance on the combined sewer network.
- *Degradation tool*: uses all the available CCTV information and the pipe characteristics data as input. The model assesses how the pipe condition affects the hydraulic performance of the pipe and calculates a new roughness coefficient for pipes depending on the specific level

of degradation. This tool helps to improve hydraulic models used in the maintenance planning.

- *GompitZ*: investigates structural condition and predicts the future condition classes of sewer pipes by defining the relationship between the current state and the expected service time of sewer pipes using input from CCTV inspections. The tool is based on a Non-Homogeneous Markov Chain (NHMC) statistical approach which is used to model the structural degradation process of sewer pipes. Results are mostly used in the rehabilitation planning of wastewater networks.
- *Corrosion*: three different models are used to investigate internal and external risk of corrosion:
  - ExtCorr: calculates external corrosion on concrete pipes based on moisture grade, soil type and pipe characteristics.
  - WATS: calculates internal corrosion by simulating hydrogen sulfide induced microbial corrosion of concrete sewers by a conceptual approach. All relevant processes in the sewer are addressed.
  - Z model: calculates internal corrosion by estimating hydrogen sulfide induced microbial corrosion of concrete sewers by a risk assessment approach.

The different approaches can be used to identify vulnerable pipes, which will be relevant for more comprehensive inspection and further maintenance measures.

- *Infiltration/exfiltration (IE) tool*: is a system for the calculation of exfiltration of sewage and infiltration of ground water to the sewer network. The results can be used in assessing necessary future maintenance measures, both in terms of quantity and geography
- *Combined Sewer Overflow Assessment Tool (CAT)*: is a software tool to assess the performance of combined sewer overflows (CSO). The tool compares results from hydraulic simulations to user defined standard values for a given number of years. The results can be used to identify needs and decide optimal maintenance measures
- *RehabDB*: is a rehabilitation database with all existing rehabilitation methods. It was created to help utilities in rehabilitating pipes with the right kind of technology. The tool helps to choose correct rehabilitation method for each single event, which is important in maintenance performance
- *LTP (Long Term Planning)*: The LTP tool can be applied on both water- and wastewater systems and is a tool which forecasts long-term (up to 50 years or more) rehabilitation needs of the pipe networks. LTP calculates residual lifetime and then the minimum necessary annual rehabilitation need of cohorts of pipes (given in km/year per cohort). All the pipes in a network are split into cohorts which are based on groups of pipes which have similar pattern of ageing, meaning they are likely to have about the same expected lifetime. One cohort can for example be ductile iron pipes with diameter up to 200 mm. Another

cohort can be ductile iron pipes with diameter of 200 mm or more. The network can be split into about 5-10 cohorts, depending on how many different materials *etc.* which are involved.

In addition to annual rehabilitation needs, the annual necessary investment for each cohort can be analysed. The financial numbers are based on input data for the cost of rehabilitation. The investment plan can be a basis for the rehabilitation program, with annual investment and rehabilitation plans for the next 5-50 years, and help managers to increase funding if necessary.

The program is thus relevant both for taking height of increased need of rehabilitation and increased investment needs in the future due to climate change. The program is therefore important for improved maintenance on a long-term basis.

AWARE-P provides a coherent set of user-configurable assessment models related to performance, cost and risk, which are used to evaluate user-defined alternative system, configurations or planning solutions. These are tools to support decision-making for planning rehabilitation in the long, medium and short terms. The tools The tools plug into the integrated environment of AWARE-P include (Coelho *et al.*, 2013):

- *PI* – An objective-driven environment for selection and calculation of performance indicators (PI), a quantitative assessment of the efficiency or effectiveness of a system, based on standardized, reference PI libraries as well as user-developed or customized ones. Available libraries include the IWA water supply and wastewater PI libraries.
- *FAIL* – Using statistical models such as Poisson and LEYP, the failure analysis tool predicts future pipe/sewer failures for a given network, e.g. in the context of estimating risk or cost metrics. The analysis requires a failure data file, containing a historical record of pipe failure events (e.g., from work orders) and the corresponding complete inventory of pipes.
- *IVI* – Infrastructure Value Index, representing the ageing degree of an infrastructure, calculated through the ratio between the current value and the replacement value of the infrastructure.
- *FIN* – Financial project planning tool with the capability to project investments, costs and revenues over a user-defined period of time and calculate NPV and IRR.

Climate factor

When dealing with improved and optimised maintenance with regards to climate change and the accompanying effects thereof, one must take into account how these will affect the wastewater systems in the long term. If not done properly, the maintenance applied today may not be in line with what is needed in the future, say perhaps in a 50 years time.

To make the use of the CARE-S tools relevant for the future it is necessary to identify how the climate change effects can be implemented in the tools. The future expected climate changes can therefore be implemented within the CARE-S tools to take into account the effects that can be expected.

The lifetime distribution and S-curves applied in the LTP tool must be adjusted according to the expected reduction in lifetime for cohorts of pipes. The expected reduction in lifetime can be expressed through a *lifetime climate factor* given in expected percentage of lifetime reduction, and should be considered individually for each cohort group in different climate regions of the world. The effects of climate change will vary depending on climate region and type of pipes (material, diameter, age, soil conditions *etc.*).

Utilities which desire to keep a certain level of service must expect a percentage of increase or decrease of value in certain performance indicators (PIs) like pipe failures, water infiltration and exfiltration *etc.* due to climate change. This percentage of increase can be called a *PI climate factor*, and should be implemented for the PIs. Utilities should have a list of the PIs today and the PIs today with climate factor included. The utilities should then measure their level of performance against the PIs with implemented climate factor so that they can reach their goals for performance when the effects of climate change start to affect their sewer system.

In a similar manner, a climate factor can be implemented in all of the CARE-S tools. A climate factor can be part of all future maintenance planning, not just within the CARE-S tools. A climate factor should be included in rehabilitation or maintenance planning, for example to be taken into account when deciding the necessary future rehabilitation rate of a utility.

An example of how this can be applied is when deciding the annual rehabilitation rate of a group of pipes or the whole network. The annual rehabilitation rate of a network is for example set to be 1.1% renewal per year. By scoping the future prospect of the network with regards to climate change it is decided that the future deterioration rate of the network is expected to increase by 5% every 10 years. The rehabilitation rate will therefore be set to:

- in 2024: 1.1% * 1.05 = 1.155%
- in 2034: 1.155% * 1.05 = 1.213%
- in 2044: 1.213% * 1.05 = 1.274%
- *etc.*

3.3 Adaptive maintenance measures

3.3.1 The PREPARED O&M database

The PREPARED 5.5.1 (Bruaset *et al.*, 2012) report lists most of the relevant operation and maintenance methods, including rehabilitation techniques and methods for repair of wastewater pipes. The Deliverable 5.5.1 consists of the report and a supplemental O&M database. The O&M database was created to couple climate change effects to relevant operation and maintenance methods. See chapter §5 and 8.3 of Deliverable 5.5.1 for extensive information on and description of maintenance methods.

Rehabilitation and repair can include the following methods/descriptions:

- Rehabilitation:
    - Includes all methods relevant for improving the performance of a pipe, both structurally and hydraulically.

- Changing of the pipes by digging and laying new pipes in the ground.
- Renovation – includes all methods which use the existing pipe to improve its performance by installation measures.
- No-dig – renovation techniques where there is little to no need of digging to improve the performance of the existing pipe.
- Some rehabilitation methods are either not using the strength of the existing pipe or are based on digging. These methods are changing the old pipe in the ground with a new one with no-dig solutions. These methods include controlled drilling and pipe bursting. With these methods, the diameter of the pipe can also be increased.

- Repair:
  - Repairing cracks, holes and other defects in the pipes
  - Removing roots and other physical obstacles in the pipes with mechanical methods.

For improved and optimal operation and maintenance it is suggested to use the CARE-S RehabDB described in 3.2.2 with the D.5.5.1 O&M database. The 5.5.1 O&M database is designed to help utilities choose the optimal maintenance methods and technologies with regards to specific problems caused by climate change effects. Information about the method/technology and how well it applies to tackle certain climate change effects is included in the database. Each method/technology is assessed as either not suitable, conditionally suitable or suitable for responding to expected climate change effects on wastewater systems (see Figure 4), which were identified in D2.2.1 (Ugarelli *et al.*, 2010).

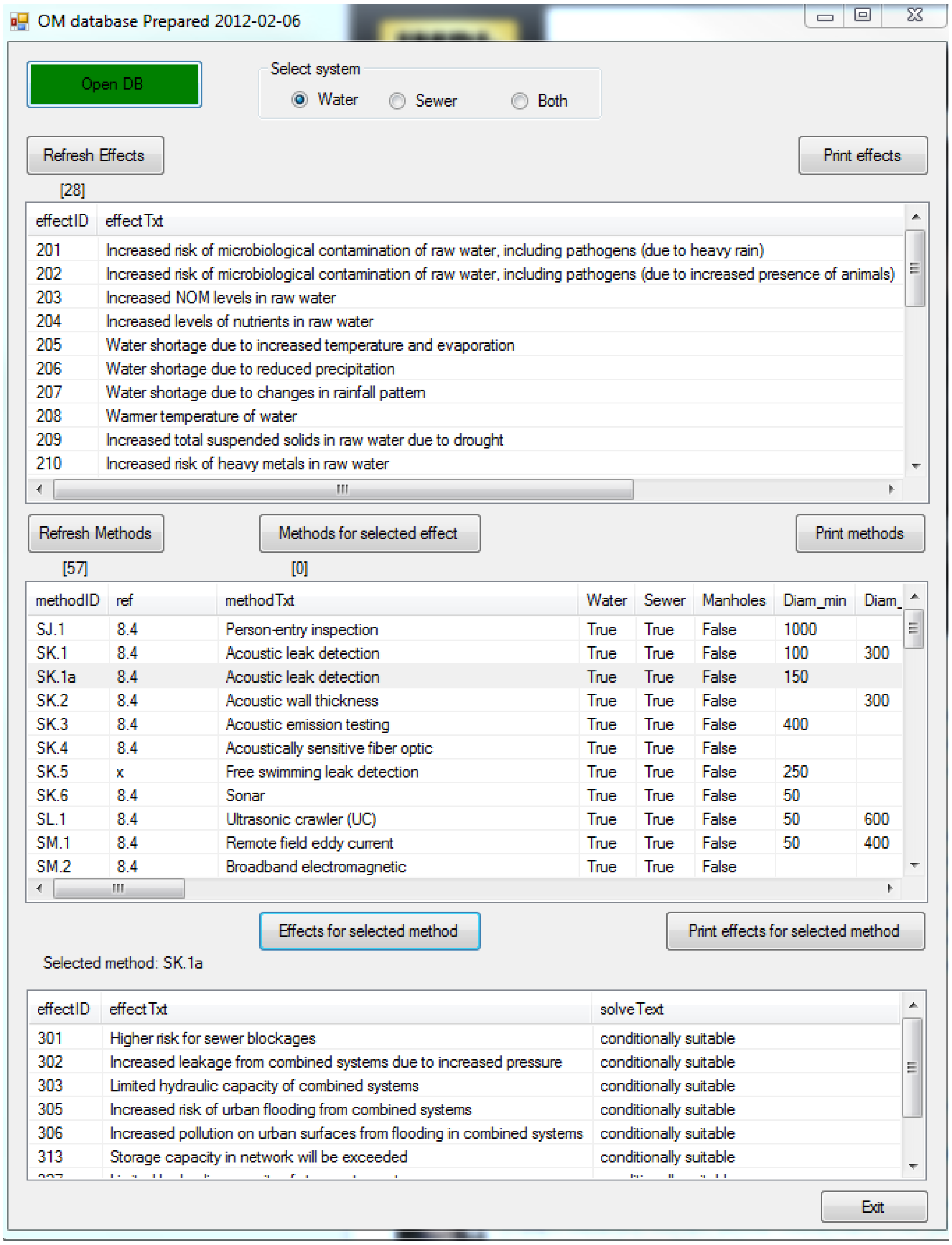

Figure 4. Snapshot of the D5.5.1 O&M database

Figure 4 shows the D.5.5.1 O&M database with its content. The database can help to identify suitable maintenance methods for specific climate change effects, and it can help to identify which climate change effects each of the listed maintenance methods can help to reduce.

The database includes more thorough information about each of the maintenance methods, including their limitations. For more thorough information about the climate change effects, see PREPARED Deliverable 2.2.1 (Ugareli *et al.*, 2010).

3.3.2 *Surveillance of pipe condition*

Surveillance of pipe condition is both an operational part and a management part of maintenance. The operational part includes applying different methods in or on the wastewater pipes to monitor and/or inspect the pipe. The condition found from the inspection/monitoring is transferred and stored in a management system. The management part includes using this data to plan future rehabilitation measures.

The different surveillance methodologies are briefly described here to give an overview of the possibilities. The methodologies and their respective technologies are more thoroughly described in Deliverable 5.5.1, chapter §8.5 (Bruaset *et al.*, 2012).

The D5.5.1 O&M database gives an indication on which surveillance technology is relevant for coping with the effects of climate change, explaining how it helps to reduce the effects of climate change on pipe conditions or not.

In surveilling the pipe condition, results are made available to support proactive maintenance through rehabilitation planning and implementation. CCTV inspections can for example be applied in the CARE-S *GompitZ* program to predict future condition classes of wastewater pipes. The positive aspects of applying surveillance technologies of the pipes (and making use of the results in proactive O&M and rehabilitation) are multiple:

- the condition of the systems will be better due to a proactive approach to rehabilitation;
- the networks will be better suited to handle rapid changes due to climate change;
- the networks will be more resilient and be able to faster restore the original functionality of the systems after extreme events due to the better state of the system, if rehabilitation planning takes the surveillance into account.

The different methodologies of surveillance include:

- *Acoustic technologies*: use measuring devices to detect vibrations and/or sound waves. In pipeline assessment, acoustic sensors are used to detect signals emitted by defects.
- *Electromagnetic inspection:* electrical/electromagnetic currents are the basis of several sewer evaluation technologies: the electrical leak location method - to detect leaks in surcharged non-ferrous pipes; Eddy Current Testing (ECT) and Remote Field Eddy Current (RFEC) - to identify defects in ferrous pipes; Remote Field Transformer Coupling (RFTC) - PCCP condition assessment; Magnetic Flux Leakage (MFL) inspection - to measure metal loss and detect cracks in ferrous pipelines.
- *Laser inspection/ Laser Profiling (LP)*: as a sonar technology laser systems are used to create an interior profile of the pipeline. Whereas sonar is used for data receiving below the water surface, laser is used in the atmosphere above the waterline. Frequently data of these two systems are combined for receiving the whole image of the interior of

pipes. Lasers can be either 2-D or 3-D depending on the level of detail required. A typical 2-D laser profile will provide an indication of the pipe ovality above the waterline as well as gross defects in the pipe wall. Fine defects such as cracks will not be apparent. The value of both sonar and laser profiles is that they provide clear evidence of pipe ovality where the human eye is easily fooled using CCTV alone.

- *Multi-sensor systems inspection*: innovative methods based on the new technologies are currently being developed for the evaluation and assessment of sewer collection systems by the use of multi-sensors. Many companies propose now the multi-sensor systems, which combine the best options of different technologies and create additional advantages with possibilities to use one inspection procedure to analyse pipe conditions over and under water line.
- *Person-entry inspection*: the main advantage of a person-entry inspection is that it is easy and fast. The inspector can get first-hand information about internal pipe conditions that is harder to obtain other methods. Video records or photographs, guided directly by the inspector, can be used to supplement and document the inspector's findings. Measurements and samples can be taken on the spot. However, inspection can be less objective than for example multi-sensor system inspection and can only be done in large diameter pipes.
- *Smoke and dye testing*: is a technique used in Australia and America. It is less applicable in European sewers, as all connections must be known prior to test (Eiswirth *et al.*, 2001). Smoke testing may be used to test new construction, pipeline rehabilitation or reconstruction projects. Using an air blower, a nontoxic, non-staining "smoke" (typically a zinc chloride mist) is forced through a manhole. The smoke then surfaces through open pipe connections and defects.
- *Visual inspection*: provides visual data on leaks, blockages, location of service laterals and sediment, and debris accumulation. This type of inspection includes CCTV technology, a well-known and widely used method, which practically is a standard for comparison for other methods and technologies.
- *CCTV inspections*: closed circuit TV (CCTV) inspections with video camera are often used to assess of the condition of the system internally.

The observations can be sorted with respect to different levels of structural and operational defects, in pipes and manholes. For example, according to the European Standard EN13508 (CEN 2011):

- Structural:
    - cracks and fractures
    - deformation
    - displaced joints
    - defective connections

- roots, infiltration, settled deposits, attached deposits, other obstacles
- subsidence
- defects in manholes and inspection chambers
- mechanical damage or chemical attack

▪ Operational:
- blockages in drains, sewers, pumps, valves and their effects
- incidents resulting from the complete structural failure of components of the system (e.g. sewer collapse rising mains burst) and their effects
- failures of mechanical and electrical equipment (e.g. pumping stations) and their effects
- failure of other ancillary equipment e.g. non-return valves, flow control devices
- pollution incidents

Each defect is given a grade and a condition grade is given to each pipe as the end result. Pipes can be prioritised for rehabilitation based on the condition grades, thus being used for planning maintenance. These types of data are stored in the internal management system of the utility and can be used to monitor and assess the quality of the sewer networks over time. In the analytical tool GompitZ (see 3.2.2), which is part of the CARE-S toolkit, the data from CCTV inspections is used to predict future condition grades and classes on all pipes in a wastewater network.

3.4 Overview of technical guidelines for adaptation

The improved guidelines given in this chapter on maintenance of wastewater networks essentially arise from applying state-of-the-art maintenance at both levels - management and operational - in all three types of O&M; corrective (reactive), preventive (proactive) and predictive (proactive). No new methods are specifically discussed here, but the profits are found in the holistic thinking and in applying the correct technology for different problems by using results from PREPARED Deliverables 2.2.1 (Ugarelli *et al.*, 2010) and 5.5.1 (Bruaset *et al.*, 2012).

Investigation of the potential implications of climate change scenarios overlaid on expected long-term changes in population and demographics and subsequent sewage flows suggest that gradual climate changes could be more readily adapted to than rapid shifts in climate. Strategies to assist the sewerage systems in adapting to climate change need to be consistent with normal planning practices and include (Howe et *al.*, 2005):

▪ Maintenance measures to reduce peak flows in wet weather:
- Increased indoor demand management activities that lower sewage flows and reduce overflow risk.
- Routine and periodic review of sewerage system strategies and operations.
- Local treatment to reduce network loading during peak flows.

- On-going review of strategies to address hydraulic constraints and overflow risks.
- Increase storage capacity within system.
- Limit expansion and/or connections to parts of the system where there are potential capacity constraints.
- Review strategies for emergency relief of structure operations.
- Monitoring and maintenance of sewer systems to reduce infiltration.
- System rehabilitation, where rehabilitation technologies should focus on full replacement of pipes and/or pipe bursting where full capacity of pipes are needed to respond to short term heavy rain incidents.
- Shut-off valves, which can prevent back-flow (in some developing countries these have not generally been installed).
- Deep tunnel conveyance and storage systems designed to intercept and store the combined sewer overflow water until it can be conveyed to wastewater treatment works.
- Separate systems for transporting stormwater and sanitary wastewater can be introduced as a replacement for ageing combined sewer systems or as a new development.
- Re-engineering parts of sewer system to provide additional storage for stormwater.
- Inflow controls:
    - Introduction of special gratings and restricted outflow pipes
    - Use of so called “green infrastructure” to capture runoff and retain it before it reaches the sewer system.

▪ Measures to manage sewage quality:
    - Lining of concrete sewers to avoid “corrosion” by sulphuric acid producing microbes.
    - Routine monitoring of trends in sewage quality, quantity and temperature.
    - Maintain or increase sewer rehabilitation and cleaning frequencies.
    - Examine potential for oxygen injection for odour control to mitigate effects of water temperature rises.
    - Small-scale systems for treating stormwater.
    - Managed reed beds used effectively as both a sink and a treatment system for combined sewer overflows.

▪ Other measures:
    - Increase levee bank height along WWTPs’ lagoons to provide buffer against sea level rises
    - Encourage cluster systems and local treatment to aid recycling options

- Seek long term improvements to sewage water quality to reduce salts, nutrients and other pollutants which will assist recycled water quality
- Industrial waste minimisation
- Domestic sewage quality e.g. soaps, detergents *etc.*
- Auditing of new installations
- Increase community education on sewers, effluent quality, garden plants *etc.* to assist in improving sewerage quality and infiltration
- Development of recycling schemes, including new developments, sewer-mining and opportunities for retrofits.

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4 Operation and maintenance of stormwater systems

Stian Bruaset

4.1 Climate change impact and challenges

The same climate changes which affect the wastewater systems will affect the stormwater ones, mostly in terms of intensified precipitation events, increased average temperature and periods of drought (see 3.1).

Stormwater systems in this chapter are defined as open and local systems for handling of stormwater, and underground installations independent of wastewater- and combined systems.

Rainwater collection systems are designed for, and therefore dependent on, a certain volume of rainfall. Both too high and too low volumes of water can therefore be difficult to adapt to. Climate change is expected to cause significant shifts in precipitation patterns (more precipitation during shorter periods of time), and high intensity rainfalls will constitute great challenges for the stormwater systems. In Nordic countries, expected higher temperatures can lead to more snowmelt during winter when the ground is frozen and infiltration is impossible, causing increased amounts of run-off. During winter, the drains are also often frozen, which will cause even more problems.

The main threats to stormwater systems due to climate change are:

- Increased flood risk and property damage due to increased rainfall intensity during storms.
- Increased risk of damage to stormwater infrastructure and facilities (e.g., underground drains, levee banks, pump stations *etc.*) due to higher peak flows.

4.2 Adaptation measures

As for wastewater networks, it is important to plan operation and maintenance of stormwater systems on a management and on an operational level. The renewal, maintenance, improvement and enlarging (in terms of capacity) of stormwater systems must be planned well ahead based on expected effects and challenges of climate change. This is where management of the stormwater systems plays an important role. However, since the stormwater systems are not based on a large infrastructure network under the ground on the same level as the wastewater systems, management planning is not as big a part of the maintenance when compared with wastewater systems.

Improved maintenance of stormwater systems is first and foremost about adapting the existing systems with flow improvement and self-maintaining technologies. These have potential to eliminate most problems of stormwater systems O&M. Normal problems that occur within the open stormwater systems are the accumulation of sediments and overgrowing of plants and weed. In any case, there will still be a need to manually clean the open systems for plants, weed and sediments, but an adaptation with flow improvement and self-maintaining technologies will reduce this need and improve the overall hydraulic capacity of the systems.

A major climate change challenge for the urban water sector is the need for reduction of runoff peak and volume, which may be achieved by implementing Sustainable Urban Drainage Systems (SUDS) and Rainwater Harvesting (RWH) (Hem, 2010). The O&M of such systems will play a major role in reducing the flood risk.

Closed stormwater systems (like detention basins below parking spots *etc.*) will normally accumulate sediments, which will be stored within the construction until it is cleaned. Detention reservoirs will function as sand traps since sand and sediments will deposit on the bottom as the stormwater flow slows down. It is therefore important that the sediments are removed with certain intervals to avoid too much sediment load in the reservoir. Reservoirs can be cleaned with the following methods:

- Flushing with hose;
- Put in self-cleaning channel at the bottom;
- Mechanical cleaning.

When flushing with hose, the reservoir needs to be drained for water so that flushing, preferably with high pressure, can be performed. However, if the goal is to reduce sediment load to the downstream stormwater system, the sediments should not be flushed, but rather cleaned with mechanical methods. Mechanical cleaning with suitable instruments can also be performed. For example, when the water is drained from the reservoir, suction pumps can be used to remove the deposits from the reservoir. The sediments can also be removed with manual methods like shovels, which are manageable in smaller reservoirs. A proactive arrangement in the construction is a self-cleaning channel at the bottom of the reservoir, which will direct the water flow during low-flow/low-precipitation. The directed flow will increase the flow velocity and thus facilitate the removal of deposits in the channel.

PREPARED Deliverable 5.5.1 (Bruaset *et al.*, 2012) deals with stormwater systems for flow improvement and self-maintaining systems. The appendices in the same report describe in detail the different specific technologies for each type of method. For extensive knowledge on the available technologies see D.5.5.1 and its appendices.

The O&M database of D.5.5.1 (Bruaset *et al.*, 2012) gives an indication on which of these different technologies are relevant for coping with the effects of climate change, explaining if they are able to reduce the effects or not. The primary effects of climate change on the stormwater systems will be increased precipitation, increased frequency of precipitation (a changed precipitation pattern) and increased risk of flooding. The stormwater systems will be exposed to more water over a shorter period of time, which will cause more flooding of the systems and their surroundings. Local systems will be exposed to harsher treatment from extreme weather events, which will increase the need for better and/or more frequent operation and maintenance of the systems. Increased intensity of precipitation can lead to increased erosion of surrounding areas. The resulting sediments from such erosion will go with the stormwater flow into closed or open stormwater constructions and deposit where the water flow stagnates. The time needed for re-filling of constructions and systems with sediments can therefore be reduced and lead to a higher need for self-maintaining and/or shorter time intervals for O&M.

It is important that the stormwater systems are resilient to adapt to the extreme weather events in order to avoid large flooding and destruction of property, both private and public. New stormwater systems can be designed and built more resilient, but with existing systems there is a need to maintain and increase the resilience through the best of state-of-the-art O&M technologies. O&M measures like improving the flow and facilitate self-cleaning during dry weather conditions will increase the capacity and the resilience.

4.2.1 Technologies for flow improvement

Technologies for flow improvement are meant to reduce the hydraulic load on urban wastewater systems, reduce flooding, detain stormwater and reduce pollution discharge to the recipients.

Flow improvement and self-maintaining systems can include the following methodologies (dark bullets) and technologies (white/ transparent bullets):

- Bioretentional systems:
  - Rain gardens
  - Bioretention basins
  - Swales (bioretentional swale)
  - Filter strips
  - Stormwater planters
  - Infiltration basins
  - Stream buffers (riparian/forested buffer)
- Surface collection systems
  - Wet ponds
- Underground stormwater collection systems
  - Soakaways
  - Detention systems
- Stormwater infiltration systems
  - Infiltration trenches
- Roof rainwater collection system
  - Green roof
  - Blue roof
  - Rain barrels
- Constructed stormwater wetlands

4.2.2 *Technologies to facilitate flow during dry weather conditions*

The effects of extended periods of dry weather, which may affect stormwater systems, are mainly: lack of the surface runoff, changed water table elevation, changed ground moisture, and changed character of incoming wastewater. These effects may cause some disturbances in the stormwater systems:

- Physical damages to the infrastructure
- Difficulties in sedimentation transport
- Clogging of stormwater channels and systems
- Reduced hydraulic capacity
- Accumulation of pollutants in the system

The difficulties in sedimentation transport and the reduction of hydraulic capacity are a result of reduced water flow to transport sediments, sand and pollutants on the ground and in the stormwater itself. O&M technologies to facilitate flow during dry weather condition are needed for following elements of the infrastructure:

- Rainwater collection systems
- Local (open) systems for handling of stormwater
- Closed systems for storing of stormwater

Dry weather conditions are, in combined sewers and stormwater systems, controlled by the weather. The amount of precipitation when it rains, the intensity of the rain, and snow melting controls when dry weather conditions will occur and how dry the systems will be. The effects of climate change are expected to be more intense precipitation events, longer periods of drought (depending on climate region) and more uneven distribution of precipitation which will facilitate longer and worse dry weather conditions. O&M of these systems and technologies to facilitate good flow and self-cleaning during dry weather conditions is therefore important to reduce the effects. If this is not prioritized, the systems will experience more damages, faster deterioration, increased problems with pollution and reduced hydraulic capacity. A review of technologies to facilitate flow in dry weather conditions in these elements of the sewer and stormwater infrastructure is found in the appendices of PREPARED Deliverable 5.5.1. There are described the different technologies that can be applied in order to reduce the effects of climate change, to enhance the resilience of the systems and increase the capacity and the ability of the systems to restore themselves to their design purpose after extreme incidents.

4.3 Overview of technical guidelines for adaptation

The improved guidelines given in this chapter on maintenance of stormwater networks result mostly from integrating proactive operation and maintenance methods within SUDS and RWH for flow improvement and self-maintaining systems, and also using the D.5.5.1 O&M database to identify relevant O&M methods for tackling climate change effects.

No new methods are discussed here specifically, but the profits are found in the holistic approach and in applying the correct adaptation technology, as prescribed in the PREPARED Deliverables 2.2.1 (Ugarelli *et al.*, 2010) and 5.5.1 (Bruaset *et al.*, 2012).

As in the case of wastewater systems, also the O&M procedures for stormwater systems are or should be adapted to climate change (Howe *et al.*, 2005). The adaptation strategies include:

- Routine and periodic review of waterways and strategies, flood modelling and/or drainage schemes to take account of potential climate change scenarios.
- Routine monitoring, including water quality and groundwater levels, particularly in wetlands.
- Water sensitive design in new developments to reduce runoff rates and improve water quality.
- Retain flood plains and floodways in new urban developments.
- Identify options for upstream flow attenuation for flood mitigation.
- Education to assist local waterway management and maintenance.
- Maintain programs for stream rehabilitation and stream frontage management.
- Routine review of planning and operational strategies for:
  - Drainage network at a local and system level to take into account current knowledge of potential climate change scenarios.
  - Floodgates, levees, storage and pump stations.
  - Sea level and system surge.
- Periodic review of environmental flows, drought plans, stream-flow management and water allocations and water allocation principles for managing diversions from waterways for climate change.
- Develop incentives to aid water use and allocation efficiencies.

4.4 References

Hem, L., Hafskjold, L.S., Pieras, R.M., Baban, A., Rouault, P., Raat, C. (2010) *Planning for resilient water supply and sanitation systems – State-of-the-art*. 7th FP project EU PREPARED - deliverable D5.0.1, www.prepared-fp7.eu.

Howe., C., Jones, R.N., Maheepala S., Rhodes B. (2005) *Implications of Potential Climate Change for Melbourne's Water Resources*. Melbourne Water and CSIRO Urban Water and Climate Impact Groups.

Ugarelli, R., Leitão, J.P., Almeida, M.C., Bruaset, S. (2010) *Overview of climate change effects which may impact the urban water cycle*. 7th FP project EU PREPARED - deliverable D2.2.1, www.prepared-fp7.eu.