Principles and Practices of Drinking-water Chlorination

A guide to strengthening chlorination practices in small- to medium-sized water supplies

World Health Organization
Regional Office for South-East Asia

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Principles and practices of drinking-water chlorination: a guide to strengthening chlorination practices in small-to medium-sized water supplies.

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Contents

Acronyms and Abbreviations

%	percent
<	less than
>	greater than
≥	greater than or equal to
AWWA	American Water Works Association
Ct	Product of disinfectant concentration and time of contact
DBPs	disinfection by-products
DPD	N,N-diethyl-p-phenylenediamine
Eq	equation
FIFO	first in, first out
g	gram
h	hour
HAAs	haloacetic acids
HWTS	household water treatment and safe storage
kg	kilogram
L	litres
L/h	litres per hour
L/min	litres per minute
m^3	cubic meters
m^3/h	cubic meters per hour
m^3/min	cubic meters per minute
MDG	Millennium Development Goal
mg/L	milligrams per litre
min	minute
min.mg/L	minutes per milligram per litre
NTU	nephelometric turbidity unit
$^{\circ}C$	degree Celsius
PPE	personal protective equipment

SEARO	South-East Asia Regional Office
SOP	standard operating procedure
THMs	trihalomethanes
UNICEF	United Nations International Children's Emergency Fund
WHO	World Health Organization
WSP	Water safety plan

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Introduction

Disinfection of drinking-water supplies with chlorine is widely regarded as one of the most significant public health interventions, reducing the incidence of waterborne disease globally. However, in 2015 663 million people still lack access to so-called improved drinking-water sources[1], with the number of people lacking access to safe drinking-water likely to be much higher[2]. In light of this, improving chlorine disinfection practices within piped water supplies is an important strategy for improving global access to safe drinking-water.

What is the aim of this guide?

This publication provides guidance on chlorine disinfection in small- to medium-sized organized water supplies in lower resource settings. This guide is intended to act as a supporting programme for staff development and training under the water safety plan (WSP) framework[3,4]. The guide forms part of a training programme, with the corresponding training presentation available to download from the World Health Organization's (WHO's) South-East Asia Regional Office (SEARO) website[5]. Guidance is not provided on the use of chlorine for treatment objectives other than disinfection. The use of chlorine gas and chloramination is not covered in this guide.

For whom is the guide intended?

This guide is intended for people involved in the management and operation of small- to medium-sized organized water supply systems. The content has been developed with particular consideration for operational-level personnel with responsibility for chlorination (for example, water treatment plant operators and technicians). The material presented within this guide may also be relevant for engineers and representatives from public health, local government, non-governmental organizations, as well as any other individuals supporting water safety planning activities for the supply of safe drinking-water.

How is the guide structured?

The guide is presented in two parts:

Part 1. Chlorination principles: Describes key chlorination concepts, providing a knowledge foundation for the implementation of effective chlorination practices.

Part 2. Chlorination practices: Describes the practical application of the concepts presented in Part 1, including calculations and procedures for safe and effective chlorination of drinking-water supplies.

In addition, a supplementary **Toolbox** section is provided, which presents generic standard operating procedures (SOPs) for chlorination, which are intended to serve as a template which may be adapted to individual water supply systems. Throughout the guide, key concepts are presented in textboxes, alongside examples and basic calculations intended to guide the reader through the principles and practical application of drinking-water chlorination.

1 WHO and United Nations International Children's Emergency Fund (UNICEF; 2015). Joint Monitoring Programme for Water Supply and Sanitation. Progress on drinking-water and sanitation: 2015 update and MDG assessment. Geneva, Switzerland.
2 Onda, K., LoBuglio, J. and Bartram, J. (2012). Global access to safe water: accounting for water quality and the resulting impact on MDG progress. International Journal of Environmental Research and Public Health, 9, 880-894.
3 Bartram et al. (2009). Water safety plan manual: step-by-step risk management for drinking-water suppliers. Geneva, Switzerland.
4 WHO (2012). Water safety planning for small community water supplies: step-by-step risk management guidance for drinking-water supplies in small communities. Geneva, Switzerland.
5 http://www.searo.who.int/en/.

Part 1. Chlorination principles

Describes key chlorination concepts in a practical context to provide the necessary understanding for effective chlorination of drinking-water

1.1 What is chlorination?

Microorganisms are microscopic living organisms found in most environments on earth, including water. Microorganisms may be naturally present in water sources, but may also be introduced through human activities (e.g. the discharge of human and animal wastes).

Some microorganisms may be harmful to human health (called pathogens). If water is consumed without adequate treatment to remove pathogens, it may cause life-threatening disease, such as diarrhoea. Disease that is spread by water is referred to as waterborne disease.

Microorganisms commonly associated with waterborne disease include:

- bacteria (e.g. *Escherichia coli*, *Vibrio cholerae*);
- viruses (e.g. Hepatitis A, poliovirus A); and
- protozoa (e.g. *Cryptosporidium*, *Giardia*).

Chlorine is a powerful disinfectant, that is, a substance which may kill or inactivate microorganisms (see Textbox A). Chlorination is a process where chlorine is added to drinking-water to kill or inactivate microorganisms, including harmful pathogens. Although chlorine is an effective disinfectant, chlorine does not kill all harmful microorganisms (Figure 1).

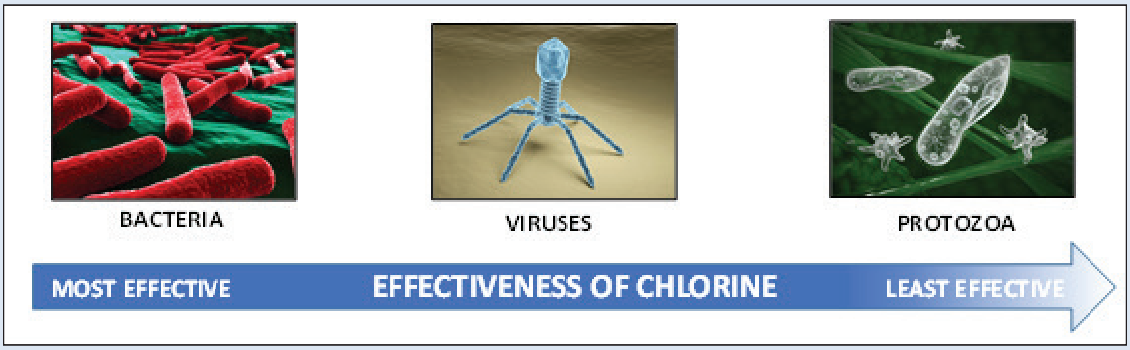
(A) The relative effectiveness of chlorine against microorganisms

The effectiveness of chlorine against different types of microorganisms is illustrated in Figure 1.

In general, chlorine is most effective against bacteria[6], is less effective against certain viruses and is least effective against certain protozoa.

Protozoa may survive for long periods in the environment by forming a type of durable shell called a cyst or oocyst. This is an important consideration for the supply of safe drinking-water, as chlorine has little practical effectiveness against these resistant protozoa (e.g. *Cryptosporidium*). Other drinking-water treatment processes may be required to effectively remove or inactivate protozoa, such as filtration or disinfection by ultraviolet (UV) light.

Figure 1. *The relative effectiveness of chlorine against different types of microorganisms*



6 Bacteria typically exists as actively growing or '*vegetative*' cells which are very susceptible to chlorine disinfection; however, under certain circumstances, particular bacteria may also form cyst-like '*spores*' for environmental survival; chlorine may be ineffective against certain bacterial spores.

1.2 Properties of chlorine

Chlorine exists as a solid (e.g. powder), liquid or gas. Key properties of chlorine with relevance to drinking-water disinfection include the following:

- chlorine is very chemically reactive, reacting with, for example, organic material, microorganisms, metals, pipe material and pipe fittings;
- chlorine liquid is volatile, meaning once exposed to air, the chlorine may be lost from the water phase and go into the air;
- chlorine has a distinctive, characteristic taste and odour, which may be detected by individuals when smelling or drinking the water;
- chlorine is corrosive, meaning it can cause severe irritation and chemical burns to human tissues such as skin, as well as damaging material such as pipes; as such, chlorine must be stored and handled carefully (see Section 2.1); and
- chlorine may remain in the water after disinfection has occurred; this may protect drinking-water from recontamination by harmful microorganisms during storage and distribution to the consumer.

(B) How to express the strength of chlorine in chlorine powder and liquid

Chlorine gas typically contains pure chlorine. However, chlorine powder and liquid do not contain pure chlorine, and are mixed with other substances (e.g. calcium, sodium or water).

Because of this, the strength of chlorine in chlorine powder or chlorine liquid is referred to as the concentration of chlorine in that substance.

Typically, this is expressed as the percentage (%) of active chlorine present.

Important properties of chlorine powder, liquid and gas with relevance to drinking-water disinfection are summarized in Figure 2.

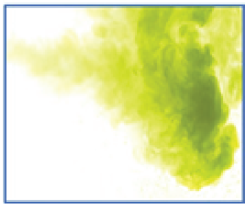
Figure 2. *Properties of chlorine powder, liquid and gas with relevance to drinking-water disinfection*

Chlorine powder

Appearance: White powder, granules or tablet
Strength: Typically 30 to 70 % active chlorine
Generally mixed with water to make a liquid solution before use (see *'Chlorine liquid'* below)
Stability: May lose strength over time; more stable than chlorine liquid
Application: Typically used for small-sized water treatment plants (i.e., < 5 000 cubic meters per day)
Examples: Bleaching powder (approx. 35 % active chlorine)
High test hypochlorite (approx. 70 % active chlorine)

Chlorine liquid

Appearance: Pale yellow to clear liquid
Strength: Typically 1 to 15 % active chlorine
Stability: May lose strength over time; less stable than chlorine powder
Application: Typically used for small- to medium-sized water treatment plants (i.e., <10 000 cubic meters per day)
Examples: Sodium hypochlorite (10 to 15 % active chlorine; commercially prepared)
Domestic bleach (5 to 10 % active chlorine; commercially prepared)
Chlorine liquid solution prepared from chlorine powder (typically 1 to 5 % active chlorine)



Chlorine gas

Appearance: Green-yellow gas
Strength: Approx. 100 % active chlorine
Stability: Most stable over time
Application: Typically used for medium- to large-sized water treatment plants (i.e., >10, 000 cubic meters per day)
Example: Chlorine gas (liquefied)

Due to its stability, strength and lower transportation costs, chlorine powder (chemical name: calcium hypochlorite) is commonly used in small-sized water treatment plants. Although chlorine powder may be added directly to drinking-water, typically, it is firstly dissolved in water to form a chlorine liquid solution, which may then be added to drinking-water for disinfection.

Due to the resource requirements and safety issues associated with regularly preparing large chlorine liquid batches from chlorine powder, commercially prepared chlorine liquid is commonly used in small- to medium-sized water treatment plants where it is available and considered cost-effective.

Chlorine gas is typically used only in larger-sized water treatment plants. This is due to several factors including (i) the high cost of the chlorine gas dosing equipment, (ii) the availability of expertise and specialist parts for operation and maintenance of the dosing system, (iii) the availability of chlorine gas supply, as well as (iv) safety considerations. For these reasons, chlorine powder and/or liquid are generally used in small- to medium-sized water treatment facilities, and as such, will be the primary focus of this guide.

1.3 Principles of drinking-water chlorination

1.3.1 Chlorine dose

The chlorine dose refers to how much chlorine is added to the drinking-water (or, the concentration of chlorine in the drinking-water). Information on how to express the concentration of chlorine present in drinking-water is presented in Textbox C.

(C) How to express the concentration of chlorine in drinking-water

The amount (or concentration) of chlorine present in drinking-water may be expressed as **milligrams per litre (or mg/L)**.

- For example, if drinking-water has a chlorine concentration of 1 mg/L, this means that there is 1 milligram of chlorine present per 1 litre of water.

The optimum chlorine dose for a water supply system must be determined on a case-by-case basis considering the specific situation (see Section 1.3.7).

1.3.2 Chlorine reactions in drinking-water

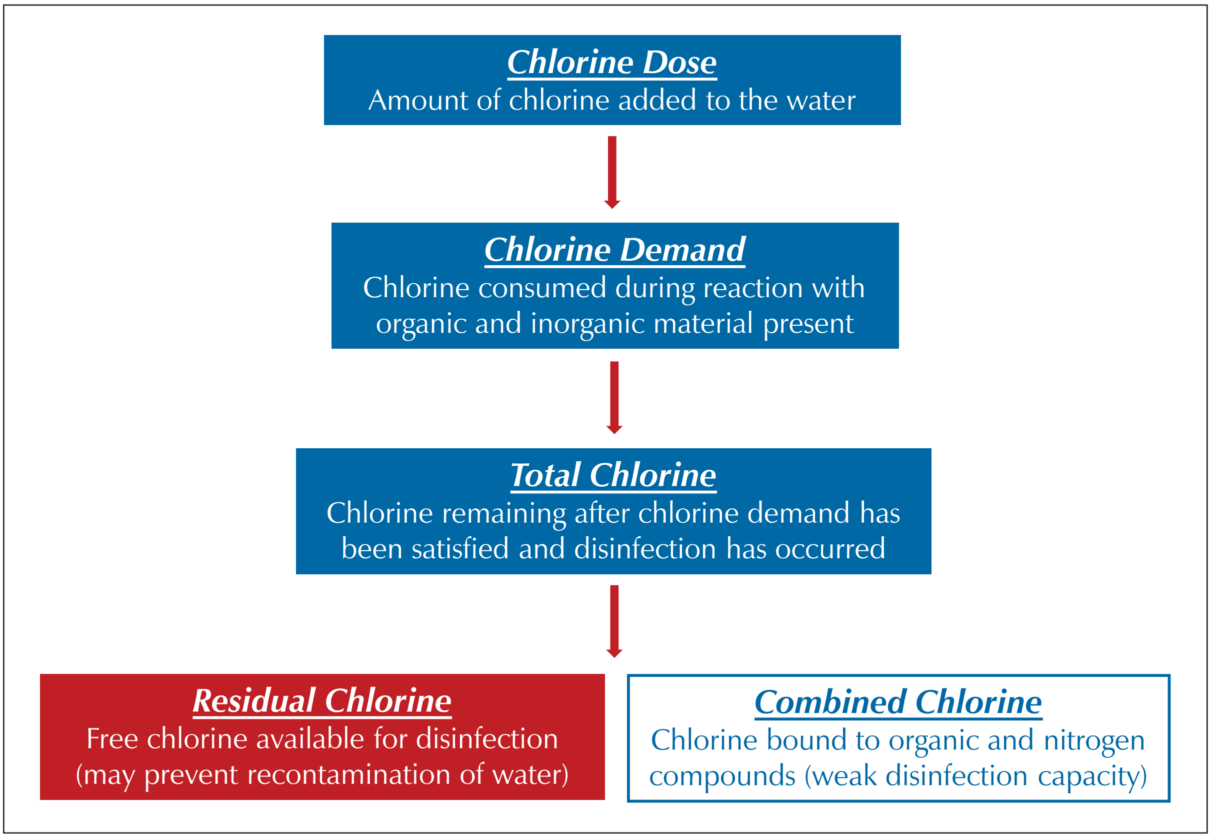
Once chlorine has been added to drinking-water, a number of chemical reactions take place. As such, chlorine exists in different forms within drinking-water. Figure 3 summarizes the main types of reactions and the different types of chlorine that may be present in drinking-water.

As discussed in Section 1.2, chlorine is very reactive. As a result, chlorine will react with any organic material (e.g. microorganisms) and inorganic material (e.g. metals, pipe fittings) that are present in the water. This organic and inorganic material may be referred to as chlorine reactive substances. Chlorine is used up (or consumed) during these reactions, so the concentration of chlorine decreases. The amount of chlorine that is consumed through the reaction between chlorine and the chlorine reactive substances present in the water is called the chlorine demand (Section 1.3.3).

Once the chlorine demand has been satisfied, and the disinfection reactions are complete, the remaining chlorine is referred to as the total chlorine. Total chlorine consists of:

- **combined chlorine:** This is the chlorine that has reacted with organic material and nitrogen compounds (such as ammonia) to form weak disinfectants; and
- **residual chlorine:** The free chlorine that is remaining and available for disinfection, and protects the water from recontamination from microorganisms to a degree (Figure 3).

Figure 3. *The relationship between the various forms of chlorine in drinking-water*[7]



Residual chlorine (also referred to as free chlorine) is an effective disinfectant. The residual chlorine concentration is one of the most important water quality parameters from a public health perspective (see Textbox D).

7 Adapted from Centre for Disease Control. Chlorine Residual Factsheet. http://www.cdc.gov/safewater/publications_pages/chlorineresidual.pdf. Visited on 8 July, 2015.

(D) The significance of the residual chlorine concentration and public health protection

The presence of residual chlorine in treated drinking-water indicates that:

- sufficient chlorine has been added to the water to ensure that adequate disinfection has taken place; and
- the water is protected to a degree from recontamination by harmful microorganisms that are susceptible to chlorine.

An adequate residual chlorine concentration is critically important to protect the disinfected drinking-water from recontamination during intermediate storage (such as treated water reservoirs and tanks) and during distribution, through to the point of delivery to the consumer[8].

To ensure that treated drinking-water is adequately protected from the risk of recontamination from harmful microorganisms, WHO recommends that a minimum residual chlorine concentration of 0.2 mg/L is maintained to the point of consumer delivery[9].

This means that a minimum residual chlorine concentration of 0.2 mg/L must be maintained in the drinking-water supply system right through to the very end of the distribution network.

However, as high concentrations of chlorine may be harmful to public health, the WHO recommends that chlorine levels in drinking-water should not exceed 5 mg/L[9]. (For aesthetic considerations for chlorine dosing, see Section 1.3.7.)

1.3.3 Chlorine demand

As discussed in Section 1.3.2, when chlorine is first added to water, it will react with the chlorine reactive substances present in the water (i.e. organic and inorganic material) and will be consumed, resulting in a decrease in the chlorine concentration. Chlorine demand refers to the extent of the reaction between chlorine and the chlorine reactive substances present in water. When discussing the chlorine demand of water, it is usually in reference to the water before chlorine has been added (i.e. upstream of the point of chlorine application at the water treatment plant).

The chlorine demand of water will influence how much chlorine is consumed, and how much residual chlorine is remaining to protect the water from recontamination during storage and distribution. Understanding the chlorine demand of water is important, as it influences how much chlorine needs to be added to the water to ensure good disinfection.

Textbox E describes the simplified relationship between chlorine demand and the concentration of chlorine reactive substances present in drinking-water.

8 Points of delivery include water meters, standpipes or public taps. Beyond these points of delivery (for example, household bulk storages, household taps, household storage containers) the maintenance of a residual chlorine concentration is beyond the control and responsibility of the water supplier.

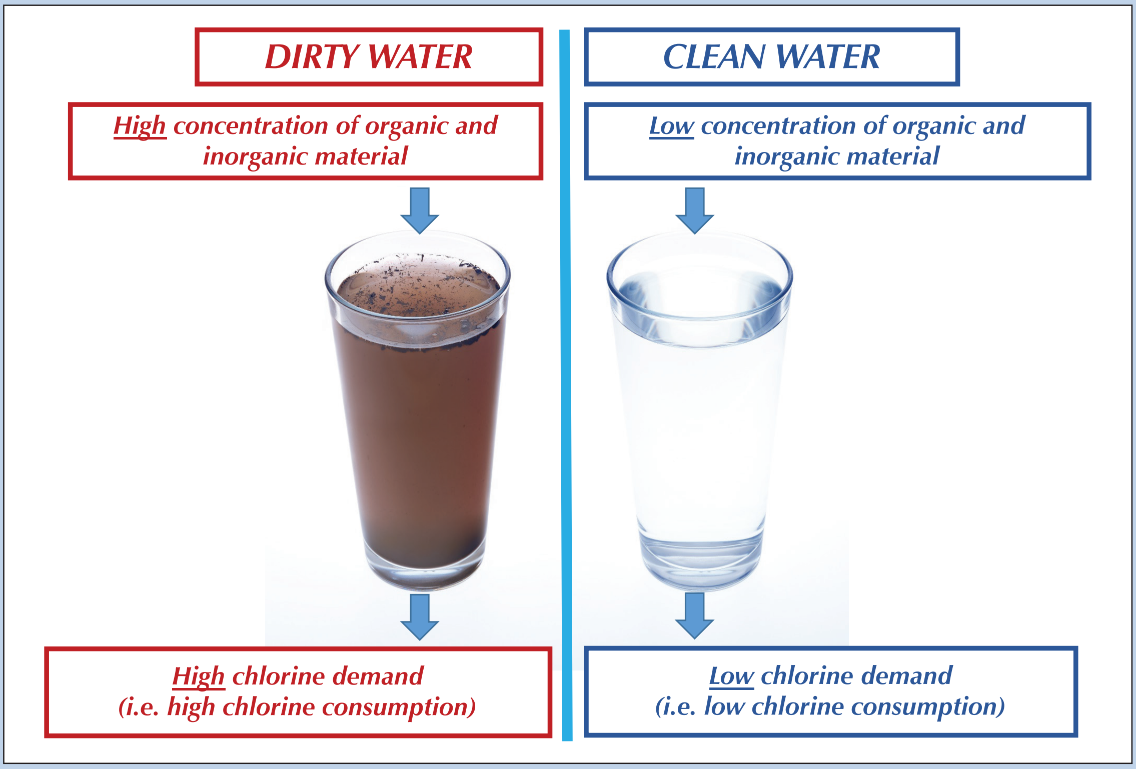
9 World Health Organization (2011). Guidelines for Drinking-water Quality. 4th Edn. Geneva, Switzerland.

(E) The relationship between chlorine demand and the chlorine dose

In general, dirty water contains a high concentration of organic and inorganic material; therefore, it has a high chlorine demand and will require a higher chlorine dose.

Whereas clean water contains a low concentration of organic and inorganic materials has a low chlorine demand and will require a lower chlorine dose (Figure 4).

Figure 4. *The relationship between chlorine demand and the concentration of chlorine reactive substances*



The chlorine demand of water will constantly change as the water quality changes. Events that cause the chlorine demand of the water to change include:

- seasonal changes in source water quality (for example, algal blooms in summer, high turbidity during the wet season);
- source water quality changes in response to severe weather events and natural disasters (for example, storms, floods, landslides, bushfires); and
- sub-optimal performance of a water treatment process (for example, failure of clarification and/or filtration processes).

For effective disinfection, it is important to understand and, where practical, monitor the chlorine demand of water before chlorine is added, as this will indicate what chlorine dose is required to ensure effective disinfection and an adequate residual chlorine concentration in the drinking-water supply. For information on calculating the chlorine demand of water, see Section 2.3.1.

1.3.4 Chlorine decay

Chlorine decay means the decrease (or reduction) in the concentration of chlorine in drinking-water as it passes from the water treatment plant through to the end of the distribution system. Once disinfection is complete at the water treatment plant, chlorine will continue to react with any organic or inorganic material that may be present in intermediate storage tanks or distribution pipes (for example, organic sediments, dissolved metals from corroded pipes, pipe fittings, pipe materials, microbial slimes [or biofilms]). As discussed in Section 1.3.2, chlorine is consumed during these reactions, so the concentration of chlorine decreases. Chlorine decay explains the decrease in chlorine concentration that may be observed as water passes through a water distribution network.

Due to chlorine decay, the concentration of chlorine at the water treatment plant is usually higher than at the very end of the distribution system. The rate and extent of chlorine decay will depend on a number of factors, including:

- the level of chlorine reactive substances that are present in the treated water as well as the distribution network (this organic and inorganic material may react with and consume chlorine); and
- how long the water remains in the distribution system (or the water age; as the chlorine concentration decreases over time, older water will typically have a lower concentration of chlorine).

Chlorine decay is an important concept with regards to the supply of safe drinking-water. Due to chlorine decay in a water supply system, drinking-water may have a sufficient amount of chlorine at the water treatment plant, but not enough chlorine remaining in the drinking-water during distribution system to protect the water from potential recontamination by harmful microorganisms (this is illustrated in Textbox F below).

The following strategies may be considered to minimize chlorine decay in a water supply system:

- optimize water treatment processes to minimize the level of chlorine reactive substances entering the distribution system;
- clean and maintain intermediate storage tanks and distribution pipes routinely (for removal of accumulated sediment and microbial biofilms);
- optimize the hydraulic regime (i.e. the flow of water) in the distribution system to minimize water age and low-flow sections (or dead-legs);
- use chlorine compatible materials (such as pipe-work, fittings and tank liners) in the distribution system; and
- where feasible, provide continuous (i.e. 24-hour) water supply.

(F) The impact of chlorine decay on chlorine concentration in a water supply system

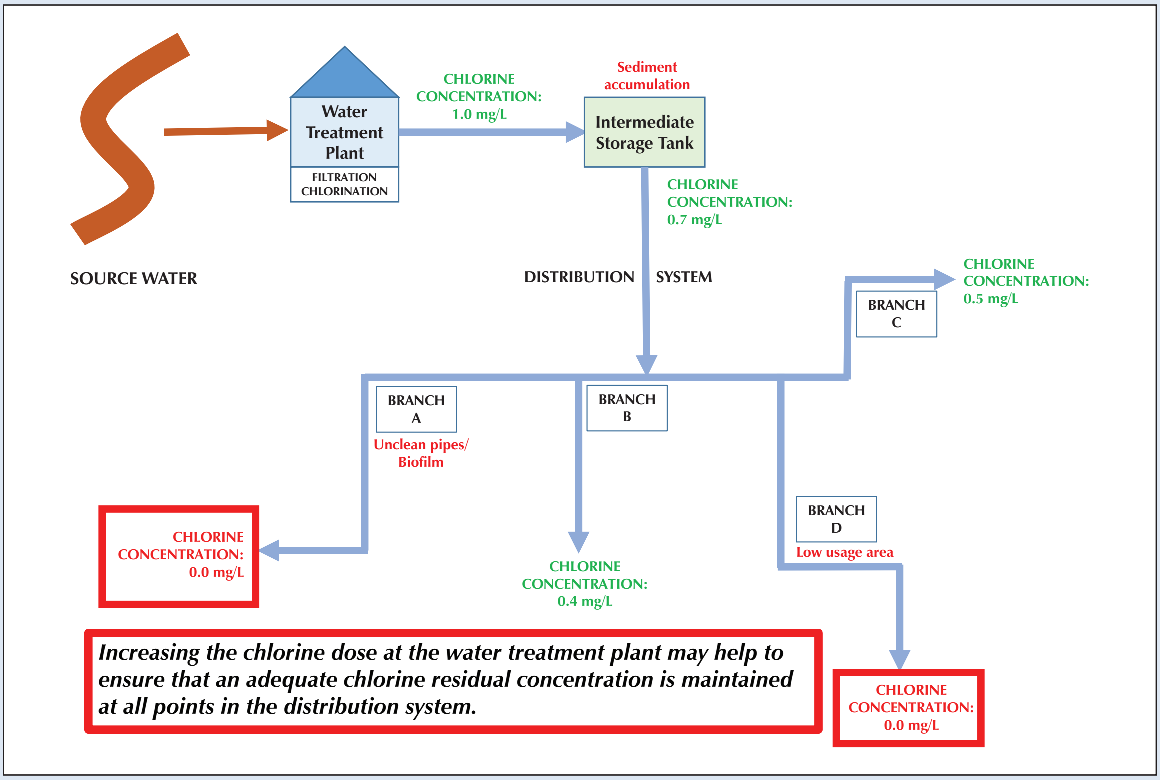
Figure 5 illustrates a simple example of how chlorine decay may affect the concentration of chlorine in a water supply system.

In this example, as chlorinated water leaves the water treatment plant and flows to the end of the distribution network, the concentration of chlorine decreases (Figure 5). The key reasons for the decrease in chlorine in this example may include:

- **Intermediate storage tank:** Contains accumulated sediment from lack of routine tank cleaning; sediment contains chlorine reactive substances, which consume chlorine;
- **Distribution system:**
  - **Branch A:** Unclean pipes are present in this area from a lack of routine pipe cleaning programme; pipes are lined with microbial biofilm, which may react with and consume the chlorine.
  - **Branch B and C:** Clean pipes with no leakages; only a slight decrease in the concentration of chlorine observed due to chlorine reaction with pipe material and fittings.
  - **Branch D:** Low usage of water in this area, which results in a long water age (i.e., old or stagnant water).

In the case of Branch A and D, the concentration of chlorine in the drinking-water is zero as a result of extensive chlorine decay. This means that the drinking-water in these branches of the network is no longer protected from the risk of recontamination by harmful microorganism; this represents a risk to public health and corrective action is required.

Figure 5. *The impact of chlorine decay on chlorine concentration in a water supply system; water quality risks are highlighted in red text*



1.3.5 Ct concept for disinfection

During the disinfection process, chlorine requires time to kill or inactivate microorganisms present in drinking-water this is referred to as contact time. The contact time must be considered in conjunction with the chlorine concentration and other factors, to ensure that effective disinfection of drinking-water occurs – this is referred to as the Ct concept for disinfection. The Ct value is the product of the chlorine concentration (C) and the contact time (t) with the drinking-water (see Section 2.3.2 for the formula to calculate the Ct value).

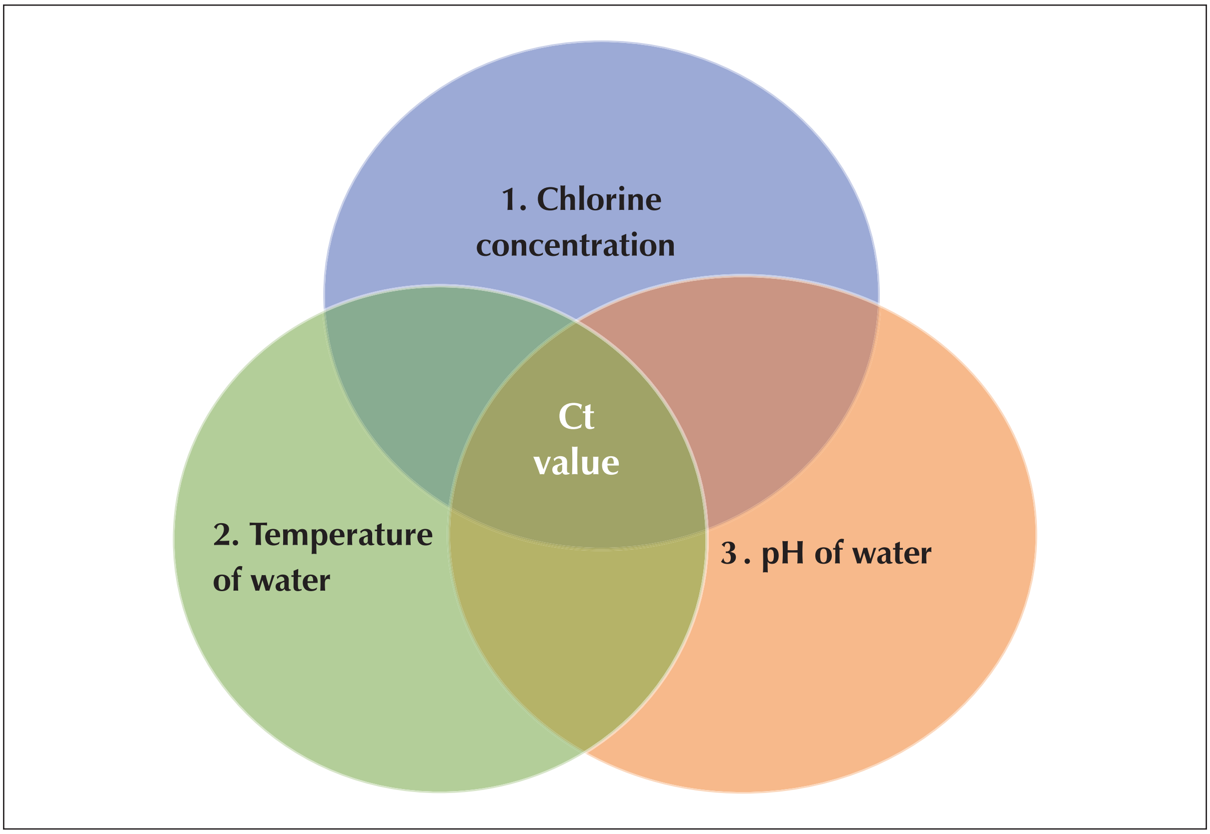
The Ct value required for effective disinfection is dependent on several factors, including the combined influences of:

(1) the concentration of chlorine in the water;

(2) the temperature of the water; and

(3) the pH of the water (i.e. a measure of the water's acidity or alkalinity[10]; Figure 6).

Figure 6. *Factors influencing the Ct value for disinfection*



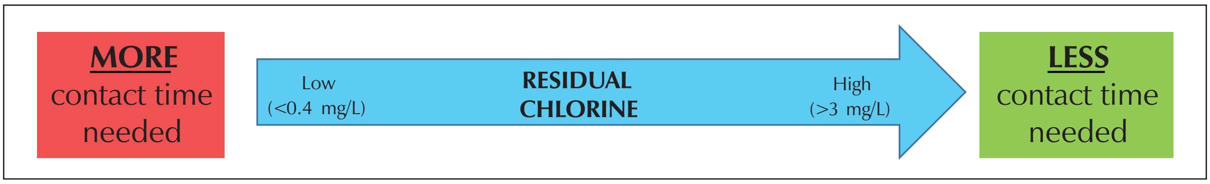
More detailed information on how to calculate the Ct value for a specific situation is given in Section 2.3.2 and Toolbox C.

10 The pH of water is measured on a scale of pH 0 to pH 14, with pH 7 considered neutral, pH <7 considered acidic and pH >7 considered alkaline (or basic).

1.3.5.1 The influence of chlorine concentration on disinfection

The relationship between the chlorine concentration and contact time required for effective disinfection is presented in Figure 7. In general, the higher the concentration of chorine, the less contact time is required for effective disinfection.

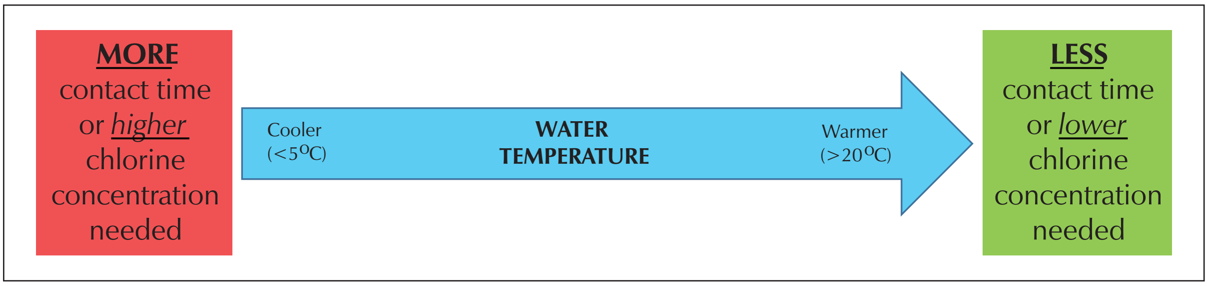
Figure 7. *Relationship between chlorine concentration and disinfection*



1.3.5.2 The influence of water temperature on disinfection

Chemical reactions generally occur more quickly at warmer temperatures; chlorine disinfection is no exception. The relationship between water temperature and disinfection is presented in Figure 8. In general, colder water requires more contact time or higher concentrations of chlorine for effective disinfection.

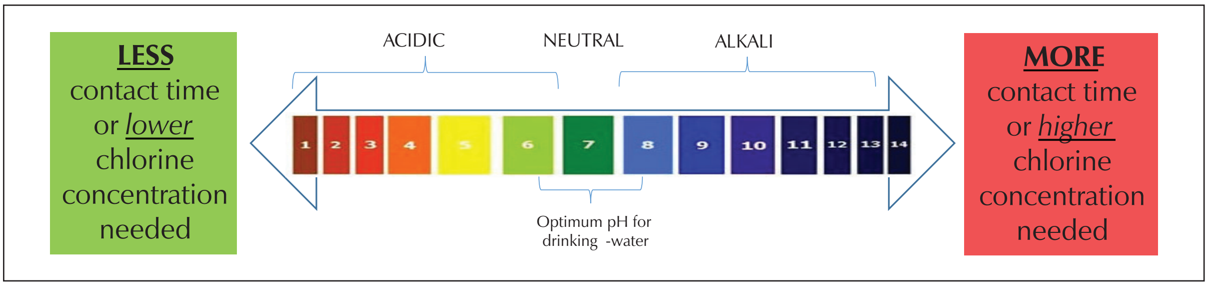
Figure 8. *Relationship between water temperature and disinfection*



1.3.5.3 The influence of water pH on disinfection

In general, chlorine is more effective under acidic conditions. For effective disinfection, the pH of drinking-water should be less than pH 8. When drinking-water is above pH 8, chlorine is less effective, and more contact time or a higher concentration of chlorine may be required for effective disinfection (Figure 9). To balance a number of water quality considerations, including chlorination, the optimum pH of drinking-water is generally between pH 6.5 and pH 8.5.

Figure 9. *Relationship between water pH and disinfection*

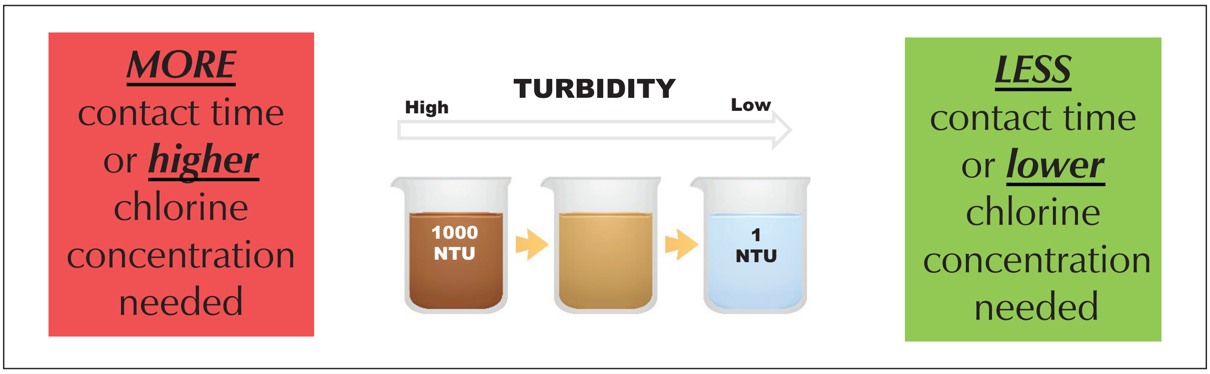


1.3.5.4 Other factors influencing disinfection

The type of microorganism may also influence the effectiveness of disinfection, with vegetative bacteria requiring less contact time or lower concentrations of chlorine, certain viruses and protozoa (such as *Giardia*) requiring more contact time or higher concentrations of chlorine, and certain protozoan oocysts (e.g. *Cryptosporidium*) and bacterial spores requiring such long contact times or high chlorine doses that chlorine disinfection is considered impractical or ineffective (Textbox A). Ct values are typically based on the inactivation of the protozoa *Giardia*, as most bacteria and viruses that are susceptible to chlorine are considered to be inactivated within this time (see Toolbox C).

Turbidity occurs in water as a result of the presence of organic and inorganic materials in water. Turbidity gives water a cloudy (or opaque) appearance. Turbidity may also indirectly influence the effectiveness of chlorination (Figure 10). Turbidity may consist of chlorine reactive substances (such as organic and inorganic material), which may consume chlorine, as well as protect (or shield) microorganisms from chlorine. For effective disinfection, the WHO[9] recommends that the turbidity of water should be <1 Nephelometric Turbidity Unit (NTU); preferably, much lower where possible. In certain settings, achieving <1 NTU in the water prior to disinfection may not be possible (for example, small supplies, lower resource settings). In such situations, the aim should be to maintain turbidity <5 NTU prior to disinfection. Above 5 NTU, chlorination should still be practised, but higher chlorine doses or contact times will be required to inactivate harmful microorganisms.

Figure 10. *Relationship between turbidity and the effectiveness of chlorine*



1.3.5.5 Contact time required for effective disinfection

Textbox G recommends the minimum required contact time necessary for effective chlorine disinfection.

(G) How much contact time is needed for effective disinfection?

For effective disinfection of drinking-water at the point of disinfection, WHO[9] recommends a minimum contact time of 30 minutes where the residual chlorine concentration is ≥0.5 mg/L and the pH of the water is <pH 8.

The formula for determining contact times, alongside an example calculation, is presented in Section 2.3.2 and Toolbox C.

1.3.6 Aesthetic considerations for chlorination

In the context of drinking-water quality, the term aesthetic means how acceptable the drinking-water is to a consumer. The acceptability of drinking-water may be based on the consumer's perception of:

(1) the appearance of the water (does the water appear clear, coloured, cloudy, milky);

(2) the taste of the water (does the water taste acceptable, or does the water have an unpleasant taste such as a chemical, stale, earthy or metallic taste); and

(3) the odour of the water (is the water odourless, or does it have an odour such as an earthy, musty or chemical odour).

Providing drinking-water that is acceptable to every individual consumer is a challenge, as different individuals have different sensitivities to the appearance, taste and odour of water. For example, water may have no smell to one individual, whereas the same water may be unacceptable to another individual who has a more sensitive sense of smell.

As discussed in Section 1.2, chlorine has a characteristic taste and odour. This may be noticeable to sensitive individuals at chlorine concentrations >0.3 mg/L[9]. If chlorine is present in drinking-water at concentrations that are too high, the stronger taste and odour of chlorine may result in an individual using alternative, less safe, water sources. For this reason the aesthetic impact of chlorine on drinking-water should be considered when optimizing the chlorine dose. However, when setting the chlorine dose, aesthetic considerations should never compromise disinfection (see Textbox H).

1.3.7 Optimizing the chlorine concentration in a water supply system

Optimizing the chlorine concentration in a water supply system may be a challenge due to the need to balance:

(1) adequate disinfection;

(2) adequate residual disinfection capacity during distribution to provide protection from recontamination to the point of delivery to the consumer, alongside;

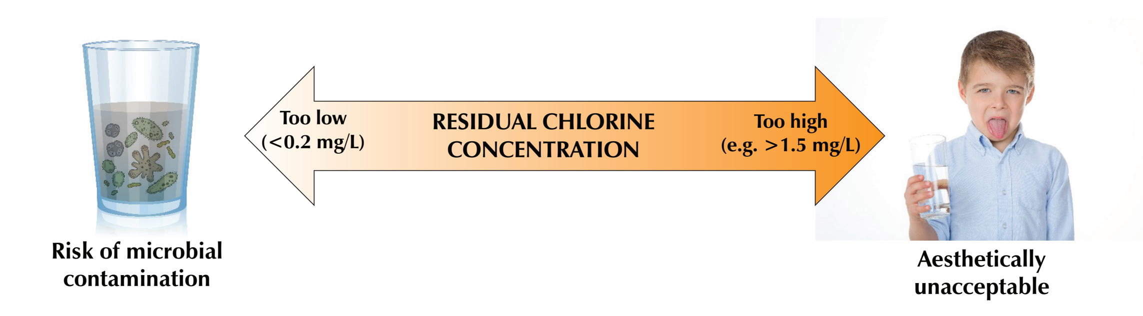
(3) consumer acceptability.

Textbox H outlines the balance required between drinking-water chlorination health and aesthetic considerations.

(H) Balancing adequate chlorine disinfection with aesthetic considerations

Figure 11 illustrates the careful balance required when optimizing the chlorine concentration in a water supply system.

Figure 11. *Optimizing the chlorine concentration for effective disinfection and consumer acceptability*



When dosing chlorine, the priority must always be to add sufficient chlorine such that:

- the minimum required contact time is achieved for effective disinfection; and
- the residual chlorine concentration at the point of delivery to the consumer is ≥0.2 mg/L[9].

To balance disinfection considerations with consumer acceptability, a chlorine residual of between 0.2 mg/L and 0.5 mg/L should generally be targeted through distribution to the point of delivery[9]. However, in some cases, it may be necessary to maintain a higher residual chlorine concentration in some parts of the distribution system (for example, early in the distribution system), to ensure a minimum residual chlorine concentration of 0.2 mg/L is achieved throughout the entire system (for example, at the very end of the distribution system). When setting the chlorine dose, adequate disinfection must never be compromised due to aesthetic considerations.

The importance of careful monitoring of the chlorine concentration throughout the water supply system is discussed in Section 2.5.3.

1.3.8 Points of chlorine application

Chlorine may be added to drinking-water at various stages in the water supply system, to achieve different water quality objectives (see Figure 12), including:

(1) pre-chlorination (immediately before water treatment);

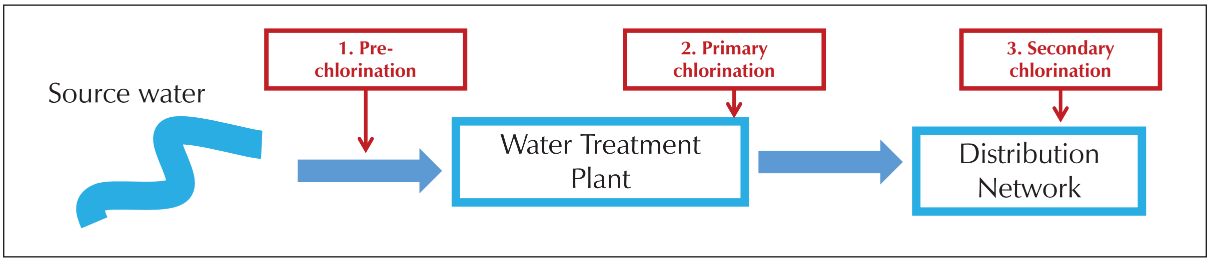
(2) primary chlorination (immediately after water treatment); and

(3) secondary chlorination (in the distribution system).

Other points of chlorine application in a water supply system that are beyond the scope of this guide include:

- disinfection of water mains (for example, for disinfection following commissioning of new water mains or repair/replacement of existing water mains); and
- at the household level, as part of household water treatment and safe storage (HWTS; relevant to both emergency and non-emergency scenarios).

Figure 12. *Examples of points in a water supply system where chlorine may be added to the water*



1.3.8.1 Pre-chlorination

Pre-chlorination of water before water treatment generally occurs for reasons other than disinfection. Typically, chlorine is added to pre-treat the water, to assist with the removal of minerals such as iron and manganese or other compounds that may cause taste and odour issues. Higher doses of chlorine are often required for pre-chlorination, due to the higher chlorine demand of the untreated water. Pre-chlorination is often associated with the potential for formation of disinfection by-products (see Textbox I).

1.3.8.2 Primary chlorination

The purpose of primary chlorination is to disinfect the drinking-water. Primary chlorination typically takes place at a water treatment plant. If water treatment processes are in place (for example, coagulation/flocculation, clarification and/or filtration), primary chlorination typically occurs after these upstream water treatment steps. These upstream processes are designed to remove turbidity, colour and organic and inorganic materials (i.e. chlorine reactive substances). If these chlorine reactive substances are not removed prior to primary disinfection, they create a higher chlorine demand (Section 1.3.3), consuming the chlorine, and potentially forming disinfection by-products (Textbox I).

1.3.8.3 Secondary chlorination

Due to sub-optimal primary chlorination (Section 1.3.7) and/or chlorine decay (Section 1.3.4), the concentration of residual chlorine may go below the minimum recommended 0.2 mg/L during distribution. Once the residual chlorine concentration goes below 0.2 mg/L, the water is considered susceptible to microbial contamination and a water quality risk exists. In situations where it is not feasible to address the reason for low residual chlorine concentration (for example, by optimizing primary chlorination, cleaning distribution pipes or optimizing the hydraulic regime to reduce water age), secondary (or booster) chlorination may be employed, to boost the chlorine residual in that section of the distribution system above 0.2 mg/L.

(I) Disinfection by-products

Disinfection by-products (or DBPs) result from the reaction of chlorine with organic and inorganic material present in the drinking-water. Some of these compounds have been linked to public health concerns.

Examples of disinfection by-products include:

- trihalomethanes (THMs);
- haloacetic acids (HAAs);
- chlorate;
- chlorite.

Strategies to control disinfection by-product formation include:

- optimizing water treatment processes to remove organic and inorganic material (i.e., disinfection by-product precursors);
- optimizing the chlorine dose to ensure adequate disinfection without adding too much chlorine (i.e., over-dosing chlorine);
- optimizing the chlorine dose point to ensure that only treated water is dosed (without compromising contact times);
- avoiding pre-chlorination (only if possible without compromising other water quality considerations; and
- reducing the water age in the distribution network (as time is an important factor for disinfection by-product formation[11]).

As the risks to health from disinfection by-products are extremely small in comparison with the risks associated with inadequate disinfection, WHO recommends that *"disinfection should not be compromised in attempting to control disinfection by-products"*[9].

11 Water Research Foundation. Strategies to control disinfection by-products. Factsheet. http://www.waterrf.org/knowledge/dbps/FactSheets/DBP-ControlStrategies-FactSheet.pdf. Visited on 13 July, 2015.

1.4 Summary of the conditions required for effective chlorination

Textbox J summarizes the conditions required for effective chlorine disinfection.

(J) Summary of the conditions required for effective chlorine disinfection

For effective primary chlorination of drinking-water, the following ideal conditions are recommended:

Turbidity: **<1 NTU (preferably lower where achievable)**
Where not achievable, <5 NTU should be the aim; above 5 NTU, chlorination should still be practised, but higher chlorine doses or contact times will be required to inactivate harmful microorganisms

pH: **<pH 8.0**
Above pH 8.0, chlorination should still be practised but higher chlorine doses or contact times will be required to inactivate harmful microorganisms

Minimum contact time: **At least 30 minutes contact time**, where the residual chlorine concentration is ≥0.5 mg/L and the pH of the water is <pH 8.

Once chlorination at the water treatment plant is complete, the residual chlorine concentration during distribution to the point of consumer delivery should aim to be between 0.2 and 0.5 mg/L.

A minimum residual chlorine concentration of 0.2 mg/L must always be maintained to the point of consumer delivery.

To achieve a minimum residual chlorine concentration of 0.2 mg/L at the point of consumer delivery, residual chlorine concentrations in the distribution system may need to be above the aesthetic target residual chlorine concentration of 0.5 mg/L under certain circumstances.

At all times, the concentration of chlorine in drinking-water supplied to consumers should be below the WHO guideline value of 5 mg/L[9].

Part 2. Practical chlorination

Applies key chlorination principles into practice, describing safe and effective procedures for drinking-water chlorination.

2.1 Safe handling and storage of chlorine

As discussed in Section 1.2, chlorine is a hazardous substance. Chlorine disinfection requires that water treatment plant staff work in contact with, and in proximity to, high strength forms of chlorine. The health and safety of staff is critical at all times. All staff in contact with chlorine should receive basic training on the dangers of chlorine, how to handle and store it safely and basic first-aid measures in the event of accidental contact (Textbox K).

(K) Safe handling of chlorine

Contact with, or inhalation of, concentrated forms of chlorine may result in irritation, chemical burns and even death. Table 1 describes the required personal protective equipment (PPE) that should be worn to protect staff when handling chlorine powder and liquid, alongside basic first-aid measures.

Table 1. *Safe handling of chlorine and basic first-aid measures in the event of accidental exposure*

Type of chlorine	Minimum recommended PPE	Basic first-aid in case of exposure
Chlorine powder	 OVERALLS  GLOVES  DUST MASK  SAFETY GLASSES	• If chlorine makes contact with clothing material, remove the affected clothing • If chlorine: – makes contact with skin, eyes, nose or mouth, immediately, rinse the affected area with running water for a minimum of 15 minutes – is ingested or inhaled, drink water; <u>*do not*</u> induce vomiting – **Seek immediate medical assistance**
Chlorine liquid	 OVERALLS  GLOVES  FACE SHIELD	

Important note: Any enclosed building used for storage or preparation of chlorine should always be well ventilated. If chlorine aerosols, mists, vapours or dust are not adequately controlled by ventilation, appropriate respiratory protection should be considered.

Over time, chlorine will begin to lose strength during storage. Chlorine liquid solutions are generally less stable than chlorine powder. If stored inappropriately, the decrease in chlorine strength will be accelerated. This may be important for water quality, as it may mean that insufficient chlorine may be added to the water (under-dosing) and disinfection is ineffective. As such, chlorine should be stored appropriately with good stock management practices, such as those described in Textbox L.

(L) Appropriate storage and stock management practices for chlorine

Over time, chlorine powder and liquid will begin to degrade and lose strength (Table 2). The rate of chlorine degradation may be accelerated through poor storage and stock management practices.

Table 2. *Approximation of chlorine degradation during storage (adapted[12,13])*

Type of chlorine (approx. % active chlorine concentration)		Loss of initial active chlorine concentration (%)[14]
Chlorine powder	Bleaching powder (35%)	5 to 18% after 40 days
	High test hypochlorite (70%)	
Chlorine liquid	Sodium hypochlorite (15%)	50% after 100 days
	Sodium hypochlorite (10%)	50% after 220 days
	Sodium hypochlorite (5%)	50% after 790 days

To minimize the rate and extent of chlorine degradation, appropriate storage conditions should be in place, including:

- always store in a cool, dry, well ventilated place;
- store away from direct sunlight and excessive humidity and temperatures;
- store in corrosion resistant containers (for example, light resistant plastic [poly vinyl chloride; high density polyethylene]);
- keep all storage containers fully sealed when not in use;
- date and mark all stock upon receipt; and
- use in first in, first out (FIFO) stock rotation principles (i.e., always using the oldest stock first).

Note: Chlorine degradation in liquid chlorine solutions may be managed by pH stabilization (i.e. the addition of sodium hydroxide to stabilize the >pH 11.9)[15].

Where accurate laboratory equipment and trained personnel are available, it is possible to measure the active chlorine concentration in chlorine powder[12] and chlorine liquid[16]. Where this is not possible, the risk of chlorine under-dosing exists, as the concentration of active chlorine may be less than expected (see Sections 2.3.4 and 2.3.5). To minimize this risk, careful monitoring of the chlorine concentration in the drinking-water should always be performed routinely, particularly after a new batch of chlorine liquid has been prepared, to verify that the correct chlorine dose is being applied (see Section 2.5).

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12 World Health Organization. Calcium hypochlorite. Fact Sheet 2.19. http://www.who.int/water_sanitation_health/sanitation-waste/fs2_19.pdf?ua=1. Visited on 13 July, 2015.

13 American Water Works Association (AWWA; 2006). Chlorination/chloramination practices and principles. AWWA Manual M20. 2nd Edn. Colorado, United States of America.

14 For example, if a 15 % chlorine liquid solution loses 50 % of its strength after 100 days, the concentration of active chlorine remaining in the chlorine liquid solution will be 7.5 %.

15 Lantagne, D. et al. (2011). Hypochlorite Solution Expiration and Stability in Household Water Treatment in Developing Countries. Journal of Environmental Engineering, 137(2), 131-139.

16 World Health Organization. Sodium hypochlorite. Fact Sheet 2.20. http://www.who.int/water_sanitation_health/sanitation-waste/fs2_20.pdf?ua=1. Visited on 13 July, 2015.

2.2 Chlorine liquid dosing systems

2.2.1 Non-pump based dosing systems

A number of non-pump based chlorine dosing systems are available and in use worldwide. Such systems are basic, simple to use, inexpensive and require relatively less specialised maintenance compared to pump-based systems. As such, these systems may be appropriate in lower resource settings. However, non-pump based dosing systems are less accurate and offer less operational control. For these reasons, non-pump based systems are more likely to result in chlorine under- or over-dosing. Table 2 summarizes some common types of non-pump based chlorine dosing systems (for more details, refer to WHO Factsheet 2.22[17]).

Table 2: Examples of common non-pump based chlorine dosing systems (adapted[17])

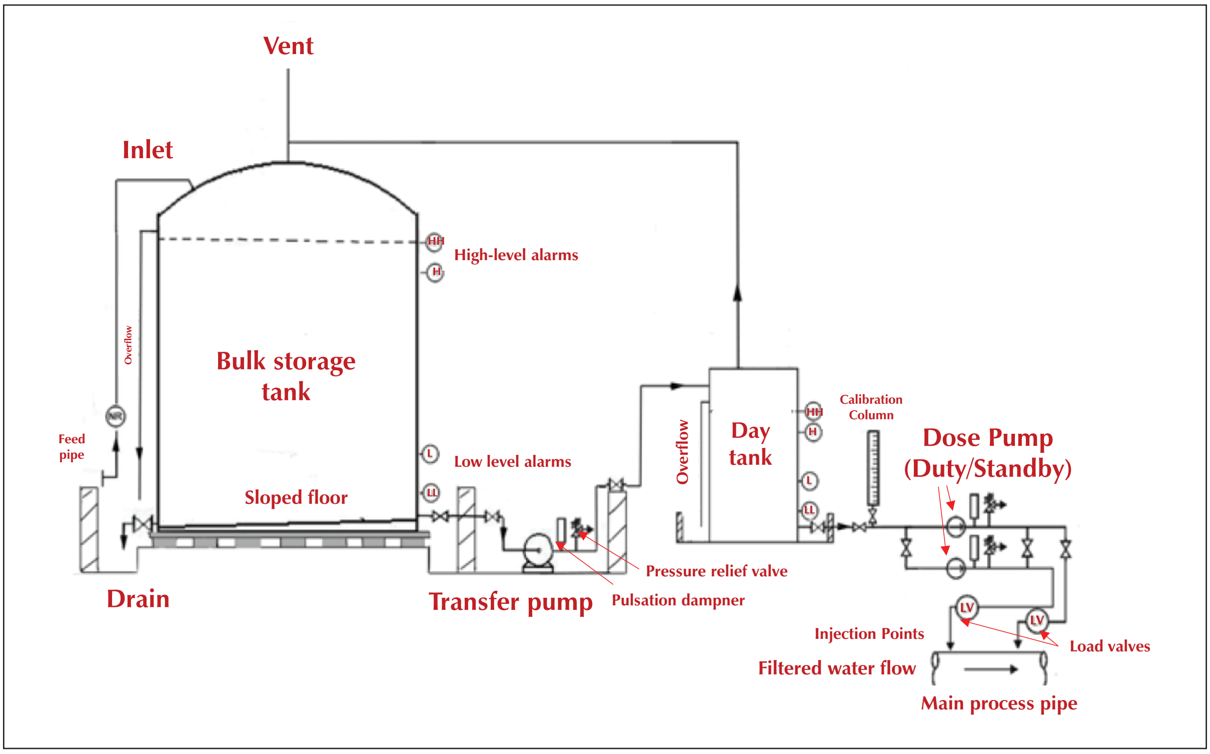
System	Basis	Comments
Drip-feed chlorinators	Feeds a constant rate of chlorine liquid solution using a constant head device to maintain the drip feed	• Assumes constant water flow rate (inaccurate dosing may occur if flow rate changes) • Suitable for small supplies • Risk of siphoning must be managed
Constant head aspirator	Drips a constant rate of chlorine liquid solution using an aspirator and glass tube; drip rate may be controlled by rotating a capillary between vertical-horizontal positions	• Simple, robust device • Durable if given appropriate basic maintenance • Easy installation • Coarse and fine drip-rate control possible • Assumes constant water flow rate (inaccurate dosing may occur if flow rate changes)
Gravity feeder	Relies on gravity and a metering orifice/valve to control the flow of chlorine liquid solution	• Requires a second tank and ball valve to maintain constant head pressure • Assumes constant water flow rate (inaccurate dosing if flow rate changes)

2.2.2 Pump based dosing systems

A simplified schematic of a typical liquid chlorine dosing system is presented in Figure 13. (Note: As chlorine powder is generally mixed with water first to make a chlorine liquid solution prior to chlorine dosing, this type of system may be relevant for both chlorine powder and chlorine liquid applications.)

17 World Health Organization. Dosing hypochlorite solutions. Fact Sheet 2.22. http://www.who.int/water_sanitation_health/sanitation-waste/fs2_22.pdf?ua=1. Visited on 12 August, 2015.

Figure 13. *Typical chlorine liquid dosing system*[18]



A typical chlorine liquid dosing system may include a bulk storage tank, which stores a large volume of chlorine liquid (for example, delivered by a chemical delivery tanker, or prepared from chlorine powder). Where chlorine powder is used to prepare chlorine liquid on-site, this bulk storage tank may also contain a fixed mechanic agitator, where chlorine powder may be mixed with water directly within the bulk storage tank itself. Bulk storage tanks are typically designed to hold sufficient chlorine liquid to supply disinfection needs at the water treatment plant for a period of days to weeks. A day tank may also be used, which may hold a smaller volume of chlorine liquid (typically, the day tank will hold enough chlorine for one day's usage). Chlorine liquid is transferred from the bulk storage tank to the day tank by a transfer pump. In some cases, bulk storage and day tanks may have high and low level alarms – these are intended to alert water treatment plant staff if the tank is about to overflow or run-out, respectively. As chlorine liquid may release gas over time (referred to as gassing-off), chlorine storage tanks should have a vent pipe to safely release gas (mostly harmless oxygen) to the atmosphere outside of the building.

Chlorine dosing pumps are used to pump the chemical from the day tank to the drinking-water process pipe. Typically, metering pumps are used, which pump precise adjustable volumes of chlorine liquid over a specified time period (peristaltic- or diaphragm-type metering pumps are commonly used). Dose pumps may be manual in operation, that is, where the plant flow rate is assumed to be constant, so the dose pumps are set to dose at that particular flow rate. However, in many cases, plant flow rates are not constant, but fluctuating. As such, the risk of chlorine under- or over-dosing with dose pumps set in manual is high. Ideally, the metering pumps should be flow-paced, that is, automatically adjust the chlorine dose rate to match the flow of water through the water treatment plant (for example, if the plant flow rate increases, the chlorine dose pump output increases to maintain a steady chlorine concentration). This minimizes the risk of chlorine under- or

18 Adapted from: Environment Protection Agency (2011). Water treatment manual: Disinfection. Wexford, Ireland.

over-dosing as a result of changes to the plant flow rate. A further level of sophistication involves residual trim, where an instrument continually measures the chlorine concentration in the water that has been dosed with chlorine (i.e. the dosed water) and adjusts the chlorine dose rate accordingly.

Where resources allow, a duty pump (i.e. the pump that is normally in use) and a standby pump (i.e. back-up pump, in case the duty pump fails) should be in place. This may minimize the risk of losing chlorine disinfection in the event of a pump failure. In addition, where resources permit, a fuel-powered generator should be available, so chlorine dose pumps may continue to operate in the event of a power failure, to avoid the loss of disinfection.

Where chlorine liquid is introduced into the drinking-water the main process pipe is commonly referred to as the injection point. To ensure effective disinfection, it is important to ensure there is good mixing between the chlorine liquid and water at this point.

Liquid chlorine dosing systems may also have a calibration column, which is used to independently verify how much chlorine liquid is being delivered by the dosing pumps to ensure chlorine under- or over-dosing is not occurring. It is important that the accuracy of the pumps is verified regularly, to ensure chlorine dosing is being optimized.

Pulsation dampers are usually located on the discharge side of the dosing pumps to minimize spikes in pressure that result from the pump pulses. Pressure relief valves should be located on the discharge side of all pumps (after the pulsation dampers), to prevent excessive pressure damaging the pump in the event of pipe blockage. Load valves are designed to prevent the chlorine liquid being drawn into the drinking-water supply in the event of a large negative-pressure event (for example, the dewatering [or draining] of the drinking-water main process pipe, which may create a significant difference in pressure, such that chlorine liquid is drawn from the storage tank through the pumps unintentionally). A load valve is designed to withstand significant differences in pressure to minimize this risk.

2.3 Chlorine dosing calculations

In the following section, basic chlorine dosing equations are presented in textboxes, alongside worked examples for practical illustration.

2.3.1 How to calculate the chlorine demand

As discussed in Section 1.3.3, understanding the chlorine demand of the water is important for optimizing disinfection. Textbox M describes the equation used to estimate the chlorine demand.

Where accurate laboratory equipment and trained personnel are available, it is possible to measure the chlorine demand using laboratory techniques[19].

19 World Health Organization. Chlorine testing. Fact Sheet 2.31. http://www.who.int/water_sanitation_health/sanitation-waste/fs2_31.pdf?ua=1. Visited on 13 July, 2015.

(M) How to calculate the chlorine demand

Equation 1 describes how to calculate the chlorine demand of a water sample.

Chlorine demand (mg/L)	**=**	**Actual chlorine dose (mg/L)**	**-**	**Residual chlorine (mg/L)**	***(Eq. 1)***

Where:

The actual chlorine dose is the theoretical concentration of chlorine being added to the water (see Section 2.3.3).

The residual chlorine is the total residual concentration of chlorine in the water; this is typically measured[20] at the water treatment plant at a minimum of 30 minutes after chlorine has been added to the water.

For example, if the actual chlorine dose is 2 mg/L (see Section 2.3.3), and the total residual chlorine is 1 mg/L after 30 minutes, then the chlorine demand may be determined using Equation 1 as follows:

Chlorine demand (mg/L)	=	2 mg/L	-	1 mg/L	(Eq. 1)
	=	1 mg/L			

Once the chlorine demand is known, this value may also be used to estimate the required chlorine dose (see Textbox O).

20 The residual chlorine may be determined using a basic chlorine test kit (see Section 2.5.1).

2.3.2 How to calculate the Ct value for disinfection

Textbox N describes a simplified approach to calculating the Ct value for disinfection.

(N) How to calculate the Ct value

The Ct value may be calculated using Equation 2, as follows:

Ct (min.mg/L) = Residual chlorine (mg/L) x Contact time (min) (Eq. 2)

Where:

The residual chlorine is the residual concentration of chlorine in the water. This is typically measured at the water treatment plant at a minimum of 30 minutes after chlorine has been added to the water (i.e., after the chlorine demand has been satisfied).

The contact time is the amount of time there is contact between the chlorine and the water, such as the detention time in a tank or pipe[21]. When calculating the Ct value, the detention time is considered to be the amount of time that the water is in contact with the chlorine.

Example contact time calculation:

If a tank has a detention time of 60 minutes, and the residual chlorine concentration is 0.6 mg/L, then using Equation 2:

Ct (min.mg/L)	=	0.6 mg/L	x	60 min	(Eq. 2)
	=	36 min.mg/L			

To ensure adequate disinfection, the WHO[9] recommends a minimum Ct value of 15 min. mg/L for disinfection when the pH of the water is <pH 8.

Based on Equation 2, this equates to 30 minutes contact time with a residual chlorine concentration of 0.5 mg/L (i.e., 30 min x 0.5 mg/L = 15 min.mg/L)

However, the minimum chlorine contact time required should ideally be determined on a case-by-case basis, considering the combined influences of:

- the temperature of the water;
- the turbidity of the water;
- the pH of the water;
- the residual chlorine concentration; and
- short-circuiting within the storage (that is the potential for preferential flow and reduced mixing/detention time).

A more detailed example for accurately determining the minimum required Ct value using Ct tables is presented in Toolbox C.

21 The detention time for a storage is calculated using the following formula:

Detention time (min) = Storage volume (m^3) ÷ Flow rate (m^3/min)

For example, if a tank has a volume of 6 000 m^3 and a flow rate of 100 m^3/min, then using the above equation:

Detention time	=	6 000 m^3	÷	100 m^3/min
	=	60 min		

For a more detailed discussion on accurately determining the detention time of a system, refer to Toolbox C.

2.3.3 How to calculate the required chlorine dose

Textbox O presents an equation to calculate the required chlorine dose vital for chlorine disinfection.

(O) How to calculate the chlorine dose

Equation 3 describes how to calculate the required chlorine dose for disinfection.

Required chlorine dose (mg/L) = Chlorine demand (mg/L) + Desired residual chlorine (mg/L)[22] (Eq. 3)

Where:

The chlorine demand is determined as discussed in Section 2.3.1.

The desired chlorine residual is the residual chlorine concentration required after the chlorine demand has been satisfied and disinfection has taken place.

Example

If the chlorine demand is known to be 2 mg/L (see Section 2.3.1), and the desired residual chlorine is 1 mg/L, then the required chlorine dose may be determined using Equation 3 as follows:

Required chlorine dose (mg/L)	=	2 mg/L	+	1 mg/L	(Eq. 3)
	=	3 mg/L			

As discussed in Section 1.3.1, the optimum chlorine dose for any particular water supply system will be different in every case and changing constantly, depending on the characteristics of that particular water supply system. As such, the chlorine concentration must be monitored closely (through operational monitoring) and optimized constantly to ensure effective disinfection is occurring (see Section 2.5).

2.3.4 How to calculate the amount of chlorine powder required to make a chlorine liquid solution

Note: This section is only relevant in situations where chlorine powder is used to prepare chlorine liquid.

Chlorine powder must first be dissolved in water before it may be pumped as a chlorine liquid solution. The amount of chlorine powder required to prepare a chlorine liquid solution (or batch) depends on a number of factors, including:

- the type of chlorine powder used and its strength (for example, bleaching powder [approximately 35% active chlorine] versus high test hypochlorite [approximately 70% active chlorine]); and
- the desired chlorine concentration in the chlorine liquid solution.

22 The desired residual chlorine concentration will be dependent on the extent of chlorine decay in the water supply system (see Section 1.3.4) and must be determined on a case-by-case basis. As a general guide, for effective disinfection the minimum desired residual chlorine concentration after disinfection should be 0.5 mg/L after 30 minutes contact time where pH is <pH 8.0 (Section 1.3.5.5). However, to maintain a minimum residual chlorine concentration of 0.2 mg/L at all points in the distribution system, a higher residual chlorine concentration after disinfection may be required (see Section 1.3.7).

In general:

- if a chlorine liquid solution is of higher strength (e.g. 5% active chlorine), you will need to dose less chlorine liquid solution to achieve the required chlorine dose; or
- if a chlorine liquid solution is of lower strength (e.g. 1% active chlorine), you will need to dose more chlorine liquid solution to achieve the required chlorine dose (in this example, five times more chlorine liquid would be required, as a 1% solution is five times weaker than a 5% solution).

The strength of a chlorine liquid solution may vary from plant to plant, based on the specific situation. Typically, chlorine liquid solutions are prepared from chlorine powder to an active chlorine concentration of between 1-5%. The appropriate concentration of chlorine liquid solution required should be determined on a case-by-case basis, based on the specific situation for that water treatment plant.

As chlorine powder contains inert material that does not dissolve in water, undissolved sediment (or sludge) may remain. This sludge accumulates over time and may cause operational issues such as pump blockages. Following preparation of a batch of chlorine liquid from chlorine powder, sufficient time should be allowed for any sludge to settle to the bottom of the mixing receptacle, before the clarified solution is decanted to a separate receptacle (for example, up to 24 hours).

If a water treatment plant has (i) high flows, (ii) limited chlorine liquid bulk storage capacity and/or (iii) limited dose pump capacity, a higher strength chlorine solution may be required. However, the strength of the chlorine liquid solution is limited by the extent to which chlorine powder dissolves in water. Attempting to dissolve large amounts of chlorine powder in water may result in excessive amounts of undissolved sludge. For this reason, chlorine liquid solutions prepared from chlorine powder are typically prepared to a concentration of active chlorine of less than 5% (typically 1-2% active chlorine solutions are used).

If an active chlorine concentration greater than 5% is required (for example, due to pump or bulk storage capacity limitations), during batch preparation excessive sludge may build up in the mixing tank. In these circumstances, the solution should be allowed to settle after mixing (for example, up to 24 hours settling time), and the chlorine liquid component should always be transferred into a separate bulk storage tank before use (following the safe handling precautions outlined in Section 2.1). Chlorine mixing tank configurations for preparing a batch of chlorine liquid from chlorine powder are presented elsewhere[12].

Textbox P provides guidance on how to calculate the weight of chlorine powder required in preparing a chlorine liquid solution.

(P) How to calculate the weight of chlorine powder required to prepare a chlorine liquid solution

Equation 4 describes how to calculate the required weight of chlorine powder to prepare a batch of chlorine liquid solution.

$$\text{Weight required (g)} = \frac{1000 \times \text{Volume of chlorine liquid required (L)} \times \text{Desired chlorine liquid concentration (\%)}}{\text{Active chlorine concentration in chlorine powder (\%)}} \quad \text{(Eq. 4)}$$

The volume of chlorine liquid solution required in litres (L) may be different for each situation and may depend on (i) how much chlorine is used per day and (ii) how many days storage is required (for example, if a water treatment plant uses 100 L of chlorine liquid solution per day, and enough chlorine liquid is required for 5 days' supply, then this figure would be 5 days x 100 L = 500 L).

The desired liquid chlorine concentration required may also be different for each application, but will typically be between 1% and 5% active chlorine (see previous section for discussion).

The concentration of active chlorine in the chlorine powder will also differ depending on the type of chlorine powder used and its age and storage conditions (see Section 2.1); for example, fresh bleaching powder may be approximately 35% active chlorine, whereas fresh high test hypochlorite powder may be approximately 70% active chlorine. If chlorine powder is old and has not been stored appropriately, a lower concentration may be estimated for the calculation based on the information presented in Textbox L (Table 2).

The multiplication by 1 000 is a standard unit conversion factor.

Example

A water treatment plant requires 500 L of a 2% chlorine liquid solution using bleaching powder with an active chlorine concentration of 35%. To determine the weight of chlorine powder required, use Equation 4 as follows:

$$\textbf{Weight required (g)} = \frac{1\,000 \times 500\text{ L} \times 2\%}{35\%} \quad \text{(Eq. 4)}$$

$$= 28\,571\text{ g (or 28.6 kg) per 500 L of water}$$

2.3.5 How to calculate the chlorine dose rate

The chlorine dose rate refers to the amount of chlorine liquid solution that must be added to the drinking-water over a fixed period of time to achieve the required chlorine concentration. Textbox Q describes the equation used to calculate the chlorine dose rate for a chlorine liquid solution.

(Q) How to calculate the chlorine dose rate

Equation 5 describes how to calculate the required chlorine dose rate for a chlorine liquid solution.

$$\text{Chlorine dose rate (mL/h)} = \frac{\text{Required chlorine dose (mg/L)} \times \text{Flow rate (m3/h)}}{\text{Chlorine liquid concentration (\%)} \div 100} \qquad \text{(Eq. 5)}$$

Where:

The required chlorine dose may be determined as described in Section 2.3.3.

The flow rate refers to the flow of water through the water treatment plant (in cubic meters per hour). Knowing the water treatment plant flow rate, and potential for flow variation, is critically important with regard to optimizing chlorine dosing. Every time the flow rate changes, the chlorine dose rate must also be changed. Otherwise, the potential for under- or over-dosing exists, which may compromise the water safety and impact public health.

The chlorine liquid concentration is the percentage of active chlorine present in the chlorine liquid solution, as discussed in Section 2.3.4. This may vary depending on the specific type of chlorine powder or commercially prepared chlorine liquid used and its age and storage conditions (Section 2.1). For example, where chlorine liquid has been prepared from chlorine powder, this will typically be between 1-5% active chlorine (Section 2.3.4); where commercially prepared sodium hypochlorite is used, this may be between 10-15% active chlorine.

The division by 100 is a standard unit conversion factor.

Example

A water treatment plant has a required chlorine dose of 3 mg/L and a water treatment plant flow rate of 100 m^3/h. A chlorine liquid solution has been prepared from chlorine powder with an active chlorine concentration of 1%. To determine the required chlorine dose rate, use Equation 5 as follows:

$$\textbf{Chlorine dose rate (mL/h)} = \frac{3\text{ mg/L} \times 100\text{ m}^3\text{/h}}{1\% \div 100} \qquad \text{(Eq. 5)}$$

$$= 30\,000\text{ mL/h (or 500 mL/min)}$$

An alternative form of Equation 5 may be used to estimate the actual chlorine dose, for example, if the current chlorine dose was unknown and needed to be determined (Textbox R). This equation may also be used when estimating the chlorine demand, as described in Section 2.3.1.

(R) How to calculate the actual chlorine dose

To determine the actual chlorine dose rate at the water treatment plant when it is unknown, or to assist with calculating the chlorine demand (Section 2.3.1), it may be useful to estimate the actual chlorine dose, as described by Equation 6.

$$\text{Actual chlorine dose (mg/L)} = \frac{[\text{Chlorine dose rate (mL/h)} \times \text{Chlorine liquid concentration (\%)}] \div 100}{\text{Flow rate (m}^3\text{/h)}} \qquad \text{(Eq. 6)}$$

Where:

The chlorine dose rate is the actual chlorine dose being delivered by the chlorine dose pump.

The chlorine liquid concentration is the percentage of active chlorine present in the chlorine liquid solution, as discussed in Section 2.3.4.

The flow rate refers to the flow of water through the water treatment plant.

The division by 100 is a standard unit conversion factor.

Example

A water treatment plant is using 2% chlorine liquid solution with a chlorine dose rate of 6 000 mL/h; the flow rate at the water treatment plant is 100 m^3/h. To determine the actual chlorine dose, use Equation 6 as follows:

$$\text{Actual chlorine dose (mg/L)} = \frac{(6\,000 \text{ mL/h} \times 2\%) \div 100}{100 \text{ m}^3\text{/h}} \qquad \text{(Eq. 6)}$$

$$= 1.2 \text{ mg/L}$$

Note – this figure is the theoretical chlorine dose and does not take into account the chlorine demand.

2.3.5.1 Adjusting the chlorine dose

When adjustment of the chlorine dose is required (for example, if the water treatment plant flow rate changes or if a low residual chlorine concentration has been detected in the distribution system), care must be taken to avoid over- or under-adjustment of the dose pump setting.

To minimize this risk, the following should be considered when adjusting the chlorine dose:

- adjust the dose gradually (i.e. little-by-little);
- before adjusting the dose further, always determine the time taken for the newly dosed water to reach a particular monitoring point in the distribution systems (for example, if a low residual chlorine result was detected at the end of the network, it may take, for example, three days for the newly dosed water to reach this point from the water treatment plant);
- always monitor the chlorine concentration in the dosed water and distribution network carefully after dose adjustments have been made to verify the new chlorine concentration is optimal (see Section 2.5).

2.4 Developing standard operating procedures for chlorination

Standard operating procedures (SOPs) document clear instructions on how to perform a particular operational task. SOPs should be prepared for any task that is performed routinely within a water supply system, including tasks associated with chlorination. Developing SOPs for chlorination assists staff members to perform the task safely and consistently.

SOPs should be clearly written, such that any staff member with appropriate training in that SOP may easily and correctly follow the procedure every time. SOPs should be targeted and concise, limiting information to only that which is necessary to performing the task safely and correctly. Where relevant, the use of pictures may be appropriate, such that staff with all levels of literacy may follow the procedure.

Important safety information should also be included in the SOP, for example, describing which training and PPE is required to safely perform the task.

Textbox S outlines some of the key chlorination tasks that should have SOPs developed, alongside guidance as to the type of information that should be included. It should be noted that this list is not exhaustive, and additional chlorination SOPs may be required depending on the specific situation.

(S) Developing standard operating procedures for chlorination tasks

The following is a list of key SOPs that are typically required to support chlorination activities at a water treatment facility, alongside examples of the type of information that is beneficial to include.

SOP for calculating the weight of chlorine powder required to make a chlorine liquid batch (see Generic SOPs 1 and 2 in Toolbox A)

- PPE required for safe completion of the task;
- The type of chlorine powder to be used (e.g., bleaching powder or high test hypochlorite);
- The desired solution strength of the chlorine liquid being prepared (e.g., 1% solution);
- The volume of chlorine liquid solution to be prepared; and
- The calculation used to determine the weight of chlorine powder required.

SOP for preparing a batch of chlorine liquid from chlorine powder (see Generic SOP 3 in Toolbox A)

- PPE required for safe completion of the task;
- The unit weight of chlorine powder required to prepare a batch of liquid chlorine (e.g., 35 g of bleaching powder per litre of water);
- The receptacle that the solution will be mixed in (e.g., dedicated concrete tank or a plastic container);
- The means by which the powder will be mixed with the water (e.g., a dedicated mixing device);
- The amount of settling time required following mixing and before use; and
- The appropriate chlorine storage conditions.

SOP for calculating the chlorine dose (see Generic SOP 4 in Toolbox A)

- PPE required for safe completion of the task;
- The calculation used to determine the chlorine dose rate based on the strength of the chlorine liquid solution and the water treatment plant flow rate; and
- Precautions to be taken when adjusting the dose rate (including increased monitoring of chlorine concentration in the drinking-water following adjustment).

SOP for chlorine stock management

- PPE required for safe handling of chlorine stock; and
- Stepwise process for receipt of bulk chlorine stock and application of FIFO stock management principles.

SOP for operation and maintenance of chlorine dose pumps

- PPE required for safe handling of chlorine;
- Stepwise guidance on adjusting the dose pump set-point;
- Stepwise guidance on maintenance and calibration of the dose pump; and
- Troubleshooting guide for resolving common dose pump faults/failures.

SOP for chlorine emergency procedures

- PPE required for safe handling of chlorine;
- Basic first-aid required in the event of exposure to concentrated chlorine;
- Contact details for the relevant emergency services; and
- Containment requirements to minimize human exposure and environmental damage in the event of accidental chlorine release.

The Toolbox section of this guide provides some examples of generic SOPs for drinking-water chlorination (Toolbox A). It should be noted that these SOPs are generic examples only, and each SOP should be reviewed and adapted on a site-specific basis.

Once in place, training and assessment of competency in these SOPs should be a core component of staff development programmes.

2.5 Chlorine monitoring

As discussed in Section 1.3.7, careful monitoring and optimization of the chlorine concentration through the water supply system is critical to ensure that sufficient chlorine is added to the water for effective disinfection, whilst minimizing consumer acceptability issues (i.e. taste, odour).

2.5.1 Chlorine testing equipment

The concentration of chlorine in drinking-water can be analysed using various commercially available test kits (Table 3). The most commonly used methods are based on a chemical reaction between the chlorine present in the water and a chemical reagent (called DPD reagent[23]). If chlorine is present, a measurable colour change occurs in the water sample (i.e. the water sample will turn from clear to pink). The intensity of the colour change may then be measured either visually (using a basic colour chart that is read by the user) or by using equipment that measures the intensity of light as it passes through the sample (called a colorimeter or chlorine analyser). These test kits typically measure total chlorine and residual chlorine concentrations at lower levels (e.g. between 0 to 10 mg/L), and are suited for routine residual chlorine monitoring in the dosed water and throughout the distribution network.

23 N,N-diethyl-*p*-phenylenediamine.

To test higher strength chlorine concentrations, such as those found in chlorine powder and chlorine liquid solutions, specialised kits and equipment are needed that require more complex chemical titrations[12,13] (e.g. portable idiometric titration kits).

Where resources permit, continuous (or on-line) monitoring of chlorine concentration in the drinking-water is recommended. Online monitoring units consist of a chlorine analyser that continuously tests the chlorine concentration in the dosed water. These units may be alarmed to notify staff that the chlorine dose is too high or too low. These units may also facilitate residual trim control of the chlorine dose pumps to ensure that the chlorine dose is optimized (see Section 2.2).

When selecting appropriate chlorine testing equipment it is important to consider:

- both capital cost (i.e. the initial cost of the instrument) and operational costs (the on-going cost of replacement reagents, parts and servicing);
- the availability of replacement reagents, parts and servicing;
- the level of operator training required to use and maintain the instrument;
- the availability of specialist knowledge for technical support and equipment maintenance;
- the durability of the instrument under the likely field conditions (i.e. ability to withstand shock, dust, water); and
- the level of accuracy and sensitivity required for the equipment balanced against the available resources.

Table 3. *Relative comparison of testing equipment commonly used for chlorine monitoring*

Test equipment	Cost	Accuracy	Resolution	Advantages	Disadvantages
Chlorine test strips	M	L	L	• Easy to use, disposable • No calibration/ servicing required	• Poor degree of resolution (e.g. may only measure in 0.5 mg/L increments) • Visual measurement (colour change); open to user interpretation • Requires supply chain for replacement strips
Chlorine comparator test kit	M	M	M	• Easy to use • Durable for field use • No calibration/ servicing required	• Visual measurement (colour change); open to user interpretation • Requires reagents (DPD powder), supply chain
Chlorine meter	H	H	H	• High degree of resolution over a wide range (0.05 to 10 mg/L in 0.01 mg/L increments) • Easy to use	• Less durable for field use • Calibration/servicing required • Requires reagents, replacement parts (bulb), supply chain

L - Low; M – Medium; H – High.

The use of a simple decision matrix can aid the selection of context appropriate chlorine testing equipment[24].

2.5.2 Chlorine sampling considerations

Chlorine is volatile. Once exposed to air, chlorine will leave the liquid phase (i.e. water) and escape into the gas phase (i.e. the air). This is an important consideration for the sample holding-time when testing the concentration of chlorine in water samples - if samples are not analysed for chlorine immediately after collection, the chlorine will start to escape (or volatilize) from the sample, and this may result in a low residual chlorine reading that is inaccurate. It is vital to process any sample immediately after collection to ensure an accurate chlorine reading is obtained to inform operational decision-making.

2.5.3 Operational monitoring for optimized chlorination

Operational monitoring[25] is a key component of a WSP to ensure that the control measures in place to minimize water quality risks are operating effectively[3,4] (control measures are the measures in place within a water supply system to prevent or eliminate a water safety hazard, or reduce it to an acceptable level). Operational monitoring plans should clearly document the type of monitoring that should be performed, how it should be performed, where it needs to be performed, who will perform it and how often. In addition, operational monitoring plans must define at what point the control measure is no longer considered to be working effectively (i.e. the critical limit) and importantly, what needs to be done to return the control measure to operation within acceptable limits (i.e. the corrective action).

Chlorination of drinking-water supplies to manage microbial risk is a key control measure whose performance must be routinely monitored to ensure chlorine disinfection is occurring within acceptable operational limits[25]. When developing a site specific operational monitoring plan for chlorination, the generic monitoring locations outlined in Table 4 and Figure 14 should be considered.

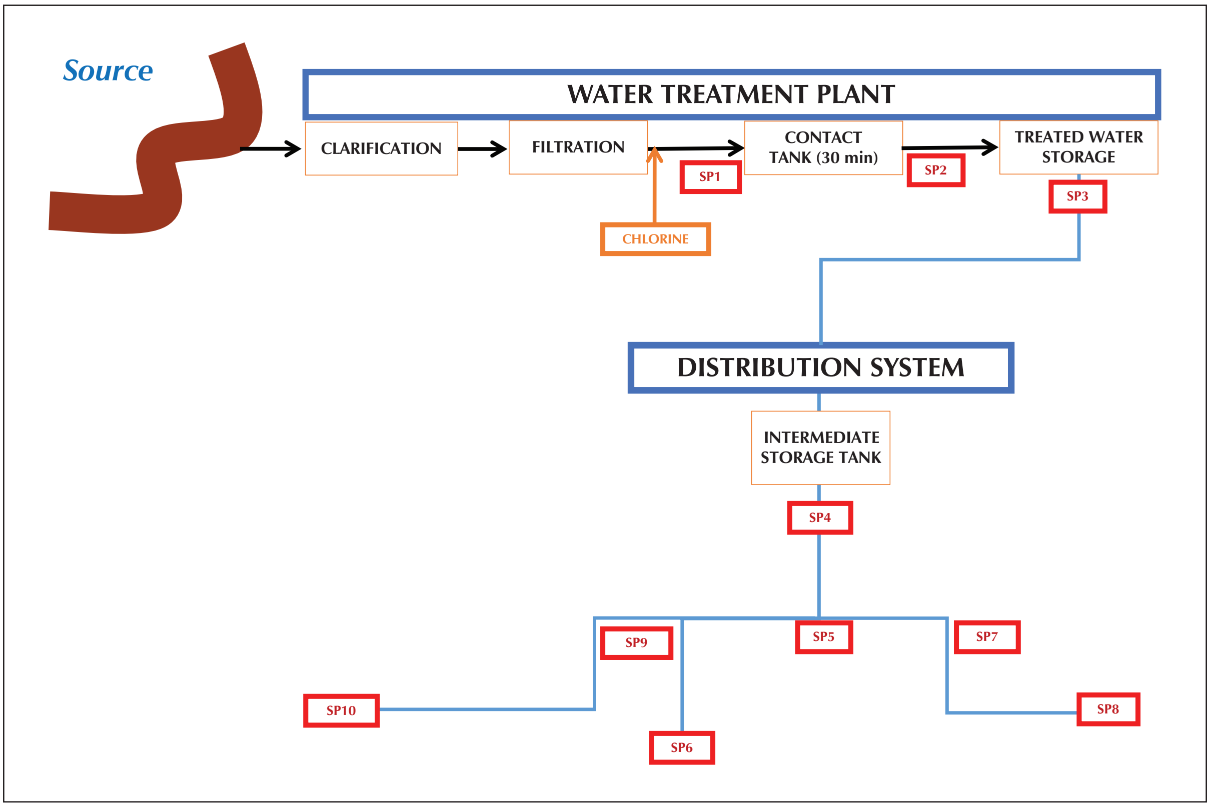
24 Murry, A. and Lantagne, D. (2015). Accuracy, precision, usability, and cost of free chlorine residual testing methods. Journal of Water and Health, 13(1), 79-90.

25 Note: Operational monitoring is separate to compliance monitoring, which involves the testing of drinking-water to ensure that it meets water quality standards; compliance monitoring is part of WSP verification, to ensure that the plan is functioning effectively[3, 4]. Chlorine monitoring may also be performed as part of compliance monitoring.

Table 4. *Example of generic sample point locations for operational monitoring of chlorination (see Figure 14 for sample point locations)*

Location	Sample point (SP)	Description	Reason
Dosed water	SP1	Immediately after chlorine has been added to the water	• Monitoring of the applied chlorine dose
Post contact time	SP2	Dosed water after the minimum required chlorine contact time has elapsed (e.g. after 30 minutes); often this may be the outlet of a treated water storage (e.g. tank, reservoir)	• Monitoring of the residual chlorine concentration after disinfection has occurred (and the chlorine demand has been satisfied) • Ensures that effective disinfection has occurred (i.e. the minimum required Ct value has been achieved)
Entry point to the distribution system	SP3	Post water treatment plant and prior to the first consumer (Note: In some water supply systems, SP2 and SP3 may be the same location)	• Monitoring of the residual chlorine concentration at the start of distribution system • Indicates if the chlorine dose is optimal at the start of the system to protect water right through the system to the point of consumer delivery, whilst minimizing aesthetic impacts
Distribution network	SP4 to SP10	Various locations within the distribution system (including intermediate water storages) and at locations representative of the entire distribution network (e.g. start, middle, end), through to the point of delivery to the consumer Note: The actual number of sample points in the distribution network will vary depending on the specific circumstances of the particular water supply system	• Monitoring of the residual chlorine concentration throughout the entire distribution system to confirm that the water is protected to the point of consumer delivery, whilst minimizing aesthetic impacts

Figure 14. *Example of generic operational monitoring sample point locations in a water supply system; SP – Sample point (see Table 4 for sample point number references)*



Where resources permit, continuous on-line monitoring of the chlorine concentration at the water treatment facility will ideally be in place. Alternatively, single (or grab) samples must be taken at a frequency that is appropriate to the specific situation to manage the risk of sub-optimal chlorine dosing. For example, where the raw water quality is constantly changing, monitoring of chlorine concentrations at the water treatment plant should be more frequent (e.g. hourly); whereas, if raw water quality is more consistent, less frequent monitoring may be appropriate (e.g. three times daily).

Operational monitoring of chlorination should include grab samples from defined sample-point locations in the distribution network to ensure the chlorine dose is optimized throughout the entire water supply system. Sample point locations should be representative of the entire distribution network, and should represent:

- the start, middle and end of the distribution network; and
- known water quality trouble spots (i.e. where poor water quality has been historically found, such as low-flow and/or end-points of the distribution network).

Similarly to the water treatment plant, operational monitoring of chlorine levels in the distribution network should be performed at a frequency that is appropriate to manage the risk of sub-optimal chlorine concentrations in that water supply system.

If operational monitoring identifies that the chlorine concentration is outside of the critical limits, the cause must be investigated immediately and appropriate corrective action should be taken. Assuming accurate chlorine readings are being taken, a high chlorine result will likely be as a result of chlorine over-dosing at the point of chlorine application. However, care must be taken when interpreting a low chlorine result. Low chlorine may occur due to chlorine under-dosing at the point of application, but may also occur as a result of water quality issues downstream in the distribution network (for example, low-flow, water age, accumulation of chlorine reactive substances over time or introduction of chlorine reactive substances through asset leakage/damage, backflow[26], cross connections[27] or illegal connections[28]). As such, the reason for the low chlorine concentration must be carefully and thoroughly investigated, as increasing the chlorine dose at the water treatment plant may not always be the only appropriate course of corrective action.

For more detailed guidance on operational monitoring, refer to *Operational monitoring plan development:* A *guide to strengthening operational monitoring practices in small- to medium-sized water supply systems*[29].

2.6 Summary

A summary of the key considerations for effective chlorine disinfection for the supply of safe drinking-water is presented in Figure 15.

26 Unintentional flow of contaminated water in the reverse direction to normal drinking-water flow.

27 Connection between drinking-water pipes and non-drinking-water pipes (such as sewerage or recycled water pipes).

28 Unauthorised connections to the drinking-water supply pipes; illegal connections are often sources of leakages, and may introduce backflow or cross connections due to poor quality work or a lack of understanding of plumbing risks.

29 World Health Organization Regional Office for South-East Asia, 2017. Operational monitoring plan development: A guide to strengthening operational monitoring practices in small- to medium-sized water supply systems.

Figure 15. *Key steps for effective chlorine disinfection of drinking-water using chlorine powder*[30] *(section references are presented in parentheses)*

30 If using commercially prepared chlorine liquid, Steps 2 and 3 may be omitted, ensuring that the safe handling and storage precautions for chlorine liquid are followed as per Section 2.1.

Toolbox

Contains generic tools to support the development of site-specific chlorination procedures

A) Generic standard operating procedures for drinking-water chlorination

The following section contains generic SOPs for chlorination of drinking-water, which are designed to be adapted to develop site-specific procedures for your own particular situation.

In particular, the following information must be based on your particular situation:

(1) the type of chlorine powder used (e.g. bleaching powder versus high test hypochlorite);

(2) the concentration of active chlorine in your powder (determined either by testing [Section 2.3.4] or estimated based on manufacturer/supplier guidance);

(3) the volume of chlorine liquid solution required;

(4) the flow rate of your water treatment plant; and

(5) the required chlorine dose for your water supply system to ensure effective disinfection and residual protection to the end of the distribution network.

Generic SOP 1: How to determine the weight of high test hypochlorite powder required to prepare a chlorine liquid solution

How to determine the weight of high test hypochlorite powder required to prepare a chlorine liquid solution

PURPOSE: To provide a safe method for determining the weight of high test hypochlorite powder (approx. 70% active chlorine) required to prepare a 1% chlorine liquid solution.

VERSION: 1 **DATE:** DD/MM/YYYY **AUTHORISED BY:** Manager Operations

TRAINING REQUIRED:	**IMPORTANT SAFETY NOTE:**
• Awareness of safe handling of chlorine. • Training in this SOP.	• Ensure gloves, overalls, safety glasses and dust mask are worn when handling powder chlorine. • Ensure the area is well ventilated to prevent build-up of fumes.

Calculation for determining the weight of powder required

The following calculation describes how to prepare 1 litre (L) of a 1% chlorine liquid solution from high test hypochlorite powder that contains 70% active chlorine:

$$\text{Powder required (g)} = \frac{\text{1 000 x Volume of chlorine liquid required (L) x Desired liquid chlorine concentration (\%)}}{\text{Active chlorine concentration in chlorine powder (\%)}}$$

Volume of chlorine liquid required: 1 L

Desired liquid chlorine concentration: 1%

Active chlorine concentration in the high test hypochlorite powder: 70%

$$= \frac{1\,000 \times 1\text{ L} \times 1\%}{70\%}$$

= **14 g of high test hypochlorite powder required per 1 L of water**

So, for example, if you wish to make a 10 L batch of 1% chlorine liquid solution, you will require 140 g of high test hypochlorite powder (i.e., 10 L x 14 g).

This 1% chlorine liquid solution may now be used in determining the chlorine dose rate (see Generic SOP 4 How to Calculate the Chlorine Dose Rate).

Generic SOP 2: How to determine the weight of bleaching powder required to prepare a chlorine liquid solution

How to determine the weight of bleaching powder required to prepare a chlorine liquid solution

PURPOSE: To provide a safe method for determining the weight of bleaching powder (approx. 35% active chlorine) required to prepare a 1% chlorine liquid solution.

VERSION: 1 **DATE:** DD/MM/YYYY **AUTHORISED BY:** Manager Operations

TRAINING REQUIRED:

- Awareness of safe handling of chlorine.
- Training in this SOP.

IMPORTANT SAFETY NOTE:

- Ensure gloves, overalls, safety glasses and dust mask are worn when handling powder chlorine.
- Ensure gloves, overalls and face shield are worn when handling liquid chlorine.
- Ensure the area is well ventilated to prevent build-up of fumes.

Calculation for determining the weight of powder required

The following calculation describes how to prepare 1 litre (L) of a 1% chlorine liquid solution from bleaching powder that contains 35% active chlorine:

$$\text{Powder required (g)} = \frac{\text{1 000 x Volume of chlorine liquid required (L) x Desired liquid chlorine concentration (\%)}}{\text{Active chlorine concentration in the chlorine powder (\%)}}$$

Volume of chlorine liquid required: 1 L

Desired chlorine liquid concentration: 1%

Active chlorine concentration in the bleaching powder: 35%

$$= \frac{1\ 000 \times 1\ \text{L} \times 1\%}{35\%}$$

= **29 g of bleaching powder required per 1 L of water**

So, for example, if you wish to make a 10 L batch of 1% chlorine liquid solution, you will require 290 g of bleaching powder (i.e. 10 L x 29 g).

This 1% chlorine liquid solution may now be used in determining the chlorine dose rate (see Generic SOP 4 How to Calculate the Chlorine Dose Rate).

Generic SOP 3: How to prepare a batch of chlorine liquid from chlorine powder

How to prepare a batch of chlorine liquid from chlorine powder

PURPOSE: To provide a safe method for preparing a batch of chlorine liquid from chlorine powder.

VERSION: 1 **DATE:** DD/MM/YYYY **AUTHORISED BY:** Manager Operations

TRAINING REQUIRED:	**IMPORTANT SAFETY NOTE:** ⚠
• Awareness of safe handling of chlorine. • Training in this SOP.	• Ensure gloves, overalls, safety glasses and dust mask are worn when handling powder chlorine. • Ensure gloves, overalls and face shield are worn when handling liquid chlorine. • Ensure the area is well ventilated to prevent build-up of chlorine fumes.

(1) Depending on which type of chlorine powder you are using, use either Generic SOP 1 (high test hypochlorite) or Generic SOP 2 (bleaching powder) to determine the weight of chlorine powder required per litre of water.

(2) Measure the desired volume of clean water and add to a suitably sized, chlorine resistant, mixing container (see below for examples of suitable chlorine-resistant containers).

(3) Measure the required weight of chlorine powder.

(4) Add the chlorine powder to the water slowly.

- Always add the chlorine powder to the water (never water to the chlorine powder).

(5) Use an appropriate mixing tool (for example, a portable mechanical agitator may be used, such as a power drill with a mixing head) to gently mix the solution until most of the powder has dissolved (minimum of 5 minutes mixing time).

- Some of the powder will not completely dissolve – this is normal.

(6) Once mixed, the solution should be allowed to settle for up to 24 hours before use.

- This will allow undissolved material to settle to the bottom of the receptacle (this material may block the chlorine dose pump, if not removed);
- Once settled, carefully transfer the chlorine liquid solution to a clean chlorine resistant container, taking care not to disturb the settled sediment.

(7) The liquid chlorine solution is now ready to be used.

Important storage information

To minimize the rate and extent of chlorine decomposition in the chlorine powder and liquid, always:

- store in a cool, dry, well ventilated place;
- store away from direct sunlight and excessive humidity and temperatures;
- store in chlorine resistant containers (for example, light resistant plastic [poly vinyl chloride; high density polyethylene], glass, cement); and
- keep all storage containers fully sealed when not in use.

Generic SOP 4: How to calculate the chlorine dose

How to calculate the chlorine dose

PURPOSE: To provide a consistent method for calculating the chlorine dose for effective disinfection.

VERSION: 1 **DATE:** DD/MM/YYYY **AUTHORISED BY:** Manager Operations

TRAINING REQUIRED:	**IMPORTANT SAFETY NOTE:** ⚠
• Awareness of safe handling of chlorine solutions. • Training in this SOP.	• Ensure gloves, overalls and face shield are worn when handling liquid chlorine. • Ensure the area is well ventilated to prevent build-up of chlorine fumes.

To determine the required chlorine dose rate in millilitres per hour (mL/h), use the following equation:

$$\text{Chlorine dose rate mL/h} = \frac{\text{Required chlorine dose (mg/L) x Flow (m}^3\text{/h)}}{\text{Chlorine liquid concentration (\%)} \div 100}$$

For example, if our required chlorine dose is 2 mg/L, the plant flow rate in this example is 100 m^3/h and the concentration of active chlorine in the chlorine liquid solution is 1%, then:

$$\text{Chlorine dose rate mL/h} = \frac{2\text{ mg/L x }100\text{ m}^3\text{/h}}{1\% \div 100}$$

$$= 20\,000\text{ mL/h (or approx. 333 mL/minute)}$$

Important notes when adjusting the chlorine dose

- Always adjust the dose in a stepwise fashion, that is, gradual adjustments (little by little)
  - Do not make large adjustments all at once or you risk over-/under-dosing.
- Always consider the time taken for newly dosed water to flow through (or turn over) in the tank or pipe before additional adjustments are made.
  - For example, it may take two days for higher chlorinated water to reach a particular testing point in the distribution system.
- Always increase chlorine monitoring following changes in the chlorine dose to ensure the dose has been optimized and under- or over-dosing is not occurring.
- Adjustments to the chlorine dose may be required following the use of a fresh chlorine batch, due to batch variation with regards to the strength of the new chorine liquid solution.

B) Chlorine dosing cheat-sheet

The chlorine dosing cheat sheet is an electronic accompaniment to this guide, which is available for download from the WHO SEARO website (http://www.searo.who.int/en/).

The cheat sheet is designed for operational staff to allow simple, quick and consistent chlorine dosing calculations to be performed. The spreadsheet prompts the user for the necessary input information and then automatically performs the calculation.

TAB 1. How to determine the weight of chlorine powder required to prepare a chlorine liquid solution.

Information you will need:

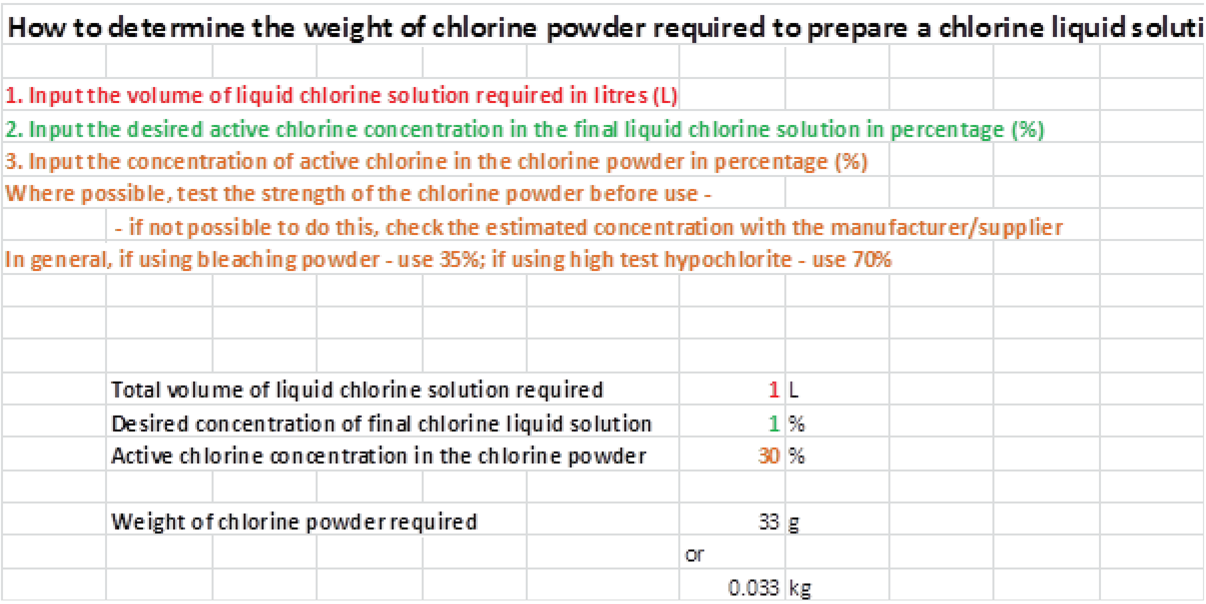
(1) Total volume of liquid chlorine solution required in litres (L);

(2) Desired concentration of final liquid chlorine solution in percentage (%);

(3) Active chlorine concentration in the chlorine powder in percentage (%).

Enter the information as per the on-screen prompt (Fig. TB 1). The weight of chlorine powder required will be calculated automatically in grams and kilograms.

Figure TB 1. *Screen shot from Tab 1 of the chlorine dosing cheat sheet*



TAB 2. How to calculate the chlorine dose rate

Information you will need:

(1) The water treatment plant flow rate in litres per hour (L/h);

(2) The active chlorine concentration in the chlorine liquid solution in percentage (%);

(3) The required chlorine dose (i.e. the chlorine demand + desired chlorine residual; see Section 2.3.3) in milligrams per litre (mg/L).

Enter the information as per the on-screen prompt (Fig. TB 2). The chlorine dose rate will be calculated automatically in millilitres per hour (mL/h) and millilitres per minute (mL/min).

Figure TB 2. *Screen shot from Tab 2 of the chlorine dosing cheat sheet*

How to calculate the chlorine dose rate			
1. Input the plant flow rate in litres per hour (L/h)			
2. Input the active chlorine concentration in the chlorine liquid solution in percentage (%)			
3. Input the required chlorine dose (i.e. chlorine demand + desired chlorine residual) in milligrams per litre (mg/L)			
The chlorine dose rate will be calculated in millilitres per hour (mL/h)			
	Plant flow rate	100,000	L/h
	Active chlorine concentration in the chlorine liquid solution	1	%
	Required chlorine dose	3	mg/L
	Chlorine dose rate required	30,000	mL/h
		or	
		500	mL/minute

TAB 3. How to calculate the actual chlorine dose

Information you will need:

(1) The water treatment plant flow rate in litres per hour (L/h);

(2) The active chlorine concentration in the chlorine liquid solution in percentage (%);

(3) The current chlorine dose rate in millilitres per hour (mL/h).

Enter the information as per the on-screen prompt (Fig. TB 3). The chlorine dose will be calculated automatically in milligrams per litre (mg/L).

Note: This is the theoretical chlorine dose and does not take chlorine demand into consideration.

Figure TB 3: Screen shot from Tab 3 of the chlorine dosing cheat sheet

To estimate the actual chlorine dose:			
1. Input the plant flow rate in litres per hour (L/h)			
2. Input the active chlorine concentration in the chlorine liquid solution in percentage (%)			
3. Input the current chlorine dose rate in millilitres per hour (mL/h)			
The actual chlorine dose will be calculated in milligrams per litre			
(Note - this is the theoretical chlorine dose and does not take chlorine demand into consideration).			
	Plant flow rate	100,000	L/hr
	Active chlorine concentration in the chlorine liquid solution	1	%
	Chlorine dose rate	30,000	mL/hr
	Chlorine concentration	**3.0**	**mg/L**

C) Calculating the Ct value for disinfection

The following section describes a detailed approach for determining the required Ct value for a particular situation. A worked example is provided, which should be adapted to the specific situation.

Remember, as described in Section 2.3.2, the Ct value is calculated as follows:

$$\text{Ct (min.mg/L)} = \text{Residual chlorine (mg/L)} \times \text{Contact time (min)} \qquad \textit{(Eq. 2)}$$

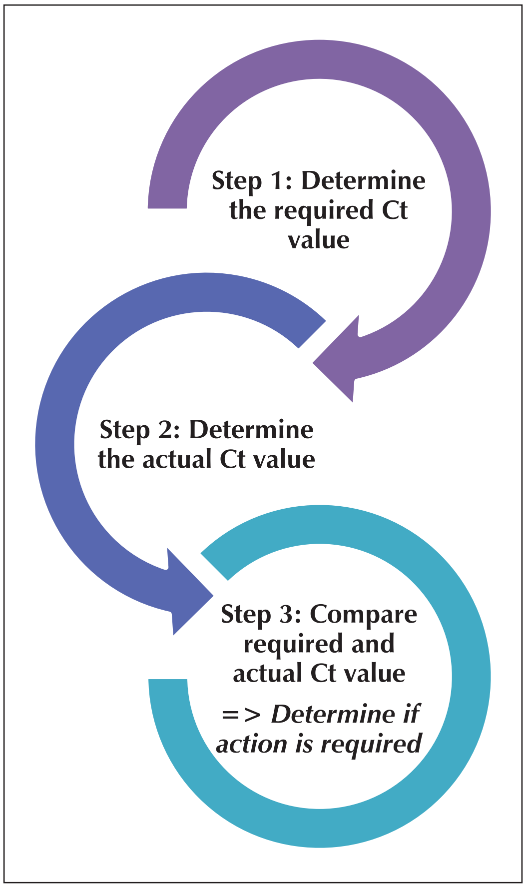
Where,

Residual chlorine: is the concentration of residual chlorine remaining in the water after the chlorine demand has been satisfied and disinfection is complete.

Contact time: is the amount of time there is contact between chlorine and the water, such as the detention time in a tank, reservoir or pipe.

The basic steps involved in calculating contact times are presented in Figure TB 4.

Figure TB 4: Steps involved in calculating the Ct value



Step 1) Determine the required Ct value

As discussed in Section 2.3.2, the minimum recommended Ct value is 15 min.mg/L (where the pH of the water is <pH 8). However, this is the minimum recommended Ct value only and the actual required Ct value for the specific situation may be different.

To determine the required Ct value for a specific situation, the following should be determined:

(1) pH of the water;

(2) temperature of the water; and

(3) residual chlorine (or free chlorine) concentration of the water.

Once this information is available, Ct tables are then required[31] (Figure TB 5). To use the Ct tables:

(1) choose the correct Ct table[31] based on the temperature of the water; this should include the heading *Giardia inactivation for free chlorine* and the minimum temperature you have recorded for your water;

Note: As the tables are presented only in 5 °C increments, if the temperature of the water falls between two temperature tables (e.g. 17 °C falls between the tables for 15 and 20 °C), then choose the lower temperature table for the calculations to provide a margin of safety (e.g. 15 °C).

(2) select the pH column for the maximum pH value recorded for the water;

Note: As the pH values within the tables are pH 0.5 increments, if the pH of the water falls between two pH values (e.g. pH 7.2 falls between pH 7.0 and 7.5 in the tables), then choose the higher pH value in the calculations to include a margin of safety (e.g. pH 7.5)

(3) within the pH column, select the appropriate Log inactivation value; this value is the extent to which *Giardia* organisms are removed during chlorine disinfection under particular conditions (for example, a 2-log reduction implies that 99% of *Giardia* are removed, whereas a 3-log reduction implies that 99.9% of *Giardia* are removed); the required log reduction values are typically based on the concentration of *Giardia* in the raw water, as well as the treatment processes present; if this information is not known, the most stringent value may be adopted (i.e. 3.0 log inactivation) to include a margin of safety;

(4) select the correct row based on the minimum residual chlorine concentration recorded;

Note: As the residual chlorine values are in 0.2 mg/L increments, if the residual chlorine concentration of the water falls between two values (e.g. 0.9 mg/L falls between 0.8 and 1.0 mg/L within the tables), then choose the lower residual chlorine concentration for the calculations to include a margin of safety (e.g. 0.8 mg/L).

(5) moving across this row, and moving down the pH/log inactivation row, will allow the required Ct value to be determined (in min.mg/L; Figure TB 5).

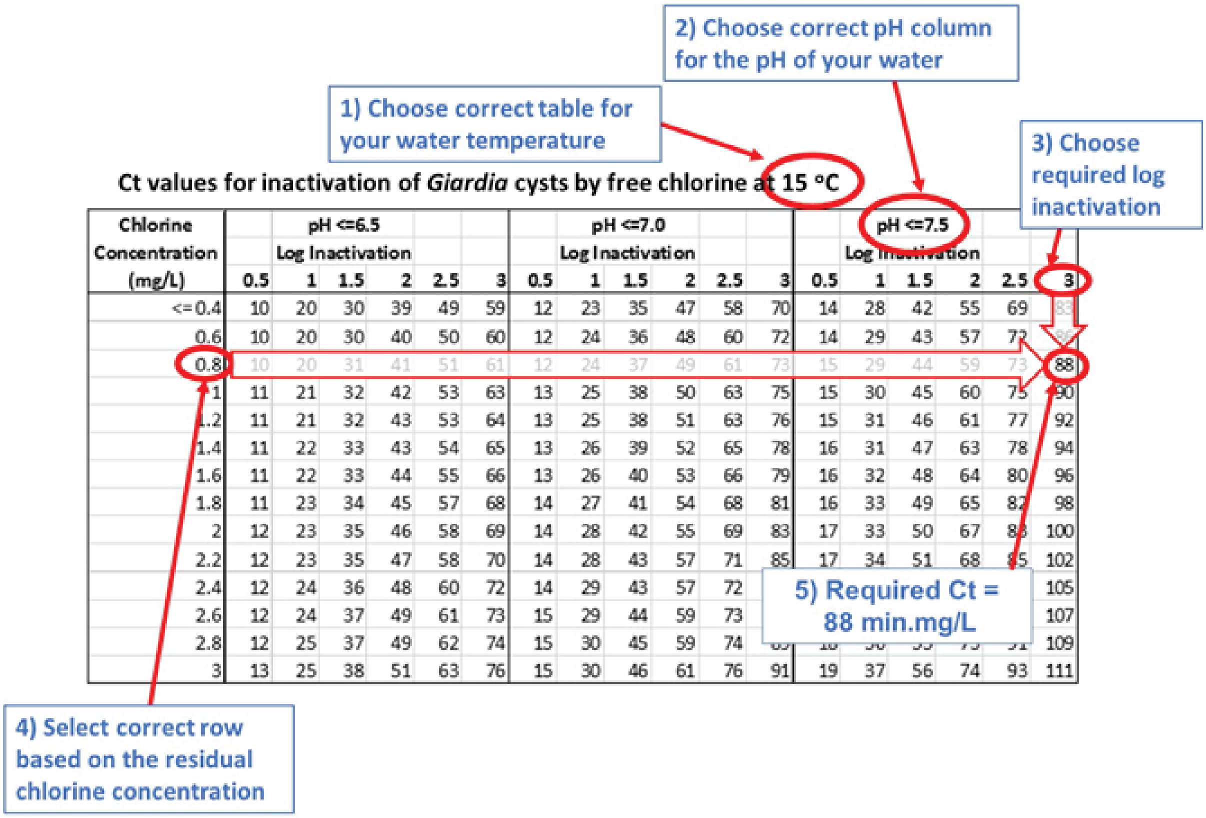
For example, let us say that water quality monitoring has determined the following information:

- the minimum temperature of the water is 18 °C;
- the maximum pH of the water is pH 7.2; and
- the residual chlorine concentration is 0.9 mg/L.

Using the guidance above, Figure TB 5 illustrates how to determine the required Ct value using the Ct tables for a 3.0 log inactivation.

31 American Water Works Association (1991). Guidance manual for compliance with the filtration and disinfection requirements. A reprinted version of these original tables is available to download from http://www.wqts.com/pdf/1999-03_DisinfectionProfiling.pdf (Appendix C).

Figure TB 5. *Stepwise guidance on how to determine the required Ct value using Ct tables (adapted[31])*



Ct values for inactivation of *Giardia* cysts by free chlorine at 15 °C

Chlorine Concentration (mg/L)	pH <=6.5 Log Inactivation						pH <=7.0 Log Inactivation						pH <=7.5 Log Inactivation					
	0.5	1	1.5	2	2.5	3	0.5	1	1.5	2	2.5	3	0.5	1	1.5	2	2.5	3
<=0.4	10	20	30	39	49	59	12	23	35	47	58	70	14	28	42	55	69	83
0.6	10	20	30	40	50	60	12	24	36	48	60	72	14	29	43	57	72	86
0.8	10	20	31	41	51	61	12	24	37	49	61	73	15	29	44	59	73	88
1	11	21	32	42	53	63	13	25	38	50	63	75	15	30	45	60	75	90
1.2	11	21	32	43	53	64	13	25	38	51	63	76	15	31	46	61	77	92
1.4	11	22	33	43	54	65	13	26	39	52	65	78	16	31	47	63	78	94
1.6	11	22	33	44	55	66	13	26	40	53	66	79	16	32	48	64	80	96
1.8	11	23	34	45	57	68	14	27	41	54	68	81	16	33	49	65	82	98
2	12	23	35	46	58	69	14	28	42	55	69	83	17	33	50	67	83	100
2.2	12	23	35	47	58	70	14	28	43	57	71	85	17	34	51	68	85	102
2.4	12	24	36	48	60	72	14	29	43	57	72	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	105
2.6	12	24	37	49	61	73	15	29	44	59	73	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	107
2.8	12	25	37	49	62	74	15	30	45	59	74	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	109
3	13	25	38	51	63	76	15	30	46	61	76	91	19	37	56	74	93	111

Using the Ct tables in Figure TB 5 illustrate how pH, temperature and chlorine concentration may influence the amount of contact time required (see Section 1.3.5.1 to 1.3.5.3 for more detailed discussion).

Step 2) Determine the actual Ct value

To determine the actual Ct value, contact time for the specific storage (e.g. tank, reservoir) must be determined first. To do this, the amount of detention time occurring in the storage must be calculated.

As described in Section 2.3.2, the detention time is calculated based on the following formula:

Detention time (min) = Storage volume (m^3) ÷ Flow rate (m^3/min)

To make sure that the actual detention time (and therefore, the Ct value) is not overestimated, it is important to use:

- the minimum volume in the storage;
- the maximum flow rate out of the storage.

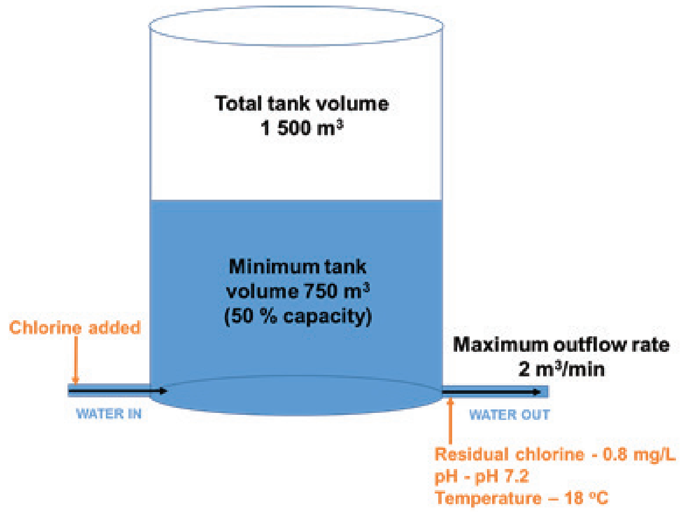
For example, a tank has a maximum capacity of 1 500 m^3, but the minimum operational level is 50% capacity (i.e. 750 m^3). If the maximum outflow-rate is 2 m^3/min (Figure TB 6), then using Eq. 2, the detention time may be calculated as follows:

$$\textbf{Detention time (min)} = \textbf{Minimum tank volume (m}^3\textbf{)} \div \textbf{Maximum flow rate (m}^3\textbf{/min)}$$

$$= 750\ m^3 \div 2\ m^3/min$$

$$= 375\ minutes$$

Figure TB 6. *Example tank parameters for calculating the contact time*



When measuring the residual chlorine concentration for Ct value calculation, it is important to measure it after the detention period (e.g. on the outlet of the storage; Figure TB 6), as this is the minimum residual chlorine concentration after the chlorine demand has been satisfied and disinfection has taken place.

For accurately determining the Ct value, it is also important to consider the potential for short-circuiting within the storage, that is, preferential water flow within the storage as a result of incomplete mixing. The presence of short-circuiting within a storage may imply that all of the water does not have the same detention time (i.e. some water passes through the storage more quickly, whereas some of the water passes through the tank more slowly). To improve mixing within the storage, and reduce the short-circuiting potential, special baffles are commonly incorporated into storage design. To account for short-circuiting within a storage, a baffling factor should be incorporated within the contact time calculations (Table TB 1). Baffling factors range from 0 (i.e. unbaffled) to 1 (i.e. perfect)[32].

32 United States Environmental Protection Agency (2003). Disinfection profiling and benchmarking (Appendix G).

Table TB 1. *Baffling factors for calculating detention times; for further explanation of the terms used in this table, alongside graphical representations of the different baffling conditions, please refer to the publication Disinfection profiling and benchmarking (adapted[28])*

Baffling condition	Description	Baffling factor
Unbaffled (mixed flow)	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities	0.1
Poor	Single or multiple unbaffled inlets and outlets, no intra-basin baffles	0.3
Average	Baffled inlet or outlet with some intra-basin baffles	0.5
Superior	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders	0.7
Perfect	Very high length to width ratio (pipeline flow), perforated inlet, outlet, and intra-basin baffles.	1.0

For this example, the tank has been rated with a baffling factor of 0.3 (i.e. poor baffling condition). To account for this in the detention time calculation, use the following formula:

Detention time (min) = [Min. tank volume (m^3) ÷ Max. flow rate (m^3/min)] x Baffling factor

= [750 m^3 ÷ 2 m^3/min] x 0.3

= 113 minutes

Using the above information, the actual Ct value may be calculated as follows:

Ct (min.mg/L) = Residual chlorine (mg/L) x Contact (or detention) time (min)

= 0.8 mg/L x 113 min

= 90 min.mg/L

Step 3) Compare the actual Ct value against the required Ct value

From above, the following is known:

Required Ct value (Step 1) = 88 min.mg/L

Actual Ct value (Step 2) = 90 min/mg/L

So, in this example, the required Ct value for these specific circumstances is being achieved in practice.

For situations where the minimum required Ct value is not being achieved within a storage at the water treatment plant, consideration of the detention time and residual chlorine concentration within the main water supply pipeline may also be accounted for in the calculation (i.e. the detention time within the pipe between the water treatment plant and prior to the first consumer)[33].

If the required Ct value is still not being achieved, remedial action is required to ensure that effective disinfection is occurring. The action required will depend on the specific situation, but may include:

Shorter-term actions

- optimizing (i.e. increasing) the chlorine dose to increase the actual Ct value (ensuring that maximum guideline values and aesthetic considerations for chlorine are taken into account);
- reducing the plant flow rate to increase the detention time (and thus, the Ct value); and
- optimize (i.e. lowering) the pH of the water to decrease the required Ct value (ensuring the pH of the water is maintained >pH 6.5 and consideration is given to any downstream water quality impacts associated with lower pH [e.g. corrosion potential]).

Longer-term actions

- improve mixing/baffling conditions within the tank;
- provide additional storage capacity (i.e. to increase detention time).

33 To calculate the detention time within a pipe before the first consumer, firstly the volume of the pipe must be calculated, using the following formula:

Volume of pipe = Radius^2 (m) x Length of the pipe to the first consumer (m) x 3.14

Pipeline flow has a baffling factor of 1 (Table TB 1), so no further consideration of the baffling factor is required. The detention time may then be determined as described in Step 2, dividing the volume of the pipe section between the water treatment plant and the first consumer by the flow rate.

Glossary of Terms

Aesthetic (in reference to drinking-water quality): Relates to the taste, odour or appearance of water.

Backflow: The unintentional flow of contaminated water in the reverse direction to normal drinking-water flow.

Baffles: Devices installed within a water storage to influence the flow of water within that system to improve mixing and increase the detention time.

Biofilm: Type of microbial slime, which develops through the dense growth of microbial communities in a complex matrix.

Chlorination: The process whereby chlorine is used as a disinfectant in drinking-water; also referred to as chlorine disinfection.

Chlorine decay: The decrease in chlorine concentration as water passes through a water supply system due to the reaction between chlorine and organic and/or inorganic materials.

Chlorine demand: The extent of reaction between chlorine and organic and/or inorganic material present in water that consumes chlorine and results in a decrease in the chlorine concentration.

Chlorine dose rate: The amount (or concentration) of chlorine added to drinking-water over a fixed period of time to achieve the required chlorine concentration.

Chlorine dose: The concentration of chlorine added to drinking-water; usually expressed in milligrams per litre (mg/L).

Chlorine reactive substances: Any organic and inorganic material that will react with and consume chlorine.

Chlorine: A chemical disinfectant.

Combined chlorine: The concentration of chlorine bound to nitrogen compounds (displays limited disinfection capacity).

Contact tank: A tank designed to provide adequate detention time for effective chlorine disinfection to occur.

Contact time: The time of contact between chlorine and water for disinfection to occur.

Control measure: The measures in place within a water supply system to prevent or eliminate a water safety hazard, or reduce it to an acceptable level.

Corrective actions: Timely action that may be taken to restore effective operation to a control measure once a critical limit has been exceeded.

Critical limit: The point at which a control measure is no longer deemed to be working effectively, and a potential water quality risk exists.

Cross connection: The unintentional connection between drinking-water pipes and non-drinking-water pipes (such as sewerage or recycled water pipes).

Cyst: A life stage of certain protozoa (e.g. *Cryptosporidium*) that is characterised by a type of durable shell for environmental survival outside of a host.

Dead-legs: A section of a water distribution network that experiences low- or no-flow.

Detention time: The amount of time it takes for water to pass through a system at a given flow rate.

Disinfectant: A chemical used for disinfection.

Disinfection: Chemical, physical or radiological processes that kill or inactivate microorganisms.

Distribution system: The network of pipes (and in some cases, intermediate treated water storages such as reservoirs or tanks) used to deliver treated water from the water treatment facility to the point of delivery for the consumer.

Dosed water: Water that has been dosed with chlorine.

Duty pump: A pump that is normally in-use.

Flow-paced (in reference to chlorine dose pumps): Pumps that automatically adjust the chlorine dose-rate to match the flow of water, for example, through a water treatment plant.

Grab sample: A form of sampling where a single, discrete, one-off sample is taken for analysis.

Illegal connections: The unauthorised connections to the drinking-water supply pipes; illegal connections are often sources of leakages, and may introduce backflow or cross connections due to poor quality work or a lack of understanding of plumping risks.

Injection point: The point where chlorine is added to drinking-water.

Inorganic material: Any material that is not derived from the wastes and remains of organisms, for example, metals or minerals.

Manual (in reference to chlorine dose pumps): Pumps that are set to dose to a fixed plant flow rate and do not automatically adjust the chlorine dose-rate to match flow rate changes.

Metering pump: Dosing pumps that deliver precise adjustable volumes of chlorine liquid over a specified time period.

Microorganisms: Microscopic organisms that are found within most environments on the earth, including water; examples include bacteria, viruses and protozoa.

On-line monitoring: A form of monitoring where samples are taken and analysed continuously to provide a near real-time data set.

Operational monitoring plan: A document which details all operational monitoring activities, critical limits and corrective actions.

Organic material: Material derived from the wastes and remains of organisms (such as plants and animals).

Over-dosing (in reference to chlorine dosing): The addition of too much chlorine.

Pathogen: A microorganism that may cause illness or disease.

pH: Units used to measure the acidity or alkalinity of water; the pH scale runs from pH 0 to pH 14, with pH 7 being neutral, $<$pH 7 being acidic and $>$pH 7 being alkaline (or basic).

Pre-chlorination: A pre-treatment stage where chlorine is added before water treatment; for example, may be employed to assist with the removal of minerals such as iron and manganese.

Primary chlorination: The addition of chlorine for disinfection of drinking-water; for primary chlorination, chlorine is generally added immediately after water treatment (e.g. after clarification and/or filtration).

Reagent: A chemical substance that is used in a water quality test.

Residual chlorine: The concentration of chlorine remaining that is free for residual disinfection after the chlorine demand has been satisfied.

Residual trim: Where an instrument continually measures the chlorine concentration in water and adjusts the chlorine dose rate accordingly.

Secondary chlorination: The addition of chlorine to boost the residual chlorine concentration within acceptable levels; generally occurs within the distribution system.

Short-circuiting: Preferential water flow within a system as a result of incomplete mixing.

Sludge: Undissolved inert material remaining after chlorine powder has been mixed with water to prepare a chlorine liquid solution.

Source water: Raw (untreated) water for drinking-water supplies; includes groundwater, rainwater and various types of surface water sources, including rivers, lakes, ponds, creeks, irrigation channels, seawater or constructed reservoirs.

Spore: A life stage of certain microorganisms (e.g. bacteria) that is characterised by a type of durable shell for environmental survival outside of a host.

Standby pump: A back-up pump, required when the duty pump fails.

Total chlorine: The concentration of chlorine remaining after the chlorine demand has been satisfied and disinfection has occurred; consists of residual and combined chlorine.

Turbidity: The opaque (or cloudy) appearance of water caused by the presence of organic and inorganic particles.

Under-dosing (in reference to chlorine dosing): The addition of too little chlorine for effective disinfection.

UV light: A particular wavelength of light that has the capacity to kill or inactivate microorganisms.

Vegetative cell: A cell that is actively growing and not producing spores.

Water age: A measure of how long it takes for water to flow from the water treatment facility to the point of delivery in the distribution network; water age is associated with water quality issues such as taste/odour and chlorine decay.

Water safety plan: A framework for assessing and managing water quality risk at all stages of a water supply system, from catchment to consumer.

Water supply system: Refers to all of the major stages in the supply of drinking-water, including the source (or catchment), raw water harvesting (and storage), treatment, distribution (including intermediate water storages) and household practices.

Waterborne disease: A disease that is spread by contaminated water (e.g. diarrhoea).

The WHO/AusAID (DFAT) Partnership for Water Quality and Health has been promoting Water Safety Plans (WSPs) in SEARO countries for more than 10 years. WSPs are designed to benefit all water users by ensuring improved water quality throughout a water supply system and are seen as a way of improving health and enhancing system sustainability.

One of the biggest challenges for sustainable implementation of WSPs and delivery of safe water, especially for smaller systems, is good chlorination practice.

WHO contracted a water treatment expert to help Bhutan and Timor Leste to improve their chlorination through the delivery of a tailored training programme and the development and implementation of supporting standard operating procedures. These are both countries with small urban water supplies being managed by small utilities with fairly limited capacity, so are representative of so many water suppliers across the region. This training and the SOPs were well-received in both countries and the SOPs are simple and clear but comprehensive so these are now published in response to a growing demand for supporting training materials and manuals for this technical area.

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