BEST PRACTICE GUIDELINES FOR MANAGING CONTAMINATION EVENTS IN WATER DISTRIBUTION SYSTEMS

AR Mosameem, JE van Zyl and C Young

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Report

to the Water Research Commission

by

AR Mosameem, JE van Zyl and C Young

Department of Civil Engineering

University of Cape Town

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EXECUTIVE SUMMARY

The integrity of the water distribution system, as the final barrier in the multiple-barrier concept to provide safe drinking water, is essential to protecting public health. The deterioration of water quality due to the intrusion of contaminants in water distribution systems has been associated with a significant proportion of waterborne and water-related illnesses internationally. The risk of these contamination intrusion events occurring is aggravated by inappropriate planning, design and construction, as well as inadequate operation and maintenance, and water quality control. These problems are expected to be exacerbated by the increasing pressures placed on infrastructure systems, which have their origin in rapid urbanisation, continued population growth, and ageing and deteriorating infrastructure. Significant investments are often required to implement the required rehabilitation measures to ensure drinking water safety. In addition, there are practical challenges in undertaking risk assessment, risk management and investment planning. The prime objectives of this study were to establish the frequency and causes of contaminant intrusions in water distribution systems, to identify the characteristics of distribution systems that contribute to these events, and to provide guidance on best practices of water quality control in water distribution systems using the Water Safety Plan (WSP) as a framework.

The aims defined for the study are as follows:

- Conduct a literature review of the latest research on contaminant intrusion and its impact on water distribution systems.
- Identify the critical aspects of intrusion mechanisms, including driving forces, contamination paths and contaminants near pipes.
- Establish the frequency and magnitude of intrusion events and the characteristics of water distribution systems that contribute to these events.
- Develop expertise on water quality and hydraulics in water distribution systems.
- Provide guidance on best practices of water quality control in water distribution system using the WSP as a useful framework for risk assessment.

Water distribution systems receive their water from treatment plants. The quality of the water they deliver to consumers is thus firstly dependent on the quality of the water they receive from these plants. This study is limited to contaminant intrusion events occurring in distribution systems and, as such, it is assumed that the water received from the treatment plant complies with all quality requirements.

There are three prerequisites for a contaminant intrusion event to occur in a water distribution system:

- A contaminant source in the proximity of the system
- A driving force
- A pathway

Intrusions may be controlled by managing any or all of these factors. It is thus essential that water distribution managers have a solid understanding of these factors.

An extensive search was conducted to find reported case studies of contaminant intrusion events in water supply systems in South Africa, both in the published literature and at local authorities. Although South Africa has a strong framework for managing water quality in distribution systems, the search showed that there is a lack of reporting, proper investigation and documentation of contaminant intrusion events in South Africa.

Only two published contamination intrusion events could be identified: a cross-contamination event in Johannesburg, and the contraction of waterborne disease from intermittent water supply in Mbombela.

Best practice guidelines, based on the WSP approach, are recommended for the improved management of water quality in distribution systems by minimising the occurrence of contaminant intrusion events. The WSP multi-barrier approach is considered internationally and nationally (through the Blue Drop programme) to be the best way of ensuring safe drinking water from source to tap.

In summary, this study found that there is ample international literature documenting the causes and types of contaminant intrusion events. However, very few case studies are documented for South Africa. While South Africa has strong legal and institutional frameworks for managing water quality and leakages in distribution systems, including the current Blue Drop and No Drop programmes, which are based on a WSP approach, the management of contamination events is fragmented and gaps were identified. From the small number of published case studies of contaminant intrusion events in distribution systems and the lack of information on such events at different levels of government, it is clear that the existing regulations and guidelines are not adequately implemented.

A number of recommendations can be made based on this study:

- The Blue Drop and No Drop programmes are to be strengthened to improve the implementation of WSPs for preventing, responding to and reporting contaminant intrusion events.
- The different guidelines for managing water quality in distribution systems should be consolidated to make it clear what is expected from WSPs and remove any ambiguity caused by having several different documents for this purpose.
- Coordination among stakeholders in South Africa is a significant problem and should be improved.
- The current electronic water quality management system (eWQMS) should be extended to include the various components of water distribution systems, including water storage reservoirs, pumping stations and pipe networks.
- Intermittent water supply systems (water shedding) are conducive to contaminant intrusion and a threat to the water quality integrity of water distribution systems. This practice should be actively discouraged.

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Reference Group	Affiliation
Dr N Kalebaila	Water Research Commission (Chair)
Ms Lelethu Bungu	Rand Water
Dr M Kumarasamy	University of KwaZulu-Natal
Mr S Moodlar	eThekwini Water and Sanitation
Ms F Nel	Rand Water
Mr M Ncube	Development Bank of Southern Africa
Mr T Westman	City of Tshwane Metropolitan Municipality
Others	
Mr Pierre Maritz	City of Cape Town
Mr Alfred Wolfgang Moll	City of Cape Town
Ms Melissa De Sousa-Alves	City of Cape Town
Mr Motale E. Selesho	Sol Plaatje Local Municipality
Mr Richard Sengani	Phokwane Local Municipality

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ACRONYMS AND ABBREVIATIONS

AC	Asbestos cement
AOB	Ammonia-oxidising bacteria
AOC	Assimilable organic carbon
ANSI	American National Standards Institute
AWWA	American Water Works Association
BDOC	Biological dissolved organic carbon
BTEX	Benzene, toluene, ethylbenzene and xylene
CDC	Centers for Disease Control and Protection
CMA	Catchment Management Agency
CWSS	Community water supply and sanitation
DBP	Disinfectant by-product
DIC	Dissolved inorganic carbon
DLPG	Department of Provincial and Local Government
DoH	Department of Health
DORT	District Outbreak Response Team
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
DWQF	Drinking Water Quality Framework
E. coli	Escherichia coli
eWQMS	Electronic Water Quality Management System
HAAs	Haloacetic acid
HCF	Health care facility
HDPE	High-density polyethylene
HPC	Heterotrophic plate count
I-THM	Iodinated trihalomethanes
IWA	International Water Association

MCL	Maximum contaminant level
MIC	Minimum inhibitory concentration
NICD	National Institute of Communicable Disease
NOB	Nitrite-oxidixing bacteria
NOM	Natural organic matter
NRC	National Research Council
PEX	Cross-linked polyethylene
PVC	Polyvinyl chloride
SABS	South African Bureau of Standards
SANS	South African National Standard
TCR	Total Coliform Rule
TDS	Total dissolved solids
THMs	Trihalomethanes
UCT	University of Cape Town
UPC	Uniform Plumbing Code
USEPA	The US Environmental Protection Agency
VOC	Volatile organic compound
VOSC	Volatile organic sulphur compound
WHO	World Health Organization
WISA	Water Institute of Southern Africa
WRC	Water Research Commission
WSA	Water Service Authority
WSDS	Water Supply Distribution System
WRF	Water Research Foundation
WSP	Water Safety Plan
WSP	Water Service Provider

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

The integrity of the water distribution system, as the final barrier in the multiple-barrier concept for providing safe drinking water, is essential to protecting public health. The deterioration of water quality due to the intrusion of contaminants in water distribution systems has been associated with a significant proportion of waterborne and water-related illnesses internationally. The risk of these contamination intrusion events occurring is aggravated by inappropriate planning, design and construction, as well as inadequate operation and maintenance, and water quality control.

Deficiencies in the integrity of the water distribution system can lead to water loss, but can also result in the entry of contaminants either through pipes walls or through breaks coming from external subsoil waters, or via cross-connections coming from non-potable water pipes or other sources. This may have serious consequences for the health of water users, and may also have negative consequences for infrastructure components such as water meters.

For instance, all water distribution systems have leaks, and continuous efforts are required to maintain water losses at acceptable levels (Van Zyl, 2014). Leaks in pipes are responsible for water losses when normal pressures are present in a distribution system. However, when negative pressures occur in a pipe (e.g. as a result of transients or fire service pumping) or when pipes are emptied (e.g. due to maintenance activities or intermittent supplies), contaminated water and soil particles on the outside of a pipe are able to enter it through the leak openings.

These problems are expected to be exacerbated by increasing pressures on infrastructure systems, which have their origin in rapid urbanisation, continued population growth, and ageing and deteriorating infrastructure. Significant investments are often required to implement the required rehabilitation measures to ensure drinking water safety. In addition, there are practical challenges in undertaking risk assessment, risk management and investment planning.

The Water Research Commission (WRC) recognised the abovementioned problems and subsequently solicited this research project based on detailed terms of reference.

1.2 AIMS AND OBJECTIVES

The prime aims of this study are to establish the frequency and causes of contaminant intrusions in water distribution systems, to identify the characteristics of distribution systems that contribute to these events, and to provide guidance on best practices of water quality control in water distribution systems using the Water Safety Plan (WSP) as a framework.

The objectives defined for the study are as follows:

- Conduct a literature review of the latest research on contaminant intrusion and its impact on water distribution systems.
- Identify the critical aspects of intrusion mechanisms, including driving forces, contamination paths and contaminants near pipes.
- Establish the frequency and magnitude of intrusion events and the characteristics of water distribution systems that contribute to these events.
- Develop expertise on water quality and hydraulics in water distribution systems.
- Provide guidance on best practices of water quality control in water distribution system using the WSP as a useful framework for risk assessment.

1.3 SCOPE AND LIMITATIONS

In this report, contaminant intrusions include all events that negatively influence the quality of water while it is in the water distribution system. The study specifically excludes water quality issues in water sources and water treatment plants, and assumes that the water entering the distribution system adheres to all quality requirements. The report does not focus on specific contamination risks, such as biofilms or water chemistry, but rather presents a broad perspective that describes potential contamination events and their mechanisms, the South African situation and recommendations for the improved management of contamination risks in distribution systems. Laboratory tests and field investigations were not part of the scope of the project.

1.4 ORGANISATION OF THIS REPORT

This report consists of six chapters that are organised as follows:

Chapter 1 provides the background, objectives and scope of the study.

Chapter 2 consists of a literature review to describe the current state of knowledge on contaminant intrusion in water distribution systems. This chapter is arranged around the three prerequisites for contaminant intrusion to occur: a contaminant source in the proximity of the system, a driving force and a pathway.

Chapter 3 consists of literature review that describes selected examples of contamination events in storage reservoirs, pumping stations and pipe networks. In addition, a selection of relevant international and South African case studies are presented. Where possible, each case study considers the relevant contaminant source, driving force pathway.

Chapter 4 provides an overview of the current South African framework relevant to water quality in distribution systems, including the legal framework, institutions, standards, guidelines and management systems.

Chapter 5 describes an interview-based survey of experienced engineers and operators of water distribution systems in South Africa, which is aimed at assessing the type and extent of contamination events that occur.

Chapter 6 provides recommendations for best practices to manage contaminant intrusion events in South Africa based on the WSP concept.

Chapter 7 presents conclusions and recommendations from the study.

CHAPTER 2: CONTAMINANT INTRUSIONS IN WATER DISTRIBUTION SYSTEMS

2.1 INTRODUCTION

Water distribution systems receive their water from treatment plants, and thus the quality of the water they deliver to consumers is primarily dependent on the quality of the water they receive from these plants. This study is limited to contaminant intrusion events occurring in distribution systems and, as such, it is assumed that the water received from the treatment plant complies with all quality requirements. According to Mansour-Rezaei et al. (2014), there are three prerequisites for a contaminant intrusion event to occur in a water distribution system: a contaminant source in the proximity of the system, a driving force and a pathway. Intrusions may be controlled by managing any or all of these factors. It is thus essential that water distribution managers have a solid understanding of them.

The aim of this chapter is to provide an overview of the different classes of prerequisites for contaminant intrusion events before discussing the types of contamination events that occur in distribution systems. A contamination event is a combination of a contaminant (and its location), driving force and pathway that results in a deterioration of water quality in the distribution system. This chapter first provides an overview of the water quality determinands and potential contaminants relevant to water distribution systems. It then presents each of the contaminant intrusion prerequisites (contaminant locations, driving force and pathway) individually. Finally, a detailed list of contamination events is presented and discussed.

2.2 CONTAMINANT SOURCES

2.2.1 Introduction

Fox et al. (2014) indicate that, for contamination ingress or intrusion to occur, it is important that the source of the contaminant coexists in the proximity of the water distribution system. The location of the source is important as it has a direct impact on the frequency, rate and intensity of the contamination intrusion process. Contamination source locations that lead to the contamination of water in the distribution system are categorised as follows:

- External contaminant sources
- Internal contaminant sources

It is worth noting that, for the contamination intrusion process to occur, three requirements or conditions must be met simultaneously: there must be a contaminant externally adjacent to the system (physical, biological or chemical), a driving force (pressure gradient, pH, etc.) and a pathway from this source into the flow (leak, badly fitted joint, air valve, etc.). Having entered the system, the contaminant would then be carried downstream to customers (Jones et al., 2014). However, the contaminant may be originating or happening inside the distributing system. Therefore, the external and internal sources of contamination are explained in more detail in the following sections.

2.2.2 External contaminant sources

External contaminant sources are defined as contaminant sources that intrude or stem from outside the water distribution system, including the pipe network and water reservoirs. For example, Fox et al. (2016) conducted a study where researchers collected soil and water samples external to existing water pipelines from six different states in the USA and tested for a range of microbial indicators and viruses.

Results of the study showed that 50% of the soil samples tested contained faecal coliforms in addition to other bacteria and viruses within the samples.

Contamination sources, such as a leaking sewer pipes and surface water ingress, were the reasons for soil (in the proximity of the pipeline) contamination and hence ingress into the water distribution network and pose a direct health risk to the consumer (Fox et al., 2016). In addition, soil particles and organic matter are contaminants in themselves. Therefore, such contaminants are said to be externally contaminated sources to water distribution systems. Another example could be that any drinking water pipeline passing through an area of contaminated water and/or soil is a potential pathogen carrier (Zloczower and Charuv, 2009). Harmful biological and chemical contaminants in the pipeline's external environs can easily intrude into the pipeline through a leak opening, endangering the consumers and presenting serious health hazards. Thus, the external contaminants that can ingress the water distribution system can be classified as physical, chemical and biological contaminants with a few made up of a mixture of all of them, which are outlined and explained in more detail below.

2.2.2.1 Physical contaminants

Physical contaminants include suspended and dissolved particles, such as silt and grit. Moreover, the sediment and suspended particles themselves may be inanimate or animate, conservative or reactive. Animate (i.e. reactive) particles are chiefly suspended bacteria, discussed in the following sections, and inanimate particles are mainly debris like pieces of pipe material or entrained dirt (Maier, 1999). The presence of physical contaminants in drinking water does not have a negative health impact (Maier, 1999). However, the presence of physical contaminants may affect water safety through choking, reducing the effectiveness of treatment and residual disinfectants or because consumers find the water unacceptable and use alternative, perhaps more contaminated water sources (WHO, 2005). Physical contaminants, such as gravel, particles, dislodged parts of the structure (e.g. reservoir structure, entailing materials on top of roofs, grass, etc.) and dusty soils, including contaminated and muddy soils, can all be potential external contaminant sources that enter the water distribution system, including pipe networks and water storage reservoirs.

2.2.2.2 Chemical contaminants

Chemical contaminants resulting from various chemical reactions can be thought of as being both external and internal sources of contamination to the water supply distribution system. Chemical contaminants, resulting from external source of contamination that eventually intrude into water supply distribution system one way or the other, include pesticides, petroleum products, fertilizers, solvents, detergents, pharmaceuticals and other compounds. Predominant pesticides in urban areas include atrazine, simazine, prometon, and diazinon (LeChevallier et al. 2003). However, some studies have identified insect repellents, fire retardants and other industrial chemicals as potential external chemical contaminants in water distribution networks.

More specifically, the most common external chemical contaminants, in reference to water distribution systems, are described as follows:

- **Naturally occurring chemicals:** There are a number of sources of naturally occurring chemicals in drinking water. All natural water contains a range of inorganic (fluoride, arsenic, selenium, in some conditions, nitrate, etc.) and organic chemicals (algal toxins, blue-green algae, cyanobacteria, etc.). The inorganic chemicals derive from rocks and soil through which water percolates or over which it flows, whereas the organic chemicals derive from the breakdown of plant material or from algae and other microorganisms growing in the water or on sediments. Many of the health problems caused by chemical constituents in water supplies throughout the world are due to chemicals of natural origin rather than those from man-made pollution (Thompson et al., 2007).

Additionally, minerals occur naturally in source water and in drinking water. These are mainly of geological origin from weathering and the erosion of rocks and soils. Minerals in drinking water are desirable, as consumers prefer water that has some mineral content, typically between 80 and 350 mg/ℓ total dissolved solids (TDS), depending on the customer's preference (Bruvold, 1968; Bruvold and Daniels, 1990; Burlingame et al., 2007; Teillet et al., 2010; Platikanov et al., 2013; Garcia et al., 2014, adapted from the American Water Works Association AWWA, 2017b). An appropriate level of minerals is necessary to avoid corrosion. However, too much mineral content, which is often measured as TDS, conductivity, or by individual cations and anions, results in a salty or mineral taste that customers find undesirable (AWWA, 2017b). Other major components that cause taste problems include sodium (salty taste), potassium (salty/bitter taste), calcium (bitter taste), magnesium (bitter/astringent taste), chloride (salty, cation-modulated taste), sulphate (salty and gypsum tastes), pH value (low: sour, bitter, metallic; high: soda, slippery feel) and TDS (objectionable taste for high values) (AWWA, 2017b).

- **Industrial chemicals:** Industries, particularly those involved in extraction, manufacturing and processing, may be significant sources of chemical contamination. For example, extractive industries, including mining, the mining of mineral deposits (principally metal-bearing ores and coal deposits), oil and natural gas production, and quarrying for building and road-making material operations, that are not well managed, can contaminate groundwater and surface water, and can adversely affect the health of nearby communities that rely on this source for drinking water or agriculture. Moreover, poorly operated or abandoned mine sites are often significant sources of water contamination. Contaminants of particular health concern from these sources include heavy metals and mineral-processing chemicals, such as cyanide. Manufacturing and processing industries are also a potential source of chemical contamination in drinking water, including chemicals, metal, textile dying, tannery, paper and pulp, electroplating and printed circuit board manufacturing (Thompson et al., 2007).

- **Human settlement chemicals:** Problems associated with human settlements do not only arise in large cities – even small settlements can carry risks for drinking water if insufficient care is taken and drinking water sources are situated close to human habitation. The chemical contamination risks to drinking water associated with human settlements can be point source, including on-site sanitation and sewerage systems (nitrate, ammonia, etc.), waste disposal (nitrate, ammonia, etc.), non-point source, entailing urban runoff (nitrate, ammonia, heavy metals, pesticides, etc.), and diffuse point source, which includes fuel storage (petroleum, hydrocarbons, benzenes, ethyl benzene, toluene, xylene, etc.), handling and disposal of chlorinated solvents (tetrachloroethylen, trichlorethane, etc.), and pesticide application for public health and vector control (pesticides, herbicides, etc.). Spills of many chemicals found in urban areas (including petroleum and fuel oils) are also a source of contamination of both ground and surface waters. The volatile components of petroleum oils may penetrate some types of plastic water pipes if these chemicals contaminate the ground surrounding the pipe. Therefore, choice of materials for water distribution should consider such risks (Thompson et al., 2007).

- **Agricultural chemicals:** Agriculture is another source of chemical contamination. In this case, the most important contaminant is nitrate, which can cause methaemoglobinaemia, or blue-baby syndrome, in bottle-fed infants under three months of age. There remains uncertainty about the precise levels at which clinically apparent effects occur and it also seems that the simultaneous presence of microbial contamination, causing infection, is an important risk factor (Fawell and Nieuwenhuijsen, 2003). Concern is often expressed about pesticides in drinking water, but there is little evidence that this is a cause of illness, except perhaps following a spill with very high concentrations. Of greater concern is the run-off of nutrients (phosphorus and nitrogen from human excrement or night soil, animal manures, fertilizers and biosolids or sewage sludge) to surface waters, often combined with sewage discharges that lead to significant growths of cyanobacteria (blue-green algae). These organisms produce a wide range of toxins and it is probable that not all the toxins have been identified to date. Where drinking water treatment is limited, there is a potential for undesirable concentrations to be present in drinking water. Concerns are particularly directed at hepatotoxins such as the microcystins and cylindrospermopsin, and neurotoxins such as saxitoxin (Fawell and Nieuwenhuijsen, 2003).

- **Endocrine disrupters:** Endocrine disrupters are chemicals that interfere with the endocrine system, for example by mimicking the natural hormones. They may be associated with a range of adverse reproductive health effects, including a decline in sperm count, hypospadias and cryptorchidism, and cancer of the breast and testes, although the current human evidence is weak. Phthalates, bisphenols, alkyl phenols, alkyl phenol ethoxylates, polyethoxylates, pesticides, human hormones and pharmaceuticals have all been implicated, and sewage effluent discharged to surface water has been shown to contain many of these substances. However, there is currently little, if any, evidence that humans drinking tap water are affected (Fawell and Nieuwenhuijsen, 2003).

- **Contaminated air:** External chemical contaminants can also be contaminated air consisting of different types of gases and molecules that may intrude into the water distribution system to contaminate drinking water.

- **Contaminated rainfall water:** Contaminated rainfall may result from contaminated air that may end up being a potential external source of contamination and may ingress water distribution systems when chances exist.

- **Permeation:** This is a phenomenon in which contaminants (notably hydrocarbons) migrate through the pipe (plastic) wall (Sadiq et al., 2003). The following three stages are said to be observable in permeation phenomena:

  - Organic chemicals present in the soil partition between the soil and the plastic wall
  - The chemicals that defuse through the pipe wall
  - The chemicals that partition between the pipe wall and the water inside the pipe

According to Sadiq et al. (2003), in general, the risk of contamination through permeation is relatively small compared to other mechanisms.

2.2.2.3 Biological contaminants

Biological contaminants can be thought of as being both external and internal sources of contamination to water supply distribution systems. Biological contaminants, resulting from external sources of contamination, include insects, animal faeces, nesting materials, human beings and the remains of dead animals (NRC, 1982). Most of the time, microbial contaminants are of greater concern because, even with dilution as a result of intrusion into the distribution system, some microbes (e.g. viruses) could cause an infection with a single organism (Fleming et al., 2006). Moreover, According to Fox et al. (2014), biological contaminants featured prominently in soil and water samples external to existing water pipelines in a study covering six states in the USA. Results of the study showed that 50% of the soil samples tested contained faecal coliforms. This source of contamination highlights the significant risk to water quality posed by the ingress of external contaminated groundwater and other materials into the potable water supply.

2.2.2.4 Intentional contaminants

There can be intentional cases where one or numerous external contaminants could be introduced into water distribution systems, including any foreign, chemical or toxic human excrement objects or body fluids thrown into water distribution systems (e.g. reservoirs, etc.) for a number of possible reasons, encompassing, terrorism, protests, curiosity, etc.

2.2.2.5 Contaminated ground water

Ground water can be contaminated with leaky sewage water, solid waste dumping sites, surface pollution (fuel and its stations, chemicals, fertilizers, etc.) and all other mixed contaminants discussed above.

2.2.2.6 Contaminated surface water

Surface water can be contaminated with leaky sewage water, animal faeces, dead animals, solid waste dumping sites, surface pollution (fuel and its stations, chemicals, fertilizers, etc.) and all other mixed contaminants discussed above.

2.2.2.7 Contaminated flood or runoff water

Flood water or runoff can pick up numerous contaminants while it moves through the environment, which may eventually strike possible water distribution systems. These can include chemical, biological and physical contaminants discussed above.

2.2.3 Internal contaminant sources

Internal contaminant sources are defined as contaminant sources that stem from the water being transported or stored in a distribution system as a result of various physical, chemical and biological reactions and effects. Moreover, Maier (1999) claims that numerous chemical and biological processes take place in a water distribution system, which has an effect on water quality parameters. On the other hand, Jones et al. (2014) point out that contaminants could be sheltered within biofilm or corrosion products stemming from within the pipe networks and reservoirs. It was also found that the presence of biofilms in the drinking water distribution system might play a role in the presence of potential pathogens, and therefore pose a threat to the quality of the water, even possibly an associated health risk (Jones et al., 2014). Therefore, specific and typical internal contamination sources in water supply distribution systems, including biofilm and corrosion by-products, are discussed below.

2.2.3.1 Biological contaminants

Biological contaminants can be thought of as being both external and internal sources of contamination to water supply distribution systems. While the nature of the biological contamination of water distribution systems results from a complex series of physical, chemical and biological reactions, primarily internal biological contaminants that include microorganisms (NRC, 1982). The most common microbial examples include the growth of biofilms and detachment of bacteria within the distribution system (e.g. pipes and reservoirs) and the proliferation of nitrifying organisms (NRC, 2006). These are explained as follows:

- **Biofilm and microbial regrowth:** These are deposits consisting of microorganisms, microbial products and detritus at the surface of pipes or reservoirs (Sadiq et al., 2003). Biological regrowth may occur when injured bacteria enter the distribution system from the treatment plant. Under favourable conditions, such as nutrient supply (e.g. biological dissolved organic carbon (BDOC), assimilable organic carbon (AOC), phosphorous, nitrogen, etc.) in the water and long residence time, these bacteria can attach themselves to surfaces, rejuvenate and grow in storage reservoirs and on the rough inner surfaces of water mains. One way in which water quality can be degraded in the water distribution system is through the growth of bacteria on surfaces as biofilms. Virtually every water distribution system is prone to the formation of biofilm, regardless of the purity of the water, type of pipe material, or disinfectant used (NRC, 2006). For instance, when chlorine comes into contact with biofilm, the detachment and dissolution of biofilm components are most likely to occur. Bacteria growing in biofilms can subsequently detach from pipe walls. Because these organisms must survive in the presence of disinfectant residual present in the distribution system, the interaction between the suspended organisms and residual is critical. If the residual has decayed due to reactions with compounds in the water or with the pipe wall, intrusion or other sufficient external contamination, it is possible for attached bacteria to be released into the water that contains insufficient disinfectant to cause their inactivation (NRC, 2006).

- **Nitrification:** Nitrification is a two-step aerobic (oxygen-using) biological process. First, ammonia-oxidising bacteria (AOB) biologically oxidise ammonia to nitrite. Second, nitrite-oxidizing bacteria (NOB) biologically oxidise nitrite to nitrate. The second step may also occur from chemical oxidation by free chlorine or monochloramine (AWWA, 2017b).

2.2.3.2 Chemical contaminants

Chemical contaminants that result from various chemical reactions can be thought of as being both external and internal sources of contamination to the water supply distribution system. Internal chemical contaminants can be the result of chemical disinfectants reacting with other substances in water to form some harmful and undesirable compounds. Disinfectants are generally highly reactive substances (Maier, 1999) that reduce in concentration over time to form new chemical species. If chemical compounds occur in sufficient concentration, they may result in acute toxicity depending on the chemical composition of the substance. Moreover, in water distribution systems, internal chemical contaminants may appear as a consequence of chemical reactions, such as the leaching of toxic compounds from pipe materials, internal corrosion, scale formation and dissolution, and the decay of disinfectant residual that occurs over time as water moves through the distribution system (NRC, 2006). However, some specific internal chemical contaminant sources can be illustrated as follows:

- **Internal corrosion:** The internal corrosion of metallic pipes and plumbing devices increases the concentration of metal compounds in the water. Different metals go through different corrosion processes, but in general, low pH value, high dissolved oxygen, high temperature and high levels of dissolved solids increase corrosion rates (Sadiq et al., 2003). Heavy metals such as lead and cadmium may leach into the water from pipes, causing significant health effects. Secondary metals such as copper (from home plumbing), iron (from distribution pipes) and zinc (from galvanised pipes) may leach into water and cause taste, odour and colour problems in addition to minor health-related risks.

  The most widely used metal for pipes and fittings in distribution systems is iron, which may give rise to corrosion products. These products can cause discolouration at the tap if the distribution system is not managed correctly. In some circumstances, iron hand pumps can give rise to discoloured water if they are corroded by water that is too acidic (lower pH values). The corrosivity of water is a function of many factors, including pH value, low alkalinity, chloride and sulphate ions, sediment and microbial activity. Lead, copper and sometime zinc may be present in drinking water, as a consequence of the use of these metals in pipework in public, commercial and domestic buildings. Copper and zinc are less likely than lead to occur at levels of concern, except in very new buildings or where highly corrosive water is supplied. However, concentrations may be increased in some circumstances when copper piping is used as a means of earthing the electrical system in a building. Lead frequently occurs at concentrations greater than the guideline value in situations where lead pipes and solders are present. Lead is also a component of brass, bronze and gun-metal, which are used in fittings in plumbing systems. In some circumstances, fittings made of these metals can be a significant contributor to concentrations of lead at the tap. Where lead pipes are present in a large number of buildings, the most important requirements are public health surveillance (to ensure that there is no significant public health problem) and the identification of buildings that have lead piping. Lead can also be present if lead solder is used in the installation of copper piping. Polyvinyl chloride (PVC) plastic pipes are also widely used in distribution systems. Lead has been used as a stabiliser in unplasticised PVC pipes, and may give rise to elevated lead levels in drinking water for a time after a new installation. Such pipe is normally of a large diameter; thus, the dilution effect of the water flowing through the pipe will reduce the concentration of lead and may result in lead concentrations below the guideline value. There have been cases where the levels of vinyl chloride monomer remaining in the plastic have been higher than desirable. However, chemical monitoring of drinking water is not normally considered to be appropriate and the most suitable method of management is by-product specification (Thompson et al., 2007).

- **Disinfectants:** Disinfectants exceeding their set limits may end up being deleterious and odorous. Chlorinous, earthy-musty (62%) and medicinal (25%) are among the most common odour and taste complaints reported by customers in the United States (Suffet et al., 1995) and in Paris, France (Bruchet, 1999). Major complaints about the taste and odour of drinking water are directly related to chlorine (bleach-like smell: chlorinous), chloramines (swimming pool smell: chlorinous), chlorine dioxide (chlorinous, kerosene-like, cat-urine like) (AWWA, 2017b).
- **Disinfectant demand and decay:** Disinfectant decay refers to the inherent disinfectant “auto-decomposition” (i.e. chloramine reacting with itself) that results in decreasing disinfectant residual levels over time. Disinfectant demand, on the other hand, refers to chemical or microbial contaminants in the water or on surfaces in contact with the water that react with disinfectants (e.g. chloramine reacting with nitrite, bromide, natural organic matter and internal pipe surfaces). As a result, they decrease disinfectant residual levels and provide a conducive environment for water quality deterioration, for example, pacing microbial regrowth and biofilm formation, etc.
- **Disinfectant by-product (DBP) formation:** Drinking water treatment is intended to remove microorganisms and, increasingly, in many cases, chemical contaminants. Nevertheless, the process can, in itself, result in the formation of other contaminants such as trihalomethanes (THMs) and haloacetic acids (HAAs) from the reaction of chemical oxidants with naturally occurring organic matter. Water treatment, however, can take many forms and can use different chemicals, including chlorine, chloramines, chlorine dioxide and ozone. Each treatment methodology has certain advantages and disadvantages, but all of them form by-products of some sort. The type and quantities of by-products formed depend on a number of factors. The formation of by-products during chlorination (one of the most common treatments), for example, depends on the amount and content of organic matter, bromine levels, temperature, pH value and residence time (Fawell and Nieuwenhuijsen, 2003). Uptake of THMs, the most common volatile DBP, can occur not only through ingestion, but also by inhalation and skin absorption during activities such as swimming, showering and bathing. For most other DBPs, ingestion is the main route for uptake. DBPs have been associated with cancers of the bladder, colon and rectum and adverse birth outcomes such as spontaneous abortion, (low) birth weight, stillbirth and congenital malformations in epidemiological studies and, to a much lesser extent, at high levels in toxicological studies (Fawell and Nieuwenhuijsen, 2003). The DBPs can also be a source of taste and odour problems formed when disinfectants are added to water. The best-known DBPs of chlorine oxidation that are related to taste and odour problems are aldehydes (origin: chlorination of amino acid, chloramination; causing: swimming pool odour), N-chloroaldimines (origin: chlorination of amino acids; causing: swimming odour), phenols (origin: chloramination of phenols; causing: medicinal, plaster-like odour), chlorophenols, and iodinated trihalomethanes (origin: chloramination, chlorination; causing: medicinal, sweet, solvent odour) (AWWA, 2017b).

- **Sulphur compounds:** Common sources of sulphur compounds are the conversion of inorganic sulphate to sulphide and degradation of sulphur-containing proteins, including methionine and cysteine, volatile organic sulphur compounds (VOSCs) are a combination of methylated olgosulphide compounds derived from hydrogen sulphide. The VOSCs cause marshy, swampy, rotten egg-type odours in drinking water (AWWA, 2017b).

- **Interior materials and leaching:** Odorous compounds that leach from polymer pipes or reservoirs and distribution materials (e.g. gaskets and lubricants) into drinking water are well-known aesthetic issues (Marchesan and Morran, 2004; Whelton and Nguyen, 2013). Odours from polymer materials can arise from several sources, including:

  - Leaching or migration of odorous chemical directly from the material
  - Chemical conversion of non-odorous compounds that leach or migrate from a material to an odorous chemical through chemical reaction in the distribution
  - Biochemical conversion of non-odorous compounds that leach or migrate from a material to an odorous chemical through a microbial reaction in the distribution system

  An overall aesthetic issue is the leaching of plastic-chemical-solvent odours directly from polymer materials. Specific odorous aromatic chemicals, including benzene (high-density polyethylene (HDPE), epoxy, cross-linked polyethylene (PEX)), toluene (PEX, epoxy), xylenes (HDPE, epoxy, PEX Class B, PEX), propyl benzene (HDPE), styrene (HDPE), methy-t-butyl ether (PEX Class A and Class C, PEX; having and causing sweet solvent-like odour), ethyl-t-butyl ether (PEX Class B; having and causing solvent-like odour) and bisphenols (HDPE, epoxy; having potential endocrine disruptor) are known to leach from polymers into drinking water. New PVC pipes have minimal odours, although pipe-joining compounds release odours, and leaching of vinyl chloride should be considered for health reasons as well (AWWA, 2017b).

- **Pipe network:** The distribution system itself may contribute microorganisms to the water. The joints between the pipe sections may provide protected habitats for large quantities of various kinds of microorganisms (Rutty and Sullivan, 1971). Gasket seals and joint packing are difficult to disinfect and sometimes serve as sources of nutrients. Many lubricants have high chlorine demand, which may create an obstacle to disinfection at the joints.

2.2.3.3 Sedimentation

Sedimentation results from the precipitation of solids in the distribution system due to low velocities. A common source of sediment is naturally occurring iron and manganese in the source water that precipitates from solution while in reservoirs or pipes. This process is accelerated with the presence of chlorine and/or dissolved oxygen. Another source of sedimentation is when sediment is carried in from disruptions in the water mains, such as fire flow, hydrant testing or main breaks. Sediment sludge can stir up or re-suspend if there are hydraulic transient events, increasing water turbidity and heterotrophic plate counts.

2.2.3.4 Collapsed material from interior surfaces

Interior surfaces of water structures, such as interior roofs and walls of water storage reservoirs, can be peeled off by different factors, including earthquakes, heavy loads, material creeping with time, etc.

2.3 CONTAMINATION PATHWAYS

2.3.1 Introduction

As mentioned earlier, Fox et al. (2014) indicate that, for contamination ingress or intrusion to occur, it is important that there should be a pathway that allows the movement between the water in the pipe and the contaminant source externally adjacent to it. Therefore the potential pathways are discussed in this section.

2.3.2 Leak opening

A leak opening is a potential pathway for contamination. Pathways for contaminant intrusion into the water distribution systems are normally also leakage paths. These are pipeline breaks and cracks, dislocated or damaged seals and joint failures (Mansour et al., 2014). All leakage openings are potential contaminant intrusion paths. Causes that lead to leak opening or pipeline damage include natural causes such as soil movement, soil erosion, extreme temperature changes resulting in the damaging expansion and contraction of pipelines, the freezing of water inside the pipeline exerting internal pressure due to the expansion of ice, etc. (Zloczower and Charuv, 2009). Granular materials and aggressive hydraulic regimes (high velocity flow, etc.) can cause the physical erosion of pipeline walls. Vehicles, digging equipment (backhoe, etc.) and other implements of everyday activity can cause external physical damage.

2.3.3 Drowned air valves

Another potential pathway can be through drowned air valves when the chamber in which they are located becomes flooded (Fox et al., 2014).

2.3.4 Doors and hatches on reservoirs

Doors and access hatches on reservoirs can serve as contaminant intrusion paths if not adequately closed, as insects, people, air and water can enter reservoirs through these openings.

2.3.5 Damaged structure

Damaged structure, with roots from any external and/or internal phenomena, such as earthquakes, wind, concrete creeping and badly installed doors with sealing, can lead to potential contamination pathways, including cracks on roofs and walls, dislodged access hatches with seals, the peeling of plaster or interior materials, etc. This is not only true for reservoirs, but also for pipe networks because damage to pipe networks can cause leaking in pipes, the shifting of valves, loosing of joints, etc., which could be potential pathways.

2.3.6 Air vent and overflow outlet pipes

Air vent and overflow outlet pipes can also be potential pathways for external contaminant sources to intrude into water reservoirs and deteriorate water quality.

2.3.7 Cross-connections

Cross-connection is a term used to describe a physical link through which it is possible for a non-potable liquid to enter into a potable water distribution network (Sadiq et al., 2006). Typically, when the pressure in the non-potable system is greater than that in the water distribution network, the existence of an unprotected cross-connection may result in the backflow of contaminants into the potable water supply system.

2.3.8 Consumer and hydrant connections

Consumer and hydrant connections could end up being potential pathways for contaminant intrusion since water delivered to consumers or private fire hydrants are not under the control of the municipality anymore and should never be allowed to return to the distribution system.

2.3.9 Chemical permeation

Chemical permeation is the process by which chemicals penetrate the pipeline material in the absence of physical portals. In water distributions systems, this normally happens with plastic pipes.

2.3.10 Internal contact and reactions

Pathways for contamination sources can also be internal, as they are already in contact with water reacting within the distribution system, including water inside the reservoirs and pipe networks.

2.4 CONTAMINATION DRIVERS

2.4.1 Introduction

Drivers for internal contamination sources are less clear and somewhat trivial, but even here processes like turbulence, hydraulic shear and diffusion drive the distribution of contaminants in the fluid.

2.4.2 Pressure differential

When negative pressures are combined with leaks, there is a risk of contaminant ingress through the leak portals. The operating conditions of drinking water systems are rarely at a true steady state (Fleming et al., 2005). All systems will at some time be started up, switched off, or undergo other rapid flow changes. Studies indicated that the pressure waves generated by these disturbances can propagate throughout the distribution system, creating low and negative pressures in several locations, and that the low or negative pressures created can provide an opportunity for the intrusion of non-potable water into the drinking water distribution network. These dynamic pressure conditions occur due to a sudden change in velocity, which may be a result of operational changes, including valve closures, system depressurisation for maintenance work and changes in demand, or due to failures such as pump trips and bursts. These extreme changes of flow within the system incur the risk of oscillating high- and low-pressure transients, where the lowest pressures may be negative (Gullick et al., 2005). Low and negative pressures are most likely to occur downstream of an imposed obstruction (e.g. valve closure) where the momentum of a flowing column of water may result in the formation of low or negative pressures bounded at water vapour pressure, resulting in the suction of external substances into the distribution system.

2.4.3 Human behaviour

The public health consequences of an outbreak or attack do not depend on the characteristics of the contaminant intrusion alone (Shafiee and Zechman, 2012). Instead, the decisions and behaviours of human actors when they interact with the pipe network can influence the number of exposed consumers and the propagation of a contaminant plume. This can happen as a result of vandalism, terrorism or negligence. In addition to pathogens, intrusion can also introduce pipe chemicals, such as pesticides, herbicides, hydrocarbons (gasoline spills) and physical contaminants, such as plant debris and soil particles (Fleming et al., 2005). These can all happen due to human interference, in most cases, during repairs. Contamination may occur if proper flushing and disinfection procedures are not implemented prior to recommissioning. Clearly, the frequency of a pipe breakage, the duration of repair jobs and the size of the network segment that can be isolated during maintenance are factors that have an impact on the risk of intrusion.

2.4.4 Animal behaviour

Animals and insects can be another factor driving the contamination of drinking water in water distribution systems. In open reservoirs where access is not controlled, animals can drink water from the open reservoir, leading to potential contamination. On the other hand, animals and insects can drown in the reservoirs, leaving their remains in the drinking water, including their nests and eggs.

2.4.5 Wind movement and pressure

Wind movement and pressure are the main forces that drive external contaminants, such as dusty and contaminated air, and precipitation (e.g. contaminated rainfall), to enter storage reservoirs through access hatches, cracks or unprotected air valves.

2.4.6 Gravity

Gravity plays an important role in contaminant intrusion events by exerting a constant downwards force on all matter. The following examples show the effect of gravity in water quality deterioration:

- **Landslides:** Due to gravity, contaminated debris and soil can intrude to contaminate water in a distribution system through open access hatches and cracks in walls and pipes.
- **Earthquakes:** The earth, building materials or other matter mobilised by earthquake forces may enter water distribution components through the action of gravity. For example, an earthquake can loosen deposit or even structural elements from the walls and roof of a storage reservoir, which fall into the water due to the action of gravity.
- **Rainfall and dust events:** Another example of the effect of gravity is the movement of contaminated rainfall from the sky, where it enters the distribution system through cracks or open hatches.
- **Sedimentation events:** When no or low velocity of water flow is experienced in pipes or storage reservoirs, particles settle at the bottom through gravity, from where they can be suspended in the water due to a high flow velocity or a change in flow direction.

2.4.7 Water velocity and pressure

Water velocity and pressure can act as driving forces that allow external contaminants to intrude into water distribution systems. For example, contaminated flood water, caused by either a storm or pipe burst, can cause intrusion through open reservoir hatches or flood air valve chambers. Water forces can damage structures, dislodge covers and expose pipes. Another example could be contaminated rainfall that builds up on top of the water supply distribution system (e.g. water reservoir roof, exposed pipeline or drown air valves).

2.4.8 Shaking of structures by earthquakes or sinkholes

Shaking of structures by earthquakes or sinkholes are driving forces that can result in biofilm detachment, sediment re-suspension and other damage to the system.

2.4.9 Biochemical reactions and decomposition

Biochemical reactions that occur within the water or biofilm to create internal contamination result from problems such as sulphur-induced odours, biofilm detachment, internal corrosion, nitrification, permeation and leaching, decay of disinfectant residual and DBP formation.

2.5 SUMMARY

The location of contamination can be either internal (inside a pipe, pumping station or reservoir, including concerns associated with design, and operation and maintenance) or external (external contaminant intrusion to the mentioned components of the water supply system), while potential pathways that lead to the movement of potential contaminants are mostly leak openings. The leak openings may be a leak opening in a pipe, or leak openings on joints and pumps or in reservoirs, including hatches, air vents, outlets, etc. However, pathways for events such as DBPs, detached biofilms, nitrification, leaching, sedimentation, discolouration and scaling, and internal corrosion do not need to have a pathway since they are already in contact with the water in the distribution system. On the other hand, the factors driving the contamination ingress in water distribution networks are pressure differential (negative pressure), velocity, pH value, temperature, water age and chemical reactions happening in the distribution system due to the presence of different elements and compounds.

CHAPTER 3: CONTAMINANT INTRUSION EVENTS IN WATER DISTRIBUTION SYSTEMS

3.1 INTRODUCTION

As indicated earlier, for a contamination intrusion event to occur, three requirements or conditions are met simultaneously: there must be a contaminant externally adjacent to the system (physical, biological or chemical), there must be a driving force (pressure gradient, pH value, etc.) and there must be a pathway from this source into the flow (leak, badly fitted joint, air valve, etc.). Having entered the system, the contaminant would then be carried downstream to customers (Jones et al., 2014). Contamination events can be classified into three major components of the water distribution system:

- Storage reservoirs
- Pumping stations
- Pipe networks

3.2 CONTAMINATION EVENTS IN STORAGE RESERVOIRS

3.2.1 Overview

A number of events are or may result in the deterioration of water quality in reservoirs. These include the decay of disinfectant residual, formation of DBPs, taste and odour problems, corrosion, leaching from internal surfaces, biofilm, nitrification, sedimentation and the intrusion of external contaminants. The major causes of these events include, but are not limited to, high temperature, leading to stratification, stagnant water, inlet/outlet configuration, dead zones and short-circuiting. These can lead to improper mixing, or no mixing at all, resulting in water ageing (RCAP, 2012). The events are summarised in Table 3-1, and are individually discussed in the sub-sections below (RCAP, 2012).

3.2.2 Water age and poor mixing

Excessive water age events mainly originate due to design (e.g. over-sizing) and operational errors, which trigger many water quality problems in water storage reservoirs. Long detention times, resulting in excessive water age, can be conducive to microbial growth and chemical changes in water quality, including microbial regrowth, disinfectant residual decay, DBP formation, nitrification, taste and odours. Excess water age may be caused by underutilisation (i.e. the water is not cycled through the reservoir), short-circuiting within the reservoir and operational errors. Poor mixing, including stratification, can exacerbate water quality problems by creating zones within the storage facility where water age significantly exceeds the average water age throughout the facility. Distribution systems with storage reservoirs where the water cascades from one reservoir to another (such as pumping up through a series of pressure zones) can result in exceedingly high water age in the most distant reservoirs (USEPA, 2002a).

<table>
<tr><th colspan="6">Table 3-1: Potential water quality events in municipal water storage reservoirs</th></tr>
<tr><th colspan="2" rowspan="2">Events</th><th rowspan="2">Driving force</th><th rowspan="2">Pathway</th><th colspan="2">Contamination source</th></tr>
<tr><th>Internal source</th><th>External source</th></tr>
<tr><td rowspan="5">Natural disaster</td><td>Wind storms</td><td>• Wind movement and pressure
• Gravity</td><td>• Open and uplifted access hatch
• Air vent pipes
• Loose joints or gaskets
• Overflow outlet</td><td></td><td>• Dust and contaminants carried in air
• Gravel or dust on reservoir roof</td></tr>
<tr><td>Floods</td><td>• Water velocity and pressure</td><td>• Cracks on roof and/or side walls
• Air vents
• Roof access hatch not sealing
• Overflow</td><td></td><td>• Contaminated flood water</td></tr>
<tr><td>Landslides</td><td>• Gravity
• Soil pressure</td><td>• Damaged structure: cracks on roofs, walls, access hatch, air vents, etc.
• Access hatch opening
• Air vent pipes
• Overflow outlet
• Others, including loose fittings, joints, etc.</td><td></td><td>• Contaminated and muddy soils</td></tr>
<tr><td>Earthquakes</td><td>• Shaking of structure by earthquake
• Gravity causing particles on roof to fall into reservoir</td><td>• Damaged structure: cracks on roofs, walls, dislodged access hatch, seals, etc.
• Internal contact</td><td>• Biofilm detachment from interior walls
• Sediment sludge stirred up
• Peeled-off materials of plaster or structure</td><td>• Gravel or particles on reservoir roof
• Dislodged parts of walls or roof</td></tr>
<tr><td>Volcanic eruption</td><td>• Gravity force
• Lava pressure</td><td>• Damaged structure: cracks on roofs, walls, access hatch, etc.
• Air vent pipes
• Overflow outlet
• Others, including loose fittings, joints, etc.</td><td></td><td>• Ash fall and lava flow containing toxic substances (lead, arsenic, etc.)</td></tr>
<tr><td rowspan="3">External contaminant</td><td>Precipitation</td><td>• Gravity
• Air movement and pressure
• Water velocity and pressure</td><td rowspan="2">• Damaged structure: cracks on roofs, walls, access hatch opening, etc.
• Air vent pipes
• Overflow outlet
• Others, including loose fittings, joints, etc.</td><td rowspan="2"></td><td>• Contaminated rainfall and runoff</td></tr>
<tr><td>Animal behaviour</td><td>• Animal behaviour, e.g. seeking shelter, breeding, water, etc.</td><td>• Animal faeces
• Nesting materials
• Dead animals</td></tr>
<tr><td>Dust</td><td>• Air movement and pressure
• Gravity</td><td></td><td></td><td>• Soil particles</td></tr>
</table>

Table 3-1 *(continued)*

Events		Driving force	Pathway	Contamination source	
				Internal source	**External source**
External contaminant	Human behaviour	Human behaviour, for example: • Need for water (e.g. for livestock) • Curiosity • Vandalism • Theft • Protests action • Terrorism	• Lack of or damage to perimeter fence • Access hatches not locked • Access hatch lock susceptible to damage • Pipework manhole covers		• Foreign objects thrown into reservoir • Chemicals or toxins thrown into reservoir • Human excrement or body fluids thrown into reservoir • People entering the water
Internal reactions causing taste and odour problems	Sulphur induced	• Biochemical reactions and decomposition	• Internal reaction	• Volatile organic sulphur compounds in water • Hydrogen sulphide in water • Inorganic sulphates and sulphides in water • Cyanobacteria in water or biofilms • Microorganisms in biofilms • Sulphur-containing proteins in biofilms or water	
	Disinfectant induced	• Disinfectant residuals and dosage • Chemical reactions • pH value • Temperature • Water age		• Disinfectants: chlorine, chloramine, chlorine dioxide • DBP: aldehydes, N-chloroaldimines, phenols, chlorophenols, iodinated THMs	
	Permeation and leaching Induced	• Chemical and biochemical reactions • Water age • Temperature		• Chemical contaminants: benzene, ethylbenzene, styrene, trichloroethane, toluene, xylene (total), N-propyl benzene, methyl-t-butyl ether, ethyl-t-butyl ether, bisphenols compounds • Biofilms	
	Metal corrosion induced	• Metal corrosion rate		• Cupric, cuprous, ferric iron	
	Mineral induced	• Mineral concentration • Temperature		• Sodium, potassium, calcium, magnesium, chloride, sulphate, pH, TDS, etc.	

Table 3-1 *(continued)*

Events	Driving force	Pathway	Contamination source	
			Internal source	**External source**
Sedimentation	• Low velocity (for sedimentation) • High velocity, change in flow direction, transients (stirring up sediment) • Disinfectant residuals and/or dissolved O2 • pH value • Temperature • Gravity	• Internal reaction	• Organic and inorganic suspended solids	
Water age and poor mixing	• Retention time of water in reservoir and gravity • Mixing efficiency of water entering tank	• Internal reaction	• Disinfectant decay • Formation of DBP	
Decay of disinfectant residual	• Chemical and biochemical reactions • Temperature • Sunlight exposure • Water age	• Internal reaction	• Organic substances (humic and fulvic acids, etc.) • Inorganic substances (iron, manganese, etc.) • Biofilms • Disinfectant-demanding compounds	
Formation of DBP	• Chemical and biochemical reactions • Disinfectant dosage • Water age • pH value • Temperature	• Internal reaction	• Natural organic matter (NOM) • Inorganic substances (bromide, iodide, nitrite, etc.) • Biofilm/microbial activity • Pipe wall materials (reacts with residual disinfectants) • Corrosion by-products • DBP biodegrades	
Internal corrosion	• Galvanic potential • Conductive environment (free O2) • High/low flow velocity (transient flow) • Biochemical reactions • pH value • Temperature • Water age	• Internal reaction	• Pipe material – dissimilar metals (iron, copper, zinc, etc.) • Sulphide, sulphate, chloride, alkalinity, etc. • CO2, TDS and disinfectant residual • Biofilms (iron-oxidising and sulphate-reducing bacteria)-causing minimum (MIC)	

Table 3-1 *(continued)*

Events	Driving force	Pathway	Contamination source	
			Internal source	**External source**
Leaching from internal coatings	• Chemical and biochemical reactions • pH value • Temperature • Curing time	• Internal reaction	• Chemical solvents and additives: benzene, toluene, compound organics, etc.	
Biofilm and microbial regrowth	• Disinfectant residual • pH value • Temperature • Water age	• Internal reaction	• Biodegradable dissolved organic carbon • Assimilable organic carbon • Nutrients (phosphorous, nitrogen, etc.) • Corrosion by-products	
Nitrification	• Biological reactions • Cl2/N ratio • Chloramine demand and/or decay • pH value • Temperature • Water age	• Internal reaction	• Nutrients: free ammonia • Ammonia and nitrite-oxidising bacteria • Nitrite, bromide, microorganisms, natural organic matter, biofilm accumulation	

3.2.3 Decay of disinfectant residual

There is a wide array of reasons why disinfectant residual decays in water reservoirs, including exposure to sunlight or high temperature, biological growth, water age, organic (humic and fulvic acids) and inorganic (iron and manganese) disinfectant-demanding compounds, along with the augmentation of chlorine-demanding compounds caused by sedimentation and contamination intrusion. The decay of disinfectant residual will result in deficiency in inactivating and killing microorganisms, which may pose potential health risks. Water sampling for chlorine residual should be monitored at the outlet point of the reservoir since it is not accurately detected inside the reservoir unless samples are taken from different levels and locations within the reservoir.

3.2.4 Formation of disinfection by-products

Disinfection by-product events are formed when organic matter reacts with disinfectants. The following factors increase the concentration of DBPs:

- **Increased time (water age):** Water age can increase significantly in stratified layers and dead zones in the reservoir.
- **Chlorine concentration:** Chlorine concentrations may need to be high in storage reservoirs in order to maintain an adequate residual in the distribution system.
- **Temperature:** Water temperature in storage reservoirs is highest in the late summer, so the concentration of DBPs will likely be the highest then.
- **Organic matter concentration:** Organic matter can come from the source water, contamination from outside the distribution system or biological regrowth inside the system.

Disinfection by-products such as THMs and HAAs cause taste and odour problems, and may even pose carcinogenic health risks.

3.2.5 Internal corrosion

Steel storage reservoirs are susceptible to corrosion events from failed coatings. The corrosion rate is dependent on water hardness, the type of disinfectant used, conductivity, dissolved oxygen, temperature, sulphides and chlorides. Customers may complain about red water and metallic taste as a result of metal corrosion. Corrosion can be prevented by periodically inspecting and repairing the coatings. It is also important to have a properly maintained and calibrated cathodic protection system.

3.2.6 Leaching from internal linings

The internal linings of water reservoirs may deteriorate over time and leach contaminants into stored water. The rate of leaching is dependent on coating age, temperature and water composition. Volatile organic compounds (VOCs) can be emitted from new coatings if insufficient curing time is allowed. Increases in pH value can result from leaching in concrete reservoirs. These may cause taste and odour problems, or even beyond, and may end up in customer complaints.

3.2.7 Biofilm and microbial regrowth

Biofilms are commonly occurring events found in nature in almost every aquatic environment. Regrowth term refers to the recovery of injured bacteria during treatment and their starting to multiply in water (September et al., 2006). Even though microbial regrowth is associated with the distribution system's piping, storage reservoirs also create an environment that is prone to regrowth because of decreased disinfectant residual, increased temperatures (temperatures above 15 °C), and the presence of biodegradable dissolved organic carbon. Other factors that affect regrowth include seasonal temperature variations, the availability of nutrients, distribution system corrosion products, disinfection practices and hydrodynamics (water residence time and velocity).

Microbial regrowth tends to occur on the interior surfaces of storage reservoirs and in the non-circulating zones of the reservoir. Microbial regrowth is a public health and compliance concern because it may contain total coliform, which can lead to issues related to bacterial compliance with the South African National Standard (SANS 241: 2015) downstream. Microbial regrowth can also exert a chlorine demand, resulting in a loss of chlorine residual.

3.2.8 Nitrification

Nitrification is associated with bacterial regrowth. Nitrification is the bacteriological conversion of ammonia to nitrate in a two-step process. Ammonia can occur naturally in the source water, or it can come primarily from the chloramination (as a disinfectant) process. Ammonia is first converted to nitrite, and nitrite is then converted to nitrate. Nitrate and nitrite are both primary contaminants. Nitrification affects water quality by degrading chloramine residuals, consuming dissolved oxygen, increasing heterotrophic plate counts, decreasing the pH value, and increasing the nitrate and nitrite levels. While exceeded values of nitrate and nitrite may pose potential health risk of shortness of breath in infants and blue-baby syndrome. According to Telfer (2014), nitrification does not have a direct impact on public health but is still an important process to control and ensure that it does not take control across distribution systems (Telfer, 2014). This is primarily because nitrification leads to a rapid loss of chloramine residuals, which are an important barrier in the management and protection of water quality in distribution systems. The loss of chloramine residual leaves the distribution system susceptible to microbiological contamination with potential public health implications (Telfer, 2014).

3.2.9 Taste and odour

Taste and odour problems can develop in water storage reservoirs from biological activity, such as the anaerobic production of hydrogen sulphide gas, high disinfectant residuals, improper chloramine and mineral concentrations, and the leaching of chemicals from the storage facility linings. These problems are exacerbated when storage water experiences a long turnover period and high water temperature.

3.2.10 Sedimentation

Sedimentation results from the precipitation of solids in the reservoir due to low velocities. A common source of sediment is naturally occurring iron and manganese in the source water that precipitates from solution while in the reservoir. This process is accelerated with the presence of chlorine and/or dissolved oxygen. Another source of sedimentation is when sediment is carried in from disruptions in the water mains, such as fire flow, hydrant testing or main breaks. Sediment can be re-suspended in the water if there are flow surges, increasing water turbidity and heterotrophic plate counts. Solids can also be released from the reservoir into the distribution system if there are high levels of pumping. Sediment can affect chlorine demand, increase coliform levels, and cause taste and odour problems.

3.2.11 External contaminants intrusion

Contaminant entry is a major problem for uncovered reservoir facilities. That is why uncovered, treated water reservoir facilities are no longer permitted in most parts of the world. However, covered facilities are also susceptible. Airborne particulates can enter through hatches and vents. Insects, birds and other animals can enter reservoir facilities through faulty screens, cracks, open joints or poorly sealed hatches. As a result, this leads to water quality failures or deterioration at varying degrees in water reservoirs.

3.2.12 Natural disaster events

Natural disaster events, such as windstorms, floods, landslides, earthquakes, sinkholes and volcanic eruptions can also occur that can not only affect the structure of water reservoirs both internally and externally, but can also try to intrude into the reservoir. For example, an earthquake disaster event (via shaking) will shake the reservoirs.

Thus, the reservoir will not only be damaged structurally, which may result in the possible falling of material into the water, but sediment may also be stirred up to mix with the stored water, while windstorms (via wind movement), floods (via water velocity and pressure), landslides (via soil pressure and gravity) and volcanic eruption (via lava pressure and gravity force) will damage the structure and try to intrude contaminants, dust, water, soil and lava respectively.

3.3 CONTAMINATION EVENTS AT PUMPING STATIONS

3.3.1 Overview

Contaminant events that are induced by pumps are mainly caused by pump stoppage, which triggers hydraulic transients in the distribution system (Table 3-2). In a pumping water distribution network, the pump may stop unexpectedly. The reasons for pump stoppage include power shut-down and pump breakdown. As a pump stops, pressure transients or water hammer occurs, leading to a sudden change in pipe flow rate, which induces an increasing or decreasing pressure wave that travels at a high speed through the pipe. When it reaches the end of the pipe, it is reflected in the opposite direction and inverted (increasing pressure waves become decreasing pressure waves and vice versa).

The intensity of the wave reduces as it oscillates until it is exhausted. If the pipes are not properly designed, increasing the transient waves can exceed the strength of the pipe, causing damage to the linings or inducing a pipe burst. One other important aspect of pump stoppage is that decreasing transient waves caused by pump stoppage may cause the pressure to fall below atmospheric pressure, creating the potential for contaminant intrusion. Having such a pressure in pipes with leak portals, the external contaminants may be sucked into the water distribution network and hence contaminate the drinking water. Since pipes are run adjacent to the sewer lines, the soil surrounding the water distribution pipes is contaminated with pathogens and industrial run-off from sewer leaks. The presence of such contaminants may have serious health implications, as well as a loss in turbidity if the leak portals are big enough to allow the passage of sand and silt into the pipes.

<table>
<tr><th colspan="6">Table 3-2: Potential water quality events induced by the pumping station</th></tr>
<tr><th colspan="2" rowspan="2">Events</th><th rowspan="2">Driving force</th><th rowspan="2">Pathway</th><th colspan="2">Contamination source</th></tr>
<tr><th>Internal source</th><th>External source</th></tr>
<tr><td rowspan="4">Hydraulic transients</td><td>Natural disaster-induced pump stoppage</td><td rowspan="4">• Negative transient pressure in the pipe system</td><td rowspan="4">• Leak openings on water supply network (e.g. pipeline breaks, faulty joint seals)
• Drowned air valves
• Cross-connection or consumer connection back-flow</td><td rowspan="4">• Biofilm detachment from interior pipe walls
• Peeling off interior adsorbed materials to interior walls – due to tuberculation, scaling and sedimentation, etc.
• Detached pieces of pipe lining</td><td rowspan="4">• Groundwater with contaminants such as sewage, contaminants from surface pollution (fuel, chemicals, fertilizers, pesticides, etc.)
• Surface water with contaminants such as sewage, animal faeces, dead animals, etc.
• Soil and dirt particles.</td></tr>
<tr><td>Human-induced pump stoppage (intentional or unintentional)</td></tr>
<tr><td>Pump design-induced failure</td></tr>
<tr><td>Installation, operational and maintenance-induced failure (intentional or unintentional)</td></tr>
<tr><td colspan="2">External contaminant intrusion</td><td>• Mechanical movement of pump machinery</td><td>• Leaks in mechanical seal of pump – motor connection</td><td></td><td>• Diesel, fuel, motor or engine oil, lubricants, contaminated water, etc.</td></tr>
</table>

3.3.2 Hydraulic transients

Hydraulic transients occur at rapid flow changes in pressurised conduits. This is due to the following (Elbashir and Amoah, 2007):

- Start and stop of pumps, especially stopping due to power failure
- Load changes in hydropower plants
- Valve operations (shut-off valves)
- Check valve closure
- Air pockets in pipelines, especially at pump start
- Discharge of air through air vent, valves

Even though the above factors are all causes of transient flow creation, pump failure is the primary and major cause. Its mitigation thus needs careful consideration. The magnitude of the transient pressure peaks depends on many factors, some of which are the following (Elbashir and Amoah, 2007):

- Pipeline length and configuration: the longer the pipeline, the stronger the hydraulic transients. Branched pipeline configuration is better in handling transients.
- Pipeline profile.
- Rate of change of the flow: the more rapidly the flow changes, the higher the generated hydraulic transients; flow change depends on the valve operation and pump characteristics.
- The elastic properties of the water and the pipe: fewer elastic pipes are associated with more extreme transient pressures.
- Formation and appearance of vapour pockets (cavities) in the water.
- Protective measures applied: these include surge chambers, air vessels, air valves, frequency-controlled pumps, etc.

3.3.3 External contamination intrusion

Another possible external contamination intrusion event could be when diesel, fuel, motor or engine oil or contaminated water intrude into the pipe network through leaks in the mechanical seal of the pump-motor connection as a result of the mechanical movement of the pump machinery (e.g. heavy vibration resulting in diesel being intruded into the pump pipeline via the pump-motor connection, etc.).

3.3.4 Natural events

Natural disaster events, such as windstorms, floods, landslides, earthquakes, sinkholes and volcanic eruptions can also damage the pump station, resulting in pump stoppage. This then leads to a negative transient in the pipe system, causing external contaminants to be intruded.

3.4 CONTAMINATION EVENTS IN PIPE NETWORKS

3.4.1 Overview

A number of events may result in the deterioration of water quality in pipe networks. These are summarised in Table 3-3, and include the decay of disinfectant residual, DBP formation, taste and odour problems, corrosion, leaching from internal surfaces, biofilm formation and regrowth, nitrification, sedimentation and external contaminants intrusion.

Table 3-3: Potential water quality events in pipe networks

Events		Driving force	Pathway	Contamination source	
				Internal source	External source
Natural disaster	Earthquakes	• Shaking of the network by earthquake • Negative transient events	• Damaged network due to pipe breaks, and joint damage and dislocation. • Cross-connection and user back-flow • Internal reaction	• Biofilm detachment from interior pipe walls • Peeling off interior adsorbed materials to interior walls – due to tuberculation, scaling and sedimentation, etc. • Detached pieces of pipe lining •	• Groundwater with contaminants such as sewage, contaminants from surface pollution (fuel, chemicals, fertilizers, pesticides, etc.) • Surface water with contaminants such as sewage, animal faeces, dead animals, etc. • Soil and dirt particles.
Natural disaster	Sinkholes	• Shaking of the network by sinkhole formation	• Damaged network due to pipe breaks and joint damage and dislocation.	• Biofilm detachment from interior pipe walls • Detached pieces of pipe lining	• Groundwater with contaminants such as sewage, contaminants from surface pollution (fuel, chemicals, fertilizers, pesticides, etc.) • Surface water with contaminants such as sewage, animal faeces, dead animals, etc. • Soil and dirt particles.
Taste and odours	Sulphur induced	• Biochemical reactions and decomposition	• Internal reaction	• Volatile organic sulphur compounds in water • Hydrogen sulphide in water • Inorganic sulphates and sulphides in water • Cyanobacteria in water or biofilms • Microorganisms in biofilms • Sulphur-containing proteins in biofilms or water	
Taste and odours	Disinfectant induced	• Disinfectant residuals and dosage • Chemical reactions • pH value • Temperature • Water age	• Internal reaction	• Disinfectants: chlorine, chloramine, chlorine dioxide • DBP: aldehydes, N-chloroaldimines, phenols, chlorophenols, iodinated THMs	
Taste and odours	Permeation and leaching induced	• Chemical and biochemical reactions • Water Age • Temperature	• Internal reaction	• Chemical contaminants: benzene, ethylbenzene, styrene, trichloroethane, toluene, xylene (total), N-propyl benzene, methyl-t-butyl ether, ethyl-t-butyl ether, bisphenols compounds • Biofilms	
Taste and odours	Metal corrosion induced	• Metal corrosion rate	• Internal reaction	• Cupric, cuprous, ferric iron	
Taste and odours	Mineral induced	• Mineral concentration • Temperature	• Internal reaction	• Sodium, potassium, calcium, magnesium, chloride, sulphate, pH, TDS, etc.	

Table 3-3 *(continued)*

Events		Driving force	Pathway	Contamination source	
				Internal source	External source
Sedimentation and discolouration		• Low velocity (for sedimentation) • High velocity, change in flow direction, transients (stirring up sediment) • Disinfectant residuals and/or dissolved O2 • pH value • Temperature • Gravity	• Internal reaction	• Organic and inorganic suspended solids	
Water age		• Retention time of water in pipe system	• Internal reaction	• Disinfectant decay • Formation of DBP	
Decay of disinfectant residual		• Chemical and biochemical reactions • Temperature • Water age	• Internal reaction	• Organic substances (humic and fulvic acids, etc.) • Inorganic substances (iron, manganese, etc.) • Biofilms • Disinfectant-demanding compounds	
Formation of DBP		• Chemical and biochemical reactions • Disinfectant dosage • Water age • pH value • Temperature	• Internal reaction	• Natural organic matter • Inorganic substances (bromide, iodide, nitrite, etc.) • Biofilm or microbial activity • Pipe wall materials (reacts with residual disinfectants) • Corrosion by-products • DBP itself biodegrades	
Internal corrosion		• Galvanic potential • Conductive environment (free O2) • High/low flow velocity (transient flow) • Biochemical reactions • pH value • Temperature • Water age	• Internal reaction	• Pipe material – dissimilar metals (iron, copper, zinc, etc.) • Sulphide, sulphate, chloride, alkalinity, etc. • CO2, TDS and disinfectant residual • Biofilms (iron-oxidising and sulphate-reducing bacteria)-causing MIC	
Leaching and perrmeation	**Leaching**	• Chemical and biochemical reactions • pH value • Temperature • Curing time	• Internal contact	• Coating age • Copper, lead, vinyl chloride (PVC), asbestos fibres (asbestos cement), aluminium (cement lining), etc.	
	Permeation	• Diffusion phenomena associated with plastic pipes	• Chemical permeation through plastic pipes/joints materials	• Hydrocarbon associated: oils, gasoline, volatile organic compounds • Chemical storage tanks, petroleum products and pump stations • Chemical solvents as additives: benzene, toluene, compound organics, etc.	

Table 3-3 *(continued)*

Events	Driving force	Pathway	Contamination source	
			Internal source	External source
Biofilm and microbial regrowth	• Disinfectant residual • pH value • Temperature • Water age/retention time	• Internal reaction	• Biodegradable dissolved organic carbon • Assimilable organic carbon • Nutrients (phosphorous, nitrogen, etc.) • Corrosion by-products	
Nitrification	• Biological Reactions • Cl2/N Ratio • Chloramine demand and/or decay • pH • Temperature • Water Age	• Internal reaction	• Nutrients: free ammonia • Ammonia and nitrite-oxidising bacteria • Nitrite, bromide, microorganisms, natural organic matters, biofilm accumulation • Other source: agricultural runoff from fertilization, or livestock wastes or contamination from sewage	
Hydraulic transients	• Negative transient pressure in the pipe system	• Leak openings on water supply network (e.g. pipeline breaks, faulty joint seals) • Drowned air valves • Cross-connection or consumer connection back-flow	• Biofilms detachment from interior pipe walls • Peeling off interior adsorbed materials to interior walls – due to tuberculation, scaling and sedimentation, etc. • Detached pieces of pipe lining	• Groundwater with contaminants such as sewage, contaminants from surface pollution (fuel, chemicals, fertilizers, pesticides, etc.) • Surface water with contaminants such as sewage, animal faeces, dead animals, etc. • Soil and dirt particles.
Depressurisation (negative pressure)	• Negative pressure in the pipe system	• Leak openings on water supply network (e.g. pipeline breaks, faulty joint seals) • Drowned air valves • Cross-connection or consumer connection back-flow		• Groundwater with contaminants such as sewage, contaminants from surface pollution (fuel, chemicals, fertilizers, pesticides, etc.) • Surface water with contaminants such as sewage, animal faeces, dead animals, etc. • Soil and dirt particles.

Table 3-3 *(continued)*

Events	Driving force	Pathway	Contamination source	
			Internal source	External source
Intermittent water supply	• Zero pressure and air in the pipe system	• Leak openings on water supply network (e.g. pipeline breaks, faulty joint seals) • Drowned air valves • Cross-connection or consumer connection back-flow		• Groundwater with contaminants such as sewage, contaminants from surface pollution (fuel, chemicals, fertilizers, pesticides, etc.) • Surface water with contaminants such as sewage, animal faeces, dead animals, etc. • Soil and dirt particles.
Pipe repair contamination	• Gravity • Water pressure	• Open pipe due to removal of damaged pipe section • Leak openings		• Groundwater and surface water with contaminants such as sewage, contaminants from surface pollution (fuel, chemicals, fertilizers, pesticides, etc.) • Surface water with contaminants such as sewage, animal faeces, dead animals, etc. • Soil and dirt particles.

3.4.2 Water age

Water age is a major contributor to the deterioration of water quality in pipe networks. The two main mechanisms for water quality deterioration are interactions between the pipe wall and the water, and reactions within the bulk water itself. As the bulk water travels through the distribution system, it undergoes various chemical, biological, physical and aesthetic changes that impact on the water quality, including microbial regrowth, nitrification, the formation of DBPs, corrosion by-products, sediment deposition, temperature increase, taste and odour challenges, etc. Depending on the hydraulic behaviour (water flow rate, velocity, pressure, etc.), finished water quality, pipe materials and deposited materials (sand, iron, manganese), these transformations will proceed to a greater or lesser extent (USEPA, 2002b). Besides, the water age can be dependent on pipe network sizing, network type (branch or looped), water supply and demand inconsistency, operational and maintenance errors (positioning/setting, opening and closing of valves, closed valves, water use, capacity loss, etc.) (AWWA, 2017b). One way or another, these all help increase the water age in pipe networks and thus need to be controlled appropriately.

3.4.3 Decay of disinfectant residual

There is a wide array of reasons for the rate of disinfectant residual decays in pipe networks, including high temperature, biological growth, water age, nitrification, organic (humic and fulvic acids) and inorganic (iron and manganese) disinfectant-demanding compounds, along with the augmentation of chlorine-demanding compounds caused by sedimentation and contamination intrusion. The decay of disinfectant residual will result in deficiency in inactivating and killing microorganisms that may pose potential health risks.

3.4.4 Formation of disinfectant by-products

Water treatment plants mostly use chlorine as a major disinfectant, even though alternative chemicals such as chloramine (chlorine reacted with ammonia to form monochloramine), chlorine dioxide, ozone and ultraviolet radiation have also been used as disinfectants, but to a much lesser extent depending upon feasibility (Nieuwenhuijsen et al., 2000). Chlorine, which exists as hypochlorous acid and hypochlorite in water, reacts with natural organic compounds (humic and fulvic acids) and inorganic materials (bromide and iodide) to form a wide range of unwanted halogenated organic compounds, including THMs and HAAs (Nieuwenhuijsen et al., 2000; AWWA, 2017b).

If bromide is present in the source water or is introduced during treatment, it will become oxidised by aqueous chlorine and then react with organic material to form brominated THMs and HAAs. Studies have shown that the rate of DBP formation is higher in water with an increased concentration of bromide (Krasner, 1999). As water travels in the distribution system piping and storage reservoirs, concentrations of THM increase as long as a disinfection residual is present. At high water ages, the brominated species may cease to form and the chlorinated species (chloroform) will continue to form due to the reaction of chlorine and existing organic matter. Although not currently regulated, iodinated THMs (I-THMs) can be formed when iodide is oxidised to hypoiodous acid by disinfectants (mainly monochloramine, but also free chlorine and ozone), which then reacts with organic materials. The I-THMs are believed to be more toxic than their chlorinated or brominated counterparts (Kargalioglu et al., 2002; Plewa et al., 2002; Woo et al., 2002) and can impart a strong medicinal odour to potable water.

The HAAs, in comparison to THMs, react differently within the distribution system. HAAs are typically highest in average residence time areas of the distribution system due to potential biodegradation at remote locations. Biological degradation is commonly found in areas with low disinfectant residuals, warmer water temperatures and higher water age, which typically equate to elevated biogrowth with the potential presence of HAA-degrading bacteria.

The HAA biodegradation potential is dependent on disinfectant residual and water age throughout the distribution system. If elevated disinfectant residuals and low biomass concentration are maintained throughout the system and the water age is low, the highest HAA concentrations are likely to be found at the maximum residence locations, not the average residence locations. Trihalomethanes and HHAs do not only cause taste and odour problems, but also potential carcinogens (cancer-causing substances); thus limits are set for THMs in drinking water in SANS 241: 2015 (Van Zyl, 2014). The type and quantities of by-products formed depend on a number of factors. The formation of by-products during chlorination depends on the amount and content of organic matter, bromine levels, temperature, pH value and residence time (Fawell and Nieuwenhuijsen, 2003). Uptake of THMs, generally the most common volatile disinfectant by-product, can occur not only through ingestion, but also through inhalation and skin absorption during activities such as swimming, showering and bathing (Nieuwenhuijsen et al., 2000).

3.4.5 Internal corrosion

An internal corrosion event is defined as the degradation of a substance or its properties due to a reaction with its environment. The term substance can be referred to as metal pipes, fixtures, pipe lining (e.g., cement lining) or an asbestos cement (AC) pipe. Water corrosivity depends on its physical and chemical characteristics. The nature of the materials with which the water comes into contact is also essential. For example, water that is corrosive to galvanised iron pipe may not be corrosive to copper pipe in the same system (USEPA, 1984). Physical and chemical actions between pipe material and water may cause corrosion. An example of a physical action is the erosion of a pipe elbow because of excess flow velocity in the pipe. An example of a chemical action is the oxidation or rusting of an iron pipe.

Biological growth in a distribution system can also cause corrosion by providing a suitable environment in which physical and chemical actions can occur. The actual mechanisms of corrosion in a water distribution system are usually a complex and interrelated combination of these physical, chemical and biological actions (USEPA, 1984). Two toxic metals that occur in tap water, almost entirely because of corrosion, are lead and cadmium. Three other metals usually present because of corrosion cause the staining of fixtures or metallic taste, or both. These are copper (blue stains and metallic taste), iron (red-brown stains and metallic taste) and zinc (metallic taste). The toxic metals lead and cadmium can cause serious health problems when present in quantities above the levels set by SANS 241: 2015. The other metals, such as copper, iron and zinc, when exceeding the set limits, can cause the water to be less attractive to consumers, and thus, may trigger them to use another, potentially less safe source (USEPA, 1984).

The corrosion products in the distribution system can also protect bacteria, yeasts and other microorganisms. In a corroded environment. These organisms can reproduce and cause many problems such as bad taste, odour and slime. Such organisms can also cause further corrosion themselves (USEPA, 1984). A large number of water quality parameters such as disinfectant residual, temperature, redox potential, alkalinity, calcium concentration, TDS concentration and pH value play an important role, both in the internal corrosion of pipe materials and the subsequent release of iron. The products of corrosion may appear in water as dissolved and particulate metals, and the particles may cause aesthetic problems because of their colour and turbidity if they are present in sufficient concentrations (NRC, 2006).

3.4.6 Leaching

A leaching event is the process whereby chemicals enter the water supply from the materials used in the distribution system and plumbing, other than by corrosion processes (Ministry of Health, 2017).

Taste and odour problems (see section 2.6.4.11) are the most likely outcome of leaching and permeation because most substances leaching into water from materials in the distribution system are non-toxic, present only at trace levels, or are in a form unlikely to cause health problems (Burlingame et al., 1994; Khiari et al., 2002). There are a few situations in which leaching may present a substantial health risk. By far the most significant is the leaching of lead from lead pipe, lead-containing solder and lead service connections. The monitoring of lead in tap water and the replacement of these lines are important (NRC, 2006). Other materials used in distribution systems that have the potential for leaching include PVC pipes manufactured before about 1977. These are known to leach carcinogenic vinyl chloride into water at levels above the maximum contaminant level (MCL) (USEPA, 2002c). Cement materials have, under unusual circumstances, leached aluminium into drinking water at concentrations that caused death in haemodialysis and other susceptible patients (Berend et al., 2001). Asbestos fibres may also be released from asbestos cement. The content of asbestos in water is regulated with an MCL, although utilities are not required to monitor for asbestos in the distribution system (NRC, 2006). Finally, excessive leaching of organic substances from linings, joints and sealing materials have occasionally been noted. Some of these substances may support the growth of biofilms, such that their use should be limited (Schoenen, 1986).

3.4.7 Permeation

Permeation events of piping materials and non-metallic joints can be defined as the passage of contaminants external to the pipe, through porous, non-metallic materials, into the drinking water. The problem of permeation is generally limited to plastic, non-metallic materials (USEPA, 2002c). Permeation by substances external to pipes and non-metallic joints may compromise the structural integrity of materials and allow contaminants to move from the external environment into drinking water (NRC, 2006). Research indicates that permeation, when it occurs, is generally associated with plastic pipes and with chemical solvents such as benzene, toluene, ethylbenzene and xylene (BTEX) and other hydrocarbons associated with oil and gasoline (NRC, 2006). These VOCs can readily diffuse through plastic pipes and migrate into water within the pipe (Stern and Lagos, 2008). Holsen et al. (1991) have reported permeation incidents in connection with plastic piping materials at abandoned industrial sites, near bulk chemical storage tanks and electroplating facilities, as well as at residential sites (adjacent to or near storage tanks at service stations or dry-cleaning operations). If sustained, contact with these VOCs may permanently degrade the integrity of the pipes (Stern and Lagos, 2008).

3.4.8 Biofilm and microbial regrowth

A biofilm is a layer of microorganisms in an aquatic environment held together in a polymer matrix (slime layer) attached to a substratum. Besides regrowth, the term refers to the recovery of injured bacteria during treatment and their starting to multiply in water (September et al., 2006). Biofilm occurrence is mainly influenced by the following factors (September et al., 2006):

- The presence of microbial nutrients in the water
- Characteristics of the pipe wall such as roughness and type of material
- Type and regularity of fouling control procedures (corrosion control)
- Microbial and chemical quality of the finished water entering the distribution system
- Water temperature and pH value
- Chlorine disinfectant residual
- Velocity of the water
- Integrity of the distribution network (cross-contamination, openings, external intrusions, etc.)

Detachment of the biofilm lining of the interior walls of the pipe has the potential to contaminate drinking water in water distribution networks. Transients can generate high intensities of fluid shear and may cause the re-suspension of settled particles, as well as biofilm detachment (Jung et al., 2007).

Excessive pressure resulting from the pressure transients may erode the lining material of the pipes in the distribution networks. This may lead to the contamination of water in the distribution network. These detached particles may be suspended or dissolved in water, depending on the nature of the materials. The consequence of the contamination by biofilm detachment depends on the type of pipe material. For steel pipes, the contamination may result in aesthetic effects as water can change the turbidity due to the presence of iron oxide, while for asbestos cement pipes, severe health implication may result from inhalation and ingestion (aerosols from showers and humidifiers). Moreover, the detached biofilm can lead to serious illness as the biofilms contain significant amounts of pathogenic bacteria. Often no disease symptoms will result. On occasion, however, health effects range from gastrointestinal illness (from ingestion) to pneumonia, i.e. from the inhalation of aerosols (San Francisco Public Utilities Commission, 2001).

3.4.9 Nitrification

Nitrification is the bacteriological conversion of ammonia to nitrate in a two-step process. Ammonia can occur naturally in the source water, or it can come primarily from the chloramination (as a disinfectant) process. Ammonia is first converted to nitrite, and nitrite is then converted to nitrate. Nitrate and nitrite are both primary contaminants. Nitrification affects the water quality by degrading chloramine residuals, consuming dissolved oxygen, increasing heterotrophic plate counts, decreasing the pH value, and increasing the nitrate and nitrite levels. While exceeded values of nitrate and nitrite may pose potential health risk of shortness of breath in infants and blue-baby syndrome. According to Telfer (2004), nitrification does not have any direct impacts on public health, but it is still an important process to control and ensure that it does not take control across distribution systems (Telfer, 2014). This is primarily because nitrification leads to a rapid loss of chloramine residuals, which are an important barrier in the management and protection of water quality in distribution systems. The loss of chloramine residual leaves the distribution system susceptible to microbiological contamination with potential public health implications (Telfer, 2014).

3.4.10 Cross-connections

Within distribution systems, undesirable points called cross-connections may exist where non-potable water is connected to potable sources. These cross-connections can provide a pathway for the backflow of non-potable water into potable sources. Backflow can occur either because of reduced pressure in the distribution system (termed back-siphonage) or the presence of increased pressure from a non-potable source (termed back pressure). Back-siphonage may be caused by a variety of circumstances, such as main breaks, flushing, pump failure or the withdrawal of emergency fire-fighting water. Back pressure may occur when heating or cooling, during waste disposal or when industrial manufacturing systems are connected to potable supplies and the pressure in the external system exceeds the pressure in the distribution system. Both situations act to change the direction of the water, which normally flows from the distribution system to the customer, so that non-potable and potentially contaminated water from industrial, commercial or residential sites flows back into the distribution system through a cross-connection. Cross-connections and back-siphonages provide the opportunity for large amounts of biological material to enter the distribution system (NRC, 1982). These events generally result in a noticeable change in water quality, including turbidity, increased content of solids and undesirable tastes and odours. During incidents of backflow, these chemical and biological contaminants have caused illness and deaths, with contamination affecting a number of service connections (USEPA, 2001).

3.4.11 Hydraulic transient flow

System flow control is an integral part of the operation a water distribution system, including the opening and closing of valves, and the starting and stopping of pumps. When these operations are performed very quickly, they can cause hydraulic transient phenomena in the pipe networks, which can result in system damage and/or water quality failure due to negative pressure and flow velocity if the transients are not minimised (Elbashir and Amoah, 2007). Any change in flow can result in transient flow (surge), which can result in a deterioration of the water quality because the surge can disturb deposits in the pipe or on the pipe wall. These operations may also cause low pressures that could allow the ingress of contaminants. The risk of significant surge, and hence water quality problems, is greater in long unbranched pipes than in branched pipes, because branched pipes reduce surge (Elbashir and Amoah, 2007).

3.4.12 Depressurisation

Depressurisation or a negative pressure event can also exist in water distribution systems due to a number of reasons, including power stoppage, main breaks, fire fighting, flushing and large demands. Negative pressure events will provide a conducive environment for external contaminants (e.g. contaminated ground water, such as sewage, and surface water contamination) to intrude into the network (via leak openings, cross-connections, drowned air, etc.) and deteriorate the quality of the drinking water.

3.4.13 Intermittent water supply

An intermittent water supply event can be defined as a system delivering water less than 24 hours a day due to a shortage of water or budget. Thus, between the hours of operation, when water is not transported, the pipe network gets zero pressure and air. Such conditions can be conducive for all possible contaminant sources, whether internal or external, to be intruded into the network and cause water quality problems. Therefore, an intermittent water supply system should be avoided where possible.

3.4.14 Pipe repairs and connections

When a section of the distribution network is isolated and opened to connect new pipes or repair existing ones, during the implementation, the contaminants can get into an empty pipe while water is shut down on a portion of the pipeline, reducing the pressure to atmospheric pressure in the isolated section, making the system vulnerable to polluted water, soil and other substances that may enter it, in addition to residual microbes if proper disinfection is not carried out. Moreover, after repairs and making new connections, as water is being led to a previously isolated pipeline, sand, debris and other potential contaminants, including microbes, get into the water. The impacts of contamination from such events depend entirely on the type of contaminants that move into the distribution system. These impacts include loss of turbidity, sickness, as well as odour. Microorganisms and nutrients that support microbial growth may gain access to water distribution systems during the installation and repair of components (NRC, 1982). During these processes, unprotected pipe sections may become contaminated by soil, sewage, storm runoff, animal faeces and debris, and can therefore contribute heavy loads of microorganisms to the pipe network directly.

3.4.15 Taste and odour

Pure water is clear and odourless. However, as water moves through the natural environment and human infrastructure, it picks up particulates and dissolved matter that may cause undesirable aesthetic events in terms of taste, odour and appearance. In general, water authority customers judge the cleanliness of their tap water based on these characteristics, regardless of whether it meets all other drinking water standards. Furthermore, such events may be the first sign of issues that can result in health risks (AWWA, 2017b). While the four main tastes (sweet, salty, sour and bitter) and colours are familiar and can usually be described, water authority personnel should be aware that it may be difficult for customers to accurately describe odours (Dietrich et al., 2014). The sense of smell is more complex than vision or taste, and there are trillions of odours and olfactory stimuli (Bushdid et al., 2014). However, the sections below discuss typical taste and odour categories.

3.4.15.1 Sulphur-induced taste and odours

If marshy, swampy, rotten egg or other odours are detected, VOSCs are most likely the cause. These are a combination of methylated olgosulphide compounds derived from hydrogen sulphide. Such compounds are produced by aerobic and anaerobic organisms in distribution system biofilms (Wajon et al., 1985; Heitz et al., 2000; Franzmann et al., 2001 and Heitz , 2002; adapted from AWWA, 2017b). Common sources of sulphur compounds are the conversion of inorganic sulphate to sulphide and the degradation of sulphur-containing proteins, including methionine and cysteine.

3.4.15.2 Disinfectant and disinfectant by-product-induced odours

Chlorinous, earthy-musty (62%) and medicinal (25%) are among the most common odour and taste complaints reported by customers in the USA (Suffet et al., 1995) and in Paris, France (Bruchet, 1999). Major complaints about the taste and odour of drinking water are directly related to chlorine (bleach-like smell: chlorinous), chloramines (swimming pool smell: chlorinous), chlorine dioxide (chlorinous, kerosene-like, cat-urine like). The chlorinous odour is pH dependent; odour intensity decreases as the pH value increases from 5.5 to 8.5 (AWWA, 2017b). Disinfection by-products are another source of taste and odour problems formed when disinfectants are added to the water. The best-known DBPs of chlorine oxidation that are related to taste and odour problems are aldehydes (origin: chlorination of amino acid, chloramination; causing: swimming pool odour), N-chloroaldimines (origin: chlorination of amino acids; causing: swimming pool odour), phenols (origin: chloramination of phenols; causing: medicinal, plaster-like odour), chlorophenols and iodinated trihalomethanes (origin: chloramination, chlorination; causing: medicinal, sweet, solvent odour) (AWWA, 2017b).

3.4.15.3 Leaching- and permeation-induced odours

Odorous compounds that leach from polymer pipes and distribution materials (e.g. gaskets and lubricants) into drinking water are well-known aesthetic issues (Marchesan and Morran, 2004; Whelton and Nguyen, 2013). To date, more than 150 contaminants that migrate from polymeric pipes have been identified and compiled (Whelton and Nguyen, 2013). Odours from polymer materials can arise from several sources, including the following:

- Leaching or migration of odorous chemical directly from the material.
- Chemical conversion of non-odorous compounds that leach or migrate from a material to an odorous chemical through chemical reaction in the distribution.
- Biochemical conversion of non-odorous compounds that leach or migrate from a material to an odorous chemical through a microbial reaction in the distribution system.

An overall aesthetic issue is the leaching of plastic-chemical-solvent odours directly from polymer materials. Specific odorous aromatic chemicals, including benzene (HDPE, epoxy, PEX), toluene (PEX, epoxy), xylenes (HDPE, epoxy, PEX Class B, PEX), propyl benzene (HDPE), styrene (HDPE), methy-t-butyl ether (PEX Class A and Class C, PEX; having and causing a sweet solvent-like odour), ethyl-t-butyl ether (PEX Class B, having and causing a solvent-like odour) and bisphenols (HDPE, epoxy, having potential endocrine disruptor), are known to leach from polymers into drinking water. New PVC pipes have minimal odours, although pipe-joining compounds release odours, and the leaching of vinyl chloride should be considered for health reasons as well (AWWA, 2017b).

3.4.15.4 Metal pipe corrosion-induced taste

Taste events due to the corrosion of metal pipes (copper, iron, zinc) are widespread (Omur-Ozbek, 2012; Dietrich and Burlingame, 2015). The corrosion of metal from public water distribution system pipes is the primary source of iron in tap water and can also be a source of zinc (AWWA, 2017b). Previous studies have also revealed that cupric, cuprous and ferrous iron at levels beyond set limits cause both taste and odour problems in drinking water (Glindemann et al., 2006; Dietrich, 2009). Aesthetic guidance for copper should be lowered to avoid the metallic/bitter flavour, astringent feel in the mouth, and blue-green staining of household plumbing fixtures (AWWA, 2017b). Ferrous iron causes a metallic flavour when its value falls between 0.003 and 0.17 mg/ℓ (AWWA, 2017b), while zinc can impart an astringent taste at >5 mg/ℓ (DeZuane, 1997; Keast, 2003).

3.4.15.5 Mineral-induced taste

Minerals occur naturally in source and drinking water, and have mainly a geological origin from the weathering and erosion of rocks and soils. Minerals in drinking water are desirable, as consumers prefer water that has some mineral content, typically between 80 and 350 mg/ℓ TDS, depending on the customer's preference (Bruvold, 1968; Bruvold and Daniels, 1990; Burlingame et al., 2007; Teillet et al., 2010; Platikanov et al., 2013; Garcia et al., 2014, adapted from AWWA, 2017b). An appropriate level of minerals is necessary to avoid corrosion. However, too much mineral content, which is often measured as TDS, conductivity or by individual cations and anions, results in a salty or mineral taste that customers find undesirable (AWWA, 2017b). Other major components that cause a taste problem include sodium (salty taste), potassium (salty/bitter taste), calcium (bitter taste), magnesium (bitter/astringent taste), chloride (salty, cation modulated taste), sulphate (salty and gypsum tastes), pH value (low: sour, bitter, metallic; high: soda, slippery feel) and TDS (objectionable taste for high values) (AWWA, 2017b).

3.4.15.6 Discolouration, sedimentation and scaling

Scale, when still attached to pipe walls, can reduce hydraulic capacity and also create surfaces that are ideal for growing bacteria. Although biofilms are generally expected to occur in any distribution system, water quality issues can be created when unmanageable quantities of bacteria begin to form and mature. Biofilms tend to exist to a greater extent in aged, tuberculated distribution pipes, providing a medium for the bacteria to grow more readily and be protected from the disinfectant (NRC, 2006). Sedimentation, on the other hand, occurs in pipes due to prolonged periods of relatively low velocity, allowing fine particles that have been carried through the treatment and/or distribution systems to settle in the pipes. Sediment may impact on water quality by increasing chlorine demand, providing a large surface area for bacteria to proliferate, and providing buried areas within the sediment where bacteria are protected from residual disinfectant (AWWA, 2017b). Changes in flow (magnitude and direction) within the water distribution system as a result of hydrant flushing, and valve and pump operation, can scour sediments, tubercles and scales from the interior pipe walls and degrade water quality. For example, when the water velocity is increased or flow direction is reversed, sediment deposited on the pipe walls during periods of low flow may be re-suspended and scales may detach. These materials may cause water discolouration, turbidity and sometimes odours (NRC, 2006). Customers may simply describe discoloured water, whether dissolved or particulates are present, as "dirty water" or use other common descriptions (Table 3-4).

Table 3-4: Common descriptions and potential sources of discoloured water events

Common description	Potential source
"Black water" or particles	Activated carbon fines and granules Anthracite particles Black rubber Bitumastic pipe coating material Manganese accumulation in pipes Lead-rich scale from distribution system plumbing materials or in pipes

Common description	Potential source
"Blue-green water" or particles	Copper-based particles Sand or dirt particles (very low concentration may be observed as a "greenish" hue in water)
"Brown water" or particles	Iron rust particles from water mains Manganese accumulation in pipes Biofilm or bacterial clumps attached to particles Sand or dirt particles
"Red water" or particles	Iron rust particles from water mains
"White or grey water" or particles	Aluminium-based particles Air in water Dip tube plastic (plastic pipe that brings cold water in water heater reservoir) Mineral deposits (such as calcium carbonate) Zinc-based particles
"Yellow water" or particles	Iron rust particles (low concentrations) Manganese accumulation in pipes Dissolved organic carbon Sand or dirt particles

Source*:* AWWA, 2017b.

As the concentration of dissolved or particulate matter of a contaminant increases, its colour may also change. An example of this is iron; at low concentrations, water appears yellow and changes to red or brown as the iron concentration increases (AWWA, 2017b). The sources of discoloured water are varied and need to be identified to mitigate discoloured water events. Sources include the internal corrosion of metal pipes, deterioration of plastic parts, and accumulation and release of metals, among others (see Table 3-4). In addition to identifying the source of the colour, the other major challenge is to identify the treatment or operational cause(s) for its appearance. These causes may be internal or external to the distribution system pipe network, and may also be continuous or temporary. Example causes include the following (AWWA, 2017b):

- Inadequate corrosion protection of metallic pipe.
- Accidental or international change in chemical dosages at the treatment plant or in the distribution system.
- Particle or turbidity breakthrough during treatment that accumulates in the distribution system.
- Re-suspension of settled particulate matter in typically low-flow and dead-end areas in the distribution system or storage reservoir.
- Vibration of existing pipe segments by nearby construction of new pipe or other infrastructure that dislodges material on the pipe wall.
- Water hammer or surges that may dislodge accumulated material on the pipe wall.
- Hydraulic releases or changes that may result from flow reversals, filling storage reservoirs and the improper use of spot flushing.

3.4.16 Natural disaster events

There can also be natural disaster events, such as earthquakes, that can shake the pipe networks and result in internal (biofilm detachments due to shaking) and external (due to negative transients leading up to external contaminant intrusions) contaminant intrusions.

3.5 CASE STUDIES

3.5.1 Overview

Previous sections focused on contaminant intrusion events in distribution systems by discussing the contamination sources, the driving forces and the pathways that lead to the contaminants being intruded into or caused in distribution systems. This section presents a review of case studies of contamination and intrusion events, their causes, potential consequences, resolution strategies, and the lessons learned. Compared to South Africa, a significant number of case studies of contaminant intrusion are available in the international literature. In this section, a number of these case studies are presented to provide an overview of the type of problems experienced and the authorities' responses to these events. To provide context to the case studies, it is useful to first consider the approach and general findings of one country.

3.5.2 Contaminant-intrusion events in the USA

Since 1971, the United States Environmental Protection Agency (USEPA), the Centres for Disease Control and Prevention (CDC) and the Council of State and Territorial Epidemiologists have maintained a collaborative surveillance system for collecting and reporting data on the occurrences and causes of waterborne disease outbreaks (Reynolds et al., 2008). For the occurrence to be included in the national surveillance system as a waterborne disease outbreak, two or more individuals must have experienced a similar illness after ingestion of the water, and epidemiologic evidence must implicate the water as the probable source of the illness. The stipulation that at least two people be ill is waived for single cases of chemical poisoning if water quality data indicates chemical contamination. State, territorial and local public health agencies have the primary responsibility for disease surveillance, detection and the investigation of waterborne disease outbreaks, and voluntarily reporting outbreaks to the CDC.

The CDC annually requests reports from state and territorial epidemiologists or from individuals designated as waterborne disease outbreak surveillance coordinators. When needed, information about water quality and treatment is obtained from the state drinking water regulatory agency. Because the waterborne disease outbreak surveillance system is voluntary, statistics do not reflect the true incidence of outbreaks or illnesses associated with the reported outbreaks. Surveillance activities, laboratory testing capabilities, requirements for reporting particular diseases and investigative priorities all differ among public health agencies. Not all waterborne disease outbreaks are recognised or investigated, and the extent to which waterborne disease outbreaks are underreported is not well known. The likelihood that individual cases of illness will be detected as a possible outbreak and investigated for a waterborne association varies considerably among localities. It has been estimated that only 10% to 30% of US waterborne disease outbreaks are reported (Craun, 1992; Craun, 1991; USEPA, 1990; Waterborne Diseases, 1986) and that outbreaks are more likely to be recognised and investigated in large community water supply systems (Reynolds et al., 2008).

The number of cases of illnesses reported in outbreaks is generally an approximate figure, and the method and accuracy of the approximation vary among outbreaks (Levy et al., 1998). In some outbreaks, only laboratory-confirmed cases are reported; in other outbreaks, cases are estimated from epidemiologic data. Although reporting of outbreaks is incomplete and the accuracy of case counts varies, waterborne disease outbreak data that identifies the types of water systems, their deficiencies and etiologic agents are considered useful for evaluating relative degrees of risk associated with different types of source water and systems, and the adequacy of current source water protection strategies, water treatment technologies and drinking water regulations (Levy et al., 1998). Documented waterborne disease outbreaks are primarily the result of technological failures or failure to treat the water (Craun et al., 2006).

From 1991 to 2002 in the USA, the majority of outbreaks occurred because of a lack of treatment, with untreated surface and ground water responsible for 1% and 32% of outbreaks respectively. Problems in the distribution system were responsible for a substantial proportion (23%) of outbreaks, making up almost a quarter of all reported cases. The causes of the remaining 12% of outbreaks are unknown. The distribution of the causes of the disease outbreaks is shown in Figure 3-1.

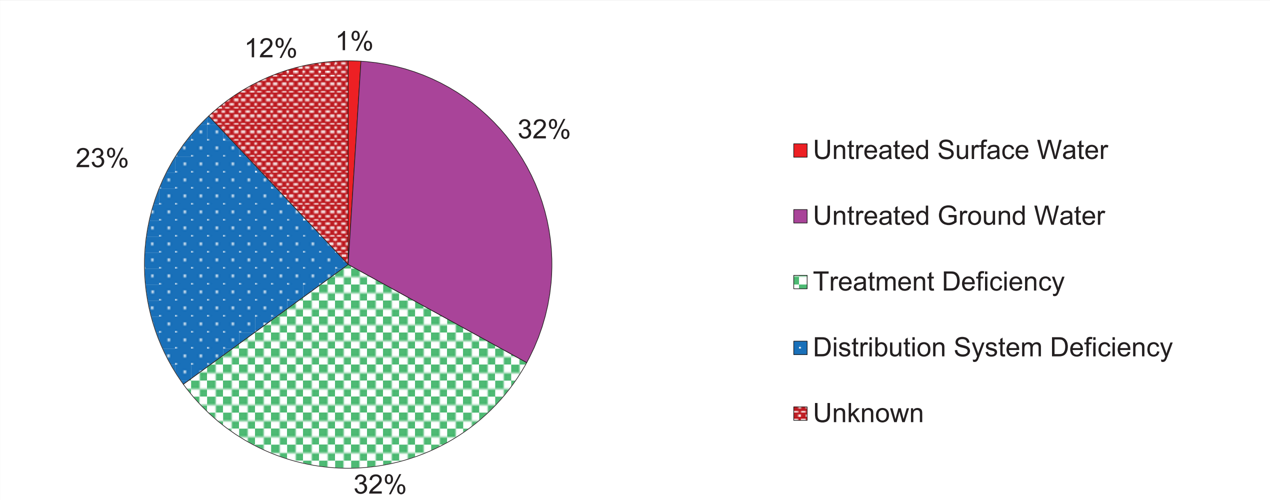
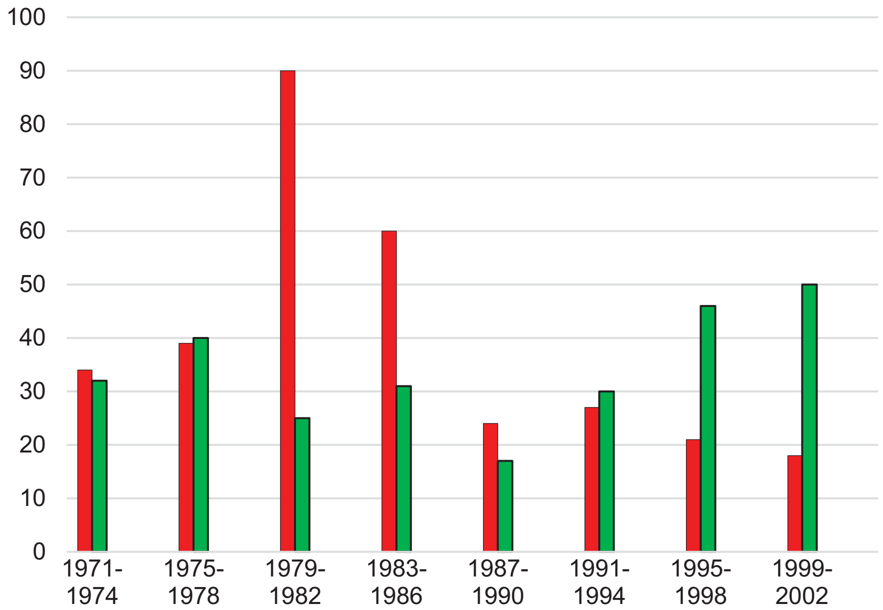


Figure 3-1: Documented disease outbreaks associated with drinking water by deficiency, 1991-2002 (n = 183) (Source: Adapted from Reynolds et al., 2008)

Although the four mentioned sites are of primary concern and must be taken into consideration at their utmost level, due to the limitations of the scope and aims of the project, the authors of this document will primarily delve into details of water contamination in water distribution deficiency, i.e. downstream of the treatment plant up to the metering point. From 1971 to 2002, there were 133 (17% of all outbreaks) documented waterborne outbreaks in the USA that were linked to distribution system contamination (Barwick et al., 2000; Blackburn et al., 2004; CDC, 1993; Kramer et al., 1996; Lee et al., 2002; Levy et al., 1998, adapted from Reynolds et al., 2008). The data of the last period included in this study (2001-2002) showed that five of 25 (i.e. 20%) of the documented waterborne outbreaks were associated with drinking water distribution system deficiencies. However, when only considering small community water systems, four of seven reported outbreaks (i.e. 57%) were linked to distribution system problems (Blackburn et al., 2004).

Figure 3-2 shows the number of reported outbreaks associated with community water systems for the full survey period. It can be seen from the figure that, although the number of outbreaks has shown a decreasing trend, the proportion of outbreaks associated with distribution systems has tended to increase. The reduction in total waterborne outbreaks is largely attributed to the promulgation of numerous regulations by the USEPA, including the surface water treatment rule, primarily aimed at reducing the risks of waterborne protozoa and improving water treatment (Pierson et al., 2001; Blackburn et al., 2004).



	1971-1974	1975-1978	1979-1982	1983-1986	1987-1990	1991-1994	1995-1998	1999-2002
Number of Outbreaks in CWS	34	39	90	60	24	27	21	18
% Due to Distribution System Deficiencies	32	40	25	31	17	30	46	50

Figure 3-2: Waterborne disease outbreaks in community water systems associated with distribution system deficiencies (Source: Adapted from Reynolds et al., 2008)

Figure 3-3 shows a breakdown of the causes of waterborne diseases linked to distribution systems for the period 1971 to 2000. The figure shows that cross-connections and back-siphonage were responsible for half (51%) of the outbreaks, followed by water mains contamination (a collective 33%) and contamination of storage facilities (16%).

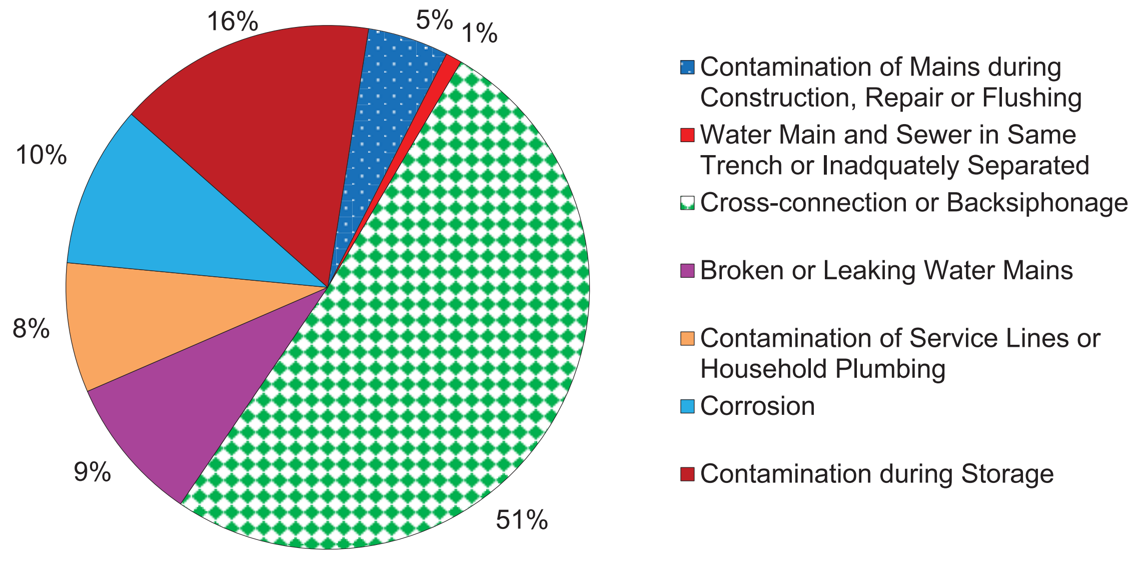


Figure 3-3: Waterborne outbreaks caused by distribution system deficiencies, 1971-2000 (n = 120) (Source: adapted from Reynolds et al., 2008)

3.5.3 Selected examples of cross-contamination events in the USA

3.5.3.1 Water contamination in Tennessee

In 1994, an outbreak of 304 cases of symptomatic illness occurred at a Tennessee correction facility housing 1,290 inmates (Kramer et al., 1996). Water for the facility was supplied by the municipal water system. Stool specimens from 110 of 423 inmates were positive for Giardia; 10% of inmates were also positive for *Entamoeba histolytica*. An epidemiological investigation was initiated after seven cases of giardiasis were reported in one month. Because an increased incidence of diarrheal illnesses was not found among municipal residents, it was initially suspected that contaminated food or homosexual activity might be routes of infection for the prisoners. Water became suspect, however, when it was learned that the facility had experienced a significant fall in water pressure resulting in low pressure for three days. High concentrations of Giardia (581 cysts/ℓ) were found in water samples collected at the facility, and a likely cross-connection with the water system was identified at the facility's wastewater pump station. In two outbreaks of nitrite poisoning in 1995, defective check valves allowed chemicals to contaminate drinking water (Levy et al., 1998).

3.5.3.2 Water contamination in California

In California, three people at a school became ill after consuming water from a system with a double-check backflow prevention valve that did not meet the industry standard and had badly deteriorated rubber gaskets. Chemicals used to treat a cooling tower and chilling system for the school's air-conditioning unit contaminated the drinking water through this double-check valve.

3.5.3.3 Water contamination in New Jersey

In New Jersey, drinking water was contaminated by boiler-conditioning fluids that flowed through a faulty check valve stuck in the open position. Six people developed acute cyanosis and were diagnosed with methemoglobinemia caused by nitrites in the conditioning fluid.

3.5.3.4 Contamination through pipe repairs in Cabool, Missouri

Between 14 and 29 December 1989, 45 water meters had to be replaced in Cabool, Missouri, because of extreme cold weather with temperatures as low as -28 °C (Geldreich et al., 1992; Swerdlow et al., 1992). In addition, two large water mains broke and were repaired between 23 and 26 December 1989. On 4 January 1990, the Health Department learned of 10 cases of individuals with bloody diarrhoea. An investigation found that 243 people had become ill with diarrhoea and abdominal cramps and these illnesses were epidemiologically associated with municipal drinking water. During the outbreak, 86 people had bloody diarrhoea, 32 people were hospitalised, and four deaths occurred. *E. coli* 0157:H7 was isolated from 21 stool specimens (58%).

The software application EPANET was used to develop scenarios to help explain waterborne contaminant transport. The computer models indicated that contaminants introduced at or near the sites of the water mains breaks would cause the highest levels of contamination in areas with the most cases. Water quality studies suggested that a single contamination event occurred. Sewage overflow into the streets near areas of meter replacements and water mains breaks may have been the source of water contamination. Wells used by the city were not disinfected, and hyperchlorination was not part of the mains repair procedure or meter replacements. The failure to disinfect, in conjunction with the main repairs, may have allowed microbial contaminants that entered the system to survive and disseminate. Laboratory tests showed that the outbreak strain could survive for long periods, and its lengthy survival in Cabool water probably contributed to the extensive spread of *E. coli* 0157 in the system over a period of several weeks.

3.5.3.5 Storage reservoir contamination in Gideon, Missouri

A waterborne outbreak of salmonella occurred in the town of Gideon, Missouri, in 1993. The CDC estimated that 44% of the local population of 1,104 developed gastroenteritis in relation to the outbreak (Clark et al., 1996). It is reported that seven people died (Angulo et al., 1997). Angulo et al. (1997) provided an overview of events:

- In late November 1993, seven cases of salmonella-related gastroenteritis were confirmed among local residents and reported to the Missouri Department of Health. Affected residents did not have recent similar food intake histories, but all had drunk water in Gideon.
- The water was tested and found to contain faecal coliforms.

Angulo et al. (1997) reported that school absenteeism increased by 250% in early December 1993. The sale of anti-diarrheal medicines rose by 600%. It was reported that, by the end of December, 15 residents had been hospitalised and illnesses were reported by 28 of 68 nursing home residents. Of these, seven died. Angulo et al. (1997) conducted a household survey (with a sample of 246), where all family members aged 18 years and over were asked about the occurrence of stomach-related illnesses during the time of the outbreak. They were also asked about compliance with the boil water order. More than half of the sample reported symptoms that matched the case definition. Of the 92 households studied, 91 were aware of the boil water notice. Nine had not heard about the notice until an information sheet was delivered a day after the notice had been issued. Thirty of the 92 households reported that at least one member of the family had drunk unsafe water during the notice period. Angulo et al. (1997) reported that the most common reasons for non-compliance were “forgetting” (44%), “not believing the initial notification” (25%) and “not understanding that ice should be made with boiled water” (17%).

Once the problem was identified, the following actions were taken:

- Residents were informed to boil their drinking water via a local radio station and a leaflet.
- An investigation was launched to determine the source of contamination, scope and magnitude of the outbreak, and the effectiveness of the boil water order (Angulo et al., 1997).

Investigations suggested that the likely cause of the contamination was from bird faeces or feathers in a stagnant water storage reservoir that was subsequently flushed into the water distribution system. Angulo et al. (1997) stated that the outbreak could have been avoided with proper water system maintenance and adequate ongoing disinfection. In their survey, Angulo et al. (1997) found that many residents continued to drink unboiled water after the order to boil water had been issued. They stated that the most likely reason that people did not comply was that they did not appreciate the severity of the situation; the initial boil water order gave no reason for being issued and did not mention the associated illness. They went on to note that compliance only improved after the provision of information sheets, which clearly explained the rationale and boiling procedure. They suggest that when boil water orders are issued, water supply operators, local movements and public health officials should ensure that all residents are adequately informed about the health risks and consequences of non-compliance. They further recommend that boil water orders are issued with easy-to-understand instructions.

3.5.4 Cross-connection contamination in Leidsche Rijn, The Netherlands

3.5.4.1 Overview

A cross-connection contamination event occurred in a green fields housing development (30,000 households) in the town of Leidsche Rijn in The Netherlands, which was supplied with dual non-potable and drinking water networks. A cross-connection between the non-potable and drinking water systems caused 200 people to be infected with gastroenteritis.

3.5.4.2 Contamination drivers

The incident was caused by human error. On 29 November 2001, after maintenance work, the drinking water system had been connected to the non-potable water system for flushing purposes. Due to an oversight, the cross-connection was not removed when the non-potable water system was put into operation again, and accidental higher pressure in the non-potable water system caused non-potable water to circulate into the drinking water pipes (Fernandes et al., 2007). On 3 December 2001, two residents complained about the unusual taste and odour of the tap water. A second incident occurred on 4 January 2002. After complaints about the taste of the drinking water of the owners of a single home, inspection showed that the house had been incorrectly connected to the drinking water system and the grey water system in the street. After this second incident, the connections of all the houses connected to the dual water supply system were checked. Five additional houses with incorrect connections were identified. Subsequently, two incorrectly connected houses were found in another project in Wageningen (Project Noordwest Wageningen) (adapted from Kelay and Fife, 2010).

3.5.4.3 Contamination event management

The local authorities took the following actions to deal with the problem:

- Samples of the tap water were taken on 4 December 2001, which showed an abnormal count of total coliform bacteria.
- On 5 and 6 December 2001, boil water advisories were issued.
- On 6 December 2001, a local doctor from the affected area informed the public health service of an excessive number of patients with nausea, vomiting and diarrhoea over the previous days.
- On 6 December 2001, the connection between the two dual systems was removed.
- On 17 December 2001, after five days of total *E. coli* counts below the mandatory level, the boiling advice was withdrawn.

After the incidents at Leidsche Rijn and Noordwest Wageningen, all dual water supply projects in The Netherlands that were operated by drinking water companies were terminated immediately. In the summer of 2003, new legislation prohibited the use of dual water supply systems on a larger scale. The only exception was the use of rainwater for toilet flushing on a local scale (one building or house) (Adapted from Kelay and Fife, 2010). Fernandes et al. (2007) reported that the decision was based on extensive environmental studies and risk assessments on six study locations. This example demonstrates how one mistake can be detrimental to a wider project (Hurlimann and McKay, 2007).

3.5.5 Cross-connection contamination in Nokia, Finland

3.5.5.1 Overview

A contamination event resulted in an extensive outbreak of gastrointestinal illness in Nokia, Finland, from November 2007 to February 2008. The main pathogens were norovirus and campylobacter (other pathogens were also found, including *E. coli,* Salmonella and Giardia), and more than 1,000 people were assisted at health centres or the local hospital's emergency department (Hulkko et al., 2008). The incident was reported as the largest waterborne outbreak ever recorded in Finland (Health Stream, 2008). It is estimated that approximately 8,000 people in Nokia and the surrounding areas suffered illnesses in relation to the incident (Accident Investigation Board of Finland, 2007).

3.5.5.2 Contamination drivers

The contamination occurred due to an "inappropriate" cross-connection between sewage effluent and drinking water pipes (Laine et al., 2010). Between 28 and 30 November 2007, approximately 400,000 litres of treated wastewater leaked into the clean water supply in Nokia city (Hulkko et al., 2008).

Health Stream (2007) reported that the contamination occurred “when a worker carrying out repairs opened a valve, which separated drinking water from water used to clean the sewage treatment plant. A pressure differential between the systems caused sewage effluent to enter the drinking water supply”. It was also suggested that the pipe connecting the two systems had been in place for 20 years, and contrary to the relevant regulations, the valve that controlled the connection had allowed water to flow in either direction (Health Stream, 2008).

3.5.5.3 Contamination event management

The contamination was discovered after two days, which coincided with reports of severe cases of gastroenteritis (Health Stream, 2007). However, in their investigation report, the Accident Investigation Board of Finland (2007) stated that, on the 28 November 2007, the waterworks received consumer complaints of an abnormal smell and taste associated with the tap water. Local police investigating the incident were also reported as saying that they believed the contamination to be accidental. However, they investigated whether the pipe that had permitted the cross-connection to occur had been illegally installed (Health Stream, 2007). Newspaper reports also said that the police were investigating two senior officials from the water authority for possible breach of duty in relation to the existence of an illegal pipe connection (Health Stream, 2008). Newspaper reports also documented the impact on local residents’ lifestyles. On 28 January 2008, it was reported that parents were reluctant to send their children to day care (Helsing, 2008a). Spiegel Online (2008) reported that the contamination had also had an impact on a local spa and a brewery, which had been closed until the water supply was deemed potable. After learning of the contaminated water, the brewery was said to have destroyed 100,000 bottles of beer. When the boil water order was lifted on 19 February 2008, newspapers reported that many residents were still cautious about drinking the water, despite declarations of safety. One resident was quoted as stating that he would continue to get water from the distribution centre for a further week: "Let's see for a while what happens to our neighbours who drink tap water.” (Helsing, 2008b).

In the investigation report, the Accident Investigation Board of Finland (2007) stated that consumer complaints about poor smell and taste associated with tap water were received on 28 November 2007. On this day, due to information technology failures, the waterworks had decided to obtain water from Tampere city. Staff therefore associated consumer complaints with the opening of the water network, and with pipe repair work that had recently been completed in the vicinity. In response to the complaints, decisions were made to flush the water network (Accident Investigation Board of Finland, 2007) and later issue a boil water advisory on 30 November 2007. The cause of the contamination was noticed on the same day. The advice to boil water was issued via the media, e.g. radio news, and the town’s website. On 3 December 2007, a newspaper reported that the Nokia Health Centre and the Nokia Waterworks had tried to warn the 10,000 residents living in the area of the tainted water network. In addition, the Finnish Broadcasting Company, text television services, the Nokian Sanomat daily newspaper, as well as the City of Nokia internet pages warned people of the danger. Nevertheless, some people apparently never received the message (Helsing, 2007a). In the same article, it was announced that written instructions about the use of water would be sent to all households.

The water company initiated a programme to hyperchlorinate and flush the water distribution system in order to clear the contamination (Health Stream, 2007). In addition, residents were required to run their taps in order to ensure that the contamination had been removed from all internal plumbing (Health Stream, 2008). Residents were advised to run their taps for 15 minutes twice a day (Helsing, 2007a). Water distribution points were made available for residents to collect bottled water (Helsing, 2008b). In addition, the Finnish Defence Forces were called in to supply water reservoirs and assist with door-to-door deliveries of bottled water to residents. Schools were closed for a week. In an effort to limit the secondary transmission of infections, health authorities urged people who were unwell not to return to work or school for at least two days after their symptoms had resolved (Health Stream, 2007).

The Accident Investigation Board of Finland announced during the outbreak that they had appointed a committee to examine the causes of the incident and the subsequent response by relevant authorities. Although the water authorities had aimed to declare the water supply as safe by 22 January, water tests revealed the persistence of norovirus in some areas of the city; in response, decontamination efforts were extended for a further four weeks (Health Stream, 2008). In addition to technical and regulatory recommendations, the Accident Investigation Board of Finland (2007) recommended that plans in relation to “preparedness and readiness” should be properly developed and, in particular, should specifically address issues of leadership and communications during waterborne outbreaks.

Health Stream (2007) reported that the Health Ministry had admitted that the outbreak had highlighted deficiencies in emergency response procedures, especially in relation to communication with the public during the crisis. A spokesman for the National Public Health Institute also stated that hospitals and local governments had trouble coping with the outbreak and more resources were needed for outbreak and emergency response programmes. In terms of how the incident was handled, the Accident Investigation Board of Finland (2007) stated that, from the beginning, the approach was piecemeal and inadequate. The contingency plan was insufficient, and staff at the waterworks had little training or education to provide the skills or leadership in handling such an event. They stated that crisis management and communication specialists should have been consulted.

3.5.6 South African case studies

An extensive search was conducted to find reported case studies of contaminant intrusion events in water supply systems in South Africa, both in the published literature and at local authorities. The search showed that very few cases had been reported, which is a clear indication that there is a lack of proper investigation and documentation of contaminant intrusion events in South Africa. This section discusses the two published case studies that were found, even though the second one is incomplete in that it does did not confirm the causal link between the intermittent supply and the disease outbreak.

3.5.6.1 Cross-contamination in Johannesburg

Johannesburg Water is an entity of the City of Johannesburg, South Africa, responsible for water and sanitation services within the city precinct. The utility provides services to 4.4 million consumers through an extensive distribution network of over 22,000 km of reticulation (WHO, 2014). As part of Johannesburg Water’s sewer refurbishment programme, a contractor was employed to replace and upgrade 2.6 km of existing sewer lines of varying pipe diameters and material within the vicinity of the Diepsloot Township, located to the north-west of the City of Johannesburg (WHO, 2014). In April 2012, the appointed contractor was excavating a section of the sewer network that was approximately 4 m deep, and replacing existing pipelines and manholes. This particular section of the sewer network was adjacent and parallel to a potable water pipeline feeding the Diepsloot area. When one of the sewer manholes was removed as part of the construction, an adjacent air valve of the water main moved, resulting in a break in the water main. Due to the break in the water main and the ongoing excavations on the sewer main, there was an immediate and apparent intermixing of water and sewage, leading to water contamination. Piped water supply was therefore interrupted to the whole of the Diepsloot area for 10 days, and an alternative supply was provided in water reservoirs for the duration of the incident. There were no known cases of customers being exposed to the contaminated water, as the water pipe break meant a disruption of service, and service was only resumed when it was ascertained that the water in the network was suitable for human consumption (WHO, 2014). Although there were other interventions and lessons learned, this case study focuses only on the infrastructure activities that led to the drinking water contamination (WHO, 2014).

The root causes of this incident have been studied and are described in a World Health Organisation (WHO) (2014) document as follows:

- ***Irregular network layout and fixtures:*** The horizontal distance between the water and sewer pipelines in this scenario was about 1.5 m, which is close considering that there was adequate space for the two pipelines to be placed further apart. Furthermore, the thrust block of the air valve (water pipeline) was built against the sewer manhole, as shown in Figure 3-4. This made the sewer and water networks interdependent and turned the sewer manhole into a structural support for the water pipeline. Both these factors do not conform to standard practice. Long distances between isolation valves on the water pipeline made its isolation more difficult.

- ***Inaccurate as-built drawings:*** While the proximity of the pipelines to each other was indicated on the as-built drawings, information on how the thrust block was anchored was not shown. Although the contractor could have exposed the manholes prior to demolishing them, there was no perceived need to do so; hence, the adopted plan of action. Had the thrust blocks been indicated on drawings, care would have been taken to ensure minimum disruption to services.

- ***Network operation and maintenance:*** Lack of valve maintenance also played a role as some valves were buried underground and could not be found during the drinking water contamination incident.

- ***Contractor capacity:*** The contractor's response to the incident was less than adequate, mostly due to lack of capacity in both experience and resources. This negatively impacted on the initial handling of the incident and extended the time between the incident and the restoration of services.

Figure 3-4: Water pipeline thrust block supported by a sewer manhole

The incident was of a magnitude requiring immediate attention and was accorded the highest level of emergency due to the extent of the problem. A crisis management team was constituted, comprising all critical functions as required by the Disaster Management Plan. The team was led by the company's executive management, and it was composed of members from operations, scientific services, capital investment, communications and stakeholder relations, among others. The team managed all activities aimed at restoring services and water quality to the Diepsloot area. Such activities included constant communication with the public through various media outlets on progress made in restoring the services. A decision was made to supply water through alternative means (reservoirs), as there was no secondary pipe feed to the area (WHO, 2014).

The water pipeline was repaired by the in-house teams in tandem with the contractor. An extended monitoring programme for the quality of the water was instituted, together with secondary dosing of chlorine. The main challenge with bacteriological monitoring was the 24-hour waiting period for the reporting of results before any decisions could be made. The service was finally restored after eight days when zero *E. coli* was consistently recorded (WHO, 2014).

The following were some of the key lessons learned from the incident that Johannesburg Water has incorporated into its daily operations to minimise the recurrence of a similar incident (WHO, 2014):

- Correct designs, construction and accurate as-built information are invaluable for the correct operation and maintenance of the networks and for minimising unintentional cross-contamination of drinking water with sewage.
- Network operation and repairs have a large impact on creating and spreading contamination and can be better managed to minimise contamination. This includes the proactive maintenance of valves and other network installations.
- Extensive water networks need to have facilities for secondary disinfection of the network.
- Rapid bacteriological testing and analyses that allow for the reporting of results within a few hours can greatly assist in decision making.
- Partnerships with other departments are important for accelerating service delivery and ensuring consistent service delivery.

3.5.6.2 Waterborne disease from intermittent water supply in Mbombela

On Sunday, 22 July 2018, the Ehlanzeni Communicable Disease Coordinator received notification from the Tekwane South Clinic about an increase in diarrhoeal cases seen at the clinic. The clinic had seen 53 diarrhoeal cases on 22 July 2018. Tekwane South Clinic was located in the Mbombela Subdistrict, Ehlanzeni District, Mpumalanga. The clinic reported that the increase in diarrhoea cases started on Friday, 20 July 2018 (14 cases). After verification of the increase of diarrhoeal cases, the District Outbreak Response Team (DORT) was activated. Cases were predominantly from the Tekwane South and Entokozweni areas in Mbombela Subdistrict (NICD, 2018).

As from 26 July 2018, more facilities started to report that they were exceeding their diarrhoea thresholds. All health care facilities in the Mbombela Subdistrict were then requested to do zero reporting of diarrhoea cases daily. An investigation was conducted with the aim of identifying case patients, identifying the aetiology, determining the magnitude of the outbreak, documenting exposure, identifying risk factors and suggesting measures for long-term prevention. Activities that were conducted included epidemiological, environmental and laboratory investigations. A total of 3,584 diarrhoeal cases were recorded from health care facilities from 20 July 2018 to 20 August 2018 in the Mbombela Subdistrict. Among all the cases where age was known, 43% were in children under the age of five.

The reported cases were interrogated to identify possible exposures and risk factors. No common event attended by the cases could be identified. The cases complained about the intermittent water supply to the community, as well as the high turbidity of the water. Results received for stool specimens indicated a multi-pathogen outbreak. The predominant pathogens that were detected included rotavirus, *Shigella sonnei*, norovirus and adenovirus. Water specimens were taken after remedial actions were implemented. These were negative for coliforms and *E. coli*. More results from stool and water specimens are still pending. Health promotion teams visited the affected communities to educate them about safe food preparation, good hygiene and the boiling of water. Residual chlorine was continuously monitored at the water treatment plant and distribution system (NICD, 2018).

3.6 SUMMARY

A water quality event leading to the deterioration of water quality can occur when three phenomena co-exist: the source of the contaminant, the driving force and the pathway. All potential water quality events that are likely to occur in water storage reservoirs, pumping stations and pipe networks are shown in tables 3-1 to 3-3, respectively. The events are categorised according to different possible locations of potential contaminants, driving forces leading to the contamination of water distribution drinking water by different types of contaminants, and pathways that could be followed by different types of contaminants.

CHAPTER 4: MANAGING DRINKING WATER QUALITY IN DISTRIBUTION SYSTEMS IN SOUTH AFRICA

4.1 INTRODUCTION

South Africa is a water-scarce country with an annual rainfall of only 492 mm, which is also unevenly distributed across the country. Government's main focus has not only been to extend the supply of treated water to all its citizens, but also to ensure that water meets acceptable water quality standards. Healthy communities require both adequate quantities of water and water of adequate quality (Water Wise, 2018). Life is water, but water of a good quality is health, since it makes a key contribution towards waterborne disease outbreaks, leading to morbidity and mortality across the country. Therefore, in line with its importance, the South African government has initiated and developed a wide variety of policies and strategies to manage the quality of drinking water throughout its history. The aim of this chapter is to present the South African framework for managing water quality in distribution systems. More specifically, the chapter will explore a wide variety of printed and distributed documents by reliable sources. These documents are all-encompassing and are based on their relation to this project and issues related to the quality of drinking water.

4.2 LEGAL AND INSTITUTIONAL FRAMEWORK

4.2.1 Background

According to many sources, in South Africa, the concept of universal access to water and sanitation was initiated after the end of the apartheid regime in 1994. In 1996, the new national government drafted a constitution depicting its vision of a novel, free country. Contained within this constitution was a Bill of Rights that provided South Africans with their first environmental liberties. Section 27(1)(b) of the Constitution of the Republic of South Africa (Republic of South Africa, 1996) provides that everyone has the right to have access to sufficient water and sanitation services.

For the first time in South African history, its citizens were legally entitled to "an environment that is not harmful to their health or wellbeing" (Republic of South Africa, 1996; adapted from CTPC, 2018) – a provision already commonplace in most of the developed world. Of the 40 million people living in South Africa at the time, more than a third were still denied access to a basic supply of water, while more than half lacked basic sanitation (Hattingh et al., 2007). The constitution mandates the Department of Water and Sanitation (DWS) with a responsibility to ensure that all South Africans have "equitable access to water supply and sanitation" (Muller, 2002; adapted from CTPC, 2018).

The DWS started the Community Water Supply and Sanitation (CWSS) programme in 1994, which targeted key areas for instituting water and sanitation systems. In the context of water quality management, two pieces of national legislation aim to give effect to this right: the National Water Act, Act No 36 of 1998, and the Water Services Act, Act No 108 of 1997. In addition to the national legislation outlined above, key regulations and bylaws are also discussed in order to address the primary legal obligations imposed on municipalities and water service providers in respect of water quality within a distribution system, and the reporting and management requirements where incidents occur, which may include emergency incidents.

4.2.2 Role players

A number of institutional stakeholders play a key role in managing the quality of the drinking water supplied through water supply distribution systems (WSDSs) for the public in South Africa (DWAF, 2005). These sectors ensure that the water supplied to consumers from source is safe, clean and does not have potential adverse health consequences. Section 1 of the Water Services Act defines the following relevant service providers in the context of the supply of water and sanitation services:

- **"water services authority"** means any municipality, including a district or rural council as defined in the Local Government Transition Act, Act No 209 of 1993, responsible for ensuring access to water services;
- **"water services institution"** means a water services authority, a water services provider, a water board and a water services committee;
- **"water services intermediary"** means any person who is obliged to provide water services to another in terms of a contract where the obligation to provide water services is incidental to the main object of that contract; and
- **"water services provider"** means any person who provides water services to consumers or to another water services institution, but does not include a water services intermediary.

The roles and responsibilities of each of the stakeholders and institutions are briefly described below.

4.2.2.1 Water services authorities

The primary responsibility for ensuring the provision of safe drinking water rests with the water services authorities (WSAs). The WSAs have a legal responsibility, as described in the regulations to the Water Services Act, Compulsory National Standards for the Quality of Potable Water (DWAF, 2005) to do the following:

- Monitor the quality of drinking water provided to consumers.
- Compare the results to national drinking water standards.
- Communicate any health risks to consumers and the appropriate authorities.

4.2.2.2 Department of Water Affairs and Forestry

The Department of Water Affairs and Forestry (DWAF) (now known as DWS) supports and regulates the role of WSAs with regard to drinking water quality by doing the following:

- Developing and maintaining a national Drinking Water Quality Framework (DWQF).
- Managing information, including a sector database and information-sharing system that covers key aspects such as tracking WSA monitoring systems and drinking water quality data.
- Undertaking periodic regulatory audits of the drinking water quality data and management systems of WSAs.
- Developing appropriate, practical and sustainable technical support documents and tools.
- Assisting WSAs by reviewing water services development plans to ensure that drinking water quality monitoring is included.

4.2.2.3 Catchment management agencies

Catchment management agencies (CMAs) are responsible for water resource planning and management at the catchment level, including the licensing of water use and discharges, monitoring abstractions and discharges, and overseeing land-use activities. The CMAs are also be responsible for the implementation of the national monitoring programmes that monitor resource quality at a catchment level (DWAF, 2005).

4.2.2.4 Department of Health

The Department of Health (DoH) supports the drinking water quality management function by doing the following:

- Collecting information on the incidence of waterborne diseases (e.g. diarrhoea) and the use of this information to facilitate interventions.
- Being the lead "early warning" authority and execution agent for medical intervention under emergency drinking water quality conditions.

At district municipality and metropolitan level, the environmental health officers support the drinking water quality management function by assuming the primary responsibility for health and hygiene education related to water and sanitation services, and undertaking drinking water quality monitoring as a routine audit function at point of use. The DoH's drinking water quality monitoring focuses on health risk-related constituents, particularly indicators of faecal contamination (DWAF, 2005).

4.2.2.5 Department of Provincial and Local Government

The Department of Provincial and Local Government (DPLG) supports the drinking water quality management function by allocating a municipal infrastructure grant, capacity-building grant and equitable share to address areas of need that impact on effective drinking water quality management (DWAF, 2005).

4.2.2.6 Civil society

Government is committed to promoting the active involvement of civil society in the provision of sustainable and affordable water services, including drinking water quality management. The Strategic Framework for Water Services notes that "the most important and effective monitoring strategy for the sector is strengthening the voice of the consumer". The DWAF should therefore establish mechanisms of engagement with civil society (organised groups of citizens) to ensure, among other things, that the drinking water quality concerns of consumers are addressed (DWAF, 2005).

4.2.3 Water Services Act

Section 9 of the Water Services Act empowers the Minister of Water and Sanitation to promulgate regulations that provide greater content in terms of the following, among other things:

- Basic sanitation
- Basic water supply
- Interruption in the provision of water services
- Quality of potable water
- Control of objectionable substances
- Disposal of grey water
- Use of effluent
- Quantity and quality of industrial effluent discharged into a sewerage system
- Water services audit as a component in the Water Services Development Plan
- Water and effluent balance analysis and determination of water losses
- Repair of leaks
- Measurement or control of water supplied
- Consumer installations other than meters
- Pressure in reticulation system
- Reporting of non-compliance

In accordance with Section 9 of the Water Services Act, the Regulations Relating to Compulsory National Standards and Measures to Conserve Water were published in Government Notice Regulation 509 of 8 June 2001.

A municipality clearly falls within the definition of a WSA, which similarly falls within the definition of a water services institution. In addition, a municipality may also be considered within the definition of water services provider (WSP) to the extent that it provides water services. A municipality (in the context of a WSA) is required to generate a water services development plan (Section 12 of the Water Services Act), which must set out the following, among other things:

"(iii) The proposed infrastructure necessary; …

(vii) The operation, maintenance, repair and replacement of existing and future infrastructure".

WSAs are also required to monitor the performance of WSPs and intermediaries, and to ensure that conditions, standards and contracts are adhered to (Section 27 of the Water Services Act). Furthermore, the "Minister and any relevant province" is required to ensure adherence to the required norms and standards by all water services institutions (Section 62 of the Water Services Act).

Where there is a failure by a water services institution to comply with its obligations, the Minister may intervene by provisionally requiring the relevant provincial authority to intervene and, where the provincial authority fails to intervene, or the interventions fail, the Minister may assume that responsibility themself, subject to the approval of the National Council of Provinces (Section 63 of the Water Services Act).

4.2.4 Drinking Water Quality Framework

The DWAF found that an unacceptably high incidence of poor drinking water quality occurs in rural areas in South Africa (DWAF, 2005) due to the following factors:

- A lack of understanding by WSAs regarding the requirements for effective drinking water quality management
- Inadequate management, including the monitoring of drinking water services
- Inadequate asset management
- Inadequate WSA institutional capacity (staffing, funding, expertise, education)
- Lack of intervention to address poor drinking water quality when detected

In recognition of these challenges, DWAF identified key stakeholders and appropriate mechanisms for their involvement in a task team and subsequent development of a Drinking Water Quality Framework for South Africa. This is a guideline and educational document and does not have any legal standing. The outcome of this project was a guideline document and a number of supportive tools to enable the effective management of drinking water quality and the protection of public health (DWAF, 2005).

The DWQF is based on an integrated system of approaches and procedures that address the key factors that govern drinking water quality and safety in South Africa. It focuses on a preventative risk management approach, which is comprehensive from catchment to consumer. This approach promotes an understanding of the entire water supply system, the events that can compromise drinking water quality and the operational control necessary for optimising drinking water quality and protecting public health.

Recognising the challenges facing WSAs in South Africa, a continual improvement approach is also advocated in the Framework, with emphasis on the fulfilment of minimum legislated requirements and the achievement of interim goals and milestones as set by the WSA to improve drinking water quality (DWAF, 2005). The DWQF addresses four key areas: institutional roles and responsibilities, system analysis and management, supporting programmes, and review and audit (DWAF, 2005). These are briefly discussed below.

4.2.4.1 Institutional roles and responsibilities

It was realised that the successful implementation of the DWQF requires the support and commitment of all water sector stakeholders. The stakeholders responsible for drinking water quality management in South Africa are identified and their roles are described.

4.2.4.2 System analysis and management

Effective management requires an understanding of the entire water supply system (from the catchment and its source water, through to the consumer, and back into the water system), an assessment of the hazards and events that can compromise drinking water quality, and the implementation of preventative measures and operational controls that are necessary to ensure safe and reliable drinking water (DWAF, 2005). As part of the drinking water system management, WSAs are required to undertake operational monitoring, which is used as a trigger for immediate short-term corrective actions to operational procedures, as required. A key element is the identification of parameters that control performance so that their status can be used to predict the ultimate output quality and provide adequate lead time for corrective action. Wherever possible, the online and continuous monitoring of key parameters should be undertaken (e.g. chlorine residual, pH value and turbidity) (DWAF, 2005).

Planning should be undertaken to establish appropriate procedures for the immediate preventative and corrective action that is required to re-establish process control when operational monitoring indicates that target limits have not been met. The adoption of internal operating guidelines that are more stringent than the South African National Standard (SANS) drinking water specification limits acceptable for lifetime consumption, and acting when these guidelines have been exceeded, will reduce the chances of exceeding the SANS 241 limits in the final product. Operating procedures should be documented and should include instructions on required adjustments and process control changes. They should also clearly define responsibilities and authorities, including communication and notification requirements. Documented procedures should include the actions required to be taken in response to exceedance of internal target limits. Where appropriate, these actions may include re-sampling, additional monitoring and/or confirming results by additional operational monitoring (DWAF, 2005).

The WSAs are also required to undertake drinking water quality compliance or verification monitoring to check that the barriers and preventative measures implemented to protect public health are working effectively. The verification of drinking water quality provides an assessment of the overall performance or compliance of the system and the ultimate quality of drinking water being supplied to consumers. This incorporates monitoring drinking water quality, as well as assessing consumer satisfaction. Drinking water quality compliance monitoring is a wide-ranging assessment of the quality of water after treatment before it leaves the treatment plant, in the distribution system and as supplied to the consumer.

Although demonstrating compliance with regulatory limits is necessary as verification, it should be recognised that the monitoring of drinking water quality is only one aspect of an overall management strategy to assure a safe and reliable supply of drinking water. The monitoring of drinking water quality should never be used to replace preventative drinking water quality management.

Monitoring consumer comments and complaints can provide valuable information on potential problems that may have gone unidentified in the performance monitoring of the water supply system. A consumer complaint and response programme, which details mechanisms for logging, recording and evaluating consumer complaints, should be established and documented for prompt response to any potential problems in the water supply system.

The WSAs are required to have a consumer service (Regulation 16 of Section 9 of the Water Services Act), which can serve as a conduit for consumers to report non-compliance to their WSA. However, notwithstanding the best possible raw water sources, adequate treatment infrastructure and optimal treatment processes, unexpected incidents can disrupt water supply and pose a significant health risk to consumers. The DWQF includes a drinking water failure emergency response model, which comprises three alert levels to respond to acute drinking water quality failures:

- **Alert Level I:** Routine problems, including minor disruptions to the water system and single sample of non-compliances (internal WSA response only)
- **Alert Level II:** Minor emergencies that require additional sampling, process optimisation and reporting or communication of the problem (internal WSA response only)
- **Alert Level III:** Major emergencies that require significant interventions to minimise public health risk (the engagement of an active emergency management team)

4.2.4.3 Supporting programmes

Support for effective drinking water quality management includes basic elements of good practice to ensure that the system has the capacity to operate and adapt to meet challenges. This includes the training of employees within the water sector, community involvement and awareness creation, research and development, the validation of process efficiency, and documentation and reporting systems. Appropriate documentation provides the foundation for the establishment and maintenance of an effective drinking water quality management system.

Documentation also provides a basis for effective communication within the organisation, as well as with the community and various stakeholders. A system of regular reporting, both internal and external, is important to ensure that the relevant people receive the information needed to make informed decisions about the management or regulation of drinking water quality. The DWQF recommends monthly, quarterly and annual reporting on drinking water quality performance to ensure a high level of transparency and public accountability. In acknowledgement of institutional capacity problems, the Framework also proposes a number of possible funding mechanisms that have been identified to support WSAs (DWAF, 2005).

4.2.4.4 Review and audit

Ongoing evaluation of water quality data and audit processes to ensure that the management system is operating satisfactorily provides a basis for continual improvement. The DWAF, as the sector regulator, will undertake drinking water quality management system regulatory audits where a wide-ranging assessment of sector performance (including compliance to national norms and standards) will be undertaken. A set of agreed drinking water quality management key performance indicators, measures and targets will be developed to assess the performance of WSAs when implementing the drinking water quality management system regulatory audit. The drinking water quality management project resulted in a number of documents and tools being developed to provide the water sector with the information needed to monitor, manage, communicate and regulate drinking water quality in order to protect public health (DWAF, 2005).

4.2.5 Blue Drop Certification Programme

The DWS is applying a multi-facetted and programmatic approach as a regulatory strategy to enable the progressive implementation of regulations that allow for both the maturity of the water sector and support developmental local government objectives. One of these approaches is that of incentive-based regulation. The concept includes the Blue Drop and No Drop Certification Programme for Drinking Water Management Regulation and the Green Drop Certification Programme for Waste Water Management Regulation (DWA, 2014).

Conventionally, water quality is managed through legislation and standards, and monitored by government. However, in a survey of municipalities conducted in 2004, it was found that more than 50% of the WSAs did not monitor the quality of tap water as required by law. In response, an Electronic Water Quality Management System was introduced to improve drinking water quality management and to allow the DWA to have access to information on the efficiency of regulation.

After the introduction of the eWQMS, it was found that all municipalities that receive money from government were monitoring the quality of their drinking water by 2007. Despite this improvement, there was an increasing understanding that monitoring drinking water for compliance was not sufficient to ensure the quality and safety of water delivered to consumers. For one thing, monitoring alone promoted reactive management instead of proper planning and proactive actions (DWA, 2014).

To address the limitations of a monitoring only approach, the DWQF for South Africa was introduced in 2005 and incentive-based legislation (Blue Drop and Green Drop programmes) in 2008. These programmes encourage the proactive management and regulation of drinking water quality by testing systems against excellence requirements, which, in turn, are based on legal requirements and international best practice (DWA, 2014). Later, the No Drop Programme, which was aimed at reducing water loss, was introduced and incorporated into the Blue Drop Programme. The handbook for the Blue Drop and No Drop programmes is divided into three major sections:

- ***Introduction and background:*** This section describes the regulatory process in terms of its aim of accelerating the adoption of water quality standards, sustainability and institutional excellence.
- ***Blue Drop certification and assessment:*** This section provides a detailed overview of each of the key performance areas that form the basis of the Blue Drop assessments, as well as a section on the No Drop requirements, including risk management, quality management and process control, drinking water quality compliance, local regulations, asset management and information management.
- ***Checklists and appendices:*** The final section contains checklists of all the data and information required for a Blue Drop assessment and a number of appendices that provide additional information.

The Blue Drop Certification Programme made a significant positive impact on the drinking water quality sector in South Africa. Significant improvements were recorded in the national average Blue Drop score. Average scores increased from 51.4% in 2009 to 67.2% in 2010, 72.9% in 2011 and 87.6% in 2012. The programme gives prominence to water safety planning as the basis for proactive, risk-based drinking water quality management. In 2009, only nine systems had water safety plans in place, while, by 2012, this number had increased to 579, with 269 of these adhering to international standards.

4.3 DRINKING WATER QUALITY MANAGEMENT

4.3.1 Overview

Section 9(1) of the Water Services Act mandates the Minister of Water and Sanitation to establish Regulations relating to Compulsory National Standards for the Provision of Water Services and the Quality of Drinking Water. According to DWAF (1996), the term water quality describes the physical, chemical, biological and aesthetic properties of water that determine its suitability for an intended use by ensuring that public health risks are eliminated, or at least minimised. These properties are mostly dictated by determinands that are either dissolved or suspended in water (DWAF, 1996). Water quality standards are defined as criteria outlining the desired condition of water for intended use, in this case domestic or potable use (DWAF, 1996). These water quality standards can serve as tools to measure the suitability of water for domestic consumption. According to DWAF (1996), using the water quality standards, the suitability of water for its intended use can range from completely unfit to being ideally fit for a specific use depending on the physical, chemical and biological determinands present in the water, together with the aesthetics.

Water quality is generally defined by a collection of upper and lower limits on selected possible contaminants in water (Maier, 1999). For water to still be fit for drinking purposes in the presence of various determinands, it is important that the determinands are present in a range of “no effects” concentration or level. Thus, the concentrations of determinands should not exceed the allowable limit.

If, at some point in time, drinking water in a distribution network has concentrations of any of the determinands exceeding allowable values, the water is said to have been contaminated. This may result in water users experiencing a range of impacts, including health, aesthetic (undesirable taste, odour and smell) or economic impacts (including increased cost due to scaling, corrosion or deposition in the distribution network) (DWAF, 1996). The determinands of water in water distribution systems can be grouped into three broad categories: physical, chemical and biological.

4.3.1.2 Physical determinands

Physical determinands of water are observable characteristics that describe the appearance of the water (Hickey, 2008). These include the clarity of the water, taste, odour and temperature. For water to be physically appealing, it must be clear in appearance or have low turbidity. The colour of the water must be low in concentration so as not to distract the consumer's attention. Water in distribution systems should be free of substances that may produce taste and odour in the presence of chlorine, or when using water for cooking purposes. It should also be free of trouble-producing organisms such as aromatic oils of algae or higher bacteria. The main physical determinands of water are the following (Van Zyl, 2014):

- ***Colour:*** purified drinking water has a bluish tint when viewed in large volumes. However, organic matter and chemicals such as iron, manganese and copper can give the water a different colour. Colour in the water is normally not harmful, but is sometimes deemed unacceptable on aesthetic grounds.
- ***Taste and odour:*** Pure water is tasteless, but, in practice, it contains many constituents that give it its taste and odour. While people normally consider the taste and odour of water to be pleasant, certain chemicals and substances created by living organisms such as algae, fungi and other microorganisms can give it an unpleasant taste or odour. These are normally not harmful, but are unacceptable on aesthetic grounds.
- ***Turbidity:*** Solids dissolved or suspended in water make water less transparent to light. Most water contains microscopic particles of clay or silt, as well as organic matter. High water turbidity may make water aesthetically unacceptable and indicate poor water quality by inefficient water treatment.
- ***The pH value:*** The pH value of water indicates whether it is acidic or alkaline. Liquids with a pH value below 7 are acidic (giving water a slightly sour smell). The pH value decreases with increasing acidity. Conversely, liquids with a pH value higher than 7 are alkaline (giving the water a soapy taste). The pH value increases with increasing alkalinity. The role of the pH value of water is important in controlling the many chemical and biological reactions in water.

4.3.1.3 Chemical determinands

The chemical properties of water are characteristics that indicate the chemical constituents present in water. These chemicals describe and give the potential reactions that could result from the water coming into contact with other materials and substances.

4.3.1.4 Biological determinands

The contamination of drinking water by biological contaminants (e.g. pathogens), which cause diarrhoeal disease, is the most important aspect of drinking water quality. The problem arises as a consequence of the contamination of water by faecal matter, particularly human faecal matter containing pathogenic organisms (Fawell and Nieuwenhuijsen, 2003). Drinking water is not, however, sterile, and bacteria can be found in the distribution system and at the tap. Most of these organisms are harmless, but some opportunistic pathogens, such as *Pseudomonas aeruginosa* and *Aeromonas* spp., may multiply during distribution given suitable conditions. A number of organisms are emerging as potential waterborne pathogens, and some are recognised as significant pathogens that give rise to detectable waterborne outbreaks of infection. The most important of these is *Cryptosporidium parvum*, a protozoan, gastrointestinal parasite that gives rise to severe, self-limiting diarrhoea and for which there is, currently, no specific treatment. Cryptosporidium is excreted as oocysts from infected animals, including humans, which enables the organism to survive in the environment until ingested by a new host (Fawell and Nieuwenhuijsen, 2003). The biological properties of water in water distribution networks are the result of the presence of biological and microbial organisms. It is inevitable that biological and microbial organisms will not be found in drinking water from the water distribution system. The biological and microbial determinands of drinking water are mainly as follows (Van Zyl, 2014):

- **Coliforms:** Under ideal circumstances, the presence of coliforms in a drinking water sample should indicate external faecal contamination of the water supply, which is the main premise behind the Total Coliform Rule. Although this concept has served the industry well, it is not without its flaws. Studies of coliform presence in distribution systems indicate that coliforms may be introduced via treatment breakthrough, intrusion events, main breaks, etc. Furthermore, on occasion, coliforms have been shown to multiply in biofilms, contributing to their detection in drinking water.

- **Heterotrophic bacteria:** These use organic carbon as a nutrient source and provide an indication of the general microbiological quality of water.

- **Cytopathogenic viruses:** These are a group of viruses that cause human diseases such as gastroenteritis, encephalitis, polio, meningitis, hepatitis, respiratory illness and diarrhoea.

- **Protozoan parasites:** These are present in water as cysts and thus have coverings (like the shell of an egg) that protect them against threats. This covering also protects them against chlorine, which means they can be transmitted through the water distribution system. The two most important protozoan parasites in water distribution are Giardia and Cryptosporidium, which both cause diarrhoea and vomiting in humans.

- **Somatic caliphates:** These are viruses that infect *E. coli* and certain related bacteria; thus, they may also be used as indicators of faecal pollution.

4.3.2 Regulations Relating to Compulsory National Standards for Provision of Quality of Drinking Water

Regulation 5 (as per the Amendment Regulations Relating to Compulsory National Standards for Provision of Quality of Drinking Water, 2016) deals with the quality of drinking water, and addresses the following:

- National standards for drinking water quality (SANS 241)
- Water safety planning
- Monitoring programme
- Water quality samples
- Provisions of drinking water during emergency situations
- Disinfection and other treatment arrangements

4.4 NATIONAL STANDARDS FOR DRINKING WATER QUALITY (SANS 241)

The SANS 241-1:2015 drinking water specification describes the minimum requirements for drinking water to be considered safe for human consumption. The SANS 241 limits are published by the South African Bureau of Standards (SABS), a body established in terms of the Standards Act, Act No. 24 of 1945, and operates in terms of the latest edition of the Standards Act, Act No. 29 of 2008, as the national institution for the promotion and maintenance of standardisation and quality with regard to commodities and services (FCS, 2018). The SANS 241 water quality requirements include the microbiological, chemical and physical properties of the water. Safe drinking water (that complies with SANS 241) does not pose a significant risk to health over a lifetime of consumption, including life stages with increased sensitivity (infants, babies, the elderly and the immuno-compromised). Appendix A provides an example of the allowable limits and ranges for physical, chemical and biological determinands.

4.5 WATER SAFETY PLANNING

4.5.1 Overview

The World Health Organisation and International Water Association (IWA) developed a proactive and holistic approach to drinking water quality management in the WSP concept. From this, the “catchment to consumer” drinking water quality management concept was developed (DWA, 2014). An integral part of the Blue Drop Certification programme discussed in Section 4.2.5 is the development of a Water Safety Plan. Due to the challenges faced by municipalities in developing WSPs, the WRC saw a need to assist municipalities, and subsequently a generic WSP for small community water supplies was developed. The WRC also saw the need to develop an easy-to-use WSP tool for municipalities. The municipal-based eWQMS was selected as the platform for making the tool available (Emanti, 2018).

4.5.2 Generic WSP for small community water supply

Since 1994, the South African government has directed its resources to ensure that the millions of under-serviced people in the country have access to a functioning basic water supply. To date, government has managed to provide clean, safe water to 18.7 million people and, in doing so, has exceeded the Millennium Development Goals (Hendricks, 2008). Water service delivery demands have resulted in an exponential growth of small treatment plants in the country, with many of these being situated in rural areas and with limited technical support. Management of these water supply systems has been very difficult, and WSAs have to rely on limited resources to ensure that the water supply meets the minimum standards in terms of quantity and quality (Thompson and Majam, 2009). As a developing country, South Africa faces many challenges in terms of providing water that meets the minimum standards for acceptable drinking water. These challenges are a result of the following (Thompson and Majam, 2009):

- Unplanned development: Informal housing settlements in the resource area and in urban or semi-urban areas make it difficult to control activities in the catchment area and to locate supply mains.
- Poor sanitation: Poor access to urban sanitation, especially from informal housing settlements, may result in the contamination of the water source and may also lead to the potential cross-contamination of water pipes.
- Locality (geographic factors): Some plants are situated in rural areas and may not have sufficient finance and/or equipment resource availability to measure the appropriate water quality parameters.
- Lack of system knowledge and technical skills: The operators and staff at the water treatment plants do not have the proper qualifications and technical training required to run a plant.
- Limited data availability: Many systems have only recently developed the culture of data collection and storage.
- Socio-economic factors: A large percentage of South Africa’s population is at or below the low-income mark and is most likely to use contaminated water sources as it cannot afford to access water sources of a better quality. Some cannot afford, or do not know how, to conduct treatment within their homes. This population group is at the greatest risk of infectious diseases and illness from poor water supply.

Although water service delivery in South Africa has reached great milestones, the quality of water produced according to drinking water quality standards cannot always be ensured. This is evident from the number of outbreaks that have occurred over time. The most recent incidents include Bloemhof in 2006, Delmas in 2005 and Kanana in 2004 (Thompson and Majam, 2009). A recent survey of disinfection efficiency at 181 small drinking water treatment plants across South Africa revealed the following critical findings (Thompson and Majam, 2009):

- Turbidity values at the point of consumption indicated that 46% of plants were compliant within Class I and 41% were compliant within Class II of SANS 241:2006.
- Free chlorine concentrations at the point of consumption indicated that 32% of plants were below 0.1 mg/ℓ and 48% were below 0.2 mg/ℓ. The target range according to SANS 241:2006 is between 0.2 and 0.5 mg/ℓ.
- At the point of consumption, 63% of plants were compliant for total coliforms and 66% were compliant for faecal coliforms.
- The majority of operators lack relevant technical skills and appropriate training for plant operation. Their qualifications range from 24% with Grade 10, 56% with Grade 12 to 20% with post-Grade 12 qualifications.
- Most plant supervisors and operators had no knowledge of the flow rates at which plants operated.
- Chemical dosing rates were determined by experience.
- The absence of a water quality monitoring programme in most plants was prominent. Some plants use an external monitoring group at least once a month, but do not receive regular feedback.
- The maintenance of equipment in some plants was not implemented.

According to the survey (Momba et al, 2007), the shortfalls noted were due to various issues, i.e. poor maintenance practices, lack of training and capacity building, poor working conditions, insufficient financial capacity and poor recording, documentation and communication (Thompson and Majam, 2009).

4.5.3 Benefits of using a Water Safety Plan

Water safety plans are a form of water quality assurance through a multi-barrier concept (WHO, 2014). The multiple-barrier principle implies that actions are required at all stages in the process of producing and distributing water in order to protect water quality. This includes source protection, treatment (when applied) through several different stages, the prevention of contamination during distribution (piped or non-piped) and maintenance within households. The role of indicators is seen as primarily a means of verifying the WSP in meeting water quality objectives, rather than a routine tool for monitoring water quality (Thompson and Majam, 2009). A WSP provides an organised and structured system to minimise the chance of failure through oversight or management lapse. The process provides the consistency with which safe water is supplied and provides contingency plans to respond to system failures or unforeseeable hazardous events. Water safety plans can be developed generically for small supplies rather than for individual supplies (Thompson and Majam, 2009).

4.5.4 Components of a Water Safety Plan

A diagram of the steps involved in conducting an assessment based on the WSP approach is presented in Figure 4-1 (Thompson and Majam, 2009).

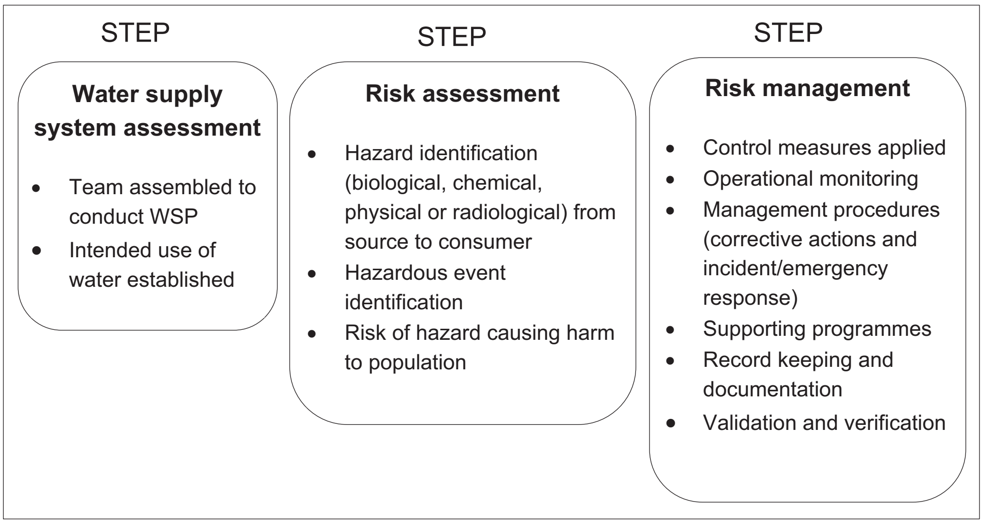


Figure 4-1: Steps to assess water supply based on the WSP approach (Source: Thompson and Majam, 2009)

A WSP includes three key components (WHO, 2014; Thompson and Majam, 2009):

- ***System assessment*** determines whether the drinking water supply chain (up to the point of consumption), as a whole, can deliver water of a quality that meets health-based targets.
- ***Identifying control measures*** in a drinking water system that will collectively control identified risks and ensure that health-based targets are met. For each control measure identified, an appropriate means of operational monitoring should be defined that will ensure that any deviation from the required performance is rapidly detected in a timely manner.
- ***Management plans*** describe actions taken during normal operation or incident conditions and document the system assessment (including upgrade and improvement), monitoring and communication plans, and supporting programmes.

The WSP guides both day-to-day actions and long-term planning. It identifies crucial aspects that collectively ensure the provision of safe water and aids system managers and operators to gain a better understanding of the water supply system and the risks that need to be managed (WHO, 2014). Some of these aspects include the following (Thompson and Majam, 2009):

- Regular monitoring and inspections that signal deteriorating water quality (and prompt action)
- Regular, ongoing maintenance to reduce the chance of failure by contamination
- Guidance for improvement and expenditure
- Additional training and capacity-building initiatives
- A list of where to get help, who needs to know the details of water quality, and how quickly they need to know it.

4.5.4.1 Web-enabled WSP tool

Initially, a spreadsheet-based tool was developed and distributed to municipalities and stakeholders to establish the requirements for a web-based tool. Following feedback and ongoing tool refinement, two web-based WSP tools are now available to municipalities: a WSP status checklist and a WSP tool (Emanti, 2018). The WSP checklist allows the user to rapidly assess progress in the WSP process. It considers typical steps of the WSP process and asks five key questions per step. A colour-coded “spider diagram” output is provided of the status (Emanti, 2018). The web-based WSP tool is used to assist municipalities with developing a WSP, and is largely based on the WSP Guidelines of both the WRC and the WHO, as well as other literature sources (Emanti, 2018).

4.6 WATER QUALITY INCIDENT MANAGEMENT

Regulation 5 of the Regulations Relating to Compulsory National Standards and Measures to Conserve Water set out above requires WSAs to notify the Director-General of DWS, as well as the Head of the relevant provincial DoH, where a health risk is identified from the results of the required routine sampling exercise. The steps to be taken to notify the consumer must include the following information:

"(a) that the quality of the water that it supplies poses a health risk;

(b) the reasons for the health risk;

(c) any precautions to be taken by the consumers; and

(d) the time frame, if any, within which it may be expected that water of a safe quality will be provided"

The City of Cape Town Water by-law also provides that the Director may take any reasonable measure to *"prevent or eradicate…imminent emergencies or situations"* (By-law 7(1)). Where such an emergency or situation arises on private property, the Director may, in writing, direct the owner to take any necessary measures. Where no owner can be found or they fail to comply with this directive, the Director may then take the necessary measures themself (By-law 7(2)). Where the Director takes measures on private property, they are required to report the incident to the City Manager (By-law 7(4)). In addition, where:

"action is necessary as a matter of urgency to prevent wastage of water, damage to property, danger to life or pollution of water, the Director may:

(a) without prior notice, cut off the supply of water to any premises; and

(b) enter such premises and do such emergency work, at the cost of the owner, and in addition, by written notice, require the owner to do such further work as he or she may deem necessary within a specified period" (By-law 7(5)).

A disaster is defined in the Disaster Management Act, Act No 57 of 2002, as:

"a progressive or sudden, widespread or localised, natural or human-caused occurrence which:

(a) causes or threatens to cause death, injury or disease; damage to property, infrastructure or the environment; or significant disruption of the life of a community; and

(b) is of a magnitude that exceeds the ability of those affected by the disaster to cope with its effects using only their own resources".

This Act is only applicable in circumstances where national legislation, such as the Water Services Act and its regulations, is not capable of dealing with the situation (Section 2). A disaster may be classified as a local, provincial or national disaster, depending on the extent of the situation (Section 23). Where a local disaster is declared, the municipality will be responsible for handling the situation (Chapter 5). Similarly, where a disaster is classified as provincial, the appropriate province will be in charge of the situation (Chapter 4). Where such an event occurs, the local municipality or province will be required to act in accordance with their disaster management framework and incident protocol management.

Incident protocol management is an essential element of the DWQF, Blue Drop Certification and the WSP (these are discussed in subsequent sections of the document) that is to be followed for any potential water quality incidents or events, including noting the following:

Protocols

- Alert level of the incident (I, II, III)
- Response times
- Roles and responsibilities
- Communication methods or vehicles

Incident registration

- Incident time, date, location and description
- Actions taken and date of resolution

Regulation 11 of the Compulsory National Standards and Measures to Conserve Water requires water services institutions to determine the quantity of unaccounted water in a supply zone, and to quantify the exact amount of water losses within a particular area. In addition, they are required to reduce the quantity of losses and maintain a record of these measurements (Regulation 11(2)). Where a water services institution, which includes a municipality, becomes aware of any "major, visible or reported leaks", it is required to repair the leak within 48 hours (Regulation 12).

Finally, pressure within the reticulation system is regulated. A water services institution is required to:

> "*design and maintain every water reticulation system installed after promulgation of these Regulations to operate below a maximum pressure of 900 kPa*" (Regulation 5(1)).

In addition, in circumstances where the prescribed pressure of 900 kPa could be exceeded within a water reticulation system,

> "*a water services institution must install a pressure control device to prevent the pressure at any domestic consumer connection from rising above 900 kPa*" (Regulation 5(2)).

4.7 OTHER RELATED DOCUMENTS FOR FURTHER READING

This section provides a summary of other South African documents related to water quality in water supply systems.

- Quality domestic water supplies guidelines: A guide for the health-related assessment of the quality of water supplies (1996). This document was published as a user-friendly guide to assist with the evaluation of drinking water supplies. It presented a simplified classification system that was widely successful, and has seen extensive use within the country. It has also attracted international interest (DWAF et al., 1998).
- Assessment of the occurrence and key causes of drinking water quality failures within non-metropolitan water supply systems in South Africa and guidelines for the practical management thereof, Water Research Commission, Pretoria, South Africa. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT-373-08.pdf.
- Guidelines for human settlement planning and design ("Red Book"), Volume 2: Chapter 9 – Water supply (2005), Department of Housing, Pretoria, South Africa. https://www.csir.co.za/sites/default/files/Documents/Red_BookVol2.pdf
- Technical guidelines for the development of water and sanitation infrastructure, 2nd edition: Chapter 14 – Reservoirs, p. 81 (2004), Department of Water and Sanitation, Pretoria, South Africa. https://www.dwa.gov.za/Dir_WS/TKC/Documents/.
- Introduction to operation and maintenance of water distribution systems, 1st edition, JE van Zyl, WRC TT 600/14, Water Research Commission, Pretoria, South Africa. http://www.wrc.org.za/Pages/Drought/4.2/Water%20loss/Water%20distribution%20systems_TT600-14.pdf.

- Water quality deterioration in potable water reservoirs relative to chlorine decay (2001), E Kruger, WRC 92/1/01, Water Research Commission, Pretoria, South Africa. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/921-1-01.pdf.
- Guidelines for ensuring sustainable effective disinfection in small water supply systems, pp. 36–40 and 71–75 (2005), MNB Momba and BM Brouckaeant, WRC TT 249/05, Water Research Commission, Pretoria, South Africa. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT-373-08.pdf.
- Quality domestic water supplies, Volume 5: Management guide, Department of Water Affairs, Department of Health and Water Research Commission. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT-162-01.pdf.
- Assessment of the occurrence and key causes of drinking water quality failures within non-metropolitan water supply systems in South Africa and guidelines for the practical management thereof, pp. 68 and 71–72 (2008), G Mackintosh and U Jack, WRC TT 373/08, Water Research Commission, Pretoria, South Africa. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT-373-08.pdf.

The following documents are recommended for a more in-depth reading of international best practice on water quality in storage reservoirs:

- Safe piped water, pp. 46–49 (2004), World Health Organization, Geneva, Switzerland. http://apps.who.int/iris/bitstream/handle/10665/42785/924156251X.pdf;jsessionid=5F677217B948B92BD42EE36CC1344FBD?sequence=1.
- Evaluation of potable water storage tanks in Newfoundland and Labrador and their effect on drinking water quality, pp. 5–25 (2011), Department of Environment and Conservation, Canada. https://www.mae.gov.nl.ca/waterres/reports/drinking_water/Tank_Report_July_12_2011.pdf.
- Protecting water quality by optimising the operations and maintenance of distribution systems, pp. 70–89 (2012), Rural Community Assistance Partnership, Washington, DC, USA. https://rcap.org/wp-content/uploads/2015/03/Distribution-Systems-guide.pdf.
- Finished water storage facilities, pp. 9–17 (2002), United States Environmental Protection Agency (USEPA), Washington, DC, USA.
- Guidelines for drinking water quality management for New Zealand, Chapter 16, pp. 647–684 (2017), Ministry of Health, Wellington, New Zealand. https://www.health.govt.nz/system/files/documents/publications/dw-management-drinking-water-guidelines-mar18-v3.pdf.
- Guidelines for human settlement planning and design (“Red Book”) Volume 2: Chapter 9 – Water supply, p. 198 (2005), Department of Housing, Pretoria, South Africa. https://www.csir.co.za/sites/default/files/Documents/Red_BookVol2.pdf
- Technical guidelines for the development of water and sanitation infrastructure, 2nd edition: Chapter 14 – Reservoirs, p. 81 (2004), Department of Water and Sanitation, Pretoria, South Africa. https://www.dwa.gov.za/Dir_WS/TKC/Documents/.
- Introduction to operation and maintenance of water distribution systems, 1st edition: Reservoirs and water towers, p. 91 (2014), JE van Zyl, WRC TT 600/14, Water Research Commission, Pretoria, South Africa. http://www.wrc.org.za/Pages/Drought/4.2/Water%20loss/Water%20distribution%20systems_TT600-14.pdf.

CHAPTER 5: FREQUENCY AND CAUSES OF CONTAMINANT INTRUSION EVENTS IN SOUTH AFRICA

5.1 INTRODUCTION

In the planning stages of this project, it was assumed that information on the frequency and causes of contaminant intrusion events in South Africa could be gathered from local, provincial and national authorities where records of such events are supposed to be kept. However, after investigating these sources widely, it was concluded that such records were not available. A different strategy to gather information on contaminant intrusion events was thus developed based on personal interviews with technical people experienced in the operation and maintenance of water distribution systems. These experienced technicians worked at the coalface in water service provision and thus had first-hand knowledge of the type and extent of potential contaminant intrusion events that occurred. This chapter begins with a description of the data collection methodology before presenting the results and discussing the implications for water supply systems in South Africa and the results of the study.

5.2 METHODOLOGY

This section describes the questionnaire used as the basis for the study, the methods used to identify and engage with respondents and the number and range of people interviewed.

5.2.1 Questionnaire

The questionnaire used in this study is included in Appendix B. The questionnaire was developed as a framework for a personal interview of a project team member, rather than one that is mailed to participants to complete on their own. Mailed questionnaires have low response rates and the researcher has no control over who completes them and how seriously they are taken. Personal interviews ensured that questions were asked consistently and allowed the researcher to gather additional and more directed information when the interview process revealed such opportunities. The questionnaire was directed at gathering in-depth information on contaminant intrusion events, their causes, effects and preventive actions being taken. The questionnaire was designed to be short and concise on the one hand, but also response friendly to support the intended aims and objectives of the research. The questionnaire consists of two main parts. The first part gathers information on the respondent, their municipality and their job description. The second part gathers information on contaminant intrusion events that occurred and are completed separately for each type of event. The questionnaire also contains a list of the different types of contaminant intrusion events that can occur in water distribution systems and was used to remind respondents of possibilities that they might have forgotten.

5.2.2 Respondents

Respondents were identified through known experts at municipalities, references from other respondents and scientific events such as the 2018 conference of the Water Institute of Southern Africa (WISA) held in Cape Town. Interviews were conducted with 21 participants, of which 14 (67%) were interviewed at WISA 2018. Based on judgement, expertise and responses given to the questions, respondents can be classified as basic, average or advanced. The basic respondents (14%) had a basic conceptual understanding of water quality deterioration events, their root causes and potential adverse impacts on the public. Average (43%) and advanced (43%) respondents were more critical in question analysis, and their responses were clearer. The respondents' position, experience, skills level and events reported are summarised in Table 5-1.

Table 5-1: Overview of people interviewed as part of this project

Participants' code	Position	Experience (year/ months)	Potential skills	Water quality failure events reported or experienced		
				Event category	**Event year**	**Frequency (year/month/ day)**
1	Depot Manager	20 years	Advanced	Cross-contamination	2012/04 (10 days)	Once in 20 years
2	Director Technical Services	5 years	Advanced	Cross-contamination	2014/03	Once in 5 years
3	HD Operational and Logistics	35 years	Advanced	Cross-contamination	2012/09	-
4	HD Operational and Logistics	35 years	Advanced	Pipe repairs	Many times	30% of all pipe bursts
5	Quality Scientist	2 years	Average	Pipe repairs	-	Once a week
6	Water Quality Technician	3.5 years	Basic	Pipe repairs	2016-2018	Once in 3 months
7	Lab Chemist	12 years	Average	Pipe repairs	2016-2017	Once in 3 months
8	Manager	-	Basic	Pipe repairs	Not much	Maybe once
9	City Engineer	20 years	Advanced	Reservoir	Mostly in summer	Once in 2 years
10	Other	-	Basic	Reservoir	2014-2016	3 times a year
11	Assistant Manager	10 years	Average	Reservoir	Mostly in summer	Once a year
12	Laboratory Technician	4+ years	Average	Reservoir	August-November 2015	Once in 5 years
13	Water Quality Technician	10 years	Average	Reservoir, pipe ageing	2017-2018	Once a year
14	Water Quality Technician	6 years	Average	Diesel pump	2016	Once
15	Area Manager	6 years	Average	Pump	May 2018	Once in 6 years
16	HD Operational and Logistics	35 years	Advanced	Water age in pipeline	-	Once
17	Programme Manager	40 years	Advanced	Water age in service pipeline	Summer	Ever since PP* pipe was introduced
18	Laboratory Manager	8 years	Average	Insufficient chlorine	-	Once in 8 years
19	HD Operational and Logistics	35 years	Advanced	Permeation (hydrocarbon)	Since plastic pipe was installed	5 times a year
20	HD Operational and Logistics	35 years	Advanced	Discolouration (tuberculation)	Up to 1995	Many
21	Water Quality Technician	7.5 years	Average	Miscellaneous (integrated type)	2010-2018	3-5 times a month

Note: Names of participants, their municipalities and other personnel details are kept confidential. PP* = Polypropylene

5.3 RESULTS AND DISCUSSION

The major water quality failure or deterioration events that have been experienced by the interviewed participants are described in the following sections.

5.3.1 Cross-contamination

Cross-contamination events seem to be at the top of the list of significant contaminant intrusion events occurring in South African water distribution systems. Even though the frequency of these events may be lower than other types of events, the degree of severity in terms of health risks is much greater. Therefore, every possible measure should be implemented to prevent cross-contamination events from occurring in water distribution systems. Several cross-contamination events were found that had negative health impacts, although the exact number of people affected was generally not known. These events had different causes and the respondents highlighted a few of them as follows:

- A cross-contamination event happened when an appointed contractor was excavating the manhole of the sewer network, which was being upgraded, and accidently hit the water pipeline's air valve located adjacent to the manhole. This resulted in the dislodgement of the air valve, which was supported by a concrete thrust block connected to the manhole chamber, which ended up damaging the drinking water pipeline. As soon as the pipeline was broken, the contractor isolated the water pipeline at an upstream point to stop the leakage, but without prior consultation with any stakeholders. This resulted in intrusion of the raw sewerage and contaminated water due to negative pressure created in the pipeline. Consequently, the event affected the downstream area for 10 days and people were reported to suffer from diarrhoea.

- In another case, excavation work was underway to fix a broken sewer line. During the work, a potable water line was struck by the excavator, which resulted in breakage of the water line. Upon isolating the potable water line, the contaminated water, being a mixture of drinking water and sewage, intruded into the pipeline. The main cause of this event was that the contractor did not have drawings of both the networks to identify their placement on the site. In addition, the team responsible did not properly coordinate their efforts and plan for handling various scenarios prior to starting the work. The event resulted in significant health impacts on downstream inhabitants, particularly children suffering from diarrhoea. The exact number of people affected is not known.

- Cross-contamination due to treated effluent is another critical issue in South Africa. The treated effluent is supplied to customers to use for functions such as gardening and toilet flushing. The treated effluent is of lower water quality and only suited for non-potable purposes. The treated effluent line is connected to private pipe or plumbing systems via a switch-over chamber, and a backflow preventer is normally installed to prevent backflow into the drinking water network. In this case, internal plumbing operations resulted in the backflow preventer being bypassed and allowing treated effluent to enter the potable water network. This problem is amplified when the potable pipe network is subjected to pressure management. The above situation, in combination with pressure reduction associated with peak demands, appears to have allowed a pressure differential in favour of the treated effluent. Treated effluent thereby entered the potable water system and a number of people suffered negative health impacts as a result.

5.3.2 Pipe repairs

Pipe breaks and leakage in pipe networks are one of the major concerns in the water supply industry internationally. Despite continued attempts to control them in the system, they seem to keep happening, even in newly installed systems. The number of pipe breaks and leakage incidents is dependent on several factors, including the ageing of the pipe networks, excessive pressure in the system, bad design and manufacture, and human activities such as traffic load and accidents.

During the repair of pipe failures, incidents happen where water contaminated with soil and bacteria enters the isolated pipe section or sediments in the pipe are stirred up when reconnecting the supply. This results in water quality deterioration affecting downstream consumers and potentially causing health problems. Thus, every care should be taken to ensure that repairs are conducted in line with the applicable regulations and standards. Since pipe breaks are common in pipe networks, South African water distribution networks experience a considerable number of pipe breaks. Several respondents commented on intrusion events caused by pipe repairs, summarised as follows:

- It was seen that insufficient flushing after pipe repairs led to discoloured water complaints by customers. Even though it did not necessarily pose health risks, discoloured water violates water quality standards and consumers were understandably unhappy with it. According to one respondent's experience, such events occur in 30% of pipe repairs. This problem could have been mitigated or prevented had the responsible officials had sufficient training and an understanding of the potential adverse consequences on water quality.

- Contaminant intrusions caused by pipe repairs occur frequently as indicated by the high proportion of respondents who had witnessed water quality deterioration, such as high turbidity, microbes, the intrusion of silt or soil particles or high levels of metal and nitrite that were caused during or after pipe repairs. The main causes included were non-adherence to standard operating procedures, lack of routine water pipe cleaning and inspection programmes, high pressure, insufficient routine maintenance and old pipes in the system.

5.3.3 Water storage reservoirs

Water storage reservoirs are key components of water distribution systems that are designed to store water to meet flexible downstream demand with constant inlet flow configuration. They also provide the capability to store the water for emergencies (e.g. when a pipe break or operational disruption occurs at the upstream side of the reservoirs) and for fire-fighting purposes. Thus, a water storage reservoir is composed of four types of volumes: active storage, emergency storage, fire-fighting storage and dead zones. In many cases, the water storage reservoir gets oversized considering the different types of volume discussed above. This leads to excessive water age and retention time in the reservoir, which is undesirable and results in water quality deterioration. These problems are exacerbated by high levels of dissolved and suspended solids passing from the treatment plant and then settling in the reservoir. Other problems, such as uncovered reservoirs, badly sealed access hatches and fittings, holes and cracks also play an important role in the deterioration of water quality. It was evident from the interviews that water quality problems caused by storage reservoirs are common in South African water distribution systems, mainly during summer when demand is high and reservoir water levels are drawn down lower, in combination with inadequate cleaning and maintenance programmes. In summary, the main causes that were raised were as follows:

- Low reservoir levels during high demand periods, particularly in summer months.
- Silt build-up on the reservoir floor due to inadequate cleaning. These sediments were reported to cause significant taste and odour problems and, in some cases, non-compliance of microbiological determinands was witnessed.
- Insufficient planning, cleaning and maintenance of storage reservoirs, coupled with a lack of proper communication between municipalities and water service providers. This was often caused by insufficient technical expertise to ensure that proper maintenance procedures were implemented in the system.

5.3.4 Pumps

Pumps are devices that are used to boost up heads or carry out liquid, i.e. water, from lower- to higher-level areas served by the distribution systems. They play prominent roles in delivering water to storage reservoirs, and in some cases in maintaining positive pressure in the system. Pumps are used in a number of locations with different aims, including between purification plants and water storage reservoirs, in bore wells and in distribution systems as booster pumps for sustaining minimum pressure. A few cases where pumps contributed to the deterioration of water quality were reported in the interviews. These can be summarised as follows:

- An incident of bad smell and diesel in drinking water was reported by a community in 2016. The result of investigations found that the tank of the diesel pump not being closed was the root cause of deteriorating water quality in reservoirs, the pipe network and at customers' taps. Since the pump vibrates during operation, the movement of the machinery caused the diesel to spill from its open tank and not only intrude into the bore well, but also through leak openings on the suction line.

- An incident of high turbidity was observed when a borehole pump was started after an extended period of non-use. Flow in previously static pipes caused sediment in the pipes to be suspended, resulting in high water turbidity. The event could have been prevented or mitigated had the pipes been flushed prior to delivering water to the customers.

5.3.5 Water age

Water age refers to the time water produced by the treatment plant spends in the supply system before it is delivered to consumers. Water quality deteriorates as it ages due to a reduction of disinfectant residuals (e.g. chlorine), microbial regrowth, corrosion by-products, nitrification and the growth of DBPs. Water age is affected by various factors, including the capacity of storage reservoirs, length and diameters of system pipes and consumption levels. The interviews identified one particular case where water quality deterioration was caused by excessive water age. Long water retention times were observed in a network pipe, which resulted in water quality deterioration and complaints by the public. The cause was found to be a closed valve that prevented proper circulation of water and resulting disinfectant residuals. The event could have been prevented if proper operation and inspection had been carried out. In addition, regular flushing and booster chlorination could have helped to prevent this problem.

5.3.6 Insufficient chlorine residuals

One of the respondents indicated an incident of low disinfectant (chlorine) residuals, which may have occurred frequently without being observed due to a lack of proper water quality control measures being in place. This was associated with an exceedance of the e-coli limit specified by SANS 241. The respondent suggested that the event could have been prevented if proper chlorine monitoring had been conducted at the treatment plant and reservoirs.

5.3.7 Exposed pipes

An event was reported of water stagnating in service pipes exposed to sunlight, which caused increased water temperature, algae build-up and bad taste in the water due to chemical reactions or leaching. Proper material selection and covering of pipes are essential to prevent water quality deterioration.

5.3.8 Permeation

Permeation is a phenomenon in which petroleum fuels (hydrocarbons) or their products diffuse through plastic pipe walls to enter the water. Such events may occur where petroleum fuels are predominant, such as near petrol stations, parking areas and chemical industries.

Based on the 21 interviews conducted, permeation events are quite frequent, happening approximately five times per year. These normally occur in service pipes between the mains network and customer premises where cars are parked. Oil spills from parked cars eventually reach the service pipes where permeation occurs. Permeation events can be prevented if plastic pipes are replaced by steel or copper pipes, or if the contaminant source is removed.

5.3.9 Discolouration

Discoloured water commonly occurs in cast iron pipes according to one of the respondents. While it was not specifically described what type of discoloured water (i.e. reddish, brown or black) the respondent had experienced, he reported that the discoloured water was caused by carbonation (having high alkalinity to protect pipes from corrosion). Such events are likely to decrease in South African water distribution systems as cast iron pipes are replaced by other materials.

5.3.10 Other

Some respondents revealed other concerns that play a role in deteriorating water quality, such as operation and maintenance errors, financial constraints and lack of capacity. The other causes that were raised during the interviews can be summarised as follows:

- Supply chain process delays prevent problems from being addressed on time and hinder proper maintenance practices.
- A lack of competent technical managers and plumbers results in practices that cause intrusions, for instance during pipe repairs and due to a lack of proper maintenance.
- A lack of budget to replace failing infrastructure.
- Insufficient chlorine contact time at reservoir outlets and boreholes to properly disinfect the water supplied.
- A lack of coordination among departments as developments, including informal settlements, are constructed and distribution systems are stretched beyond their design capacity, resulting in high water demand, low pressures and contaminant intrusions.

5.4 SUMMARY

It became apparent from the research that South Africa has done admirable work in developing a proper framework for the management of water quality in distribution systems. This is reflected in the establishment of WSPs, incident protocol management systems, the Blue Drop programme, legislation, standards and guidelines. However, it also became evident that the implementation of this framework has severe shortcomings leading to significant problems in preventing contaminant intrusion events in distribution systems. This is reflected by the lack of reporting and investigation of contaminant intrusion events that clearly happen frequently at local and national levels. In addition, the interviews with water practitioners revealed a lack of knowledge, experience and reporting of the contaminant intrusion events that occur, with a few exceptions.

Respondents had different levels of understanding of the requirements for reporting and investigating contaminant intrusion events. In many cases, the causes of observed contaminant intrusion events were not known and proper investigation of these were missing.

Another noteworthy point is the lack of proper coordination between stakeholders, such as DWS, DoH and accredited laboratories. Cases were reported where these departments were continuously redirecting cases between them, preventing progress to be made on investigations. It may be that one of the reasons for a lack of proper incident investigation is that the demarcation of responsibility between departments is not clear. South Africa evidently needs to invest in training and capacity building to ensure that a good framework for dealing with contaminant intrusion events in distribution systems is correctly implemented so that it serves the public as intended.

CHAPTER 6: BEST PRACTICE GUIDELINES FOR WATER QUALITY MANAGEMENT IN THE DISTRIBUTION SYSTEM

6.1 INTRODUCTION

This chapter explains best practice guidelines that help sustain and improve water quality in water supply distribution systems. Since the development of WSPs, a multi-barrier approach has been the best way of ensuring safe drinking water from source to tap. This chapter uses the WSP as a framework for presenting best practice guidelines. The WSP approach comprises 11 steps, which can be grouped into the categories of system assessment, monitoring and management, and communication. The steps are shown in Figure 6-1.

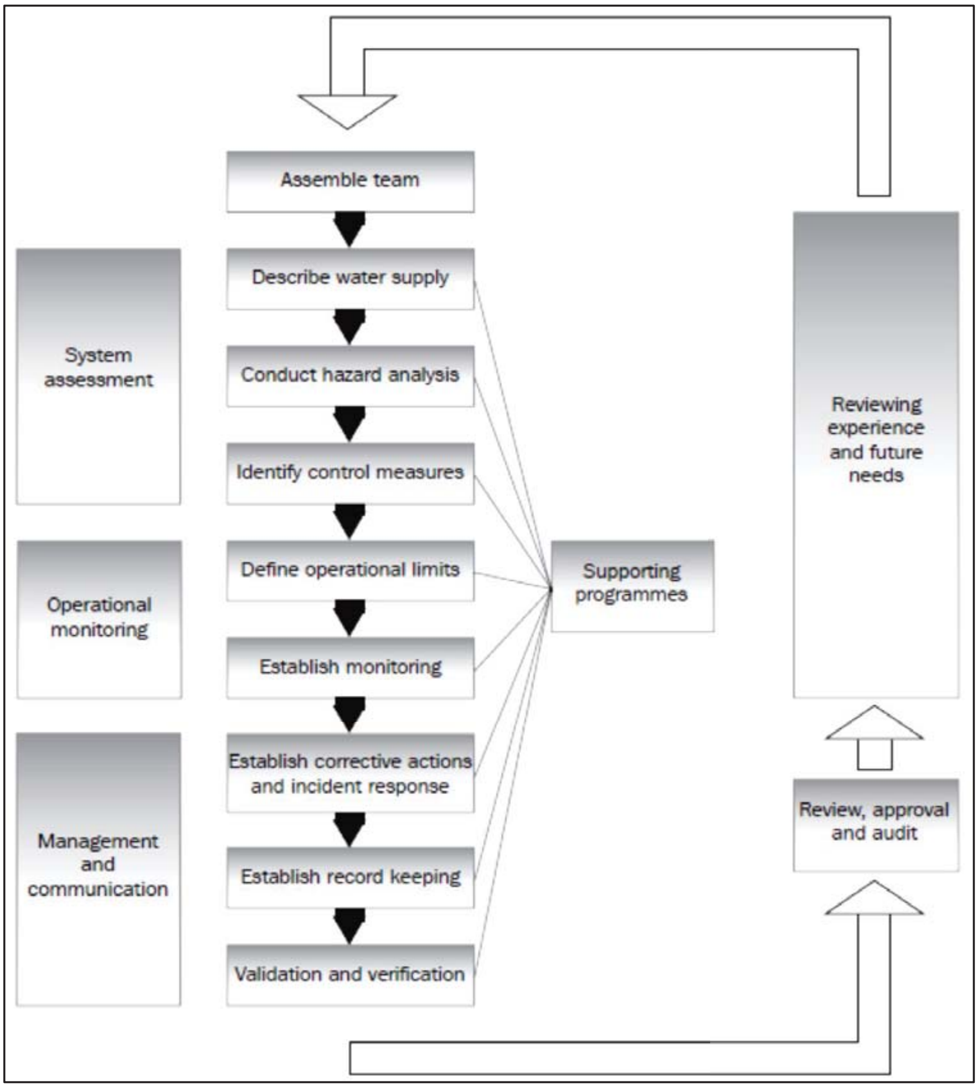


Figure 6-1: Steps in a Water Safety Plan (Source: Davison et al., 2004)

6.2 THE WATER SAFETY PLAN APPROACH FOR MANAGING WATER QUALITY IN DISTRIBUTION SYSTEMS

6.2.1 Overview

The aim of this section is not to write a new WSP, but to discuss best practice guidelines based on the work done in this project using the steps in the WSP as a framework. The latest WSP document of the WHO is a comprehensive and user-friendly document that includes a number of South African examples. In addition, the WRC has done excellent work in developing guidelines and tools for WSPs aimed specifically at the South African situation. In some instances, South Africa can be seen as an international leader in the WSP field. The documents related to the WSP include the following:

- The development of a generic water safety plan for small community water supply, WRC TT 415/09 (Thompson and Majam, 2009).
- Guidelines for using the web-enabled Water Safety Plan tool, WRC TT 515/12 (Jack and De Souza, 2012).
- Water safety and security: Emergency response plans, WRC Report No. 2213/1/16 (Jack and De Souza, 2016).
- Water safety and security: Emergency response plans – Guidance on developing and implementing emergency response plans for community water systems, WRC TT 656/16 (Jack and De Souza, 2016).

Where feasible, this section discusses best practice guidelines according to the municipal water storage reservoir, the pumping station and the pipe networks.

6.3 STEP 1: ASSEMBLE THE TEAM

The first step in developing a WSP is to describe the roles and responsibilities of the stakeholders who influence the safety of water quality in distribution systems and to assemble a WSP team that represents all stakeholders. This step is described in detail in the WHO guideline on WSPs for distribution systems (WHO, 2014) and other South African WSP published documents discussed in section 6.2.1.

6.4 STEP 2: DESCRIBE THE WATER SUPPLY

6.4.1 Storage reservoirs

Municipal storage reservoirs are used to accommodate demand fluctuations without adversely affecting hydraulic integrity. They are important for ensuring continuous water supply to consumers during periods where the supply from the source is interrupted, for instance due to the maintenance of treatment plants, upstream pipe bursts or contamination incidents (Ainsworth, 2004). Water storage is found in different forms, including elevated reservoirs, standpipes, aboveground reservoirs and underground reservoirs. They are also made from different materials such as welded steel, bolted steel and reinforced concrete (DEC, 2011).

It is important that each responsible authority, be it a WSA or a WSP, should have comprehensive documentation for each of their storage reservoirs, including construction drawings and a maintenance record file, which should include details of all maintenance, inspections and cleaning that have been performed.

6.4.2 Pumping stations

Pump capacity criteria are based primarily on water demand. Pumps are sized to provide the maximum day demand in cases where storage is available to meet peak hour, fire and emergency demands. If storage is not available, the latter three considerations will impact on pump sizing (AWWA, 2017b).

Designers must consider the full range of possible demands, including minimum, average and maximum demands, and select a pump or pumps that will operate within the manufacturer's recommended operating range under the range of anticipated demand conditions. Pump sizing typically starts with maximum day demand conditions (design flow) and pressure design criteria (design head). A pump curve describes the relationship between flow and head for a given pump, and pumps operate at different efficiencies along this curve.

The operating point for a given centrifugal pump in a given system is determined as the point at which the pump curve intersects the system head curve. System head curves are graphic representations of the first law of thermodynamics (Bernoulli's equation for water) and are calculated as a function of the elevation (static head) and head loss in the system. System curves can be calculated for different design conditions, such as for high and low tank levels. System curves can also be developed for different demand conditions, different pipe roughness coefficients and multiple pumps running in parallel. To properly size a pump, multiple system curves should be developed to represent the full range of operating conditions that the pump or pumps are expected to experience in the system. The most efficient pump selection is one with a curve that crosses the average day system curve (i.e. the curve on which the pump will operate for the majority of the time) at or near its best efficiency point, and otherwise falls within the envelope of all the system curves (AWWA, 2017b).

The desired head is related to system pressure criteria. Most municipalities seek to maintain system pressures of at least 24 m at all times of the day. In some cases, lower pressures are maintained in order to reduce leakage through pressure control.

Water authorities must also size pump stations for the proper firm capacity. Firm capacity is defined as the capacity of the pump station when the largest pump is out of service. For systems with storage, pump stations are typically designed to ensure that existing and future demand conditions can be met with the installed pumps. However, it is important from both hydraulic and water quality standpoints to not oversize individual pumps for future demand conditions. Multiple smaller pumps are often a better choice as they function more efficiently under existing demands. Multiple pumps of different sizes or variable-speed pumps can also be considered to accommodate a range of demands. Providing space for future pumps allows flexibility, while avoiding excessive installed capacity under existing conditions (AWWA, 2017b).

Pump capacity should always be considered in conjunction with pipe and storage capacity. A capacity restriction in any given area could potentially be resolved using a pump upgrade, pipe improvement, storage improvement or a combination of these (AWWA, 2017b).

Water distribution networks consist of several components, including pipes, control and isolation valves, fire hydrants and water meters. A number of South African documents deal with water distribution networks, including designing network capacity, operation and maintenance, the corrosion control of steel pipes through coating or lining, and biofilm formation and control. In the following sections, the main issues of the water supply distribution network are discussed in relation to water quality.

6.4.3 Pipes

The primary design criteria for pipe capacity are velocity and pressure. The goal is to select pipe sizes that are sufficient to prevent excessive head losses and adequate pressure at peak flow rates (including under fire flow conditions).

Fire flows impact on both pipe and storage sizing and can be the dominant factor in pipe sizing. These can be found in the published documents discussed in the previous chapter, particularly DWA (2014) and Van Zyl (2014). Determining system pressure in pipes under existing or future conditions can be accomplished in different ways.

To investigate an existing pressure issue, pressure gauges are installed in accessible locations such as hydrants and pumping stations. Several options exist for online distribution pressure monitors that can detect low pressures during various demand conditions and over long periods of time. However, pressure measurements cannot predict pressure in a network under future demand conditions when operations are significantly different and modifications are made to the system. Hydraulic models have to be used for this purpose. Models can, for instance, assist in identifying higher elevation areas where low-pressure issues are most likely to occur.

6.4.4 Valves

Isolation valves are sized based on the pipe diameter and are located at regular distances to allow segments of the distribution system to be isolated. Control valves are used to make operational changes to the distribution system and include pressure-relief valves, pressure-sustaining valves, throttling valves and check valves. Size, type and settings are system specific and depend on the valve's intended purpose. Pressure-relief valves, for example, are often used in low-elevation areas. The use of pressure-relief valves to avoid over-pressurisation can help reduce water loss. However, this can also lead to higher water age in the pressure-relief valve zone due to isolation from surrounding demands. Pressure-relief valves can be used for fire protection at zone boundaries where the boundary needs to remain closed unless a certain low pressure is reached during a fire-flow condition. The pressure setting allows the valve to fully open, providing flow across the zone boundary as needed during a fire. Valve settings and control should be determined with both hydraulic and water quality goals in mind. For example, allowing more flow through pressure-relief valves by having a small bypass line (approximately 1 inch in diameter) that is open at the zone boundaries can relieve pressure at both sides of potential dead-ends and improve water age (Cruikshank, 2010).

6.5 STEP 3: CONDUCT HAZARD ANALYSIS

Key hazards within distribution systems should be identified and assessed. These include faecal contaminants, microbial growth and biofilms, chemicals and materials, DBPs, high pH (concrete pipes), water treatment chemicals, aesthetic issues, etc. In addition, risks associated with hazardous events should also be identified and assessed. These include risks such as intermittent water supply, physical faults leading to ingress of contamination, illegal connections, leakage and low pressure, plumbing issues, the management of storage reservoirs, securing assets to prevent sabotage, construction work, renovations and repairs, the release of hazards from materials and equipment, including corrosion and scaling, treatment process changes, microbial growth and biofilms, etc. In this document, hazards and hazardous events are explained as determinands, contaminants and their location, and events resulting from the driving force, pathways and contamination source, which can be found in Chapter 2 and thus do not need to be discussed further here.[1]

6.6 STEP 4: IDENTIFY CONTROL MEASURES

Identifying control measures includes describing control measures, such as leakage detection and repair, pressure control, managing disinfectant residuals and DBPs, using appropriate materials and chemicals (including certification), controlling biofilms, design controls (including water quality specifications), cross-connection controls, asset security control, etc.

[1] For risk assessment, refer to WHO (2014), the published South African documents mentioned in Section 6.1, and SABS (2015), where this is explained extremely well.

In the following sections, control measures in terms of best practices (more from an engineering, operational and design perspective to help control water quality in water supply distribution systems) of storage reservoirs, pumping stations and pipe networks are discussed.[2]

6.6.1 Storage reservoirs

Water quality in storage reservoirs can be improved through hydraulic measures such increasing the turnover rate, adjusting fill and drain schedules (deep cycling), altering the inlet-outlet configuration, baffles and by forced mixing. Water quality can also be improved through chemical measures such as increasing the chlorine residual, shock chlorination and aeration (RCAP, 2012).

The turnover rate of storage reservoirs can be increased by decreasing storage volume, partially draining and refilling, and changing high and low levels based on seasonal water usage variations. Operators may need to close down some storage reservoirs during low-usage seasons or operate them at lower levels. However, it is important to ensure a certain minimum storage at all times for emergency purposes (e.g. a supply pipe failure). A minimum water level may also help prevent the re-suspension of sediments.

Deep cycling is accomplished with large water level fluctuations that facilitate mixing and help increase turnover rates. However, operators should avoid rapid filling when the tank is unusually low, since this can cause scouring and sediment release. Deep cycling may not achieve mixing of the upper layers in a highly stratified reservoir.

Even in a storage facility with a fast turnover, dead zones can occur due to thermal stratification and short-circuiting. Adequate mixing can break up stagnation and promote consistent water quality. Passive mixing systems use nozzles (water jets), separate inlet-outlets and baffles. Baffle walls can be added to the storage facility to make the interior “channel-like” and enhance plug flow. This will make water age more uniformly and reduce short-circuiting. Active mixing uses mechanical mixers. In both cases, the goal is consistent water quality and water age throughout a reservoir.

Increasing the chlorine residuals of water prior to storage will increase contact time and may thus achieve better disinfection. It may also be necessary to boost chlorine residuals at the reservoir outlet to ensure that adequate disinfectant concentration can be maintained in all parts of the distribution system. Chlorine is usually dosed continuously, paced by flow, or it can be added in batches. The choice of chlorine dose (concentration) and location depends on several factors, including DBP formation considerations, biological growth in the storage tank and taste complaints.

Aeration can be used to remove volatile and semi-volatile chemicals, such as radon, total THMs and hydrogen sulphide. Aeration will increase pH value (by removing CO_2) and can provide some additional mixing. To use aeration, the reservoir will require some re-engineering to facilitate the aerators.

Storage reservoirs may be isolated from the system during low-demand seasons. Low demands can increase detention time and, therefore, water age. By reducing storage volume, water age during low-demand seasons can be reduced to acceptable values.

In very cold climates, ice may form in reservoirs during winter. Ice can form at the wall and water surface of tanks in the winter. Ice can degrade the tank’s coating and can have an adverse impact on water quality.

[2] For the validation of these risks, as well as their reassessment and risk prioritisation, refer to WHO (2014) and other published South African WSP documents, as contemplated in Section 6.2.1.

An ice doughnut may form inside the tank against the walls and damage internal components as it moves up and down. Continuous water movement from mixers or deep cycling can minimise the formation of ice.

Control measures to manage specific water quality challenges in storage reservoirs are discussed according to chemical, biological and physical factors.

6.6.1.1 Chemical factors

Decay of chlorine residual: Water sampling for chlorine residual monitoring is normally done at the reservoir outlet since problems inside the reservoir may not be detected unless samples are taken from different levels and locations

Corrosion: Corrosion can be prevented by periodically inspecting and repairing reservoir linings. It is also important to have a properly maintained and calibrated cathodic protection system in steel reservoirs.

6.6.1.2 Biological factors

Biofilm and microbial regrowth: Microbes can continue to multiply within storage facilities if excess water age causes loss of disinfectant residual and temperature increases. Microbes can also develop biofilm on storage facility walls and within accumulated sediments.

With respect to water quality problems associated with microorganisms, improved operational practices, such as increased turnover and mixing in storage facilities, can help reduce water age, increase disinfectant residual levels and reduce sediment accumulation. In cases where improved turnover and mixing cannot be achieved or if the water quality is degraded before the water enters the tank, booster disinfection should be considered. This water disinfection can be temporary or permanent. Impacts on DBP formation and other water quality conditions must also be considered.

Nitrification: The best way to control nitrification is through management practices of the storage facility, such as decreasing detention time and promoting mixing. Breakpoint chlorination to remove source water ammonia and switching from chloramines to chlorine will also help control nitrification.

6.6.1.3 Physical factors

Sedimentation: Reservoirs should be regularly cleaned of sediment to prevent the impacts of adverse water quality. Sedimentation problems can be reduced through the use of an outlet that is raised above the reservoir floor. However, this solution also reduces the available storage volume. Reservoir hydraulics can be modified in other ways to prevent sedimentation. The regular flushing of lines entering the tank can reduce sediment entering the reservoirs. Tank cleaning to remove sediment periodically will also reduce sedimentation problems (this is explained under Step 8). The appropriate frequency of cleaning will be specific to each reservoir and needs to be based on local experience.

Contaminant intrusion: Routine maintenance and inspections can reduce or eliminate the threat of external contaminant entry.

6.6.2 Pumping stations

Sizing multiple pumps so that there is continuous pumping from a pump station helps to minimise water age by preventing stagnant water in transmission mains. The energy costs of different sizing options and operational strategies should be considered when evaluating pumping alternatives. Energy costs can vary significantly, depending on the electricity rate structure being used. Authorities (water service authorities or water service providers) need to balance water age improvement with energy costs or find opportunities to improve both.

6.6.2.1 Operational effects of pumps on water age

The way that pumps are operated can have a significant impact on water age. Some examples of how pump operation can be modified to improve water age include the following (AWWA, 2017b):

- ***Change pump settings to improve reservoir turnover:*** Adjust pump on and off settings to produce the maximum amount of volumetric turnover allowable without compromising pressure or fire-flow capacity.

- ***Control variable-speed pumps efficiently:*** Many variable-speed pumps are controlled based on maintaining a pressure setting. This produces consistent system pressure, but can result in low turnover in tanks. Controlling variable-speed pumps based on a flow setting can improve tank turnover by allowing the pumps to shut off and the tank to draw water (Cruikshank, 2010). Variable-speed pumps can also be controlled based on tank level, which can improve water age even more. In this case, running the pump at a high speed when the tank drops to a certain level and at a low speed as it approaches full can produce optimal results.

Pumps' capacity and operations have a direct impact on water age and water quality. Pump maintenance directly impacts on pump capacity and operations. As pumps age, impellers wear, leading to loss of capacity. Pumps also have a number of components that need periodic checks and replacement, such as seals and bearings. A pump that is vibrating excessively due to worn bearings or improper balancing will wear out more quickly than one that is maintained. A pump maintenance programme should include scheduled maintenance based on the typical useful life of these components (AWWA, 2017b).

6.6.2.2 Transient control strategies

Ideally, a hydraulic system design process will include an adequate investigation and specification of equipment and operational procedures to avoid undesirable transients. However, in reality, transients will still occur despite the design parameters; hence, remedial measures are required to keep transient conditions from disturbing the proper functioning of an existing system. Unexpected sources of unsteady flow also appear in some newly constructed systems (Wylie and Streeter, 1993; Elbashir and Amoah, 2007). Two possible strategies for controlling transient pressures exist (Walski et al., 2003):

- Focusing on minimising the possibility of transient conditions during project design by specifying appropriate system flow control operations and avoiding the occurrence of unusual system operations.

- Installing transient protection devices to control potential transients that may occur due to uncontrollable events such as power failures and other equipment failures.

6.6.2.3 Transient preventive measures and protection devices

To the extent possible, the engineer would like to design flow control equipment such that serious transients are prevented. Using a transient model, the engineer can try different pump operating speeds and controls, along with valve operating speeds and pipe sizes (these are discussed in the next section), to see if the transient effects can be controlled to acceptable levels. If transients cannot be prevented, specific devices may be needed to control transients. A brief overview of various commonly used surge preventive measures, protection devices and their functions are provided below.

Some methods of transient prevention include the following (Walski et al., 2003):

Proper pump controls**:** Except for power outages, pump flow can be slowly controlled using various techniques. Changing pump speeds up and down with soft starts or variable-speed drives can minimise transients, although the slow opening and closing of pump control valves downstream of the pumps can accomplish a similar effect, usually at a lower cost. The control valve should be opened slowly after the pump is started and closed slowly prior to shutting down the pump, which can be explained in the following sections.

Variable speed drives: Variable speed drive systems have become an important element in the control of pumps, enabling gradual speed control from zero up to the rated speed or vice versa, i.e. soft start and soft stop respectively.

Air chambers and surge ranks: Air chambers and surge tanks work by allowing water out of the system during high pressure transients and adding water during low pressure transients. They should be located close to a point where the initial flow change is initiated. An air chamber is a pressure vessel that contains water and a volume of air that is maintained by an air compressor. During pump stop, the pressure and flow in the system decreases and, as a result, the air in the air chamber expands, forcing water into the system. A surge tank is a relatively small open tank connected to the hydraulic system. It is located such that the normal water level elevation is equal to the hydraulic grade line elevation. During pump stop, the surge tank substitutes the pump and feeds the system with water by gravity. This controls the magnitude of the low-pressure transient generated as a result of the pump stop.

One-way tank: This is a storage vessel under atmospheric pressure that is connected to the hydraulic system. It has a check valve (normally closed) connected to it that only allows water from the tank into the system. One-way tanks are primarily used in conjunction with pumping plants (Wylie and Streeter, 1993). The significant advantage of using a one-way tank rather than a surge tank is that the check valve allows the one-way tank to have a much lower height (Walski et al., 2003).

Air valves: Air valves are installed at high points along the pipeline system to prevent vacuum conditions and potential column separation. Air enters the pipeline system during low-pressure transients, and this air should be expelled slowly to avoid creating another transient condition. Before restarting the pumps, sufficient time should be allowed for the air that entered the pipeline to be expelled (Walski et al., 2003).

Pump bypass: Pump bypass with a valve is another protective device against pressure transients. Two pressure waves are generated as a result of reduction in flow due to booster pump stop; the wave travelling upstream is a positive transient, and the wave that travels downstream is a negative transient. A check valve in a bypass line allows free flow to the pipeline to prevent low pressures and column separation (Wylie and Streeter, 1993). The effectiveness of using a booster station bypass depends on the specific booster pumping system and the relative lengths of the upstream and downstream pipelines (Walski et al., 2003).

6.6.3 Pipe networks

6.6.3.1 Pipe sizing

A consequence of sizing pipes to provide fire flows is higher water age under normal demand conditions (Snyder et al., 2002), especially with limited demand. While fire-flow criteria may be pre-determined and some dead ends are inevitable due to topography, land use limitations and cost, utilities can evaluate solutions such as looping pipes and providing small-diameter bypasses on zone boundary valves in order to eliminate dead ends with water age issues. Alternatively, utilities should consider flushing to improve water age. When analysing alternatives, it is beneficial to consider the trade-offs between increased fire flow and reliability, and the potential for water quality deterioration in a looped system compared with a branched system.

When planning for future demand, the installation of very large transmission mains can add significantly to water age and the degradation of water quality, especially in the early years of development before a new area is fully developed. Phased parallel piping may be preferable in some cases. Although higher in cost, the near-term improvement in water quality is often favourable, and, in the long-term, parallel pipes provide added redundancy.

Alternatively, phasing capital improvement projects by demand triggers instead of planning years can help reduce over-capacity issues. Demand forecasts, while helpful for capital improvement planning, are often based on population projections that vary over time, which are based on assumptions that may change. For major hydraulic upgrades to meet future demand scenarios, tracking water demand in specific areas of the system is useful as a trigger to schedule construction on large transmission mains. In this way, the full capacity that is needed in the future does not cause water age problems in the present. For example, a utility may track demand by district or pressure zone and initiate a new pipe project when demand in that district or zone reaches 80% of the demand at which the pipe is needed. Water age modelling may be used to assess the impacts of pipe improvements under different demand conditions, and the results may be used to aid in the phasing of capital improvements.

6.6.3.2 Operation

Adjustments to piping configurations to improve water age may be made operationally by changing valve positions or settings. Examples of changes that can be made to improve water age include the following:

- ***Allow flow through zone boundary valves:*** Closed valves at pressure 1 boundaries often function as dead ends in a distribution system. Allowing these valves to bleed back a small amount of flow from a higher-pressure zone to a lower-pressure zone by opening a bypass around a gate valve, throttling a valve, or changing the opening setting of a pressure-release valve can improve water age in the area of the valve without consuming any water (Cruikshank, 2010). Care should be taken when throttling valves to ensure that integrity is not compromised.

- ***Close storage reservoir bypass pipes:*** Keeping bypass piping closed also helps maintain a higher rate of flow through the reservoir. It also facilitates a higher inflow jet velocity, which improves mixing.

- ***Close valves to change flow patterns:*** One way to improve circulation through an area with high water age is to strategically close the valves to increase flow through those areas. Closure options should be tested using a hydraulic model or water quality sampling to ensure that new areas of high water age near the closed valves will not be an issue. Note that a sudden increase in velocities could cause a release of accumulated sediments. Flushing to remove sediment prior to the change can help prevent this.

- ***Encourage water use at system extremities:*** The utility can consider selecting zone boundaries to place large users at the extremities of the zone, or to encourage users at extremities to use more water. Additionally, spot flushing can reduce water age at selected locations.

- ***Consider the effect of multiple supply sources:*** If there is a choice between multiple supply locations, the source can be chosen to minimise water age in the distribution network of pipes. For example, two sources on opposite sides of a distribution system tend to produce lower water age results than two sources that are close together, as both sides have low water ages at the entry points (Cruikshank, 2010). This can also be a consideration in evaluating future supply alternatives. The quality of the source water and treated water from each supply should also be taken into consideration, depending on the system’s water quality challenges.

6.6.3.3 Valve-induced transients

Transients can be prevented through the following measures:

- ***Slow opening and closing of valves:*** The longer the pipeline, the slower the required valve operating times should be. Field staff should be trained in proper valve operation to avoid causing transients.

- ***Proper hydrant operation:*** Closing fire hydrants too quickly is the leading cause of transients in smaller distribution pipes. Fire services and distribution system staff need to be trained on proper hydrant operation.

- ***Lower pipeline velocities:*** Pipeline size and thus cost can be reduced by allowing higher velocities. However, the potential for serious transients increases with decreasing pipe size. It is usually not cost-effective to significantly increase pipe size to minimise transients, but the effect of transients should be considered in the design process.

6.6.3.4 Internal corrosion control

The internal corrosion of distribution system piping and home plumbing can cause several water quality problems, including potential health concerns, discolouration, particles, and taste and odour problems. These problems can be the result of the corrosion of metal pipe surfaces, pipe solder, asbestos cement pipes, cement linings and plumbing fixtures or the dissolution of existing pipe scales. Thus, in order to control corrosion, the control measures can be classified into two major categories: water quality modification, and distribution system design, operation and maintenance (maintenance is discussed in Step 8) (AWWA, 2017a).

- **Water quality modification**

In many cases, the easiest way to reduce corrosion is to modify the water quality at the treatment plant or well house. Chemical treatment options include pH adjustment, dissolved inorganic carbon (DIC), and the application of corrosion inhibitors. These are discussed as follows (AWWA, 2017b):

Adjustment of pH and/or alkalinity

The adjustment of pH is the most common method for reducing corrosion in distribution systems. The primary factor that determines the solubility of most pipe materials and the films that form from corrosion by-products is pH. Most materials in the distribution system dissolve faster at lower pH values.

The relationships between pH, DIC, alkalinity, CO_2 and ionic strength govern the solubility of metal carbonates, which are commonly involved in protective scale formation on interior pipe surfaces. The type of alkalinity present and the pH of the water are dependent on each other.

The solubility of metals typically decreases as the pH value increases. Increased pH may, however, prove troublesome for water that contains elevated levels of iron and manganese, which could cause discoloured water and elevated hardness, which can result in excessive calcium and magnesium precipitation. Excessive calcium and magnesium can lead to increased pipe friction and pipe clogging.

Caustic soda (sodium hydroxide), quick lime, potassium hydroxide, soda ash, limestone contactors (calcite filters) and aeration air stripping (where sufficient dissolved CO_2 exists in the groundwater) are the principal methods for increasing the pH value. Soda ash, potash and limestone contactors also increase DIC; aeration decreases DIC in the process of increasing pH value. Further details on comparing the relative use of chemical additives for pH and/or alkalinity adjustment can be found in AWWA (2017b) and USEPA (2016).

Chemical inhibitors

Corrosion control chemicals are commonly used in the drinking water industry. However, each chemical has different properties and may not truly inhibit corrosion. Some chemicals simply mask the effects of corrosion to prevent aesthetic problems such as red or black water. Currently, the most common inhibitors used in the drinking water industry are orthophosphates, polyphosphates, blended phosphates and silicates:

- *Orthophosphates:* Orthophosphate is most commonly used for lead and copper control. It has also been shown to reduce the corrosion rates of iron (AWWARF and TZW, 1996). Orthophosphate is significantly less expensive than all other inhibitors, and is available as phosphoric acid. There are also neutral orthophosphate products such as potassium and zinc orthophosphate. The optimal pH range is between 7.0 and 8.0 for controlling lead and copper. Pipe loop studies have demonstrated an immediate increase in lead concentrations whenever the pH falls out of the range. At pH values around 8.0 where copper release is diminished because of the pH increase, orthophosphate addition shows no additional benefit (AWWARF and TZW, 1996; Schock and Sandvig, 2006). Orthophosphate addition has been shown to be an effective copper control measure, even in challenging distribution systems with seasonally varying blends of multiple source water, such as groundwater, surface water and desalinated seawater (Taylor et al., 2008). In some cases, orthophosphate may be effective for controlling corrosion at pH values as high as 9.0 (USEPA, 2016). Typical dosages of orthophosphate range from 0.5 to 3 mg/ℓ as PO_4. In some cases, higher orthophosphate concentrations (>3.0 mg/ℓ) have been found to form a precipitate when in contact with aluminium, calcium and iron that can cause complaints of milky water at the customer tap (Tesfai et al., 2006; Fromwell, 2004). In addition, higher phosphate doses may cause issues with wastewater discharge limits.

- *Polyphosphates:* In general, polyphosphates are used as a sequestering agent for iron and manganese in source waters and are not generally used for corrosion control. Polyphosphates are best used to sequester metals in order to prevent red or black water where lead and copper are not already significant. Low doses of polyphosphate (2 to 4 mg/ℓ) are typically used and will help reduce the red water as dissolved iron and manganese are bound as a complex molecule. Corrosion rates, however, are not reduced and may actually increase (Cantor et al., 2000). Polyphosphates should only be considered when it is known that lead and copper levels will not substantially increase (Clement et al., 2002).

- *Blended phosphates:* Blended phosphates are proprietary mixtures of ortho- and polyphosphate. The fraction of orthophosphate in blended formulas ranges from 5% to 70%. While it is possible for blended phosphates to sequester metal and reduce the release of metals, the exact mechanism of protection is not well understood and blends should be used with caution (USEPA, 2016).

- *Silicates:* The protective mechanism of silicates appears to be the formation of a thin layer over the corroded metal layer. The films are self-limiting and do not build up in thicker layers with increased dosages. The films also break down relatively quickly if there is an interruption in feed. Silicates are expensive and typically cost more than phosphates. In general, silicates have been found to be less effective for corrosion control than orthophosphates. The use of phosphate-silicate blends has increased in recent years. The blends appear to be as good as phosphate products alone, but are used at lower concentrations. It is important to note that more research on the use of silicates for control corrosion is required. The high costs associated with silicate and the time required to lessen corrosion in the distribution system have eliminated the use of silicates as a possible corrosion treatment for many water systems.

- ***Distribution system design and operation***

Implementing and maintaining optimum corrosion control treatment not only requires an adequate quality of water leaving the treatment plant, but also maintaining that quality throughout the distribution system. Many factors can alter water quality, making the system susceptible to corrosion. These factors include long detention times, tuberculated pipe scales that can provide a haven for microbes that can alter water chemistry, and velocity that is too high or too low. Therefore, distribution system design, and operation and maintenance play a key role in controlling corrosion throughout the distribution system, as explained below (AWWA, 2017b):

Distribution system design

A water system can minimise distribution system pipe corrosion by selecting the correct distribution system materials and having a good engineering design. The reality is, however, that most water systems are forced to deal with existing distribution systems that were designed based on priorities other than corrosion, such as sufficient fire protection. Nonetheless, water systems can take advantage of system design for corrosion control during system upgrades, planned system materials replacement and expansion of the distribution system.

- *System and pipe materials:* Piping material should be selected based on the system's water chemistry and cost. The piping material's mechanical properties will also influence material selection (see Table 6-1). Comparable materials should be used throughout the system. Galvanic corrosion should be minimised by not having two materials with different electrical potentials, such as copper and steel pies, come into direct contact with each other. The placement of dielectric (insulating) couplings between dissimilar metals reduces galvanic corrosion.

- *System layout:* The design and layout of pipes and structures in the distribution system can be as important as the selection of materials. Some important design-related steps that can be taken include the following:
    - Avoid dead ends and stagnant areas as these can increase particulate accumulation and biological activity.
    - Provide a looped design to reduce stagnation and particulate accumulation.
    - Plan for asset types and locations that support effective main flushing and cleaning.
    - Consider hydraulic modelling to reduce mechanical stresses, such as pipe flexing, water hammer and change in the direction of flow, as these can disrupt pipe scales.
    - Reduce sharp turns and elbows to avoid erosion corrosion.

Table 6-1: Corrosion properties of materials frequently used in water distribution systems

Plumbing material	Corrosion resistance	Primary contaminant from pipe
Asbestos cement, concrete and cement linings	Good corrosion resistance. Immune to electrolysis. Aggressive waters can leach calcium from the cement. Polyphosphate sequestering agents can deplete the calcium and substantially soften the pipe.	Asbestos fibers (from erosion), increase in pH, aluminium and calcium Trace metals (cadmium, chromium, barium and aluminium) due to presence in some cements
Brasses and bronzes	Good overall resistance. Different types of brass respond differently to water chemistry. Subject to dezincification by waters of pH >8.3 with high ratio of chloride-to-carbonate hardness.	Lead, copper, zinc, selenium, bismuth, and phosphorus

Plumbing material	Corrosion resistance	Primary contaminant from pipe
Copper	Good overall corrosion resistance. Subject to corrosive attack from high flow velocities, soft water, chlorine, dissolved oxygen, low pH and high inorganic carbon levels (alkalinity). Subject to microbiologically influenced corrosion. May be prone to pitting failures.	Copper and possibly iron, zinc, tin, antimony, arsenic, cadmium and lead from associated pipes and solder
Galvanized iron or steel	Subject to galvanic corrosion of zinc by aggressive waters, especially of low hardness. Corrosion is accelerated by contact with copper materials. Corrosion is accelerated at higher temperatures such as in hot water systems. Corrosion is affected by the manufacturing process of the pipe and galvanised coating.	Zinc and iron Cadmium, chromium, barium, aluminium and lead are possible because of impurities in the galvanisation process
Iron, unlined cast or ductile	Can be subject to surface erosion by aggressive waters and tuberculation in poorly buffered waters	Iron, resulting in red water, complaints and turbidity
Lead	Corrodes in soft water with pH <8 and in hard waters with high inorganic carbon levels and pH <7.5 or >8.5	Lead
Plastic	Resistant to corrosion	Some pipes contain metals in plasticisers, notably lead Plasticisers are an emerging contaminant issue.
Steel, mild	Subject to uniform corrosion. Affected primarily by high dissolved oxygen and chlorine levels and poorly buffered water.	Iron Resulting in red water, complaints and turbidity
Source: AWWA, 2013.		

Distribution system operations

Routine system maintenance and actions in response to monitoring triggers can reduce corrosion and/or remove the by-products of corrosion. These actions include maintaining disinfectant residuals, controlling hydraulic detention times, cleaning pipe and rehabilitation pipe.

- *Maintaining disinfectant residuals:* Disinfectant residual concentrations decay as water passes through the distribution system because of reactions with materials present in the bulk water and at the pipe wall. At the treatment plant, long-lasting disinfectant residual can be promoted by removing chlorine-demanding material, particularly natural organic matter. Good control of pH and alkalinity can also result in low bulk decay for disinfectant residuals. Once the finished water has left the treatment plant, decay is inevitable. Disinfectant-demanding materials present in the pipes include corrosion products and biofilm materials. In a synergistic way, cleaning out the accumulation of corrosion materials and biofilms will help maintain disinfectant residuals, which in turn will help manage corrosion and biofilm growth. While it is preferable to remove as much chlorine-demanding material from the water and pipe as possible, it is sometimes the case that disinfectant booster stations are needed to maintain adequate disinfectant at the farthest ends of the distribution system.

- *Controlling hydraulic detention times:* Control of hydraulic detention time will help maintain disinfectant residuals and reduce corrosion rates. Several operational strategies can be implemented to reduce hydraulic detention time. One of the most important operational issues to address is storage reservoir turnover. Most distribution system include a large quantity of stored water, and many customers receive water that has passed through several storage reservoirs. Good reservoir turnover will refresh the volume of water and ensure that stagnation does not occur. Reservoir turnover is especially important when water temperature increases above 60 °F, which favours accelerated microbial activity (LeChevallier et al., 2010). In addition to volumetric cycling, alterations to inlet and outlet geometry, as well as the installation of active mixers, can reduce stagnation in the storage reservoir. Hydraulic detention times are highly site specific; therefore, hydraulic analyses of the distribution system are recommended to identify areas of low reservoir turnover and low velocity, such as dead ends. Stagnant areas can also be created within a distribution system at the boundary created by pumping or flow from different pressure zone entry points. In such a case, modifications to the zone supply strategies in order to alternate sources or variations of flow can help reduce the extent of stagnation.

6.7 STEP 5: DEFINE OPERATIONAL LIMITS

This includes aspects of investment planning, and linkages with asset management in response to the challenges identified above. This step is described in detail in the WHO guideline on WSPs for distribution systems (WHO, 2014) and other published South African WSP documents, as introduced in Section 6.1.

6.8 STEP 6: ESTABLISH MONITORING

This includes selecting appropriate operational monitoring parameters, sampling spots, frequency, guidance on reviewing operational monitoring data, etc. Operational monitoring parameters, sampling spots, frequency, etc. are well described and explained in South African Bureau of Standards (SABS, 2015). Therefore, it is highly recommended to study it in order to understand national specific best practices, regulations, obligations and requirements. However, the sections following are still believed to have been discussed to help develop a better understanding of these, where deemed necessary.

6.8.1 Storage reservoirs

6.8.1.1 Monitoring parameters

Monitoring is critical when ensuring continuous adherence to water quality requirements in storage reservoirs and distribution systems and to identify problems early. Water quality is monitored from samples. This can be done through continuous sampling (using *in-situ* sensors) or grab sampling, performed by an operator through access hatches or sampling taps. The safety of the operator is of paramount concern when designing grab sampling procedures and locations. A calibrated cord may be needed to ensure that samples are taken at a consistent depth within the reservoir (RCAP, 2012).

Sampling taps provide a convenient way to take grab samples. However, a single sample location may not represent conditions throughout the storage reservoir. For example, accumulated sediment at the bottom of the tank cannot be detected from a clear effluent sample when the outlet is above the bottom. Similarly, chlorine residual at one sampling point cannot indicate the presence of a dead zone in the reservoir.

The configuration of the tank and water flow dynamics should be considered when choosing sampling locations. The configuration of the inlet and outlet piping affects the circulation and mixing characteristics of the water and thus determines the location and number of samples required to obtain representative samples. Samples taken from common inlet/outlet facilities may represent inflow or outflow depending on when the sample is taken.

Even though these and other relevant details are described well in SANS 241-2: 2015, several aspects relevant to water quality that can be monitored in storage reservoirs, including the water itself, sediment and biofilms, are described in Table 6-2.

Table 6-2: Typical water quality parameters to monitor

Parameter	Purpose	Procedure
pH	Indicates changes from the water source and corrosion.	Grab sample or continuous sampling
Alkalinity	Indicates potential buffering capacity.	Grab sample or continuous sampling
Chlorine residual	Indicates conformance to MCL. Provides early warning sign of water quality deterioration.	Grab sample or continuous sampling
Total coliform	Indicates presence of indicator bacteria.	Grab sample
Heterotrophic bacteria	Indicates conformance to MCL. Provides early warning sign of water quality deterioration.	Grab sample
Temperature	Temperature difference within tank may indicate stratification.	Grab sample or continuous sampling

Source: RCAP, 2012.

Sediments at the bottom of storage reservoirs can be sampled and analysed when the reservoir is drained, for instance, for cleaning purposes. A sediment gauge can also be used to monitor sedimentation depth and collect samples. Table 6-3 provides a list of sediment characteristics that may be monitored.

Table 6-3: Sediment characteristics and their indicators

Parameter	Distribution system indicator
Iron hydroxide	Distribution system corrosion
Aluminium hydroxides	Treatment plant issue
Calcium carbonates	Minerals in hard waters
Heterotrophic plate count (HPC)	Possible taste and odour indicator, potential source of recurring bacterial counts
Depth of sediment	Rate of accumulation, cause of chlorine residual degradation
Gross microbial examination	System cross-connections, poor hydraulics, faulty screening

(Source: RCAP, 2012)

Storage reservoirs should be monitored for the formation of biofilm, which grows and accumulates on the surface of storage facilities. Biofilms may cause water quality problems as they harbour pathogens. They also cause disinfectant loss (chlorine demand) and may cause taste and odour problems.

6.8.1.2 Inspection of storage reservoirs

Prior to the interior internal inspection of reservoirs, it is necessary to inspect the outside and surroundings to identify potential security and contamination risks. The following items should be investigated by suitably qualified and trained staff, records updated and actions taken to correct any deficiencies found (EPA, 2011):

- The fence surrounding a reservoir should be adequate to protect it from people and animals.
- It should be inspected for potential risks of contamination posed by vents, access hatches (open or unlocked) and overflows.
- It should be inspected for potential risks of contamination posed by structural vulnerability such as leaks, holes, cracks or deterioration of the exterior surface of the structure.

- It should be inspected for plants growing on top of the reservoir roof or walls that could enter or undermine the structure.
- Adequate draining should be done of the land surrounding the reservoir to protect it from rainfall run-off.
- The structural stability of the reservoirs should be assessed and any structural deficiencies, weaknesses or infringement of structural codes and standards evaluated.
- Since a reservoir with excessive water retention time establishes water dead zones and/or decay in chlorine residuals, a detailed assessment is required to check and balance the situation of water volume and retention time of the reservoir based on recommendations revealed in previous sections.
- Reservoirs' filling/outing flow regime is an important assessment of the reservoir in terms of whether or not the reservoir ever runs dry, and whether the sediments are disturbed and mixed when the water refills the reservior.
- It is essential to know the reservoirs' hydraulic performance in order to know whether the flow is plug or mixed.
- It is essential to investigate the reservoirs' water quality performance, including the monitoring of chlorine residuals, to ensure appropriate water quality compliance with SANS 241: 2015.

Internal inspection can be classified into three general methods, as follows (EPA, 2011):

- Fully emptying the reservoir
- Inspection through divers
- Usage of technology such as remote operating vehicles

Fully emptying the reservoir is the only method that allows the reservoir to be cleaned and is the most popular. However, it can create problems when there is high demand at the downstream side that will be disrupted when the reservoir is off-line. The following solutions should be applied (EPA, 2011):

- When multiple reservoirs are connected to the same network or when the inside of the reservoir has independent compartments, the reservoir to be cleaned can be bypassed without disruptions to supply.
- If this is not possible, one could temporarily connect the inlet and outlet pipes directly (temporary bypassing).
- As a general principle, cleaning should be undertaken during the lowest demand period, which would normally be at night in the winter season.
- Consumers affected by reduced service or cessation of service should be given adequate warning.

To use one of the other two methods, it is essential that the reservoir's access hatch should give access to the divers or equipment used, and that proper sanitary, health and safety measures are complied with.

When using divers, all clothing and tools should be properly disinfected before entering the reservoir. In addition, it is essential that the reservoir be isolated from the distribution system for the period of the inspection to prevent accidental contamination from entering the network, and to protect divers from being trapped by the outlet pipe flow (EPA, 2011). Remote operating vehicles with close-circuit video is another option for inspecting the reservoir. Some of these are able to clean the inside of the reservoir in a similar way to a pool cleaner.

For proper inspection, cleaning and disinfection, the following issues should be considered (EPA, 2011):

- On an average basis, inspection, cleaning and disinfection takes one day, but this depends on the size and nature of the reservoir concerned.

- All inspections and evaluations should be carried out by suitably qualified and experienced personnel.
- Internal supervision of the reservoirs should be conducted. This entails the inspection of corrosion, cracks and pitting, as well as other factors that create the potential for contaminant intrusion.
- A roof flood test can be used to check for cracks that may allow contaminated rainwater to enter the reservoir. In this test, the roof is inundated with water while checking the inside of the reservoir for signs of ingress.
- In-depth analysis of flow patterns through the reservoirs should be done, including a study of the interior configuration (whether separate or using the same inlets/outlets, for example), baffle layout and mixing devices.
- Detailed written procedures are essential for reservoir inspection, cleaning and refilling.

6.8.2 Pumping stations

Pump capacity can be checked using a pump test. The pump is operated using a minimum of three delivery valve settings while the following parameters are measured (AWWA, 2017b):

- Suction pressure
- Delivery pressure
- Flow rate, measured using an installed meter
- Pump speed, if variable speed pump (multiple speed points can be used to develop a system curve)
- Electrical current to calculate efficiency

The results are then plotted against the original pump characteristic curve from the manufacturer, and the system curve is developed either from the test data or from hydraulic modelling. The results show how much the pump has changed, whether it still meets the original design specifications, and whether its efficiency has decreased to the point where it needs to be repaired or replaced. Replacing inefficient pumps with more efficient units provides operational cost savings. (AWWA, 2017b).

Even if the pump has not changed significantly, the system may have, and the pump test results will show how the system is actually operating and whether the pump is still an appropriate choice for the system. Well-maintained pumps that operate as intended can reduce water age, allowing authorities (WSAs or WSPs) to implement appropriate operational strategies (AWWA, 2017b).

6.8.3 Pipe networks

Operational monitoring parameters, sampling spots, frequency and so forth in pipe networks are well described and explained in SABS (2015). Therefore, it is highly recommended to study it in order to understand national specific best practices, regulations, obligations and requirements.

6.9 STEP 7: ESTABLISH CORRECTIVE ACTIONS AND INCIDENT RESPONSE

This includes the analysis and interpretation of data for predicting within the WSP framework, customer feedback, auditing, etc. This step is described in detail in the WHO guideline on WSP for distribution systems (WHO, 2014) and other published South African WSP documents as introduced in Section 6.1.

6.10 STEP 8: ESTABLISH RECORD KEEPING

This includes typical standard operating procedures in distribution systems organised by hazardous events and associated control measures, incident criteria and protocol management procedures for new systems and major upgrades.

6.10.1 Storage reservoirs

The following sections explain the procedures of how to clean and disinfect storage reservoirs.

6.10.1.1 Reservoir cleaning

Van Zyl (2014) explains the cleaning procedure for storage reservoirs. However, some additional aspects should be considered (EPA, 2011):

- Following the inspection and preparation of storage reservoirs for clean-up, all the equipment should be sufficiently checked and declared suitable for use in drinking water reservoirs.
- The responsible team should ensure that all equipment and clothing have been disinfected and not have been used for other purposes in the past.
- Special considerations are required for reservoirs located in areas with a potential risk of faecal contamination stemming from agricultural or domestic activities.
- Before entering reservoirs, shoes should be disinfected using a foot bath with chlorine or other disinfectants.
- All outlet pipes from the reservoir should be closed off before and during clean-up activities.
- Pressure washing is an effective way of removing all contaminants, including chemicals, loose concrete, dirt and biofilms.
- The scour sump should be used to drain the cleaning water, and solids removed from the reservoir should be suitably disposed of.
- Care should be taken not to contaminate local water courses or land with the wash water from the reservoir.

6.10.1.2 Reservoir disinfection

Basic disinfection steps are outlined in DWS (2015) and Van Zyl (2014). However, a number of critical aspects of disinfection need further elaboration.

For clean-up, when a reservoir gets off-line and is emptied completely, all the interior surfaces should be disinfected by highly skilled operator(s), who should be equipped with all the necessary protection. Careful consideration is required when selecting suitable disinfectants due to their reaction with materials used for the construction of the reservoir, particularly where liners are used inside the reservoir (EPA, 2011).

Some of the main methods used for disinfection are as follows (EPA, 2011):

- Sodium hypochlorite is dissolved in water to a concentration of 25-35 mg/ℓ of chlorine residuals. It is then sprayed on all the internal surfaces of the reservoir. All outlet pipes should be closed off while spraying to prevent contamination of the environment. The disinfection starts from the furthest points moving towards the access hatch, during which time all objects and points, including ladders and columns, are disinfected. The disinfection water is kept in the reservoir for a minimum of 24 hours and is then drained off completely before filling the reservoir with potable water.
- A method recommended by the American Water Works Association (AWWA C-652) requires the reservoir to be completely filled with chlorinated water of 10 mg/ℓ for six hours when gas-feed equipment or a chemical pump is used, or for 24 hours when sodium hypochlorite or calcium hypochlorite is used. Finally, the reservoir is completely emptied and then refilled with potable water.
- In another method recommended by AWWA C-652, residual chlorine of 200 mg/ℓ is directly applied by brush or spray to all internal surfaces of the reservoir for at least 30 minutes of contact.

- In a final method recommended by AWWA C-652, the reservoir is filled to 5% of its capacity with chlorinated water of 50 mg/ℓ for at least six hours, and then further with potable water with normal chlorine residuals to the overflow level and left for 24 hours.

Note that water samples should be taken following the clean-up and disinfection of the reservoir to check whether the water complies with SANS 241: 2015. However, in practice, this may not always be possible, especially when the supply should be connected as a matter of urgency. In such cases, the residual chlorine concentrations should be checked to see if the water is suitable.

6.10.2 Pumping stations

Pumps' capacity and operations have a direct impact on water age and water quality. Pump maintenance directly impacts on pump capacity and operations. As pumps age, impellers wear, leading to loss of capacity. Pumps also have a number of components, such as seals and bearings, that need to be checked and replaced periodically. A pump that is vibrating excessively due to worn bearings or improper balancing will wear out more quickly than one that is maintained. A pump maintenance programme should include scheduled maintenance based on the typical useful life of these components (AWWA, 2017b).

6.10.3 Pipe networks

6.10.3.1 Maintenance

While every distribution system requires some reactive maintenance, proactive maintenance programmes or asset management programmes can function to reduce reactive maintenance needs, manage costs and, in general, produce a better functioning system. Therefore, pipes and valves that affect water quality are explained as follows:

- ***Pipes***

Pipe condition and maintenance impact on many aspects of distribution system water quality, including chemical and microbial interactions with the pipe, as well as capacity and water age issues.

Tuberculation or other deposits on the interior pipe wall can result in greatly reduced capacity. The head loss in such a pipe can create a capacity problem, particularly for fire flows, and also exacerbate water quality issues, such as increased microbial activity. Utilities can use fire-flow capacity needs and water age as criteria when prioritising a capital improvement programme. For example, a flow path to move water directly to an area with high water age or low fire flow may be created by rehabilitating or replacing certain sections of pipe first.

- ***Valves***

Valves are a system component that are often overlooked. If not maintained, they can lead to an increased risk of property damage and service disruption during mains breaks, as well as hydraulic restriction that diminishes the quality of service. There are two basic components to a valve maintenance programme (Bloetscher, 2011):

- Locating and accessing the valves
- Operating the valves on a regular schedule (annually is a good goal): any valves that are not found to be operational should be repaired or replaced.

Additionally, all utilities (WSAs or WSPs) find valves that are closed, but should be open. More closed valves can be identified if all valves are located and operated on a regular basis. Closed valves create hydraulic constriction that can impede fire flows and reduce hydraulic capacity in an area. Areas isolated by closed valves can also exhibit increased water age (and deteriorated water quality) due to the lack of flow. Depending on their location, closed valves have the potential to impact on water age and quality in large areas of the distribution system.

6.10.3.2 Main pipe repairs, cleaning and disinfection

The construction, rehabilitation and repair of water mains occur on a regular basis in water distribution systems. The relative frequency and nature of these activities represent a potential contamination risk to water distribution systems if proper procedures and standards are not followed. The installation and repair of water mains provide the potential for direct contamination of the distribution system (EPA, 2002).

In South Africa, WRC and DWS have published a number of documents, which explain the steps involved in water mains pipe repair, cleaning and disinfection, including Van Zyl (2014), Mackintosh and Jack (2008) and DWS et al. (2002). Of these, Van Zyl (2014) describes the repair and disinfection methodology with more focus on mechanical fittings and behaviour, structural protection, stability and surrounding safety, Mackintosh and Jack (2008), on the other hand, illustrate procedures involved in the repair and disinfection of pipe networks with more focus on proper flushing, water quality and management aspects in comparatively greater detail, based on the WHO's technical notes. DWS et al. (2002) raise the contamination intrusion issue when repairing the mains, but do not describe measures to prevent this from happening.

The City of Cape Town uses a range of forms and checklists prepared for job hazard analysis, which consists of job descriptions, control measures and responsible personnel. These forms are established for different jobs that describe the steps entailed, including the disinfection and cleaning of the existing mains, emergency repairs of burst mains and fittings, mains flushing, mains replacement and extension, and rising mains repair. However, it is worth noting that these forms provide the general guidelines that are involved in each mentioned section without explaining the technical step-by-step procedures.

A number of internationally recognised procedures have been published for both new and existing pipe repairs. The guidelines of the Water Research Foundation (WRF) are representative of good practice and were used to recommend the following procedures for two types of pipe shut-down (WRF, 2014):

- Controlled shut-down
- Uncontrolled shut-down

Type 1: Controlled shut-down: When repair is possible while maintaining positive pressure in the line. This involves throttle flow in the pipe section using isolation valves and maintaining positive pressure in the pipe to prevent intrusion or run-off contamination and to pinpoint the location of the leak:

- Identify if there is depressurisation elsewhere in the water distribution system (minimum 15 m everywhere in the system) based on topographic or other factors.
- Excavate to expose the mains break and control the water level in the working repair pit.
- Throttle flow again as needed, maintaining positive pressure.
- Visually observe the positive flow at the break site or use a nearby hydrant or tap at a higher elevation than the break site.
- During the repair (from the start through to completion), visually confirm that water was flowing strongly from the pressure verification hydrant or tap, or at the break site to indicate that positive pressure was maintained during the repair.
- Shut down the affected service lines within the immediate break area and notify the affected customers.
- Dewater as necessary to maintain water in the excavation pit at least 300 mm below the bottom of the exposed pipe being repaired.
- Dispose of and dechlorinate water in accordance with local regulations.

- Ensure that no obvious contamination, such as sewage or chemical contamination, is present at the site.
- Physically clean visible dirt from the pipe and fittings – exterior and interior.
- Record the pipe material, its outside diameter and repair fittings (repair clamps, sleeves and pipe) necessary to perform the work.
- Clean and spray all tools and fittings using water with a chlorine content of 1% before installation.
- Keep repair materials as clean as possible as they are installed.
- Keep pipe caps, plugs and other protective coverings in place until the pipes are joined.
- Keep gaskets clean all the time.
- Complete the repair.
- Open valves and flush the pipe from a nearby hydrant as needed.
- Measure disinfectant residual and make sure that it is within the range specified by SANS 241: 2015.
- Return the pipe to normal service.
- Backfill and compact pipe bedding per applicable SABS pipe installation standard and/or local requirements.
- Repair ground surface to withstand any traffic loading.

Type 2: Uncontrolled shut-down: This is when pressure is not maintained during excavation, and controlled shut-down is not possible:

- Isolate the pipe section using valves.
- Notify the appropriate authorities of any dangerous conditions.
- Shut down service lines within the affected area.
- Excavate to expose the main break.
- Dewater as necessary to maintain water in the excavation pit at least 300 mm below the bottom of the exposed pipe being repaired.
- Dispose of or dechlorinate water in accordance with local regulations.
- Physically clean visible dirt from the pipe and fittings – exterior and interior.
- Note any possible contamination such as sewage or chemical contamination intrusion at the break site.
- Record the pipe material, its outside diameter and repair fittings (repair clamps, sleeves and pipe) necessary to perform the work.
- Keep repair materials as clean as possible as they are installed.
- Keep pipe caps, plugs and other protective coverings in place until pipes are joined.
- Keep fittings, valves and appurtenances covered and protected until ready for installation.
- Keep gaskets clean all the time.
- Clean and spray all tools and fittings using water with a chlorine content of 1% before installation.
- Complete the repair.
- Fill the line slowly and use hydrants first to remove any entrapped air.
- Flush the hydrant to achieve 1 m/d velocity in the largest diameter pipe section to remove air and dirt (at least three times the pipe volume).
- Dispose of or dechlorinate water in accordance with local regulations.
- Fill the pipe with chlorinated water at a concentration of 5 mg/ℓ for a minimum of 20 minutes contact time.
- After the appropriate disinfection contact time, flush the chlorinated water from the mains.
- Dispose of and dechlorinate the water according to applicable regulations.
- Measure disinfectant residual and make sure that it is within the range specified by SANS 241: 2015.

- Return the pipe to normal service.
- Assess the risk of contaminant intrusion in the repaired pipe section or rest of the network and issue consumer warnings if required.

In addition to the above, the following supplemental recommendations should be made when performing pipe maintenance:

Notification: If possible, inform the public in advance of any pipe problem, interruption of service, scheduled period of work, potential traffic disruption or other public hazard. The following parties should be informed as appropriate:

- Affected and critical customers
- Departments dealing with public infrastructure
- Departments dealing with public health
- Departments dealing with traffic and public transport
- Local law enforcement
- Media in the form of a press release

Safety equipment, fittings and repair tools: The repair teams should be provided with the following:

- Protective clothing, including gloves, reflective vests, hard hats, protective goggles, etc.
- Flow and pressure measurement equipment
- Disinfection and dechlorination chemicals and equipment
- Repair and excavation tools (saws, wrenches, buckets, shovels, pickaxes, ladders, flashlights, working lights, etc.)
- Pipes, fittings and repair clamps, etc.
- Flow and surface run-off diversion equipment, such as sand bags and trench covers
- Dewatering pumps
- Emergency generators
- Tapping equipment
- Water sampling equipment, including bottles, gloves, transport cooler, ice packs and reporting sheets

Site control: The following issues should be considered:

- Public warning and road hazard signs, traffic cones and barriers
- Measures for sediment or dust control
- Locating and marking all existing utilities in the vicinity of the mains excavation, including water, sewer, stormwater, phone cables, gas, power lines and fibre optic lines
- Assess how groundwater levels, inclement weather and other factors may affect the repair, and determine compensatory methods

6.10.3.3 Internal corrosion prevention

Internal corrosion can be prevented by proper pipe maintenance, as discussed below:

- ***Pipe cleaning:*** The benefits of maintaining clean pipes include enhanced disinfectant residual stability, reduced bacterial levels and improved aesthetic water quality as reflected by customer reactions. These outcomes are typically cited by water systems as the primary drivers for cleaning the mains. However, recent research that focused on pipe water interactions, both within the distribution system and in premise plumbing systems, has shed additional light on the wide-ranging impacts posed by deposits. The research also demonstrated that effective routine mains cleaning plays a vital role in controlling internal corrosion in premise plumbing, limiting metals release and protecting the integrity of the system’s infrastructure (Hill et al., 2014; Schock et al., 2014).

- ***Pipe rehabilitation:*** One technique to keep corrosive water away from pipe walls is to line the wall with a protective coating. With new pipes, these linings are usually applied during the pipe manufacturing process, but can also be applied in the field when the pipe is installed. Some linings can be applied even after the pipe is in service. Linings can also be installed to prove the structural integrity or to improve a pipeline that has been in service for a long time. Linings are categorised using structural classification Class I through Class IV, with Class I linings being considered non-structural coatings and Class IV linings being considered structurally independent. These classifications are further defined in AWWA (2014). The most common pipe linings are coal-tar enamels, epoxy paint, cement mortar and polyethylene. It is common practice to reline cleaned pipes to protect the new exposed pipeline material.

  In South Africa, these pipe linings are extensively explained in DWS (1994), in which different SABS/SANS standards are outlined, highlighted and suggested for further study. The various SABS/SANS codes in relation to coatings and linings are also listed in Golder and Associates (2006).

6.10.3.4 Biofilm and microbial regrowth preventive strategies

The following sections describe biofilm and microbial regrowth preventive strategies:

- ***Pipe materials:*** With respect to biofilm removal from piping materials, strategies such as increasing disinfectant dose or changing disinfectant type are less effective on established biofilms. Systems may need to rely on methods that dissolve, shear or otherwise dislodge biofilm from the pipe surface. For smooth piping and a pipe diameter of 12 inches or less, unidirectional flushing at high velocity (>6 fps) can be effective. However, more aggressive techniques, such as ice pigging or swabbing, are often needed for more effective biofilm removal (Friedman et al., 2016).

- ***Nutrient concentration:*** Although sometimes overlooked as a cause of total coliform presence, nutrient loading to the distribution system can contribute significantly to persistent biofilm growth, loss of disinfectant residual and coliform occurrences. Limiting nutrient levels in the treated water are critical in providing biologically stable drinking water. Organic nutrients are measured using AOC and BDOC. Select microorganisms can also use inorganic nutrients such as ammonia, iron, manganese, sulphur and other chemicals. Nutrient levels affect the biostability of finished water, and the different processes used to treat source waters can greatly impact on the water's biostability. Microbial growth associated with the presence of nutrients in drinking water should be addressed at the treatment plant before the water enters the distribution system.

- ***Adequate disinfectant residual:*** Low to no disinfectant residual in the distribution system can contribute to bacterial growth. LeChevallier et al. (1996) found that low to no residual (<0.2 mg/ℓ for free chlorine and <0.5 mg/ℓ for monochloramine) in distribution system dead ends corresponded with more positive coliform samples. The following recommendations have been made with respect to secondary disinfectant residual maintenance in the distribution system:

  - Friedman et al. (2010) recommend minimum levels of 0.2 mg/ℓ for free chlorine and 0.5 mg/ℓ for total chlorine in 95% of samples collected from the location, including total coliform rule (TCR) and other recommended sites. The TCR sites are typically selected to capture representative water quality conditions, such as d/s of storage facilities, blending zones or areas with known water age problems. These types of sites should be included in a secondary disinfection evaluation.

  - LeChevallier et al. (1996) recommend maintaining at least 0.2 mg/ℓ free chlorine or 0.5 mg/ℓ chloramine at the far ends of the distribution system. The authors cite chlorine threshold criteria for increased coliform occurrence as <0.5 mg/ℓ free chlorine and <1.0 mg/ℓ chloramines.

Many factors influence the concentration of disinfectant residual in the distribution system, including the following:

- Bulk water chlorine demand and decay reactions
- Water age and hydraulic conditions
- Accumulated sediments, including in storage reservoirs
- Blending of sources
- Nitrification
- Reactions with pipe walls

Water authorities (WSPs or WSAs) that experience difficulty with disinfectant residual levels in the distribution system can make the following evaluation:

- Consider increased dosage for the overall system
- Assess the need for boosting within specific areas
- Consider water age management techniques, including reducing demand, implementing or optimising a flushing programme, and enhancing storage turnover and mixing
- Control blending of sources
- Assess and control nitrification

6.10.3.5 Cross-connection due to backflow

Cross-connection is backflow and/or back-siphonage, which may occur when a pressure difference exists between the environments or systems. Some sources of cross-connection on account of backflow include beverage dispensers, hosepipe sprayers, water jetting equipment and fire sprinkling systems.

The following are some strategies that are helpful in preventing backflow:

- The installation of backflow preventive devices on each potentially hazardous location
- Maintaining positive pressure in the water distribution system or minimising disruption to the system
- Awareness to consumers on the potential dangers of cross-connections
- Implementation of a cross-connection management programme

In addition to the above, SABS (2011) explains mechanical backflow prevention devices. The SANS 1808-15:2011 focuses more on building scenarios, rather than distribution and other networks. However, there are a number of internationally recognised management concerns and best practices regarding cross-connection, which are either less explored or not discussed at all in the above documents. These are explained in a stepped manner as follows:

- ***Indicators of a backflow incident:*** A clear indication that a backflow event has occurred is the presence of contaminants in the potable water systems, such as faecal coliform or *E. coli*, detergents, pesticides, nitrate, etc. However, not all indicators are monitored routinely, except for the first two, but other possible reasons for water systems to monitor for cross-connections include customer complaints regarding water quality, a drop in operating pressure, a drop in disinfectant residual, water meters running in reverse and coliform detections (AWWA, 2017b).

- ***Responding to backflow incidents:*** Backflow events are transient in nature. They can move slowly or quickly through the water distribution system. They can be readily obvious as sweet-smelling, pink and foamy water, or they can lend no colour or odour to the water at all. At the basic level, a water provider should perform an investigation, sometimes referred to as a customer service inspection, in response to cross-connection and backflow incidents that include the following steps (AWWA, 2017b):

- Locate the source of the contamination (as discussed under potential indicators of backflow above).
- Isolate that source to protect the water distribution system from further contamination.
- Determine the extent of the spread of contamination through the distribution system and provide timely, appropriate notification to the public and to regulatory agencies.
- Take corrective action to clean the contamination from the distribution system and eliminate the cross-connection.
- Restore service to customers.

A post-incident investigation is typically a team effort. The investigation should be led, at least initially, by the cross-connection control programme manager, or someone trained in cross-connection control and backflow prevention. Alternatively, the water quality manager can lead this effort. Additional team members include the following (AWWA, 2017b):

- Water distribution system manager and/or operators
- Local health inspector
- Property managers
- On-site plumber or maintenance worker
- Communication specialist
- Utility manger
- Lab technicians and available certified laboratories to confirm the parameters

A report should be generated detailing the backflow incident, and the corrective actions that were taken. This is often referred to as a backflow incident report. This report documents details of the investigation and subsequent corrective action taken for reportable backflow incidents.

- ***Best practices:*** It is the responsibility of the cross-connection control programme manager or water quality manager to be knowledgeable about the water distribution system, for example (AWWA, 2017b):

  - How it operates (the normal flow patterns of the system)
  - Where valves are located
  - Where backflow prevention devices and assemblies are installed (customers)
  - Where industrial and residential areas are located
  - Local impacts from seasonal weather, e.g. in a cold climate, winterisation of irrigation systems could increase the number of dirty water calls
  - Locations with high hazards
  - Locations that have not complied with the cross-connection control programme requirements
  - The location of cooling towers, wells, ponds, auxiliary water supplies and similar structures
  - Projects, e.g. new construction, water mains replacements, flushing, fires and contractors who are permitted to use fire hydrants for construction water.

  Ideally, this wealth of knowledge resides with one individual. In larger organisations, a team may be gathered to coordinate the detailed information that is needed.

- ***Backflow incident response plans:*** Generally, emergency response plans that cover a wide range of emergency conditions are beneficial to water suppliers when protecting water quality. A backflow incident response plan, as part of an overall emergency response plan, provides for a more efficient response by personnel to quickly respond to backflow incidents, prevent further contamination, and then investigate and document both the incident and utility response (AWWA, 2017b).

A backflow incident response plan includes defined roles and responsibilities, action plans and corrective measures. A key component of the plan is the investigation of any water quality complaints that could indicate backflow contamination. According to AWWA (2017b), a proper backflow incident response plan contains the following:

- Purpose and scope of the plan
- Identification of roles and responsibilities: organisations and departments (e.g. water department, health department, communications departments, mayor's office), and teams and team members (water distribution manager and distribution operators)
- Definitions and common backflow indicators
- Action plans and tasks
- Notification protocols
- Corrective measures
- Reporting protocols and forms (e.g. backflow incident report)
- Close-out procedures

- ***Cross-connection control and backflow prevention programmes:*** The purpose of a cross-connection control and/or backflow prevention programme is to avoid contamination of the public water supply by preventing, eliminating and/or controlling cross-connections. The water supplier should carry out a comprehensive and effective cross-connection control programme to ensure that public health is protected, regulatory requirements are met, and the quality of the water supply is maintained.

  An effective cross-connection control programme should have a documented plan that includes the following components (AWWA, 2017b):

  - Purpose
  - Definitions
  - Establishment of authority and legal requirements
  - Programme administration and budgeting
  - Roles and responsibilities
  - Coordination with local authorities
  - Approved backflow prevention methods and codes
  - Risk assessment
  - Public outreach and education customer communication
  - Training of internal and external personnel
  - Certification of backflow testers, installers and repair personnel
  - Documentation and recordkeeping
  - Inventory and database of backflow prevention assemblies
  - Backflow prevention assembly testing
  - Enforcement
  - Site inspections and surveys
  - Backflow incidence response plan (as discussed above)
  - Quality assurance procedures (see following section)

- ***Quality assurance programmes:*** A quality assurance programme is important for all aspects of operating a public water system. For cross-connection control, the minimum quality assurance programme should include a review of the performance of certified testers and monitoring of field test equipment (AWWA, 2017b).

A review of the performance of certified backflow prevention assembly testers includes the following (AWWA, 2017b):

- Reviewing accepted backflow prevention assembly tester certification programmes to ensure a validated written examination that adequately measures the expected range of knowledge; a proctored hands-on performance component that simulates properly functioning and failed assemblies; periodic recertification utilising both written and hands-on elements; and a clear separation between the trainer and the certification authority
- Spot-checking (auditing) the tester's work by observing the backflow prevention assembly field test and/or by inspecting and retesting assemblies
- Comparing field test data with manufacturer's data and previous field test reports
- Checking on the proper completion of field test report forms
- Verifying with the certification agency that the tester's certification is valid
- Reviewing the field test results submitted for backflow preventers to determine if the results are unsatisfactory (i.e. component(s) failed performance criteria); replacement or repair is needed; the backflow preventer has been replaced, relocated, repaired, modified or removed without the water supplier's prior knowledge; and the backflow preventer is improperly installed or in an improper application.

Monitoring field test equipment to ensure that accuracy is within tolerances may be done by means of the following:

- Requiring that field test equipment has its calibration checked by an independent manufacturer-certified or industry-recognised laboratory
- Having the water supplier verify the field test equipment annually, at a minimum

Part of the programme should also include recordkeeping and data management, as well as a comprehensive inventory of backflow prevention devices and assemblies and their location.

6.10.3.6 Leaching and permeation mitigation

- ***Maintenance:*** Stagnation of water can exacerbate permeation and leaching incidents. Poor convective dilution of permeated or leached solvents are associated with stagnant areas of the distribution system. The extent of leaching of cementitious and organic material exhibits some relationship to the contact time between the pipe and internal water. Unidirectional flushing and reservoir turnover can be used to encourage fluid movement, minimise residence time and replace stagnant water. Flushing does not suppress the process of leaching, but the movement of fluid helps prevent the accumulation of contaminants in a localised area. Studies have demonstrated the ineffectiveness of flushing to mitigate a permeation incident. While flushing may replace the contaminated water, the pipeline retains its swollen, highly permeable state. In these instances, pipe replacement is an effective practice.

  With respect to permeation, most incidents occur along service connections due to their small diameter and frequent stagnation. However, service lines are not owned by the utility (USEPA, 1999). Thus, in the event of a permeation event involving a service connection, the consumer would need to flush the tap long enough to draw water from a point beyond the service line to avoid exposure to potentially contaminated water.

- ***Design and installation*:** Prevention of permeation and leaching requires proper materials selection and installation practices. The phenomena of permeation and leaching require consideration of the environments surrounding and within the pipe, respectively. From a design perspective, permeation can be precluded by identifying the area of installation and recognising the potential for past or future gross spillage of organic chemicals and petroleum products.

The national standards of the American National Standards Institute (ANSI), AWWA C900 to C950, state that if a water main must pass through an area of gross contamination, the manufacturer should be consulted regarding the permeation of pipe walls and joint fittings prior to selecting the material. The Standards also note that research has documented that pipe materials such as polyethylene, polybutylene, polyvinyl chloride and asbestos cement, and elastomers may be subject to permeation by lower molecular weight organic solvents or petroleum products. The Ten State Standards, published by the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers in 1997, states that non-permeable materials shall be used for all portions of the system, including water mains, service connections and hydrant leads in areas of distribution systems where the groundwater is contaminated by organic compounds. The Uniform Plumbing Code (UPC) does not discuss permeation directly. It states that clean soil will be used as backfill around buried pipes, and seems to recognise some potential for contamination from the pipe-embedment environment. The UPC does not, however, specifically address installation through contaminated soils or permeation as a pathway of exposure.

6.10.3.7 Maintaining disinfectant residuals

There may be times when the required level of free chlorine residual in a distribution system is not met. If a low residual is observed at one or more of the approved sampling locations, the following actions should be taken to return the chlorine residual to a compliance level (Nova Scotia Environment and Labour, 2005):

- ***Verify the result by re-testing:*** If re-testing indicates an acceptable residual above the requirement, then there is no need for further action. However, if re-testing indicates the free chlorine residual remains lower than the level required, the owner shall increase the chlorine dosage and/or flush lines until the residual is returned to an acceptable level.

  The inspector/supervisor or responsible monitoring agent must notify a higher authority of the situation and continue actions to try to achieve and/or maintain a residual within compliance of SANS 241-1: 2015. Once the test results indicate that the residual has been returned to compliance level, the pipeline can return to normal operation following discussions with a higher authority. If chlorine residual test results continue to indicate a residual that is not in compliance with SANS 241-1: 2015, the inspector/supervisor or responsible monitoring agent must notify the higher authority and prepare an action plan advising what other actions are required, complete with a proposed timeline for implementation. For example, a permanent continuous blow-off station or residual booster station may be required. Consideration may also be given to increasing the frequency of testing for coliform bacteria and/or HPC bacteria at locations that experience chronically low chlorine residuals. A sudden increase in HPC bacteria can serve as an early warning of water quality deterioration.

  If it is determined that gross contamination of the distribution system has occurred due to cross-connection, a boil water advisory may be necessary. Based on incident protocol management, all involved parties must be informed and necessary corrective actions taken until the root cause is found and eliminated, and disinfectant residual is met in accordance with SANS 241-1: 2015. All residual analyses and corrective actions are to be documented and provided to the higher authority upon request.

6.11 STEP 9: VALIDATION AND VERIFICATION

This step includes capacity building aspects for operators and plumbers, the management of planning and design of new assets, etc. This step is described in detail in the WHO guideline on WSP for distribution systems (WHO, 2014) and other published South African WSP documents as introduced in Section 6.1.

6.12 STEP 10: REVIEW, APPROVAL AND AUDIT

The WSP should be reviewed periodically to consider its appropriateness and make changes where necessary. This step is described in detail in the WHO guideline on WSP for distribution systems (WHO, 2014) and other South African published WSP documents as introduced in Section 6.1.

6.13 STEP 11: REVIEW EXPERIENCE AND FUTURE NEEDS

The WSP should be reviewed following any incident to ensure that future occurrences can be prevented or better managed.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

This study found that the causes and types of contaminant intrusion events are well understood internationally, as documented in Chapter 2. At the same time, South Africa has a strong legal and institutional framework for managing water quality in distribution systems, although the guidelines are fragmented and gaps were identified.

From the small number of published case studies of contaminant intrusion events in distribution systems and the lack of information of such events at different levels of government, it is clear that the existing regulations and guidelines are not adequately implemented.

7.2 RECOMMENDATIONS

Based on the outcome and investigation of this study, the following recommendations are made:

- It was found that some water distribution system have problems that are highlighted in the documents published in 2000 (16 years before this document was published), but those problems still exist in water distribution systems. This indicates that the responsible authorities should study the water quality guidelines and documents published nationwide so that water quality problems can be mitigated and improved with the passage of time.
- Internationally, many countries have various codes of practice for different engineering purposes, including road and building construction (e.g. the American Association of State Highway and Transportation Officials, the American Society of Civil Engineers, the American Concrete Institute and the International Standards), and water supply design and construction, similar to the SABS in South Africa, which are compulsory. However, when it comes to South Africa, even though it has an SABS code covering many issues, it has not laid down any control procedures against the potential water quality events in water distribution systems discussed in this document. Moreover, while the DWS's technical guidelines (DWS, 2004), DWAF's documents and the WRC's reports have discussed different water quality issues in water distribution systems, there is still not a comprehensive water quality control code for South African water distribution systems that covers all water quality aspects in an officially recognised and authorised book that includes guidelines for WSPs and standard operating procedures that must be followed by all involved parties, practitioners, engineers and contractors. Therefore, it is recommended that all the sources in relation to water quality in water distribution systems should be combined and enforced. By ensuring that the responsible entities comply with them, drinking water quality can be ensured for public consumption.
- Coordination among stakeholders, including water authorities (DWS, WSAs, and/or WSPs), the DoH and South African accredited water quality laboratories (who are responsible for water quality sampling), is another highly recommended issue. Water quality deterioration events with reference to water distribution systems, having a known root cause, duration and time, affected area and location, are either recorded differently or not recorded at all. Therefore, it is highly recommended that a committee be established, which consists of all stakeholders involved, to share their views on how to manage and record water quality deterioration events in water distribution systems, including a well-designed database for such events approved by them. This committee can also overlap in terms of these recorded data in order to find vulnerable zones and suggest corrective and preventive measures accordingly per site.

- South African has a good electronic water quality management system, primarily designed for WSP application by Emanti Management (Pty) Ltd. It generates WSP status graphically, indicating the performance of each step in the WSP, so it is recommended that it be extended or modified to show the overall water quality performance of various components in the water distribution system as well, including water storage reservoirs, pump stations, pipe networks, water treatment plants and tap water, as it gives one an indication of each component of the water supply distribution system that requires more attention and corrective measures.
- Since zero pressure due to empty pipelines provides a conducive environment for external contaminants to be intruded, which, in turn, causes water quality deterioration, it is recommended that an intermittent water supply system is avoided, even though it is impractical in water-scarce regions.

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APPENDIX A: NATIONAL STANDARDS FOR DRINKING WATER QUALITY (SANS 241)

A1: Physical determinands

Table 1: Physical determinands

No	Determinand	Units	Standard limits	Risk
1	Colour	mg/L Pt-Co	≤15	Aesthetic
2	Conductivity at 25 °C	mS/m	≤170	Aesthetic
3	TDS	mg/ℓ	≤1 200	Aesthetic
4	Turbidity	NTU	≤1	Aesthetic
		NTU	≤5	Operational[a]
5	pH at 25 °C[b]	pH units	≥ 5 to ≤ 9.7	Operational

[a] Values more than the standard limits may adversely affect disinfection.
[b] Low pH values may contribute to structural deficiencies in the distribution system.

Source: SABS, 2015.

A2: Chemical determinands

Table 2: Chemical determinands

No	Determinand	Units	Standard limits	Risk
A. Macro determinands				
1	Free chlorine as Cl_2[d]	mg/ℓ	≤5	Chronic health: eye/nose irritation; stomach discomfort
2	Monochloramine[cd]	mg/ℓ	≤3	Chronic health
3	Nitrate as N[et]	mg/ℓ	≤11	Acute health: shortness of breath in infants, blue-baby syndrome
4	Nitrite as N[efg]	mg/ℓ	≤0.9	
5	Combined nitrate plus nitrite[efg]	-	≤1	
6	Sulphate as SO_4^{2-}	mg/ℓ	≤500	Acute health: diarrhoea
		mg/ℓ	≤250	Aesthetic: bitter or salty taste
7	Fluoride as F^-	mg/ℓ	≤1.5	Chronic health: pain and tenderness of the bones; mottled teeth
8	Ammonia as N	mg/ℓ	≤1.5	Aesthetic: taste and odour problems
9	Chloride as Cl^-	mg/ℓ	≤300	Aesthetic: salty taste and increasing corrosion rate of metals
10	Sodium as Na	mg/ℓ	≤200	Aesthetic: salty taste
11	Zinc as Zn	mg/ℓ	≤5	Aesthetic: milky appearance, opalescence or bitter taste

B. Micro determinands				
12	Antimony as Sb	μg/ℓ	≤20	Chronic health: increase blood cholesterol; decrease blood sugar
13	Arsenic as As	μg/ℓ	≤10	Chronic health: skin damage, and probable increase risk of cancer
14	Barium as Ba	μg/ℓ	≤700	Chronic health: increase blood pressure
15	Boron B	μg/ℓ	≤2 400	Chronic health: metabolism, acute: diarrhoea, vomiting, signs of irritability, etc.
16	Cadmium as Cd	μg/ℓ	≤3	Chronic health: kidney damage
17	Total chromium as Cr	μg/ℓ	≤50	Chronic health: allergic dermatitis
18	Copper as Cu	μg/ℓ	≤2 000	Chronic health: liver or kidney damage
19	Cyanide (recoverable) as CN^-	μg/ℓ	≤200	Acute health: nerve damage or thyroid problems
20	Iron as Fe	μg/ℓ	≤2 000	Chronic health: excessive ingestion may result in haemochromatosis, wherein tissue damage occurs after iron accumulation
		μg/ℓ	≤300	Aesthetic: rust-coloured silt, reddish colour, slimy coatings
21	Lead as Pb	μg/ℓ	≤10	Chronic health: infants and children – delays in physical or mental development; children – low attention and learning abilities, adults – kidney problems; high blood pressure
22	Manganese as Mn	μg/ℓ	≤400	Chronic health: neurotoxic effects, chronic toxicity
		μg/ℓ	≤100	Aesthetic: turbidity, odour and taste problems
23	Mercury as Hg	μg/ℓ	≤6	Chronic health: kidney damage
24	Nickel as Ni	μg/ℓ	≤70	Chronic health: loss of weight, heart and liver damage, dermatitis
25	Selenium Se	μg/ℓ	≤40	Chronic health: hair/fingernail loss; numbness in fingers/toes; circulatory problems
26	Uranium as U	μg/ℓ	≤30	Chronic health: increased risk of cancer, kidney toxicity
27	Aluminium as Al	μg/ℓ	≤300	Operational: helping discolouration with iron and manganese

• **Organic Determinands**				
28	Total organic carbon as C	mg/ℓ	≤10	Chronic health:
29	Trihalomethanes[h]	μg/ℓ	≤300	Chronic health: liver, kidney or central nervous system problems; increased risk of cancer
	Chloroform	μg/ℓ	≤100	
	Bromoform	μg/ℓ	≤100	
	Dibromochloromethane	μg/ℓ	≤60	
	Bromodichloromethane	μg/ℓ	≤300	
30	Combined trihalomethanes[h]	-	≤1	
31	Total microcystins[j]	μg/ℓ	≤1	Acute health: abdominal pain, headache, sore throat, vomiting and nausea, dry cough, diarrhoea, blistering around the mouth, and pneumonia
32	Phenols	μg/ℓ	≤10	Aesthetic: unpleasant tastes and odours to water

[h] See Annex C of SANS 241-2: 2014 for an example of the sum of the THM ratio. The sum of the ratios of the concentrations of each to its respective guideline value should not exceed 1.

[j] Mircrocystin only needs to be measured where an algal bloom (>20 000 cyanobacteria cells per millilitre) is present in a raw water source. In the absence of algal monitoring, an algal bloom is deemed to occur where the surface water is visibly green in the vicinity of the abstraction, or samples taken have a strong musty odour.

Sources: SABS, 2015; USEPA, 2018

A3: Biological determinands

Table 3: Microbiological determinands

No	Determinand	Units	Standard limits	Risk
1	*E. coli*[a] or faecal coliforms[b]	Count per 100 mℓ	Not detected	Acute health: gastrointestinal illness (such as diarrhoea, vomiting, and cramps, etc.)
2	Protozoan parasites[c] Cryptosporidium species Giardia species	Count per 10 ℓ Count per 10 ℓ	Not detected Not detected	Acute health[g]: gastrointestinal illness (such as diarrhoea, vomiting, and cramps)
3	Total coliforms[d]	Count per 100 mℓ	≤10	Operational: used to indicate if other potentially harmful bacteria may be present
4	Heterotrophic plate count[e]	Count per mℓ	≤1 000	Operational: an analytic method used to measure the variety of bacteria that are common in water
5	Somatic coliphages[f]	Count per 10 mℓ	Not detected	Operational: indicator for faecal pollution and viruses

[a] Definitive, preferred indicator of faecal pollution.

[b] Indicator of unacceptable microbial water quality, could be tested instead of *E. coli*, but is not the preferred indicator of faecal pollution. Also provides information on treatment efficiency and aftergrowth in distribution networks.

[c] Confirms a risk of infection and faecal pollution, and also provides information on treatment efficiency. The detection of selected protozoan parasites confirms a human health risk.

[d] Provides information on treatment efficiency and aftergrowth.

[e] Process indicator that provides information on treatment efficiency, aftergrowth in distribution networks and adequacy of disinfectant residuals.

[f] Process indicator that provides information on treatment efficiency.

[g] Determinand that is presently not easily quantifiable and lacks information pertaining to viability and human infectivity, which, poses immediate, unacceptable health risks if present in drinking water.

Sources: SABS, 2015; USEPA, 2018

APPENDIX B: QUESTIONNAIRE

Drinking water quality failures in water distribution systems

(Incidents, health impacts, causes, control measures or actions taken)

Dear Sir or Madam,

My name is Abdul R. Mosameem and I am a PhD student in the Department of Civil Engineering at the University of Cape Town (UCT) under the supervision of Prof Kobus van Zyl. The aim of my PhD research is to establish the frequency and causes of water contamination events that occur in water distribution systems (i.e. downstream of the water treatment plant) and the characteristics of distribution systems that contribute to these events. The results of this study will assist municipalities in providing high-quality water to consumers and minimise contamination risks.

The research is funded by the Water Research Commission through Project K5/2573. The results of the study will be made available free of charge through a research report published by the Water Research Commission.

This letter serves to invite you to participate in a survey on your experience with or knowledge of contamination events that occurred in water distribution systems. Your name will be kept confidential and you can withdraw from participating in the project at any time. You will not be compensated for participating and you will be provided with a free copy of our research report on request.

Should you have any queries or comments on the research project, you are welcome to contact me (email MSMABD001@myuct.ac.za) or Prof Kobus van Zyl (Office phone 021 650 2325; email Kobus.vanzyl@uct.ac.za).

Yours faithfully,

Abdul Rahman Mosameem

PhD student

University of Cape Town, SA

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Phone: (+27) 630 7825 73

Email: MSMABD001@myuct.ac.za;

Rahman.shaheen2003@gmail.com

Web: http://www.uct.ac.za/

Questionnaire

Drinking water quality failures in water distribution systems

(Incidents, health impacts, causes, control measures or actions taken)

General information

1.	**Respondent**
	Name (optional):
	Email address (optional):
	Contact phone number (optional):
	Position(s) at Municipality reported on:
	Name of Municipality:
	Number of consumers served by Municipality:
	Does the Municipality have an internal reporting system for water quality failures in the distribution system? If yes, please provide details below:
2.	**Incidents or processes negatively affecting water quality in distribution system**
	Are you aware of any incidents where the water quality in a distribution system was negatively affected by an incident or process related to the water distribution system (including pipes, pump stations, reservoirs, elevated reservoirs, flow meters and other components)? Yes ☐ No ☐ If your answer is "yes", please answer the following questions available on the next page. Please complete one form for each type of incident you are aware of:

Questionnaire

Drinking water quality failures in water distribution systems

(Incidents, health impacts, causes, control measures or actions taken)

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2. Incidents or processes negatively affecting water quality in distribution system

- If your answer to the previous section of this document in relation to incidences that have negatively affected water quality in water distribution system (Section 2) is "yes", please proceed with responding to the following questions.

2.1	**How would you describe this type of incident, i.e. type of failure?**
2.2	**How do/did you know about this incident?**
2.3	**How was the water quality affected?**
2.4	**Where did it occur?**
2.5	**How many times or how frequently did it occur?**
2.6	**Over approximately what dates or date range did these events occur?**

2.7	**Was the health of any person negatively affected by this event? If so, please provide details.**
2.8	**What were the causes of this event?**
2.9	**Was the event reported by anybody? If so, to whom was it reported and how did the authorities respond?**
2.10	**How could this event have been prevented?**
2.11	**Could you please provide any other comments or information on the event that will assist our research?**

Possible sources and/or causes of water contamination incidents in the water supply distribution system

(List of possible intrusion events in the water supply distribution system)

1. Possible/potential sources or causes of water contamination incidents in reservoirs and pumps

1.1 Clear water reservoir

- **1.1.1** Damage or destruction of reservoir due to natural disasters (earthquakes, hurricanes, floods, landslides, volcanic eruptions).
- **1.1.2** Damage or destruction of reservoir due to human-caused accidents (car, truck or aircraft collision, landslides caused by reservoir leakage or nearby excavation).
- **1.1.3** Intentional damage or destruction of reservoir (terrorism, sabotage, vandalism, arson).
- **1.1.4** Reservoir structure damage due to excessive internal pressure build-up.
- **1.1.5** Wrong water level metering or data processing system malfunctioning.
- **1.1.6** Intentional contamination of the network water (terrorism, sabotage, vandalism, arson).
- **1.1.7** Introduction of contaminants by improper use of material or operational errors.
- **1.1.8** Poor hygiene during reservoir construction, repair or cleaning.
- **1.1.9** Intrusion of contaminants (e.g. bird and animal faeces), dust or vermin through improperly sealed access openings or hatches and faulty or fouled screening of vents and overflow pipes.
- **1.1.10** Intrusion of contaminants though cracks in the reservoir roof.
- **1.1.11** Intrusion of contaminants though cracks in the reservoir walls or floor.
- **1.1.12** Ageing of water due to low turnover rates or uneven hydraulic mixing.
- **1.1.13** Excessive accumulation of sediments on the reservoir floor.
- **1.1.14** Excessive biofilm accumulation on reservoir walls.

1.2 Pumping station

- **1.2.1** Destruction of pump station due to natural disasters (earthquakes, hurricanes, floods, landslides, volcanic eruptions).
- **1.2.2** Damage or destruction of pumping station due to human-caused accidents (car, truck or aircraft collision, landslides caused by reservoir leakage or nearby excavation).
- **1.2.3** Intentional damage or destruction of pumping station (terrorism, sabotage, vandalism, arson).
- **1.2.4** Damage or destruction of network pipes due to water hammer, caused by absent or malfunctioning surge reservoirs.
- **1.2.5** Pump malfunctioning/failure.
- **1.2.6** Pump stoppage due to power failure or disruption and failing power back-up supply.
- **1.2.7** Excessively high pressure in the network due to wrong settings or deficient control of pumps' operation.
- **1.2.8** Low pressure in the network due to wrong settings, deficient metering or deficient control of pumps' operation.
- **1.2.9** Contaminants pulled in at the suction side of a pump.
- **1.2.10** Introduction of pollutants by improper use of material or operational errors.
- **1.2.11** Poor hygiene during pump installation, maintenance or repair.
- **1.2.12** Pump operation leading to rapid changes in water flow rate or direction.

1.3 Valves (both in the reservoirs and pumping stations)

- **1.3.1** Inadequately designed or operated valve, malfunctioning valve.
- **1.3.2** Damage or destruction of network pipes due to water hammer.
- **1.3.3** Introduction of contaminants by improper use of material or operational errors.
- **1.3.4** Poor hygiene during installation, maintenance or repair of valves.
- **1.3.5** Inadequate settings or control, or malfunctioning or failure of pressure-reducing valve.

2. Possible/potential sources or causes of water contamination incidents during transport and distribution

2.1 Network

2.1.1 Pipe C47:C67 due to extreme external stresses (e.g. storms, earthquakes, landslides, freezing and thawing, traffic incidents, etc.).
2.1.2 Pipe burst due to increased external stresses on pipe (e.g. traffic, soil movement, etc.) in combination with a reduced pipe condition.
2.1.3 Pipe burst due to bad condition of pipe (e.g. internal or external corrosion).
2.1.4 Pipe burst or leakage due to increased internal stress (e.g. pressure, transients).
2.1.5 Loss of pipes' hydraulic capacity due to scaling or tubercle formation.
2.1.6 Insufficient network capacity due to inadequate design.
2.1.7 Poor hygiene during pipes' installation or repair.
2.1.8 Intrusion of contaminated water due to low (negative) pressure in the network, in combination with cracks or leaking joints.
2.1.9 Migrating substances from polymer material (e.g. vinyl chloride leaching from PVC pipes).
2.1.10 Leaching of contaminants from cement-made or lined pipes.
2.1.11 Leaching of organic compounds from bituminous sealants and linings.
2.1.12 Permeation of organic pollutants in the soil through rubber joints or the (PE or PVC) pipe wall.
2.1.13 Backflow or back-siphonage of non-potable water (e.g. wastewater) or fluids (e.g. industrial).
2.1.14 Too long residence times of water in the network.
2.1.15 Deficit in disinfectant residual, excess in water AOC/BOC.
2.1.16 Too high dosage of disinfectant residual (e.g. malfunctioning dosing pump(s)).
2.1.17 Re-suspension of sediments or sloughing of tubercle or biofilm due to rapid changes in water.
2.1.18 Intentional contamination of the network water (terrorism, sabotage, vandalism, arson).
2.1.19 Malfunctioning or failure of valves and/or (boosting) pumps.
2.1.20 Valve pit flood allowing contaminant intrusion though defective valve sealing, in combination with low pressure in the network.
2.1.21 Inadequate settings or control, or malfunctioning or failure of pressure-reducing valve.
2.1.22 Defective or clogged fire hydrant.

2.2 Water meters and non-return valves

2.2.1 Wear of water meter mechanical parts.
2.2.2 Freezing of water within meters and/or external pipes exposed to extremely low temperatures.
2.2.3 Fouling of water meter due to sediments or biofilm.
2.2.4 Fouling of non-return prevention devices due to sediments or biofilm.
2.2.5 Absent, inadequate or defective non-return prevention devices allow backflow or siphonage of contaminated water from costumer premises or fire hydrants.
2.2.6 Meter pit flood allowing contaminant intrusion though defective sealing, in combination with low pressure in the network.

3. Possible/potential sources or causes of water contamination incidents in internal piping

3.1 Drinking water installation

3.1.1 Bad design of the installation or low pressure in distribution network.
3.1.2 Failure of booster pump in multi-storey buildings.
3.1.3 Pipe burst due to poor pipe material, excessive pressure, water hammer, building activities (e.g. drilling).
3.1.4 Excessive pressure in the distribution system.
3.1.5 Poor hygiene in plumbing systems installation or repair.
3.1.6 Backflow or back-siphonage of contaminated water from other systems (e.g. waste, fire protection, garden watering and irrigation).
3.1.7 Microbial regrowth enhancement by relatively high water temperature or heating of water by warm objects at close distance.
3.1.8 Loss of pipes' hydraulic capacity due to incrustation build-up.

3.1.9 Corrosion of plumbing system materials, which is promoted by low pH, temperature, insufficient or excessive alkalinity in the water.
3.1.10 Migrating substances from polymer material (e.g. vinyl chloride leaching from PVC pipes).
3.1.11 Plumb solvency of lead pipes, which may be promoted by water with low pH and low alkalinity.
3.1.12 Sediment accumulation and microbial growth in water stagnated at dead-end branches.
3.1.13 Iron corrosion from iron or steel pipes.
3.1.14 Water hammer, high velocities and/or turbulence or cavitation.
3.1.15 Microbial growth due to too long residence time of water, warm temperatures, sediment accumulation or exposure of the water to light.

3.2 Hot water plumbing system

3.2.1 Microbial growth in hot water system (heaters, storage reservoirs, pipes, taps and shower heads) with water below 65 ºC.
3.2.2 Scaling build-up leads to reductions in heater or reservoir heating efficiency, storage capacity and lifetime.
3.2.3 Water from shower or bath taps supplied above 55 ºC.

3.3 Point-of-entry and point-of-use treatment devices

3.3.1 Fouling of treatment devices by suspended solids, iron, manganese or copper.
3.3.2 Inadequacy of the treatment process for a targeted compound (e.g. (mis)use of cation exchange to remove lead from hard water; (mis)use of activated carbon to remove arsenic).
3.3.3 Failure of the contaminant removal process (e.g. exhaustion of the resin or carbon adsorptive capacity; UV lamp bulb or housing opaque by dirt).
3.3.4 Enhanced corrosion of plumbing system and appliances materials (e.g. lead, copper) due to excessive water softening.
3.3.5 Backflow of liquid waste streams (e.g. reverse osmosis, ionic exchange resins) or backwash water (adsorptive media filters) to the treated water lines.
3.3.6 Growth or release of microorganisms from treatment devices (e.g. granular-activated carbon filters).
3.3.7 Unsafe handling or storage of strong caustics or acids used for adsorptive media regeneration.

4. Possible/potential sources or causes of water contamination incidents at consumer's premises

4.1 Water storage and transportation

4.1.1 Exposure to airborne substances, such as dust, dirt, flies or other contaminants.
4.1.2 Dissipation of chlorine residuals.
4.1.3 Poor sanitation conditions by consumers.
4.1.4 Soiled nappies or dirty children washed directly at the ground reservoir.
4.1.5 Poor condition and age of the containers, leaking containers.
4.1.6 Top not fitted correctly over the reservoir allowing dirt and dust to enter the reservoir.
4.1.7 Biofilm formation from the inner walls of the ground reservoirs.

5. Possible/potential sources or causes of water contamination incidents due to WSAs

5.1 Institution/organisation

5.1.1 Use of out-of-date guidelines.
5.1.2 Inappropriate financial or technical conditions.
5.1.3 Inappropriate personal organisation (e.g. no assignment of responsibilities, no responsible person, inappropriate qualification).
5.1.4 Insufficient on-call-duty.
5.1.5 Insufficient and/or unqualified staff (e.g. certified, adequate labour).
5.1.6 Insufficient internal coordination and scheduling.
5.1.7 Operational fault in the automatised process due to programming by unqualified staff.
5.1.8 Operational fault in the automatised process due to inappropriate IT policy.
5.1.9 Lack of feeling, unawareness of technical status of installations due to automatisation.
5.1.10 Low quality of data input to information systems, incomplete, errors, etc.
5.1.11 Use of out-of-date or inappropriate software that cannot be used by others.