Guidelines for Ensuring Sustainable Effective Disinfection in Small Water Supply Systems

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GUIDELINES FOR ENSURING SUSTAINABLE EFFECTIVE DISINFECTION IN SMALL WATER SUPPLY SYSTEMS

by

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FOREWORD

These Guidelines have developed as part of WRC project K5/1391: Strategies to Ensure Sustainable Effective Disinfection in Small Municipal Water Distribution Systems. This project investigated the causes of poor microbial quality of treated water supplies in rural areas and strategies for ensuring effective sustainable disinfection. The Eastern Cape town of Alice, home of the University of Fort Hare where the research team was based, was used as a case study. The guidelines draw on the authors' experiences in Alice and in several other small towns in the Eastern Cape which have been visited as part of a new WRC Project Improving the Efficiency of Disinfection in Small Drinking Water Treatment Plants.

There are currently several other Guidelines on various aspects of water services provision available from the Water Research Commission, the Department of Water Affairs and Forestry and other government departments. This document is written primarily for drinking water treatment plant operators, supervisors and municipal officials in rural municipalities and focuses on issues relating to the microbial safety of water supplied to consumers. Several common operating and management problems that the authors have encountered are discussed.

In the authors' experience, there a general lack of understanding of what an acceptable quality of potable water is and what measures are required to operate treatment plants more efficiently. On the other hand, personnel who are directly involved in water treatment in rural areas are very interested in learning more about water treatment processes and how to improve the operation of their own plants. It is hoped that these guidelines will assist them in assessing the adequacy of their own facilities and operating procedures and identifying for themselves where improvements need to be made. In most cases, assistance from external organisations will be required to implement many of the recommendations made here but small municipalities will be able to take more advantage of technical assistance and training programmes if they already understand what needs to be achieved.

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INTRODUCTION

1.1 GENERAL CONSIDERATIONS

Of all the advances made possible through science and technology, the treatment and distribution of safe drinking water is truly one of the greatest. Abundant, clean water is essential for good public health. It has been increasingly recognized by world leaders that safe drinking water is a critical building block of sustainable development. **Disinfection**, a chemical process whose objective is to control disease-causing microorganisms by killing or inactivating them, is critically important in drinking water treatment.

The purpose of a water supply is to deliver to each consumer safe drinking water that is adequate in quantity and acceptable in terms of taste, odour and appearance. Safe water can be defined as water that does not contain harmful chemical substances or microorganisms in concentrations that could cause illness in any form. Safe drinking water is yet to be achieved in many rural and peri-urban communities including many of those which have a treated water supply.

Small water treatment plants are generally installed in areas which are not well serviced and typically fall outside the confines of urban areas. They include systems which chlorinate borehole and spring water, small treatment systems for rural communities, treatment plants operated by small municipalities and treatment plants for establishments such as rural hospitals, schools, clinics, forestry stations, etc. Most of these applications treat less than 2.5 Ml/d, although plants of up to 25 Ml/d may sometimes also fall into this category (Barkley, 2002).

The South African vision for the water services sector in 2002 was stipulated as follows (DWAF, 2002a):

i) All people living in South Africa should have access to an **adequate, safe and affordable supply of potable water**, live in a healthy environment with safe and acceptable sanitation, be able to engage in sustainable livelihoods, be economically empowered and be able to participate actively in a vigorous and healthy civil society.
ii) All people should be **knowledgeable** about healthy living practices and use water wisely.
iii) There should be adequate water available for economic development.
iv) Water supply and sanitation services should be **sustainable** and be provided by **efficient and effective service providers** who are **accountable and responsive** to the customers they serve.

The above are expected to give the outcome of a healthy population, a healthy environment and economic growth that improves the quality of life and livelihoods of the whole population, especially of the poorest (DWAF, 2002a). The 1994 White Paper (DWAF, 1994) also made commitments to the effective monitoring of the sector performance to ensure that universal access to basic services is progressively achieved, financial resources are used efficiently and effectively and that water service institutions are accountable to local communities and standards are maintained.

The provision of adequate water services was one of the more difficult and pressing challenges inherited by the new South Africa. Prior to the change of government in 1994, an estimated 30 - 40% of South Africa's population (14 -18 million people) was without adequate water supply services and some 21 million people were without adequate sanitation (Van der Merwe, 2003). As of 2004, some 10 million additional people have been supplied with drinking water, thereby reducing the backlog in 2004 to some 4 million (Kasrils, 2004). Although great strides have been made in the effort to provide safe and clean water to all South Africans, studies have shown that in small rural towns and small remote villages with adequate water supply services, the drinking water quality is generally poor and often not fit for human consumption at the point of use (Pearson and Idema, 1998; Swartz, 2000; Momba and Kaleni, 2002; Momba *et al.*, 2004). Therefore water supplied by these plants is adding to the number of deaths caused by waterborne diseases.

> Diseases related to contamination of drinking water constitute a major burden on human health. Interventions to improve the quality of drinking water provide significant benefit to health (WHO, 2004).

The key issues contributing to poor performance of small potable water supply systems include the installation of inappropriate treatment systems, a lack of knowledge of basic treatment principles, the inadequate maintenance of equipment, financial constraints and a lack of community involvement during the conception of the plants (Swartz, 2000, Momba *et al.*, 2004). Other contributing factors include:

- Some Water Service Authorities are not familiar with the minimum requirements for the quality of potable water as defined under South African law (Mackintosh *et al.*, 2004a).
- There is **inadequate monitoring** of water quality and inadequate intervention when monitoring indicates poor water quality.
- There is a **lack of technical and managerial** capacity in many of the newly established municipalities.

- The focus of development activities in the water sector has understandably been on improving **access** to water with insufficient attention on the **quality** of water produced.
- There is a **lack of public awareness** about water quality, health and hygiene issues in rural communities. Consequently these communities usually do not exert pressure on municipalities to improve the quality of their potable water.

The key to ensuring clean, safe and reliable drinking water is to implement **multiple barriers**, which control microbiological pathogens, and chemical contaminants that may enter the water supply system. This includes adopting sound management practices and continuously reviewing both the state of the water treatment and distribution infrastructure and the quality of the water produced. Application of a disinfection barrier is a critical component of primary treatment of drinking water (LeChevallier, 1998). Disinfection is important because the turbidity removal by sedimentation and filtration does not remove all microbial pathogens from water. The **disinfectant residual** in the drinking water distribution system is also one of the key factors controlling the microbial quality of water, preventing bacterial proliferation in the water phase (regrowth) and limiting viability of bacteria released from pipe wall biofilms. The disinfection of small water supplies in South African rural areas is almost universally accomplished by the use of chlorine. The ability of chlorine to kill pathogenic microorganisms and to maintain a residual in the distribution system, as well as its availability at moderate cost, make it well suited for small water supplies (LeChevallier *et al*., 1987).

It has been observed that the chlorine decay is influenced by the **chlorine demand** of the water and the reactions with deposits such as organic and inorganic sediments. It is therefore important for operators to understand and compensate for the way disinfectant decreases in the distribution system. Although chlorine is used to reduce bacterial numbers, the mere use of chlorine does not guarantee the removal microbiological pathogens; it is essential to apply the correct dose at the correct frequency.

1.2 LESSONS LEARNED FROM THE ALICE WATER TREATMENT PLANT CASE STUDY

These guidelines have been developed as an end product of Water Research Commission Project K5/1391 which investigated the factors affecting disinfection efficiency in rural water treatment plants using the Alice water treatment plant in the Eastern Cape as a case study. This research was undertaken by the microbiology group at the University of Fort Hare in collaboration with Umngeni Water and Pollution Research Group at the former University of Natal. This section briefly outlines the major lessons learned from the Alice experience. While the situation at each treatment plant is slightly different, the problems faced by the Alice water treatment plant are fairly typical of rural water services providers.

1.2.1 Dosing failures

During, the study period one of the major reasons for poor water quality in Alice was found to be faulty dosing equipment and lack of functioning stand-by equipment. Furthermore, it typically took days to months to get faulty equipment repaired or replaced. A second major cause of dosing failures was that treatment chemicals often ran out before new supplies were delivered. As result, the plant sometimes operated for days without coagulant and/or chlorine. Researchers had to assist municipal staff in finding companies who could make the necessary repairs to their equipment. At the time of the study, municipal officials did not regard dosing failures as an emergency and made no attempt to warn the community that the safety of their drinking water was at risk.

In order to avoid these sorts of problems, the following must be taken into account:

- First it is important for both operators and municipal officials to realise that **disruptions in chemical dosing are unacceptable**.
- Treatment plants need to have **standby dosing systems** for both coagulants and disinfectants and they need to be kept in good working order.
- **Maintenance** of critical equipment such as dosing systems must be considered a top priority. If the skills to repair specialised equipment do not exist in-house, then municipalities need to have plans for getting repairs or replacements as quickly as possible when required. These plans should be developed before a problem occurs to avoid unnecessary delays.
- Municipalities must pay greater attention to getting treatment chemicals to all of their treatment plants before they run out.

1.2.2 Filter problems

The Alice water treatment plant had installed three valveless filters to replace the existing conventional filters. The operators and municipal officials were initially unaware of how these filters worked or that the backwash design is inherently limited in its effectiveness. After 2 to 3 years of operation, the filters were no longer able to backwash properly and the state of the filter beds had deteriorated. Consequently, overall turbidity removal at the plant was poor and disinfection also suffered. After the filter media was replaced and the backwash pipes cleaned out, filter performance was restored and the plant was able to produce filtered water turbidities of less than 1 NTU.

Municipalities need to realise that the **filter media in rapid filters tends to deteriorate over time** and backwash flow rates can also decline as a result of blocked pipes. Filter media will generally have to be replaced every 1 to 2 years and all pipes and valves should be inspected and cleaned at the same time. Only companies with experience in filter maintenance and refurbishment should be used.

1.2.3 Coagulant dosing

The Alice water treatment plant could make substantial savings on chemical costs if coagulant **dose optimisation** was conducted. The cost savings would easily cover the purchase of the **jar test equipment** required for dose optimisation. Coagulant dose optimisation could also lower the **chlorine demand** of the filtered water and hence the cost of disinfection. This is probably also true for many other small treatment plants.

1.2.4 Flow measurement

It is critically important that operators are able to measure the plant flow rate in order to make appropriate dose adjustments. This was particularly true at AWTP where a lack of balancing capacity meant that operators had to make frequent adjustments to the flow rate. The plant's only flow meter was located in a 2 m deep sump and was submerged in water. Consequently, it was difficult and dangerous for the operators to read. A **V notch weir** was located close to the raw water inlet; however, this was also difficult to read due to the turbulence of the flow at that point.

It is very important that flow meters are installed in such a way that operators can easily access and read them at least once a day. Operators should also be trained to measure flow using V-notch weirs at plants which have them.

1.2.5 Clarifying roles and responsibilities

There appeared to be a lack of clarity about who was responsible for the management and some aspects of the operation of the plant. This included a number of critical activities such as ensuring chemicals were delivered on time, adjusting coagulant doses and repairing equipment. As a result many evident problems were left unattended to for long periods of time. Furthermore, municipal management did not act when plant performance data collected by the operators clearly indicated the plant had major problems.

There needs to be a **clear framework clarifying roles and responsibilities** for all municipal workers and officials who are involved in ensuring the safety of drinking water in small water treatment systems. Equally important is the need for the municipal management structures at all levels to support this framework by providing adequate resources to fulfil these various roles.

1.2.6 Operator training

During the course of the Alice water treatment plant investigation, the operators received on-site training from both the Municipal Mentoring Programme (MMP) and the University of Fort Hare research team. The operators responded very positively to the training and made significant advances in both skills and confidence over the study period. Some of the key lessons emerging from the interaction with the operators were as follows:

- The operators wanted their relationship with the research team to be one of **mutual co-operation and support**. While the project team had a superior theoretical knowledge about water treatment in general, the operators had years of practical experience of the plant and its problems.
- The operators were able to grasp the conceptual aspects of the water treatment process fairly easily but struggled with the **quantitative aspects**. Follow up training sessions on **dose adjustment and optimisation** were critical and special attention was paid to the concept of **chlorine demand**.
- The operators wanted training materials, instructions and safety information translated into their own languages. They also preferred training materials and procedures to be illustrated.

1.2.7 Communication between operating staff and management

Operators complained about a lack communication with the municipal management. They felt that their concerns were ignored and they were usually blamed for poor plant performance even if it resulted from factors they had no control over. Operators play a critical role in protecting a community's drinking water supply, but they generally occupy a very lowly position in the municipal hierarchy. It is important that municipal managements understand that they and not the operators are ultimately held responsible for the quality of the drinking water. Consequently, it is most important that management works to establish a more co-operative and supportive relationship with operating staff.

1.2.8 Need for public education on water quality issues

During the course of the Alice case study, the project team came to appreciate that **the level of awareness about water quality issues among the local population is very low**. This included the relatively educated University of Fort Hare community. In this context, the lack of priority placed on water quality issues by the local municipality was quite understandable. The municipality, like the local community, was simply more interested in increased access to water services and low cost housing. The connection between the prevalence of enteric diseases and water quality was not appreciated. **Education of both the public and municipal officials** on health issues related to water quality is essential if municipalities are to see merit in expending resources to improve the microbial safety of their water supplies.

1.2.9 Role of partnerships

Over the course of the study, interaction between the operating staff and both the Municipal Mentoring Programme and the University of Fort Hare research team resulted first in a substantial improvement in operator skills and finally an improvement in treated water quality after the many equipment problems were resolved. In the process, an ongoing relationship between the AWTP operating staff and the microbiology group at UFH has been established. This experience has shown that partnerships between municipalities, capacity building organisations and local tertiary organisations can yield results but a **long-term commitment** is required to ensure improvements can be sustained.

Since the inception of the Alice project, there have been several major developments in the water services sector in the Eastern Cape including the implementation of the Department of Water Affairs **Masibambane** plan and the introduction of **water quality monitoring programmes** by several water services authorities. As a result, municipalities are becoming more aware of water quality issues. However, most still have long way to go to achieve what can be considered an acceptable level of performance. These guidelines build on the Alice experience taking into account current developments as well some additional issues encountered at other small treatment works in the province.

1.3 TARGET AUDIENCE, OBJECTIVES AND SCOPE OF THE GUIDELINES

1.3.1 Target Audience

These guidelines are primary directed at municipal officials, water treatment plant supervisors and operators outside the major urban centres, as well as groups and institutions trying to assist them in improving their drinking water quality.

1.3.2 Objectives

The objectives of the guidelines are first to help municipalities to understand their legal obligations with regard to the quality of water that they are supplying to consumers and then to explain how specifically the microbial quality of the water can be improved.

1.3.3 Scope

The focus of these guidelines is on improving the **microbial quality** of potable water in rural municipalities since this has the most immediate impact on consumers' health. Several technical and management issues relating to the **treatment** and **distribution** of water are discussed as well as the role of surveillance and co-operative partnerships in improving water quality. The discussion of technical issues is limited to **conventional treatment** (coagulation, flocculation, sedimentation, filtration, disinfection and stabilisation) only. Community education in water related health and hygiene matters is not discussed but the importance of two-way **communication between consumers and water services institutions** is emphasized.

The guidelines specify a minimum set of practices that water service authorities and providers need to put in place to ensure water supplied to consumers meets the compulsory national standards as soon as possible. However, they should be seen only the first step and water service institutions need to continue to work towards all of the goals articulated in the *National Framework* (DWAF, 2003), particularly the integrated sustainable management of water resources, in order to ensure an adequate quantity and quality of potable water.

1.4 STRUCTURE OF THE GUIDELINES

Section 2 discusses the **legal aspects** of the provision of safe drinking water. Both the **regulations** relating to drinking water quality and the **responsibilities of the various role-players** in the water sector are discussed.

Section 3 discusses **technical aspects** of the production of safe drinking water including the operation of treatment plants and distribution systems and the need for adequate process control measures. The focus is on specific problems and deficiencies which typically plague the operation of small treatment plants in rural areas.

Getting the technical issues right requires **effective management**. **Section 4** describes several management issues which require attention in small municipalities providing water services. These include defining responsibilities, improving communication, developing effective partnerships and capacity building, surveillance and quality control.

Section 5 provides a summary and overview of **strategies** for ensuring the sustainable production of microbiologically safe drinking water.

1.5 IMPORTANT SOURCES OF FREE INFORMATION

These guidelines make frequent reference to several other documents and guidelines published by the Department of Water Affairs and Forestry (DWAF) and the South African Water Research Commission (WRC). These include

- *Quality of Domestic Water Supplies*
    - *Volume 1: Assessment Guide*
    - *Volume 2: Sampling Guide*
    - *Volume 3: Analysis Guide*
    - *Volume 4: Treatment Guide*
    - *Volume 5: Management Guide*
- *The South African Water Quality Guidelines*

The above publications can be downloaded at http://www.dwaf.gov.za/IWQS/report.htm. Several important documents on water services regulation and policy can also be downloaded from http://www.dwaf.gov.za/Documents/ from the **Government Notices: Related to Water Services**, **Other: Water Services** and **Water-Related Legislation** sections. These include

- *Water Services Act - 1997 (No. 108 of 1997)*
- *Regulations Relating to Compulsory National Standards and Measures to Conserve Water*
- *Strategic Framework for Water Services* (Previously called Draft White Paper on Water Services)
- *Guidelines for Compulsory National Standards and Norms and Standards for Water Services Tariffs*

The internet addresses of all these publications are given in the References section. In addition, anyone in South Africa can request free copies of most WRC publications. These include research reports on many of the technologies currently used in rural treatment plants including many not discussed in these guidelines. Unfortunately, many of the municipal personnel involved in water supply are not aware that these resources exist or do not know how to access them. A list of WRC publications can be found on the WRC web page: http://www.wrc.org.za. Click on the **publications** link. Information for ordering publications is also provided on the website or can be obtained by calling 012-330-0340 or faxing 012-331-2565.

1.6 DEFINITIONS, TERMINOLOGY AND ACRONYMS

Biofilms: coatings of living bacteria on the walls of pipes, tanks, reservoirs, clarifiers and filters.

Calcium carbonate precipitation potentional (CCPP): the amount of calcium carbonate which can be precipitated from water (in mg/L).

Coagulant: a chemical added to raw water to produce floc. Sometimes also referred to as a flocculant.

DWAF: Department of Water Affairs and Forestry.

Distribution system: this refers to the network of pipes, storage reservoirs and pumps between the treatment plant and the consumer's tap.

Filter media: sand or other granular material used in filters.

Finished water: finished water refers to the water leaving the on-site storage reservoir or chlorine contact chamber and entering the distribution system.

Free chlorine: the sum of hypochlorous acid and hypochlorite ions in water (in mg/L).

Free chlorine residual: the amount of free chlorine remaining in water after a 30 minute contact time.

Organics/organic material: material or chemical compounds of plant, animal or bacterial origin.

Pathogens: microorganisms which cause diseases.

Point of delivery: this refers to the tap at which water is collected. It may be a tap in a building or private residence, a yard tap or a public stand pipe. It may not be the same as the **point of use**. For example, consumers or water vendors may collect water at public standpipe and then use it somewhere else. The water service provider is responsible for the quality of the water up to the point of delivery only.

Surface water: water resources which flow above the ground (rivers, lakes, dams) as opposed to below the ground (groundwater).

Solubility: the tendency of a chemical to dissolve in water.

Water services institutions: institutions involved in the provision of water services.

Water treatment: in this document, water treatment refers to the treatment of raw water to produce drinking water.

WSA: Water Services Authority.

WSP: Water Services Provider.

WHO: World Health Organisation.

2

REGULATORY ISSUES

This section discusses the legal requirements for the safety of drinking water in terms of the Constitution and the 1997 Water Service Act. Section 2.1 discusses the responsibility of the water service and authorities to provide consumers with an adequate **quality** of water while Sections 2.2 and 2.3 discuss the **specifications** for drinking water quality which have to be met (Compulsory National Standards). Section 2.4 discusses the responsibility of Provincial and National government to monitor the performance of Water Service Authorities with respect to drinking water quality and to support efforts to comply with the compulsory national standards.

2.1 RESPONSIBILITY FOR THE PROVISION OF SAFE DRINKING WATER

The Constitution of South Africa (1996) defines access to safe drinking water as a basic human right. The responsibility for providing access to water services (water and sanitation) is assigned to local government while national and provincial government are tasked with supporting, monitoring and regulating local government in the performance of its constitutionally mandated functions (Mackintosh *et al*., 2004a).

The Water Services Act (1997) and *Strategic Framework for Water Services* (DWAF, 2003) define various types of institutions which are responsible for providing water services.

- A **Water Service Authority** (WSA) is a municipality which has executive authority to supply water services to its area of jurisdiction in terms of the *Municipal Structures Act* (1998) or the ministerial authorisations made in terms of this Act (DWAF, 2003). According to the *Municipal Structures Amendment Act* (2000), the role of WSA is usually assigned to **District Municipalities**. The responsibilities of WSAs include:
    - Progressively ensuring access to basic water services to all people living under their jurisdiction.
    - Making and regulating contracts for the provision of water services with water service providers (WSPs) in their areas of jurisdiction. Regulating WSPs **includes** monitoring their performance in terms of producing water of a **quality** which conforms to **compulsory national standards** (discussed in Section 2.2).
    - Ensuring adequate investments are made in water services infrastructure, including maintenance, repair and replacement of equipment when necessary (Section 4.2 in *Strategic Framework for Water Services*, DWAF, 2003).

District Municipalities, whether they are WSAs or not, have primary responsibility for health and hygiene education related to water and sanitation services (Section 3.6.4 in *Strategic Framework for Water Services*, DWAF, 2003).

- A Water Service Provider (WSP) is an organisation which assumes **operational responsibility** for the provision of water services to consumers or other water service providers. The role of water service provider is typically assigned to **local municipalities** but in some areas, this function is performed by **Water Boards**. In some cases, Water Service Authorities may also act as Water Service Providers. Specifically, the Engineering or Water Services Department of the WSA is assigned the role of WSP. However, since WSAs are required to regulate WSPs it is preferable for them to be separate institutions in order to avoid conflicts of interest. When a WSA is also a WSP, the Engineering Services Department usually assumes the role of WSP (DWAF, 2003).

Responsibility for the safety of water supplied to consumers is therefore shared by both the WSAs and the WSPs: the WSPs are required to provide water of a safe quality while the WSAs must ensure that they do so through monitoring and regulation (by-laws). Section 2.2 discusses the legal requirements for monitoring the safety of drinking water while Section 3 provides guidance on operational issues which affect the microbial quality of the water. Both types of water institutions must work together to ensure that water treatment works, storage reservoirs and distribution networks are properly maintained and have adequate resources and appropriately trained personnel to ensure the efficient provision of safe drinking water.

> **Water Service Providers** are responsible for the provision of safe drinking water while **Water Service Authorities** are responsible for monitoring and regulating the performance of the Water Service Providers.

2.2 COMPULSORY NATIONAL STANDARDS FOR POTABLE WATER

According to Section 9 (l) of the 1997 Water Services Act, the Minister of Water Affairs and Forestry may introduce compulsory national standards for various aspects of water services delivery. Regulations relating to compulsory national standards for **potable water quality** were published in the *Government Gazette, Vol. 432 No. 22355, 8 June 2001*. Guidance on the interpretation and implementation of these regulations is provided in *Guidelines for Compulsory National Standards and Norms and Standards for Water Services Tariffs* (DWAF, 2002b). The regulations require that water supplied by water service providers which is intended for drinking or domestic purposes must be of a quality consistent with **SABS 241** (Specifications for Drinking Water, South African Bureau of Standards), as may be amended from time to time. In order to ensure that these standards are met, the regulations also specifically require WSAs to **monitor** and **report** on the quality of water produced. Furthermore, the regulations specify the **steps which must be taken** if quality of water does not meet the required standards. The relevant regulations state the following:

Sub-regulation 5.(1)

Within two years of the promulgation of these regulations (i.e. by June 2003) every WSA must have developed a programme for sampling the quality of potable water provided to consumers in its area of jurisdiction.

Sub-regulation 5.(2)

The sampling programme must specify the sampling points, frequency of sampling and for which substances and determinants the samples will be tested.

Sub-regulation 5.(3)

Water services institutions must compare results from the sampling programme with ***SABS 241: Specifications for Drinking Water*** or the ***South African Water Quality Guidelines*** published by DWAF.

Sub-regulation 5. (4)

Should the comparison of the results as contemplated in sub-regulation (3) indicate that the water supplied poses a health risk to consumers, the water services institution must inform the Director-General of the Department of Water Affairs and Forestry and the head of the relevant Provincial Department of Health and **it must take steps to inform its consumers –**

a) that the quality of the water that it supplies **poses a health risk;**
b) of the reasons for the health risk;
c) of any **precautions to be taken by the consumers**; and
d) of the time frame, if any, within which it may be expected that water of a safe quality will be provided.

With respect to sub-regulation 5. (3), *SABS 241* (SABS, 2001) provides specific allowed ranges of values for regulated contaminants while the *South African Water Quality Guidelines*

(DWAF, only discuss the health affects associated with different levels of contaminants. The revised definition of potable water (Annexure 3 of the *Strategic Framework for Water Services*, DWAF, 2003) refers only to SABS 241, i.e. water quality samples are required to be compared to these standards only. However, the *Water Quality Guidelines* provide the rationale behind the standards so personnel involved in treatment and water quality issues should be familiar with its contents.

SABS-241 can be purchased from the South African Bureau of Standards (Pretoria South Africa) while the *Water Quality Guidelines* (DWAF, 1996) can be downloaded free of charge from the DWAF website. Another DWAF publication *Quality of Domestic Water Supplies Volume 1: Assessment Guide* (DWAF *et al*., 1998) provides water quality guidelines which closely correspond to *SABS –241*. See Section 1.5 for information on how to obtain these publications. Note that all three of these publications will be updated from time to time and Water Service Institutions need to keep up to date with any changes introduced.

Where local government structures lack the resources to carry out the required monitoring, co-operative government requirements specify that Provincial and National Government must ensure that monitoring takes place (Mackintosh, 2004a).

- Each Water Service Authority must implement a programme for monitoring the quality of drinking water provided to consumers.
- Compulsory national standards for the quality of the water provided are defined in **SABS-241**.
- If water testing indicates that the quality of water poses a health risk to consumers then **both** the authorities listed in Sub-regulation 5.(4) and the affected consumers must be informed immediately

If the new regulations relating to the compulsory national standards are contravened, the Water Services Authority (District or Local Municipal council) will be held accountable (Mackintosh *et al.*, 2004b). If the responsibility for water services has been delegated to a specific official such as a Chief Executive Officer or City Engineer/Town Engineer/Technical Director, he becomes co-responsible. If the responsibility is delegated, and the designated technical officer/Town Engineer cannot perform his duties in accordance with the regulation, he is obliged to inform the Water Services Authority of the situation and the possible repercussions. If he neglects to inform council, he becomes liable. If he does notify council, the onus is on council to make available sufficient resources to enable the technical officer to implement the necessary, to conform to the regulation.

The *Water Services Act* in its current form does **not** criminalise non-compliance with national standards (Mackintosh et al., 2004a), however, it does make it an offence for any person to "fail or refuse to give information or to give false and misleading information when required to give information in terms of this Act". Therefore, as long as Water Service Authorities comply with their obligations under Sub-Regulation 5.(4) they minimise their risk of incurring penalties under the this Act.

2.3 POTABLE WATER QUALITY AND MONITORING REQUIREMENTS AS DEFINED BY SABS-241

In all, *SABS 241-2001* specifies compulsory standards for 36 physical, chemical and organoleptic parameters and 8 microbial contaminants. However, it is accepted that routine analysis for the full range of contaminants specified will often be prohibitively expensive, especially for smaller municipalities. Therefore, the following minimum list of parameters for monitoring of ongoing operation efficiency: **conductivity or dissolved solids, pH, turbidity, faecal coliforms or E. coli** and **residuals of treatment chemicals and disinfectants** (for example, if the coagulant used contains aluminium, the aluminium content of the finished water should be measured).

In addition, the following 6 contaminants should be monitored in the **raw water** to determine its continued acceptability as a raw water source: **fluoride as F^-, nitrate and nitrite as N, heterotrophic plate count, iron as Fe, manganese as Mn** and **arsenic as As**. The acceptability of the raw water source is assessed in terms of being able to meet at least the minimum allowable standards (maximum contaminant levels) in the treated water. For guidance on assessing the suitability of raw water sources, see *Quality of Domestic Water Supplies Volume 1: Assessment Guide* (DWAF *et al.*, 1998). Some water treatment plants have the option of switching between multiple raw water sources depending on water quality. Others may need to consider developing alternate raw water sources and/or implementing environmental

> Minimum set of water quality parameters to monitored:
>
> *Finished Water*
>
> - Conductivity or TDS
> - pH
> - turbidity
> - faecal coliforms or *E.Coli*
> - treatment chemical residuals (Al or Fe and free chlorine)
>
> *Raw Water*
>
> In addition to the above
>
> - fluoride
> - nitrate and nitrite
> - heterotrophic plate counts
> - iron

control measures to improve the quality of their current source.

Note that all water treatment plants and all water service providers should at the very minimum have their own equipment to monitor **turbidity, pH** and **free chlorine residual** as part as their routine operation (See Section 3.4). The other determinants will often be measured at off-site laboratories usually by external organisations.

SABS-241- 2001 specifies three different classes of water in terms of physical, microbial and chemical quality:

- Class 0: an ideal standard largely based on first world standards (pertaining to the European Union and United States of America).
- Class I: water that is known to be acceptable for a whole lifetime of consumption.
- Class II: water that is considered to be the minimum allowable quality for short-term consumption (usual and continuous daily consumption for periods not exceeding one year).

South African water service institutions are required to aim to consistently achieve at least Class I quality drinking water with respect to **physical**, **chemical** and **organoleptic** parameters. The inclusion of the Class II category in the standards is an acknowledgement that at present and for the foreseeable future many WSPs will not be able consistently produce and distribute Class I quality water and that labelling municipal piped water as ”unfit for human consumption” if it only marginally fails to meet Class I standards may drive consumers to potentially worse quality and possibly illegal sources of drinking water (Mackintosh *et al*., 2004a). The standards specify the maximum allowable time periods for Class II levels of each contaminant. Table 1 lists the standards for the minimum suggested set of physical and chemical parameters.

SABS 241 – 2001 does not specify upper or lower limits for the **free chlorine residual**, however, with the exception of plants which do not use chlorine disinfectants, this is a parameter which **must** be monitored on a daily basis. Guidelines for free chlorine residuals are discussed in Section 3.2.2.

The requirements regarding the **microbial** quality of the water are more complicated. The microbial standards are reproduced in Table 2. For any given year, at least 95 % of samples must not exceed the value given in Column 3 (Class 0), no more than 4 % may be greater than Column 3 but less than Column 4 (Class I), and no more than 1 % may be greater than Column 4 but less than Column 5 (Class II). If any sample exceeds the value in Column 5 then immediate re-sampling and appropriate remedial reaction is required until the water quality complies at least with Column 5.

TABLE 1 *SABS 241 – 2001*: PHYSICAL, ORGANOLEPTIC AND CHEMICAL REQUIREMENTS					
Determinant	Units	Upper limit and Ranges			Max. allowable period for consumption of Class II water
		Class 0 (Ideal)	Class I (Acceptable)	Class II (Max. allowable)	
Conductivity at 25 ^{0}C	mS/m	< 70	70 - 150	150 - 370	7 years
pH at 25 ^{0}C	pH units	6.0-9.0	5.0 – 9.5	4.0 – 10.0	No primary health effect – extreme pH's can cause structural problems in the distribution system
Turbidity	NTU	< 0.1	0.1 - 1	1 - 10	No limit but high turbidities indicate treatment inefficiencies and risks associated with pathogens
Fluoride as F^-	mg/L	< 0.7	0.7 – 1.0	1.0 – 1.5	1 year
Nitrites and nitrates as N*	mg/L	< 6.0	6.0 – 10.0	10.0 – 20.0	7 years
Iron as Fe^-	µg/L **	< 10	10 - 200	200 - 2000	7 years based on aesthetic rather than health effects
Manganese as Mn	µg/L **	< 50	50 - 100	100 - 1000	7 years
Arsenic as As	µg/L **	< 10	10 - 50	50 - 200	3 months
Aluminium as Al	µg/L **	< 150	150 - 300	300 - 500	1 year

* Note that nitrates are a component of commercial fertilisers and therefore may be a problem in agricultural areas

** 1 µg/L = 0.001 mg/L and 1000 µg/L = 1 mg/L

TABLE 2 *SABS 241 – 2001*: MICROBIAL REQUIREMENTS				
(1)	(2)	(3)	(4)	(5)
Determinant	Units	Allowable compliance contribution		
		95 % min.	4 % max.	1 % max.
		Upper Limits		
Heterotrophic Plate Count	counts/mL	100	1000	10000
Total Coliform	counts/100 mL	Not detected	10	100
Faecal coliform	counts/100 mL	Not detected	1	10
Somatic coliphages	counts/10 L	Not detected	1	10
Enteric viruses	counts/100 L	Not detected	1	10
Protozoan parasites	counts/100 L	Not detected	1	10

The requirements for compliance with the microbial standards are stricter than for the chemical and physical requirements because the chemical contaminants typically found in drinking water generally only have significant adverse affects after long-term exposure, whereas poor microbial quality poses an immediate health risk to consumers.

Water services providers which are unable to meet Class I standards are required to take action to improve the quality of their treated water. Water that fails to meet Class II standards, in particular with regard to bacteriological standards is considered unfit for human consumption and urgent action is required including notification of the authorities and consumers as specified Sub-Regulation 5.(4) discussed previously.

> Sampling and analysis for regulatory compliance must be carried out by properly trained personnel using approved techniques Guidance on sampling and analysis techniques are provided *SABS ISO 5667* and Volumes 2 and 3 of *Quality of Domestic Water Supplies* (DWAF *et al.*, 2002a and b).

It is important that all sampling and analysis for regulatory compliance is carried out by properly trained personnel using approved techniques Guidance on sampling techniques and the design of sampling programmes is provide in *SABS ISO 5667*-1 (SABS, 1980) which can be purchased form the South African Bureau of Standards and. *Quality of Domestic Water Supplies Volume 2: Sampling Guide* (DWAF *et al.*, 2002a) Guidance on sample analysis can be found in *Quality of Domestic Water Supplies Volume 3: Analysis Guide* (DWAF *et* *al.*, 2002b). Both DWAF publications can be downloaded free from the DWAF website or ordered from the Water Research Commission (See Section 1.5).

The number of samples that should be collected for monitoring purposes depends on a wide range of factors including climatic (weather) conditions, human and industrial activities, volume of water treated and distributed, area covered by the reticulation system and the capabilities of the analytical facility (SABS, 2001). These all need to be taken into consideration in drawing up an appropriate sampling plan. The minimum suggested frequency of sampling based on population served is given in Table 3.

TABLE 3

MINIMUM SUGGESTED SAMPLING FREQUENCY (*SABS 241-2001*)

Population served	Minimum number of samples per month*
More than 100 000	10 per 100 0000
25 001 – 100 000	10
10 001 – 25 000	3
2 500 – 10 000	2
Less than 2 500	1

* Sampling should be more frequent during rainy season

EXAMPLES

1) A WSA collects 36 samples from consumers taps in a given supply area over the course of one year. The results of the faecal coliforms analysis are as follows:

- Number of samples with 0 Faecal Colifoms = 35 samples = 97 %
- Number of samples with 1 Faecal Coliform/100 mL = 1 sample = 3 %
- Number of samples with > 1 Faecal Colifomr/100 mL = 0

Based on these results, the water in this supply area complies with the compulsory national standards for microbial quality of potable water.

2) A different WSA collects 36 samples from a similar town as in example 1). This time, the results are as follows:

- Number of samples with 0 Faecal Colifoms = 34 samples = 94 %
- Number of samples with 1 Faecal Coliform/100 mL = 1 sample = 3 %
- Number of samples with > 1 Faecal Colifomr/100 mL = 1 sample = 3 % (actual result is 3 Faecal Coliforms/100 mL)

According to these results, the water in this supply zone technically fails to meet the Compulsory National Standards. However, the failure is marginal. Part of the problem is that if so few samples collected, if even one falls in column 5, then the results overall fail to comply with the standards. One solution may be to increase the number of samples collected to at least 100 per year. The WSA and WSP should also look for possible reasons for the one bad sample e.g. heavy rainfalls a few days earlier, temporary disruption in dosing, a pipeline leak close to where the sample was taken.

3) In a different municipality, 50 samples are collected over a one year period. The results are as follows:
   - Number of samples with 0 Faecal Colifoms = 5 samples = 10 %
   - Number of samples with 1 Faecal Coliform/100 mL = 3 sample s= 6 %
   - Number of samples with > 1 Faecal Colifomr/100 mL = 42 samples = 84 %

In this supply zone, the water fails to meet microbial standards by a wide margin and poses a significant risk to consumers' health. Urgent action is required to determine the cause of the failure and to correct the problem.

4) If any one sample contains more than 10 Faecal Coliforms/100 mL then sub-regulation 5.(4) applies.

2.4 REQUIREMENTS FOR NATIONAL AND PROVINCIAL GOVERNMENT TO MONITOR AND SUPPORT LOCAL GOVERNMENT

As the national **regulatory** authority, DWAF has the responsibility of ensuring that water services institutions producing water for drinking and domestic purposes comply with the Compulsory National Standards. However, co-operative governance principles as well as the realities of the South African situation require both national and provincial government to play a **supportive** role (capacity building) in assisting local governments to achieve progressive improvements in their performance. Therefore an appropriate balance has to be struck between the regulatory and supportive functions in order to best serve the interests of the public in the long term. Key issues are the **openness** of municipalities in admitting and reporting problems, their **willingness** to make necessary corrections to their operations and their **capacity** to do so.

Section 62 of the **Water Services Act** requires the Minister of Water Affairs to monitor **every water services institution** in order to ensure compliance with prescribed national standards. This is primarily done through a **water services audit** which each Water Services Authority is required to submit as part of its annual report on the implementation of its water services development plan (Sub-regulation 10 under *Regulations Relating to Compulsory National Standards and Measures to Conserve Water, Government Gazette No. 22355, June 2001*). The water services audit must include the **water quality sampling programme** contemplated in regulation 5(1), the results of the comparison set out in regulation 5(3) and any occurrence reported in compliance with regulation 5(4). In addition, each WSA must report on the number of households (and % of total households supplied by formal piped system) which **do not** receive water of an adequate quality as defined by *SABS-241* (Annexure 2: Key Performance Indicators for Water Service Authorities in *Strategic Framework for Water Services,* DWAF, 2003).

If a WSA fails to comply with legislative requirements, including those for the quality of water supplied, then DWAF must take the following steps (Section 7 in *Strategic Framework for Water Services*, DWAF, 2003):

1) First DWAF must **request compliance**.

2) If the WSA expresses a sincere **willingness** to comply but has **genuine constraints** which make it unable to comply then DWAF and provincial must provide **support** to correct the problems through one or more of the following mechanisms (For details, see *Strategic Framework for Water Services*, Section 8, DWAF 2003):

   (a) Capacity building grants
   (b) Establishing knowledge networks
   (c) Providing advisory services
   (d) Development of guidelines and tools (this document is an example)
   (e) Strategic support including technical assistance
   (f) Training and skills development

3) However, if a WSA **refuses to comply** or is **negligent in complying** and has the capacity to do so, then DWAF and provincial government may attempt to secure compliance through any of the following mechanisms:

   (a) **Publicize the failure** so that the public will exert pressure on the WSA to comply
   (b) Together with the National Treasury, Department of Provincial and Local Government (DPLG) and relevant provincial departments, DWAF can exert **financial pressure** by withholding capital funds.

(c) If options (a). and (b). fail to secure compliance then **direct intervention** may be considered. This may include taking over the running of the water services for a limited period of time.

(d) As a final resort, DWAF may take **legal action** against the WSA.

3

ACHIEVING EFFECTIVE DISINFECTION - TECHNICAL ISSUES

Ensuring that the water that consumers receive is safe to drink from a microbial point of view involves four steps:

1. Protecting the source water from contamination e.g. from pollution from human and animal faeces, rubbish and litter, sludge and inadequately treated effluent from municipal wastewater treatment plants and from industry.
2. Adequate purification and disinfection of the water in the water treatment plant.
3. Maintaining the integrity of the distribution system and ensuring an adequate chlorine residual throughout the system
4. Safe handling and storage of water by consumers.

It is envisioned that the **source water protection** (Step 1) will be the joint responsibility of **Catchment Management Agencies**, Water Service Authorities and Water Services Providers. This is discussed briefly in **Section 3.1**.The second two steps are primarily the responsibility of the Water Service Providers with the Water Services Authorities closely monitoring their performance. These two steps are the main focus of these guidelines. **Water treatment** for pathogen control is discussed in **Section 3.2** while the **operation of distribution systems** is discussed in **Section 3.3**. **Safe handling and storage of water** is the responsibility of **consumers**, however, **District Municipalities** are responsible for **public education** on matters of health and hygiene related to water and sanitation. For more information on step 4, see Jagals *et al.* (1997), Momba and Kaleni (2002), Momba and Nosthe (2003) and Nala *et al.* (2003). For more details on the responsibilities of various spheres of government as well as consumers, see DWAF's *Quality of Domestic Water Supplies Volume 5: Management Guide* (DWAF *et al.*, 2002d). A critical part of the efficient operation of both the treatment plant and the distribution system is the introduction of appropriate **process control measures**. These are discussed in **Section 3.4**.

3.1 SOURCE WATER PROTECTION

3.1.1 Sources of contamination

Pathogens in the raw water generally come from a variety of sources with **faecal matter** from humans, livestock and wild animals being the primary concern. Major sources of faecal contamination include inadequate sanitation facilities, leaking pit latrines, overflowing sewers, livestock farming and inadequately treated sludges and effluents from water and wastewater treatment plants. Chemicals which are harmful to water quality and human health may wash into rivers and dams from cultivated lands (fertilizers and pesticides), off roads and parking lots (petrol and oil products), and from rubbish and litter including abandoned cars dumped closed to the water source. Industrial wastewater discharges and leaking chemical storage tanks are also a concern in some areas. High levels of nitrate and phosphate (usually from agriculture and industrial and wastewater effluent discharges) promote the growth of algae in surface waters. Algae cause problems with the settling and filtration steps of treatment and may also release toxic substances into the water. Soil erosion during heavy rainfall and as a result of poor land management practices increases both the turbidity and number of pathogens in the raw water.

In general, **groundwater** (from boreholes) has less microbial contamination than **surface water** (from rivers, lakes and dams) because soil tends to filter microbes out. However, groundwater can still be contaminated by pit latrines and leaking septic tanks. Furthermore, the closer a borehole is to a body of surface water, the more likely the groundwater is to be contaminated with the same chemicals and microorganisms as the surface water. For more details on the types of and sources of contaminants expected in South African raw water supplies, see DWAF's *Quality of Domestic Water Supplies Volume 5: Management Guide* (DWAF *et al.*, 2002d).

3.1.2 Need for source water protection

The quality of the raw water being used for drinking water production is of concern because the lower the levels of contaminants in the raw water, the less likely they are to survive purification and disinfection to find their way into the finished water. Conversely, if pathogen levels in the raw water become very high, it becomes increasingly difficult for treatment plants to consistently meet the compulsory national standards, even if the efficiency of pathogen removal (total % removed) is high. For example, if there are an average of 10 faecal coliforms/100 mL in the raw water, a 99 % removal efficiency (easily achievable even in plants not performing optimally) will result in an average of 0.05 faecal coliform/ 100 mL or an average of one faecal coliform detected in 5 % of samples. This would comply with *SABS-241* (See Table 2 in Section 2.3).

> The higher the quality of the source water, the less likely microbial contaminants will be present in the finished water.

However, if the raw water contained 100 faecal coliforms/100 mL then 99 % removal would mean an average of 1 faecal coliform/100 mL for all samples, which would not comply with

SABS-241. Consequently, source water protection should be considered an integral part of water treatment for domestic use.

3.1.3 Strategies for source water protection

Source water protection is a major topic on its own and will only be discussed briefly here. Source water protection varies widely from country to country. In some developed countries all discharges into watersheds are strictly regulated and in some cases no swimming or other recreational activities are allowed in lakes and dams used as raw water sources. In other countries, raw sewage and toxic industrial wastes are routinely dumped into rivers and lakes irrespective if they are used for drinking water, presenting a major health hazard to consumers.

In South Africa, the *National Water Act* (1998) requires that the management and protection of all water resources in a given catchment area is to be taken over by **Catchment Management Agencies**, which are currently in the process of being established. These agencies will play a major role in the protection of the raw water sources used in to producing drinking water. However, water services institutions also have a number of specific responsibilities.

Under current South African regulations, water service institutions must take measures to prevent any substance other than uncontaminated storm water from entering any storm water drain; or any watercourse, except in accordance with the provisions of the *National Water Act* (1998). This requires that every institution that discharges effluent into a water body (river, stream, lake, and reservoir) must have an authorisation to do so from the Department of Water Affairs and Forestry. The authorisation would specify the types and maximum levels of contaminants that the effluent is allowed to contain.

The progressive provision of basic sanitation facilities for poor communities as required by the *Water Services Act* (1997) should also go a long way towards reducing microbial contamination of water resources. Municipalities should also discourage the development of informal settlements on riverbanks as this is hazardous both to the residents when flooding occurs and to water quality in the river. Furthermore, while there are currently no regulations requiring it, it is in the interest of Water Services Authorities and Water Services Providers to take steps to protect their source water close to the point of abstraction. At present, it is common to find livestock grazing on river banks and people swimming and washing clothes in rivers and dams close to the abstraction point. These all contribute to the microbial contamination of the raw water. Restricting access by humans and animals to dams and sections of the river is likely to be a controversial issue. However, water service providers should at a bare minimum attempt to do the following:

- Fence off small raw water holding dams to prevent access by livestock and unauthorised personnel
- Fence off sections of larger dams close to the abstraction point
- Fence off sections of rivers upstream of river abstraction points
- Where possible, locate boreholes away from human settlements and livestock
- Locate new housing developments away from or downstream of abstraction points wherever possible.

Education about water quality issues and source water protection is essential if the local community is to accept restrictions on land use and access to raw water sources.

Communities have to be educated about source water protection if they are to accept and support these measures and alternate ways for accessing water should be considered. For example, water for livestock might be transferred (gravity or pumping) to an alternate point downstream and/or well away from the abstraction point to prevent large quantities of faecal matter getting into the raw water.

In addition, regular inspections of the raw water source, abstraction point, in-take structure and transmission line should be carried out (e.g. once a week). Any rubbish or debris should be promptly cleared away and any problems such as algae blooms or evidence of contamination should be noted.

Strategies for source water protection

- Establishment of Catchment Management Agencies and implementation of integrated water resource management (led by DWAF)
- Delivery of basic sanitation
- Effective treatment of wastewater before discharge into water bodies
- Restricting access to raw water sources close to abstraction
- Public education
- Regular inspection and maintenance of intake facilities
- Regular monitoring of raw water quality
- Development of alternate raw water sources

Ongoing monitoring of the quality of the raw water is also a regulatory requirement (See Section 2.2). This should be used to monitor the success of water source protection measures as well as assess the acceptability of the raw water source. Some water treatment plants have the option of switching between multiple raw water sources depending on water quality and treatability (may vary seasonally). If there is a serious and irreversible deterioration of raw water quality which makes effective treatment too expensive or too difficult, WSAs and WSPs have to seek alternative raw water sources.

3.2 WATER TREATMENT OPERATIONS

3.2.1 Overview

Water treatment plants have two important and complementary functions:

- First to remove contaminants from the water
- Second to add sufficient disinfectant (usually chlorine) to the water to kill any remaining microbes and ensure an adequate disinfectant residual at the consumer's tap.

Contaminants in water can be in the form of small particles (including dirt and microbes) or in dissolved form (e.g. colour, iron and manganese). **Turbidity** is a parameter which should be measured at all treatment plants and provides an indication of the concentration of particles in water. Turbidity in the raw water is usually removed by a combination of **chemical coagulation**, **flocculation**, **settling** and **granular media filtration**. Up to **99.99 %** of microbes in the raw water can be removed by these processes before any disinfectant is added to the water (LeChevallier and Au, 2004). Furthermore, the cleaner water is (the lower the turbidity and colour) when the disinfectant is added, the more efficient the disinfection process. Consequently the more effectively particulate and dissolved contaminants are removed prior to disinfection; the less disinfectant has to be used. Therefore effective turbidity removal is very important for efficient disinfection.

> Efficient disinfection requires effective turbidity removal.

The number of treatment steps required to produce good quality water from different raw water sources depends on the type and quantity of contaminants in the source water. Most municipal water treatment plants include some or all of the steps listed in Table 4.

TABLE 4 TYPICAL TREATMENT STEPS IN POTABLE WATER PRODUCTION		
Step	Description	Purpose
Pre-chlorination	Addition of chlorine to the raw water.	Remove of colour, iron and/or manganese. Prevent biofilm growth in channels, settling tanks and filters.
pH adjustment/ Stabilisation	Addition of chemicals such as lime, soda ash or carbon dioxide which change the pH.	Adjust the pH to fall in a required range for good floc formation and/or to prevent corrosion or excessive scaling in the distribution system.
Coagulation	Addition and flash mixing of coagulants (also called flocculants) such as alum and/or polymer solutions to raw water	Add chemicals which produce floc. Floc contains many of the contaminants present in the original raw water.
Flocculation	Formation of floc in channels or pipes between coagulant addition and the settling tanks.	Form floc which are easily removed in the settling tanks.
Settling	Floc sinks to the bottom of the settling tank while settled water flows over the top into the settled water channels.	Removal of floc formed in coagulation and flocculation steps.
Filtration	Water is filtered through a granular media (sand and/or anthracite).	Removal of floc or particles not removed in the settling tanks.
Disinfection/ post-chlorination	Addition of chlorine to the filtered water or final water storage reservoir.	Kill off any microbes in the filter water and provide a chlorine residual to prevent later re-infection.
Finished water storage	After disinfection, the treated water flows to a storage reservoir on or near the plant.	Allow sufficient time for the chlorine to act and ensure an adequate supply of water during periods of high demand or disruptions to the operation of the plant.
Sludge settling and washwater recovery	Dirty backwash and or sludge from the settling tanks is held in settling ponds where the sludge settles to the bottom of the ponds and the supernatant is recycled to the top of the plant.	Reduces water losses on the plant and avoids discharging sludge and spent backwash water to either natural water bodies (which is illegal) or to the sewer (which requires a permit).

Fig. 1 is a schematic representation of a typical conventional treatment plant. Raw water is pumped or flows under gravity from the abstraction point to the treatment works. Some water treatment plants have a small **holding dam** or **raw water tank on-site**. **Coagulant** is added to the raw water just before **flash** or **rapid mixing**. Many plants also add a **pH adjustment chemical** at this stage and a few add an **oxidant chemical** such as chlorine. Floc start to form in the **flocculation** stage, which usually consists of a baffled channel. Most small treatment plants have at least two settling tanks and two filters operating in parallel (In the Fig. 1, there are 3 of each). The flow is usually split just before or just after the flocculation channel(s). Most of the floc formed should be removed in the **settling tanks** (clarifiers) with a small amount of remaining floc being removed by the **filters**. Some treatment plants have balancing tanks between the settling tanks and filters (not shown).

The filtered water is then **disinfected**, usually by the addition of some form of **chlorine**. Some plants also add a pH adjustment chemical to the filtered water for **corrosion control** (Section 3.2.7). However, post-pH adjustment is not common in small treatment plants in South Africa because of the additional equipment and expense involved. After chlorine addition, the treated water usually flows to an **on-site storage reservoir** before entering the **distribution system.**

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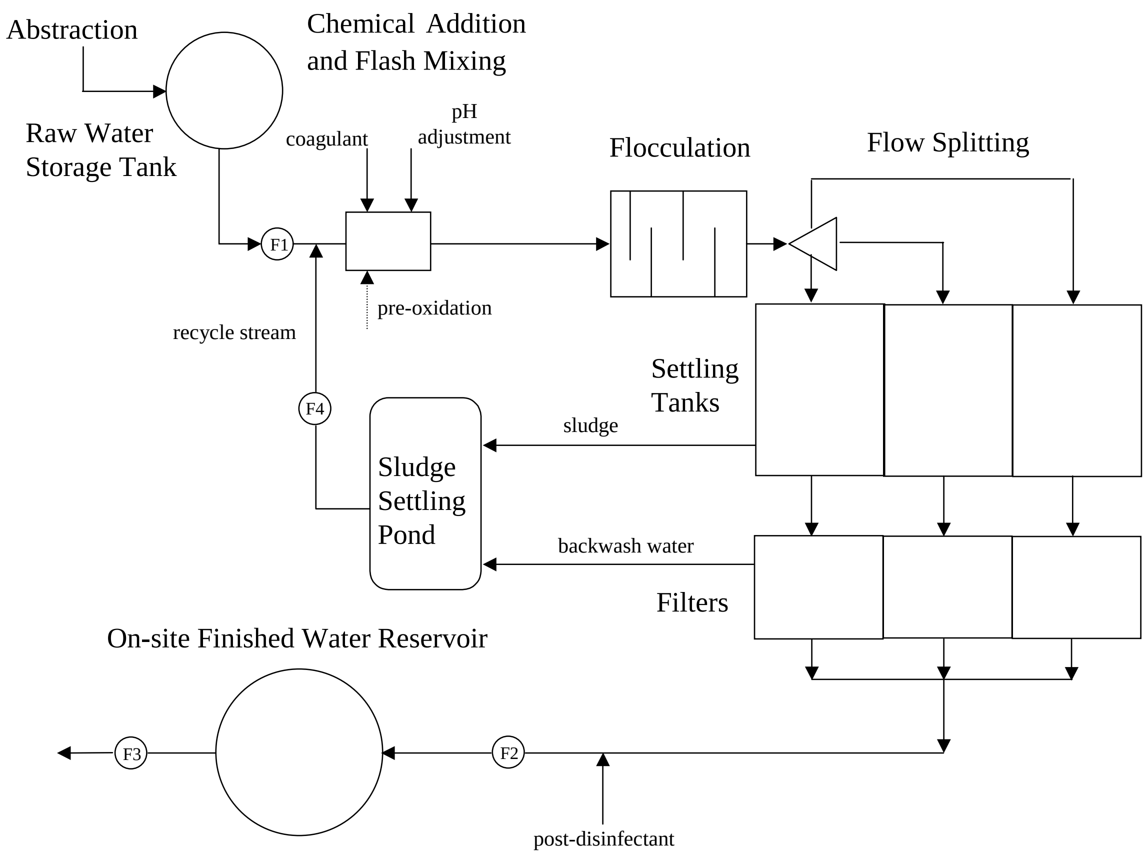


Fig. 1 Schematic of a conventional water treatment plant

Settling tanks have to be "**desludged**" periodically to remove settled floc. This involves opening a valve at the bottom of the settling tank to drain out the sludge that forms there. Filters clog up over time and have to be cleaned either by **backwashing** (for rapid filters) or scraping off the clogged surface layer (slow sand filters). Fig. 1 also includes a system to recover water from the spent backwash and settled sludge. Sludge and dirty filter backwash water are sent to a **sludge pond** and allowed to settle out. The **supernatant** (clear upper layer formed after settling) is then pumped back to the head of the works before coagulant addition. The recovered water could also be returned to the raw water storage reservoir.

Many small treatment systems do not currently have a washwater and sludge recovery system and instead discharge sludge and spent backwash water into a nearby river, dam or onto land downhill from the plant. However, discharges of untreated sludge or backwash water tend to negatively impact the quality of the receiving water body. Under the 1998 *National Water Act*, every institution that discharges effluent into a water body (river, stream, lake, and reservoir) must have an authorisation to do so from the Department of Water Affairs and Forestry. The authorisation would specify the types and maximum levels of contaminants that the effluent is allowed to contain (DWAF, 2002b). Furthermore, DWAF is currently working on a **Waste Discharge Tariff System** which will require all institutions including water service providers to pay tariffs for all effluents discharged with the size of the tariff depending on the quantity and quality of waste. Consequently, water treatment works will face increasing pressure to install wash water and sludge treatment systems. For more information on sludge handing and disposal se Section 6.E in *Quality of Domestic Water Supplies Volume 4: Treatment Guide* (DWAF *et al.*, 2002c).

The following sections discuss each of the treatment steps in greater detail with emphasis on the **importance of each step in ensuring the microbial safety of the water**. For additional information on various treatment processes see DWAF *Treatment Guide* (DWAF *et al.*, 2002c).

3.2.2 Disinfection

The most critical step determining the microbial safety of water is **disinfection**. Although disinfection is usually the last step in conventional treatment it will be discussed first, because the requirements for efficient disinfection affect all the treatment processes which come before it. Water which has not first been purified (removal of particulate and dissolved contaminants) can still be disinfected, however, the disinfection process will be less efficient and the overall quality of the water will be poorer.

3.2.2.1 Disinfectants used

Several different types of disinfectant are in use today including various chlorine compounds, bromine, ozone and UV radiation. Chlorine compounds are by far the most commonly used disinfectants worldwide and the discussion here will be limited to the three types of chlorine most commonly used in small treatment plants: **chlorine gas**, **sodium hypochlorite** (supplied as a liquid or generated on site by electrolysis of a salt solution) and **calcium hypochlorite** (usually supplied as granular HTH). During emergency situations, for example the cholera outbreaks in KwaZulu-Natal, households may be advised to disinfect their own drinking water using household bleach (Jik) which is a sodium hypochlorite solution. Chlorine based disinfectants **not** discussed here include chlorine dioxide and chloramines.

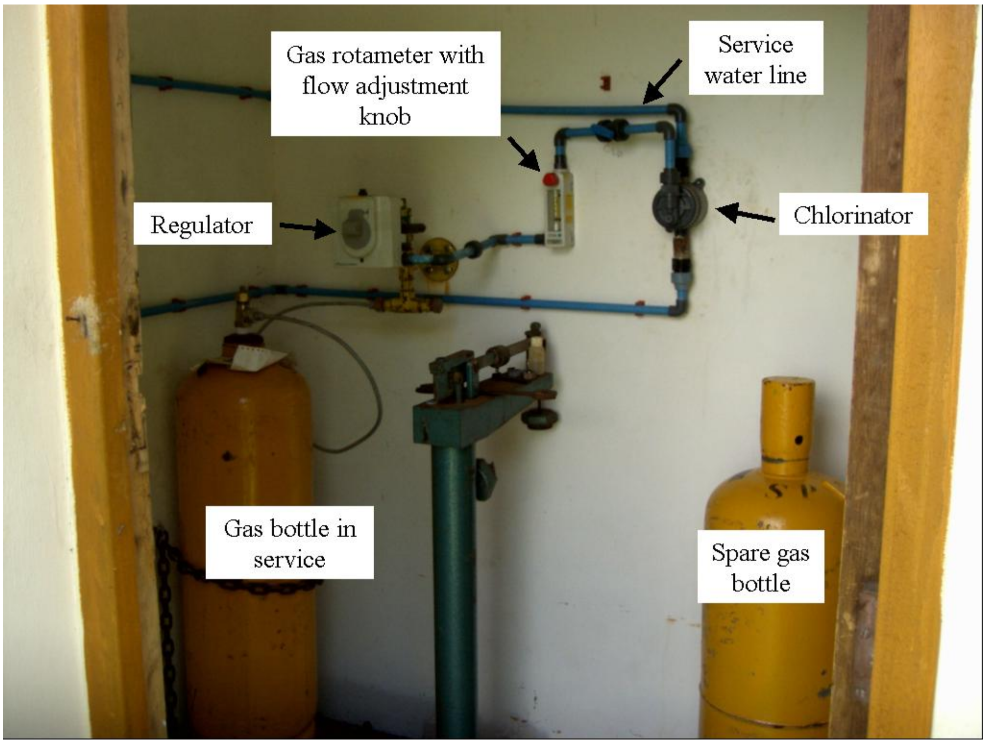


Fig. 2 Gas chlorination system at a small water treatment plant

Using chlorine gas is usually the cheapest option, however, there are significant safety issues involved. Consequently, many smaller plants opt for granular HTH ($Ca(OCl)_2$) which is much safer and easier to transport, handle and store and which does not require specialized dosing equipment. A few small plants as well as some major urban plants use sodium hypochlorite ($NaOCl$) solution generated on site.

Chlorine gas is supplied in pressurised gas bottles or tanks. The gas is dissolved in a small side stream of water in a device known as the **chlorinator** and then dosed into the main flow. The gas flow from the tank is controlled by a **regulator** on the gas bottle and is typically measured by a device known as a rotameter. A control knob on the rotameter is usually used to set the gas flow rate.

Fig. 2 shows a gas chlorination system at a small treatment plant. Note that there are two problems with the set up in the photograph. First, although there is a spare gas bottle, there is no back up dosing system. Since chlorination is critical to the production of safe drinking water, all plants need to have a back up dosing system. Secondly, for safety reasons, the gas bottles including the bottle in service should be kept in a separate room to the chlorinator and the gas rotameter (Kawamura, 1991; Thompson, 2003).

Solutions of sodium hypochlorite and HTH dissolved in water are usually dosed using **dosing pumps**. Dosing pumps for liquid solutions are discussed further in Section 3.2.4.2.

3.2.2.2 Chlorine chemistry and disinfection efficiency

In order to use chlorine disinfectants most effectively, it is important to understand something about their chemistry and disinfectant (microbe killing) power. When chlorine gas ($Cl_{2(g)}$) dissolves in water (H_2O), it forms one molecule of **hypochlorous acid** (HOCl) plus one chloride ion (Cl^-) for each molecule of $Cl_{2(g)}$ dissolved (For an explanation of molecules and ions see Note Box 2 page 12 of *Quality of Domestic Water Volume 3: Analysis Guide* (DWAF *et al.*, 1998))

$$Cl_{2(g)} + H_2O \rightarrow HOCl + H^+ + Cl^-$$

Hypochlorous acid dissociates (splits up) to form hydrogen and **hydrochlorite ions** (OCl^-)

$$HOCl \Leftrightarrow H^+ + OCl^-$$

All of the disinfectant capability of the chlorine gas resides with either the undissociated HOCl or the OCl^- ion – the chloride ion (Cl^-) has no ability to kill microbes at the concentrations which occur in drinking water. If either sodium or calcium hypochlorite is used as the source of chlorine, each will yield OCl^- upon dissociation in water. Sodium hypochlorite will release one hypochlorite ion per molecule sodium hypochlorite while calcium chlorite will release two hypochlorite ions per molecule

$$NaOCl \rightarrow Na^+ + OCl^-$$

$$Ca(OCl)_2 \rightarrow Ca^{2+} + 2OCl^-$$

The hypochlorite ions can recombine with hydrogen ions water to form hypochlorous acid in the reverse of the dissociation reaction above (The double arrow shows that the reaction can go both ways). The distribution between HOCl and OCl^- (relative amounts of each formed) depends on the pH of the water. HOCl and OCl^- are present in approximately equal amounts at pH 7.4. At lower pH's, more HOCl will be formed while at higher pH's more OCl^- will be formed. This is important because HOCl is estimated to be about 100 times more effective as a disinfectant than is OCl^-, making chlorine disinfection more effective at low pH (Hrudey and Hrudey, 2004). Table 5 shows the relative amounts of hypochlorite ion and hypochlorous acid at pH's between 7.0 and 10.0.

TABLE 5
DISSOCIATION OF HYPOCHLOROUS ACID AS A FUNCTION OF pH
(SNOEYINK AND JENKINS, 1980)

pH	% HOCl	%OCl^-
7	78	22
8	28	72
9	4	96
10	0	100

Disinfection is most efficient in the pH range 5 to 7. However, the lower the pH of the finished water, the more **corrosive** it tends to be to materials used in the distribution system. pH and corrosion control are discussed further in Section 3.2.7. The optimum pH for each treatment system depends on the characteristics of both the water and the materials in the distribution system. However, as a general rule, it tends to fall in the pH range 6.5 – 8.0 (Chapter 10 in WHO, 2004). The WHO guideline for effective disinfection is based on a finished water pH not greater than 8.0 (WHO, 2004).

The optimum pH of the finished water typically falls in the range **6.5 – 8.0** depending on the characteristics of the water and the materials used in the distribution. This is a compromise between maximizing disinfection efficiency and minimizing the potential for corrosion.

Note that dissolving **chlorine gas** in water tends to **decrease** the pH of the water due to the formation of hydrochloric acid whereas the addition of either **sodium** or **calcium hypochlorite** tends to **raise** the pH. Adding calcium hypochlorite also tends to increase the calcium concentration of the water which can be beneficial for corrosion control (See Section 3.2.7).

The sum of the concentrations of HOCl and OCl^- in a water sample is known as the **free chlorine** concentration (usually given in units of mg/L Cl).

Free chlorine = HOCl + OCl^-

Since these two forms of chlorine are available for killing microbes, free chlorine is sometimes also referred to as **free available chlorine**. In addition to destroying microbes, free chlorine also tends to react with other compounds and particles in the water, especially organics (chemical compounds of plant, animal or bacterial origin) to form a range of chlorinated compounds. Compounds formed from the reaction of chlorine with ammonia or organic amino compounds are collectively termed **combined chlorine**. The sum of the free and the combined chlorine is known as the **total chlorine**.

Total chlorine = Free chlorine + Combined chlorine

Chlorinated organics generally have a negligible ability to kill germs at the concentrations involved, consequently, only the free chlorine component of the total chlorine is relevant to disinfection. An exception occurs when ammonia is deliberated added to water along with chlorine to form inorganic chloramines in a process known as chloramination. However, chloramination is seldom used in small treatment works because of safety issues. Therefore it is not discussed here.

The **free chlorine residual** (usually referred to simply as the chlorine residual) is the free chlorine concentration measured in a water sample after the chlorine has had some specified time (referred to as the **contact time**) to react with various chlorine consuming compounds in the water. It is important for plant supervisors to make sure that they are measuring **free chlorine** (**DPD 1** tablets or equivalent) and not one of the other forms of chlorine (DPD greater than 1). During a recent survey of treatment plants, the authors found some plants were using DPD 3 tablets instead of DPD 1 which means that they were actually measuring total chlorine rather than free chlorine. Consequently, they may have been overestimating the chlorine residual actually available for disinfection.

Plant supervisors must ensure that they are measuring the free chlorine residual in their finished water. The tablets or powders used should be labelled "**DPD 1**" or "**Free chlorine**".

One of the main advantages of using chlorine compounds as disinfectants is their ability to produce **free chlorine residuals** which may persist for days during storage and distribution of the treated water. This offers some protection against re-infection of the water and helps to prevent the growth of biofilms (coatings of living bacteria) on the pipe walls. The chlorine residual remaining in a sample after a given **contact time** depends on the initial dose and the concentrations of all compounds which will react with the free chlorine. The **chlorine demand** is defined as the difference between the free chlorine dose and the chlorine residual (all expressed in units of mg/L Cl).

Chlorine demand = Free chlorine dose – Chlorine residual

Note that half of the chlorine added as chlorine gas will initially form free chlorine whereas all of the chlorine in sodium or calcium hypochlorite will initially form free chlorine.

The chlorine demand varies with the turbidity and dissolved organic content of the water. If the chlorine demand increases, e.g. as a result of an increase in turbidity of the water, then the chlorine dose must be increased by the same amount to achieve the same chlorine residual.

3.2.2.3 Factors affecting disinfection efficiency

The success of chlorination is determined by several factors. The effects of pH and turbidity on disinfection efficiency have already been discussed. The turbidity should be reduced to less than 1 NTU and preferably less than 0.5 NTU prior to disinfection (DWAF *et al.*, 2002c). In addition, the efficiency of disinfection increases with increasing free chlorine concentration, temperature and contact time and decreasing chlorine demand. For routine operational monitoring, the adequacy of the chlorination step is assessed based on the free chlorine residual leaving the plant and the contact time, rather than on the chlorine dose.

For efficient disinfection, the turbidity should be less than 1 NTU and preferably less than 0.5 NTU.

The **contact time** can be defined as the time between the addition of the disinfectant and the time that the disinfected water reaches the closest consumer’s tap. This includes the time that it takes for the water to pass through the on-site storage reservoir, the distribution lines and any off-site reservoirs between the treatment plant and the closest consumer.

The *WHO Guidelines for Drinking-water Quality* (Annexure 4, WHO, 2004) state that effective disinfection requires a residual of at least 0.5 mg/L free chlorine after a contact time of at least 30 minutes at pH less than 8. To ensure adequate contact

Adequate disinfection requires a free chlorine residual of at least 0.5 mg/L, an effective contact time of at least 30 minutes and pH of not greater than 8.0.

time, the on-site reservoir is often designed to have a hydraulic retention time of at least 30 minutes. The hydraulic retention time is defined to be the ratio of the volume of water in the reservoir to the flow through the reservoir

$$\theta = \frac{V}{Q}$$

θ	Hydraulic retention time, min
V	Volume of water in the reservoir, kL
Q	Flow through reservoir, kL/min

However, because of **mixing effects**, some of the water remains in the reservoir for less than the full hydraulic retention time. This means that it may not be adequately disinfected by the time it leaves the reservoir. The best way to overcome this problem is to design the reservoir to minimize mixing and short-circuiting. This can be achieved by constructing **baffles** to force all of the flow to follow the same path through the reservoir. The effect of baffling on the flow is illustrated in Fig. 3. Note that this only applies to reservoirs where disinfectant is being added at or close to the inlet. For storage reservoirs with no disinfect addition, mixing tends to improve water quality (Ainsworth, 2004). Table 5 shows effective contact times for various reservoir designs (USEPA, 2003).

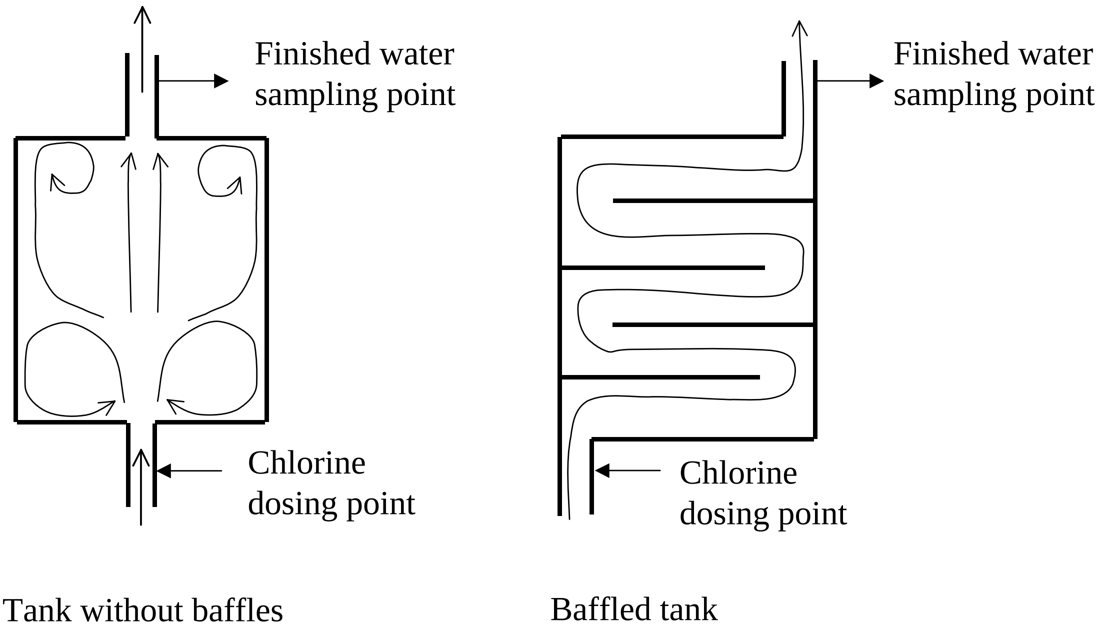


Fig. 3 Effect of baffles on flow patterns in tanks and reservoirs

TABLE 6 APPROXIMATE EFFECTIVE CONTACT TIMES FOR DIFFERENT TANK/RESERVOIR DESIGNS (USEPA, 2003)		
Baffling	Effective contact time	Description
None (mixed flow)	10 % of θ	No baffles, low length to width area (e.g. circular tanks), high inlet and outlet flows. Typical of most clearwells where the inlet and outlet are submerged pipes.
Poor	30 % of θ	Single or multiple inlets and outlets without baffles. A few **intra –basin** (in the main body of the tank) baffles. Many **conventional clarifiers** and storage tanks with two or three baffles fit this description.
Average	50 % of θ	Baffled inlet and outlet with some intra-basin baffles in the main body of the tank. A few clarifiers and highly baffled storage tanks fit this description.
Superior	70 % of θ	Perforated inlet baffles (walls with evenly distributed holes that the water passes through). Serpentine or perforated intra-basin. Serpentine baffled contact tank (similar to the baffled tank example in Fig. 3). **Filters** have approximately the same effective contact time.
Perfect plug flow (pipe flow)	100 % of θ	Very high length to width ratio. Perforated inlet, outlet and intra-basin baffles. Sections of pipe with lengths at least 10 times their diameter have this effective contact time.

In order to determine whether disinfection is effective, the effective contact time for the **shortest hydraulic retention time** (highest flow and lowest typical reservoir volume) should be calculated. The effective contact time can also be **determined directly** by conducting the following experiment:

The chlorine dose should be temporarily increased by at least 1 mg/L. Samples of water leaving the on-site reservoir (finished water sampling point in Fig. 3) should be collected every 5 minutes and immediately analysed for free chlorine residual. The time at which the free chlorine residual measured at the outlet increases by 10 % of the total increase is the effective contact time.

Example

Suppose the free chlorine residual leaving the on-plant storage reservoir/chlorine contact chamber is 0.53 mg/L. If the chlorine dose at the inlet is increased by 2 mg/L then the effective contact time will be the time taken for the chlorine residual at the outlet to increase by 10 % of 2 mg/L i.e. by 0.2 mg/L. In other words the effective contact time corresponds to the time taken for the outlet chlorine free residual to increase to 0.73 mg/L. Sampling should continue for at least 15 minutes after the effective contact time is reached in order to confirm the result.

Assume the results of the sampling are as follows:

Time	Free chlorine residual in the outlet
0 min	0.53 mg/L
5 min	0.52 mg/L
10 min	0.58 mg/L
15 min	0.62 mg/L
20 min	0.63 mg/L
25 min	0.65 mg/L
30 min	0.70mg/L
35 min	0.79 mg/L
40 min	0.90 mg/L
45 min	1.21 mg/L

In this case, the effective contact time is between 30 and 35 minutes. This means that as long the free chlorine residual is at least 0.5 mg/L and the pH is not greater than 8.0, then disinfection may be considered adequate (provided microbial analysis does not indicate otherwise).

Note that the effective retention time should be determined when **the flow through the plant is at its highest and the reservoir is at it its lowest typical operating level**. If the effective contact time is too short, then the following steps can be taken:

1. Repeat the experiment but this time collect samples at the closest consumer’s tap (closest in terms of length of pipeline). If the effective contact time, chlorine residual and pH are at least 30 min, 0.5 mg/L and not greater than 8.0 respectively, then disinfection may be considered adequate unless microbial analysis indicates otherwise.

2. Increase the chlorine dose. Table 7 lists required chlorine residuals as a function of effective contact time for pH less than or equal to 8.0. For example, if the effective contact time is 15 minutes then the chlorine residual should be approximately 1.2 mg/L for pH 8.0 and temperature greater than 10 ^{o}C.
3. Install baffling to increase the effective contact time.

TABLE 7

REQUIRED CHLORINE RESIDUAL AS A FUNCTION OF CONTACT TIMES WATER TEMPERATURE AND pH (MANCL, 1989)

Contact time (minutes)	Necessary chlorine residual (mg/L)		
	pH 7	pH 7.5	pH 8
Water temperature not less than 10 ^{o}C			
40	0.2	0.3	0.4
30	0.3	0.4	0.5
20	0.4	0.6	0.8
10	0.8	1.2	1.6
5	1.6	2.4	3.2
2	4.0	6.0	8.0
1	8.0	12.0	16.0
Water temperature 0 - 10 ^{o}C			
40	0.3	0.5	0.6
30	0.4	0.6	0.8
20	0.6	0.9	1.2
10	1.2	1.8	2.4
5	2.4	3.6	4.8
2	6.0	9.0	12.0
1	12.0	18.0	24.0

3.2.2.4 Chlorine dosing point

The optimum point for disinfectant addition is the filtered water (**post-disinfection**, see Fig. 1). This is because clean filtered water has the lowest chlorine demand. Consequently less chlorine needs to be added to achieve the required chlorine residual. Furthermore, chlorine can react with organic matter in water to produce what are known as **disinfection by-products**. These are suspected of being harmful to human health. The filtered water should have the lowest level of all kinds of contaminants and therefore the lowest potental to form disinfection by-products.

However, there are valid reasons why a plant may need to dose chlorine into the raw water at or before coagulant addition (**pre-oxidation** in Fig. 1). One reason may be to remove colour and/or dissolved iron and manganese. The addition of chlorine to the raw water oxidises these compounds causing them to precipitate (go from a dissolved to a particulate form) so that they can then be removed by coagulation, flocculation, settling and filtration. While there are other **oxidant chemicals** which can be used such as ozone or permanganate, chlorine is usually the most practical option for small treatment plants.

The other reason to use pre-chlorine is to prevent the growth of algae and biological slimes in the settling tanks and filters. Note that chlorine should **never** be added to the raw or settled water ahead of **slow sand filters** as it will interfere with the biological removal mechanisms in the filters. Slow sand filtration is discussed in Section 3.2.6.2).

> The optimum chlorine dosing point for disinfection is the filtered water. Pre-chlorination may be used for removal of colour, iron and manganese and for controlling algae and bacteria slimes in the clarifiers and filters.

Depending on the raw water source, pre-chlorination may only be required at certain times of the year. Because of the high chlorine demand of raw water, plants using pre-chlorination should also have post-chlorination to ensure an adequate disinfectant residual without having to use excessive amounts of chlorine in the raw water.

Unfortunately, some small treatment plants only apply pre-chlorination because they do not have the facilities for post-chlorination. This is an unacceptable situation and requires the upgrading of the facilities. Some plants using pressure filters find that the pressure in the filtered water line is too high for the chlorine dosing equipment. This is an issue which has to be addressed in the design phase. Since the floc which accumulates in the filters exerts a high chlorine demand it is not desirable to have continuous chlorine dosing in the filter influent. (Sometimes chlorine may be added to filter influent to control the build up of bacteria in filters).

3.2.2.5 Manual dosing of chlorine

In the event of a failure of the chlorine dosing system, small treatment plants typically resort to manual dosing of HTH directly into the final water storage reservoir. Plants should avoid this situation in the first place by:

1. having a standby dosing system which is maintained in working order

2. conducting regular preventative maintenance
3. maintaining an adequate stock of disinfectant on site and ensuring regular delivery of chemicals.

To prevent disruptions in chlorine dosing

- Have backup dosing systems
- Conduct preventative maintenance
- Maintain adequate stocks

However, if it becomes necessary to resort to manual dosing, the following guidelines need to be strictly adhered to:

1. The amount of HTH added must be sufficient to ensure a residual of at least 0.5 mg/L and preferably higher in the finished water (leaving the on-site reservoir).

On one occasion when the chlorine dosing system at Alice water treatment plant failed, the authors found that the amount of HTH the operators were adding amounted to less than 5 % of the actual chlorine demand of the filtered water and therefore was insufficient to maintain an adequate residual. Each treatment plant needs to draw up clear guidelines on manual dosing of HTH when the chlorine system fails.

2. Continuous dosing is better than batch dosing (dosing a large amount all at once).

It is **no**t acceptable to dose chlorine once or twice a day while treated water is flowing into the distribution system. Dosing once or twice a day would result in some water having a very high concentration of chlorine while some will not have enough to effectively kill bacteria. This is also true of treatment plants which currently have no chlorine dosing equipment. It is acceptable to batch dose HTH into on-site storage reservoirs while the outlet is closed. The HTH should be dosed at least 30 minutes before the outlet is opened to ensure sufficient contact time.

Batch dosing is also acceptable for **booster dosing**. For example, some plants which shut down overnight may add HTH to their finished water reservoir before starting up, even though they have continuous dosing of the filtered water while the plant is running. Booster HTH should be added as close to the reservoir inlet and as far from the outlet as possible.

To achieve continuous dosing without dosing pumps, HTH should be mixed with water in a 100 – 200 L drum fitted with a tap at its base. The tank should be set up so that solution drips into the filtered water channel or into the clearwell or finished water reservoir close to the inlet. Some plants are already using this system for routine operation because they do not have dosing pumps. It is **not** an acceptable alternative to a proper metered dosing system because it does not maintain a constant dose, however, it can be used in emergencies. (Therefore, plants which are replacing this inferior system with dosing pumps should keep their old dosing tanks for emergencies).

If there are no drums available for continuous dosing and the operator has to dose by hand, then HTH must be dosed at least every 2 h. For example, if the plant is operating 12 h a day, then one sixth of the total daily dosing requirement should be dosed in the finished water reservoir close to the inlet every two hours. The operator should initially check the residual in the finished water (reservoir outlet) every 30 minutes to make sure that it does not drop below 0.5 mg/L. If it does, she should either increase the dosing frequency or the dose. The chlorine residual at the reservoir outlet should never exceed 5 mg/L (base on the maximum chlorine limit recommended by WHO, 2004). If HTH is being dosed by hand only, then **the plant should be shut down when there is no operator on duty.**

> If HTH is being dosed by hand only, HTH must be dosed at least every **2 hours**. The chlorine residual at any time **must not be more than 5 mg/L or less than 0.5 mg/L**. The plant should be shutdown when there is no operator to continue the chlorine dosing.

3.2.2.6 Ensuring an adequate chlorine residual at the point of use

In addition to ensuring the finished water meets the WHO Guidelines for adequate disinfection, it is also necessary to maintain a disinfectant residual in the distribution system to prevent re-infection of the treated water and to prevent the growth of biological coatings (biofilms) on the pipe walls. The WHO Guideline (WHO, 2004) for the minimum chlorine concentrations at the point of delivery is 0.2 mg/l in normal circumstances and 0.5 mg/l in high-risk circumstances (discussed next). An increasing number of people are likely to object to the taste between 0.6 mg/L and 1 mg/L (WHO, 2004). DWAF *et al*. (1998) Section B2 in Part 2 provides more detailed guidelines on the safety an acceptability of various levels chlorine at the point of use. These are partially reproduced in Table 8 below.

> The chlorine residual at the point of delivery should be at least 0.2 mg/L under normal circumstances and 0.5 mg/L during periods of high risk of microbial concentration. Lower concentrations will not provide adequate protection against microbial contamination.

An acceptable maximum chlorine limit will depend on what consumers are used to. Water Services Providers must monitor the chlorine residual at consumers' taps at various points in the distribution system, including the closest and farthest points from treatment, in order to ensure the residual remains in an acceptable range throughout the system. The operation of distribution systems is discussed further in Section 3.3.

TABLE 8 SAFETY AND ACCEPTABILITY OF THE CHLORINE RESIDUAL IN DRINKING WATER (ADAPTED FROM DWAF *et al.*, 1998)		
Free Chlorine Residual (mg/L)	Health Effects	Taste
Less than 0.05	Serious risk of infection if raw water source is microbiologically contaminated.	Acceptable to consumers.
0.05 – 0.1	Disinfection may not be effective.	Acceptable to consumers
0.1 – 0.2	Slight risk of infection.	Acceptable to consumers
0.2 – 0.3	Disinfection adequate.	Slight small of chlorine.
0.3 – 0.6	Disinfection good.	Slight smell and taste of chlorine.
0.6 – 0.8	Disinfection good. Insignificant risk of health effects due to chlorine.	Distinct smell and disinfectant taste.
0.8 – 1.0	Slight risk of mucous membrane irritation.	Unpleasant smell and taste.
1.0 – 1.5	May cause nausea and mucous membrane irritation.	Unpleasant smell and taste.
More than 1.5	Danger of toxic effects, nausea and vomiting.	Repulsive odour and taste.

Some Water Service Providers unfortunately believe that a free chlorine residual of only 0.1 mg/L is acceptable at the point of use and even in the finished water (before distribution). This is not the case, particularly for the majority of South African municipalities, where there is a high risk of faecal contamination of the raw water. Since increasing the chlorine dose can have an adverse effect on the taste, the WSP needs to inform consumers of the reason for the change in taste and assure them that it makes the water safer to drink. Consumers can reduce the chlorine taste in the water by allowing it to stand for half in hour in a **clean** cup or jug before drinking it.

3.2.2.7 Chlorine dosing for adverse conditions

Operators and supervisors need to be aware that pathogens can break through into the finished water even when a treatment plant appears to be operating normally and especially when any disruption in treatment (planned or unplanned) occurs. Whenever there is reason to suspect an increased risk of microbial contamination or pathogen breakthrough, the chlorine dose should be increased to increase the efficiency of disinfection (% of microbes killed by chlorine). Raising the finished water residual by 0.3 to 0.5 mg/L is recommended. Typical high-risk situations include the following:

- Heavy rainfall in the catchment area for the raw water source (some treatment plants already automatically increase their chlorine dose when heavy rains occur).
- Other events leading to a sudden increase in raw water turbidity.
- Other evidence of contamination of the raw water source e.g. a herd of cows breaks into the enclosure around a raw water holding dam.
- When a failure of any of the chemical dosing equipment occurs.
- When switching from one type of coagulant to another.
- When the filtered water turbidity increases for any reason.
- When there is a sudden increase in flow for any reason.
- When a filter or settling tank is taken off-line for maintenance resulting in an increase in flow through other units.
- When the plant is started up after being shut-down for a period of time (and for all plants which do not operate continuously i.e. 24 h/d).
- Whenever there is any construction going on at the plant.
- Whenever a new plant is commissioned.
- Whenever a new storage reservoir (on- or off-site) is commissioned or a new section of distribution system is opened.
- Whenever sampling from the distribution system indicates problems with water quality at point of use, whether microbial, physical or chemical (turbidity and chlorine residual). The chlorine dose should be temporarily increased while the cause of the problem is investigated and fixed.
- Whenever there is an outbreak of a waterborne disease in the local community e.g. cholera or shigellosis, whether or not the source of disease is drinking water and regardless of whether the part of the population receiving treated water is affected. In other words, even if it appears that only people drinking untreated water are at risk, the WSP should still take precautions with its treated water supply.

Whenever possible, the frequency of sampling for microbial contaminants (raw, finished water and point-of-use samples) should be increased to at least twice a week during high risk situations in order to determine the effectiveness of the increased chlorine dose and how long it needs to be applied. This information all needs to be carefully documented to assist the WSP in responding effectively to future adverse conditions.

> During high risk situations, the chlorine residual in the finished water should be increased by at least 0.3 - 0.5 mg/L. Microbial analysis should be increased to at least twice a week to ensure the response is effective.

3.2.3 Flow measurement and control

3.2.3.1 Flow measurement and dose calculations

It is not possible to run a water treatment plant efficiently without flow measurement. Flow measurement is required for:

1. Adding the correct amount of treatment chemicals to the water.
2. Estimation of contact times as described in Section 3.2.2.3
3. Calculation of water losses both on the plant and between the point of treatment and the point of delivery.

The amount of chemical which has to be added to the water being treated to achieve a certain **dose** (in mg/L) depends on the amount of flow. The required chemical **dosing rate** is given by the following formula:

$$dose\,rate(mg\,chemical/time) = dose(mg/L) \times flow(L/time)$$

The details of the calculation depend on the dosing system and will therefore vary from plant to plant. If the operators and supervisors do not have experience in dosing calculations, they should seek assistance from the various organizations involved in mentoring and capacity building in the water services sector (See Section 4.6). Dosing calculations should also be an integral part of on-site training.

> Flow rate measurements are required for dosing rate calculations and are therefore critical for effective water treatment. At a bare minimum, both the raw water and final water flow rate must be metered.

The dose rate equation should be used when trying to adjust the chlorine residual in the final water and when applying the results of the jar test to coagulant dosing (described in Section 3.2.4).

It is also very important that dosing rates are adjusted to maintain constant doses of coagulant whenever the raw water flow rate is changed.

Many small treatment plants still do not have flowmeters, or their flowmeters are broken, or the operators do not know how to read them. Water services institutions are already required to install water meters to measure the quantity of water provided to each supply zone (Section 11 of regulations promulgated under Section 9 of the *Water Services Act, Government Gazette, Vol. 432 No. 22355, 8 June 2001*). They should at the same time have meters installed (or repaired) at the treatment works itself.

At a bare minimum, there should be one meter for the raw water (F1 in Fig. 1) and one for the finished water (F3 in Fig. 1). Ideally, the filtered water and recycle flow should also be metered (F2 and F4). The contract for installing the meters **must** include **training** the operators and supervisors to use the meters to measure and calculate the **instantaneous** and **daily average flows**. In addition, flowmeter must be checked and re-calibrated at least once a year. (Some types of meter may need more frequent recalibration). Meters must also be easy to access and read if they are to be useful for process control.

> Companies which install flow meters must also train the plant supervisors and operators to read the meters. Requirements for calibration must also be specified at the time of installation. Meters must be easy to access and read.

3.2.3.2 Flow control and balancing capacity

As a general rule, treatment plants should avoid sudden changes of flow rate as far as possible. Sudden increases in flow tend to have a negative impact on settled water and particularly on filtered water quality. Furthermore, changes in flow rate require changes in chemical dose rates, which most small treatment plants struggle to get right. This is why Section 3.2.2.7 recommends increasing the chlorine dose when the flow rate changes.

Ideally, a treatment plant should be operated continuously (24 h/d) at a constant flow rate. The problem is that water demand varies continuously throughout the day. To avoid adjusting the flow every day or every few days, it should be set the daily average flow rate (total volume of water over a 24 h period). However, for this to be feasible, the plant must have sufficient **balancing capacity** in its finished water storage reservoirs. The balancing capacity is the amount by which the volume of water in the reservoirs can change without overflowing and while still providing adequate **chlorine contact time**.

> Ideally, treatment plants should be operated 24 h/d at the daily average flow rate. This requires adequate balancing capacity in the finished water reservoirs.

Providing adequate balancing capacity is a design issue and has to take into account future increases in demand. Some of the better designed and managed small treatment plants already operate in this mode. Plants which currently make daily adjustments to flow rate should also look into whether they have sufficient capacity to operate at constant rate. The calculations required are site specific and small water suppliers will probably require assistance to perform them. (See Section 4.6).

> Plants which turn on and off automatically based on reservoir levels require fewer dosing adjustments but there is generally a period of poor filtered water quality after start up. Nonetheless, this arrangement is a practical option for plants which are not manned 24 h/d and/or have very large seasonal variations in demand.

Alternatively, many small plants are set up such that the whole plant including all chemical dosing equipment shuts off automatically when the finished water reservoir level reaches a specified maximum level and starts up again when the level drops to its minimum limit. While the plant is running, the flow remains constant. The main advantage of this arrangement is it minimizes the number of dosing adjustments which have to be made. Chemical doses only have to be changed when the raw water quality changes. The disadvantage of this stop-start system is that it is not an ideal way to operate filters and settling tanks because of the sharp increase in flow at start up. (This is also true of plants which operate for fixed number hours per day because they are not manned at night). However, in the current South African situation, the advantages of more reliable chemical dosing probably outweigh the disadvantages. It also may be the most practical option for plants which have very large seasonal variations in demand, e.g. those serving holiday resorts. Nonetheless, these plants should consider reducing their flow rate to the average daily demand in order to operate continuously.

> Manual flow adjustments should be gradual rather than abrupt. Appropriate adjustments to chemical dosing rates need to be made at the same time.

Whenever it is necessary to change the flow rate manually, the rate change should be made **slowly** rather than abruptly e.g. over 5 to 10 minutes depending on the size of the required change. This will reduce the impact on settling and filtration. If the flow is to be increased, the chlorine dose rate should be increased to its new required value before starting to change the raw flow. However, if the raw flow is to be decreased, then the chlorine dose rate should only be changed afterwards. The coagulant dose rates need to be adjusted continuously in proportion to the flow.

3.2.4 Coagulation and Flocculation

3.2.4.1 Types of coagulant and dose optimisation

The most commonly used coagulants in South Africa are alum (aluminium sulphate) and various commercially available polymeric coagulants/flocculants. Some plants, especially those treating coloured waters, use ferric chloride. Adding alum or ferric chloride reduces the pH of water so when these coagulants are used, lime or soda ash is usually used as well. For alum, the pH after chemical addition should be kept between 6.0 and 7.4 to ensure good coagulation and acceptable levels of dissolved aluminium in the finished water. For ferric chloride, the acceptable pH range for coagulation is 5.0 to 8.0 (DWAF *et al.,* 2002c). By contrast, most polymers do not change the pH of the water significantly. Alum tends to be effective over a relatively wide range of doses; however, overdosing can lead to poor filtered water turbidity as a result of excess alum precipitating in the filter (post-precipitation). Furthermore, larger doses of alum compared to polymer are usually required to achieve the same final water quality, resulting in the production of greater volumes of sludge. Polymers tend to work well in a smaller range of conditions than alum. Both under-dosing and overdosing lead to poor floc formation and turbidity removal so proper control of the dose is especially important when polymers are used.

> Both overdosing and under-dosing coagulants/flocculants result in treatment problems. Therefore it is important to get the dose right.

The coagulant dose required to achieve the optimum level of turbidity removal is known as the **coagulant demand** (expressed in units of milligrams of coagulant per litre of water treated). The coagulant demand is function of several factors including the type of raw water, type of coagulant, raw water turbidity, pH and temperature. In general, higher raw water turbidities and lower temperatures require higher coagulant doses.

The coagulant demand varies with the raw water quality and in some cases, it may be necessary to adjust the coagulant dose several times a day. The optimum coagulant dose for a given water sample can be determined using the **jar test** (also sometimes referred to as the beaker test). This involves adding a range of doses of coagulant and pH adjustment chemical to 1 or 2 L samples of raw water and mixing them using the standard jar test apparatus. Floc is allowed to form and settle in each of the samples and the turbidity of the settled water is then measured. The optimum dose is the one which produces the lowest settled water turbidity.

The general procedure for the jar test is described on page 23 of *Quality of Domestic Water Supplies Volume 4: Treatment Guide* (DWAF *et al*., 2002c). However, each plant will have to work out what doses they need to test and how to apply them. This will depend on the dosing equipment, coagulants and doses used. Assistance may be required with the necessary calculations. Note: jar stirrers may be supplied with cylindrical or square beakers. Square beakers provide better mixing and should be used whenever possible. An example of a standard jar test apparatus is shown in Fig. 4.

Fig.4 Jar test apparatus

In order to apply the results of the jar test, the **raw water flowrate** and **chemical dose rates** (supplied by the dosing pumps, manual or dry feeders) must be known. Ideally, the jar test should be carried out at least once a day to achieve the most effective coagulation and whenever there is a change in the raw water quality. If the coagulant demand does not vary much, then the frequency of testing may be reduced accordingly.

However, operators must be aware that the coagulant demand will always vary when the raw water turbidity varies. If a significant increase in raw water occurs e.g. after heavy rains, operators need to be aware that the coagulant demand will also increase. If the raw water turbidity is increasing rapidly, then the operators should not wait to perform the jar test before increasing the dose. They should keep adjusting the dose up based on experience while continuing to check the raw, settled and filtered water turbidities **at least once an hour**. Once the raw water turbidity has stabilised, the jar test should be conducted in order to determine the optimum dose.

Most small treatment plants do not currently own jar test apparatuses. Operators determine whether coagulant doses are adequate from the appearance of the floc formed before the sedimentation tanks and sometimes from the taste of the water (especially when alum and lime are used). However, **these methods do not guarantee the efficient use of chemicals or optimum turbidity removal efficiency**. For example, in the Alice water treatment plant case study, it was determined that the plant could have saved in the order of R 100 000 per year on the cost of alum and lime by implementing dose optimisation using the jar test. This would easily cover the cost of purchasing the jar test apparatus (~ R 20 000).

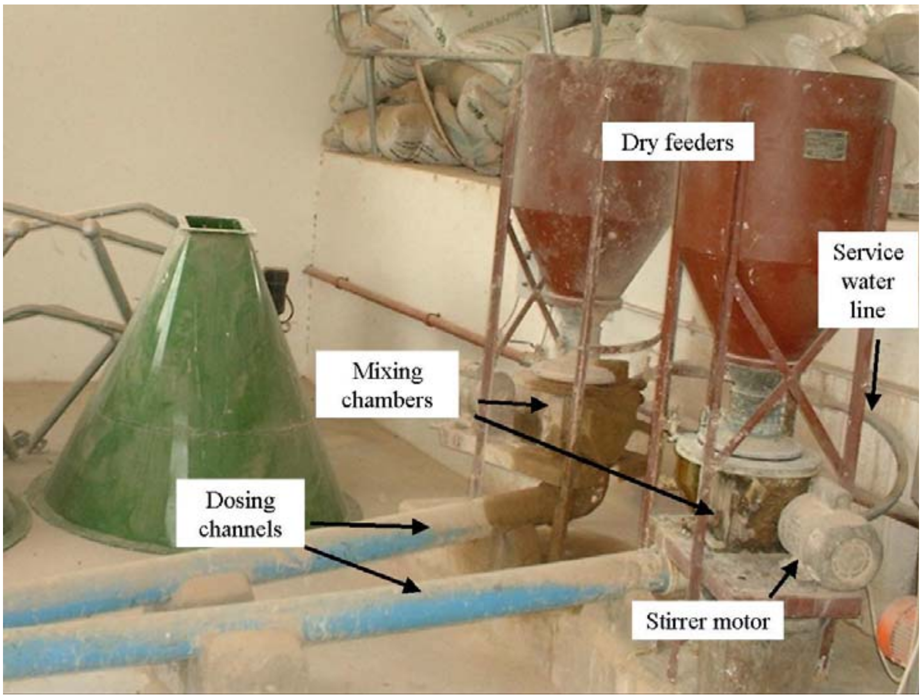
Using the jar test to obtain the optimum dose improves treatment and may save chemical costs.

3.2.4.2 Coagulant dosing systems

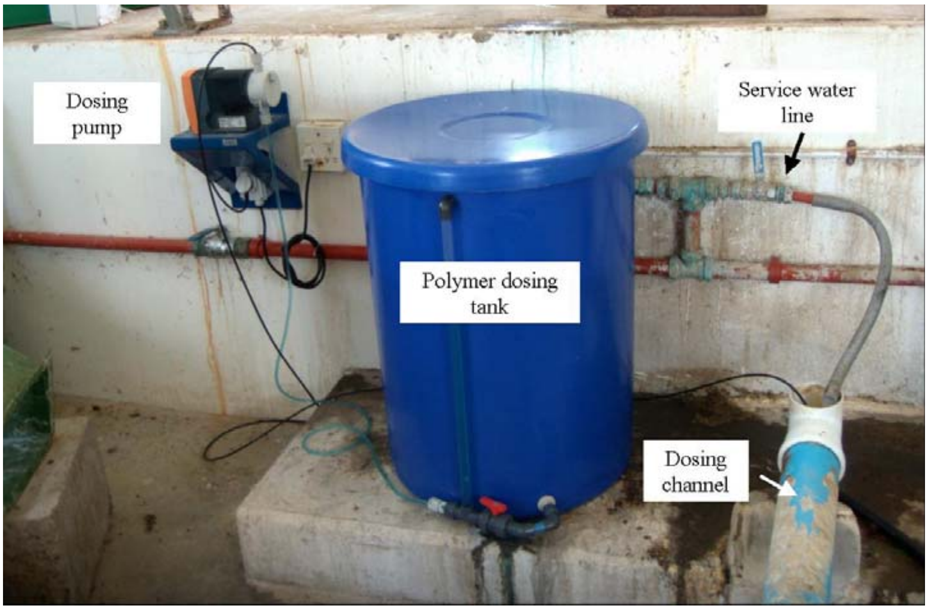
Coagulants and flocculants are usually added to the raw water as liquids, solutions or slurries (a slurry is a suspension of a granular or powdered chemical carried by water). In very small treatment plants (< 2 ML/d), chemicals such as alum which are supplied in dry form are usually first dissolved in water in **dosing tanks** (dosing solution prepared in batches). The chemical supplier or contractor who installs the dosing equipment usually provides instructions on how to make the dosing solution up (for example, 10 kg of alum in 100 L of water). The water used to make up all dosing solutions should be as clean as possible (filtered or tap water) to prevent dirt or floc particles reacting with the coagulant before it is dosed into the raw water. Dry chemicals should always be stored in a dry area at moderate and fairly uniform temperature. Most chemicals will harden and cake if exposed to moisture, so bags should be stored on pallets to allow air circulation beneath them (Thompson *et al.*, 2004).

In larger plants (> 2 Ml/d) powdered chemicals are often dosed using **dry feeders** as in Fig. 5(a). The dry feeder drops powdered chemical into a small mixing chamber at a controlled rate. A continuous stream of water carries the chemical from the mixing chamber to the dosing point. The actual flow of water through the dosing system is not important provided that it is much smaller than the raw water flow but large enough to prevent the dry chemical depositing in the chamber and dosing channel. Raw water can usually be used here as it does not spend much time in the mixing chamber before being combined with the main flow. Polymers (supplied as liquids) are sometimes also diluted in water before being dosed into the raw water channel.

When dry feeders are used, the rate of chemical addition is controlled by increasing or decreasing the gap through which the dry chemical is fed. The dosing rate can be measured by collecting and weighing the amount of chemical dropping into the mixing chamber in a fixed time period e.g. 30 s. The weight of dry chemical can be measured using a simple **kitchen scale** or balance purchased from most supermarkets. As discussed in Section 3.2.3.1, the details of dosing rate calculations for both solutions and dry chemicals are site and equipment specific and should be developed with expert help.



(a) Dry feeders for alum and lime.



(b) Polymer dosing system with dosing pump.

(c) Constant header dosing tanks. These tanks are designed to maintain a constant dosing rate without dosing pumps.

Fig.5 Coagulant dosing systems

For coagulants in liquid or solution form, the dosing rate is usually controlled by an electrically powered **dosing pump** as in Fig.5(b). However some plants use hydraulic or mechanical devices such as constant header tanks which do not require electricity. Figure 5(c) shows an example of constant header tanks.

Whatever device is used, it is important that: a) the operator can **easily** and **accurately** adjust the dosing rate when required and (b) the dosing rate remains **constant** as the dosing tank empties, unless the operator adjusts it. In some small treatment plants which currently do not have proper or functioning dosing equipment, the dosing solution is made up in a small tank or large bucket and then allowed to drip into the raw water channel via an outlet tap (This is the same system that was described in Section 3.2.2.5). The problem with this arrangement is that the dosing rate decreases as the level in the tank decreases so it is not possible to maintain the dosing rate constant unless the variation in the level in the dosing tank is kept to a minimum. Consequently, plants relying on such a system should have properly designed dosing equipment installed as soon as possible.

In addition to having a dosing system which can maintain a constant dosing rate, the operators need to know how to **set and measure the dosing rate**. The equipment supplier or consultant should demonstrate the calibration of the equipment to the operators when it is installed. The **calibration** is the relationship between the settings on the equipment and the actual dose rate delivered in litres/hour. For example, the rate setting on most dosing pumps is marked off in %. If the pump is set at 50 %, it should deliver approximately 50 % of its maximum flow. The maximum flow is given in the operating manual and may also be engraved on the pump itself, usually in units of litres/hour (L/h).

> Liquid dosing systems must be able to deliver a **constant dose rate**. The operator must also be able to **easily** and **accurately** adjust the dose rate when required.

However, the operators and their supervisors must be aware that **the calibration of dosing pumps does not always remain constant**. Over time, as the pump becomes worn, the maximum dose rate is likely to drop. In the short term, clogging and/or the development of air bubbles in the dosing lines may also cause variations in the dosing rate. The operators should check the dosing lines to make sure they have not become clogged at least once a day and whenever there is an unexplained increase in settled water turbidity. The operators or supervisor should also check the calibration of the dosing pump or other dosing device once a month. If the measured flow at a given setting is more than 5 % different than it should be

> The calibration of dosing pumps for all chemicals dosed should be checked at once per month and the calibration redone if it is more than 5 % in error.

based on the calibration data, the operator should first check that there is no clogging in the line and then redo the calibration if necessary.

Checking the dosing rate and calibrating the dosing device is greatly facilitated if a clear plastic **sight glass** is installed on the dosing tank as shown in Fig. 6. A rigid tube should preferably used but a flexible tube is also acceptable provided that it is clamped firmly in a vertical position. When the valve between the sight glass and the tank is open, the level should be the same in both. (This also gives the operator a quick check on the dosing tank level). When the valve is shut off, the level in the sight glass will start to drop rapidly. The operator can measure the time taken for the level to drop between calibration marks on the sight glass in order to determine the dosing rate.

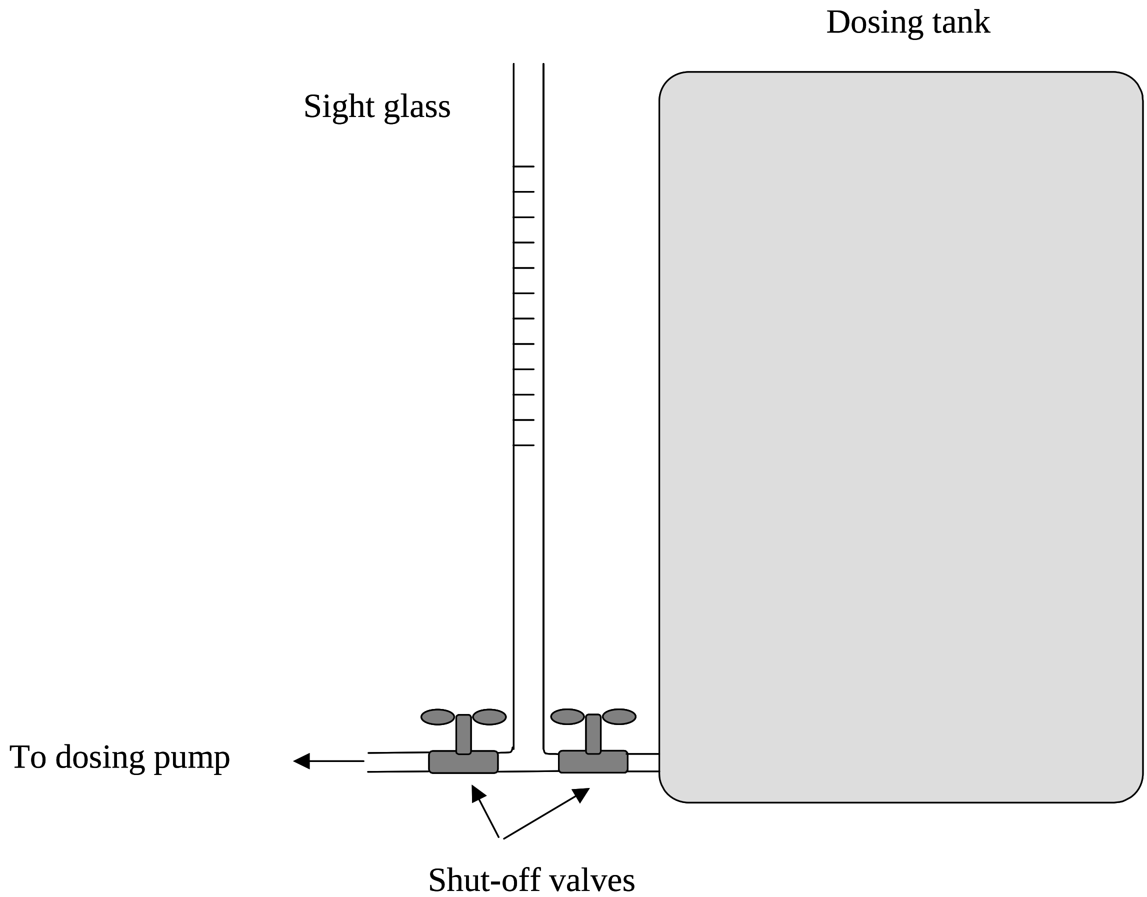
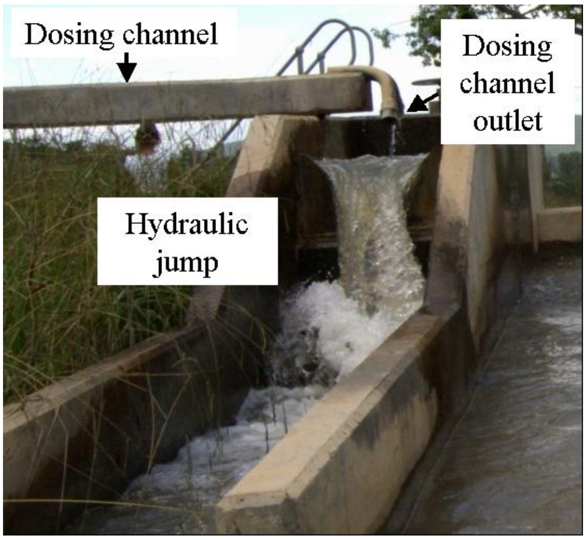


Fig. 6 Dosing tank with sight glass.

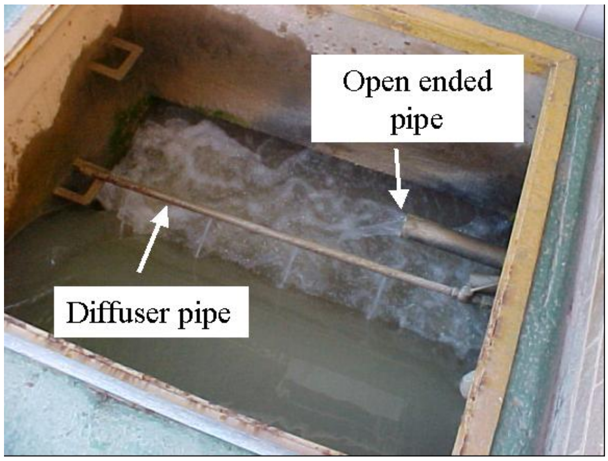
3.2.4.3 Mixing for coagulation and flocculation

Mixing plays an extremely important role in the efficient use of coagulant and the growth of settlable floc. Failure to provide adequate mixing can result in poor turbidity removal and/or waste of coagulant. First, the coagulant must be rapidly and evenly mixed with the raw water (rapid or flash mixing) and then a period of gentle mixing is required to promote the growth of large, rapidly settling floc.

Rapid or flash mixing for small conventional treatment plants is usually accomplished with hydraulic jumps. These are steep drops of at least 50 cm over which the raw water flows (DWAF, 2004). The coagulant and pH adjustment chemical are usually added either at the top of the jump or just below it where maximum mixing occurs. Examples of chemical dosing at hydraulic jumps are shown in Fig. 7. Chemical diffusers consisting of pipes with small holes through the coagulant flows are often used to ensure a more even distribution of chemical in the raw water, especially when dosing into wider channels. An example of a diffuser pipe is shown in Fig. 6(b). Diffusers can be constructed cheaply and easily from short lengths of PVC pipe. However, the required size of the diffuser holes depends on the type, strength and flow rate of the chemical solution and expert assistance may be required to determine the correct size. Diffuser holes are prone to clogging and operators should inspect and clean them on a regular basis.



(a) Hydraulic jump



(b) Diffuser pipe above hydraulic jump

Fig. 7 Coagulant dosing at hydraulic jumps

Some larger plants use mechanical mixers (stirrers) to provide flash mixing but this option is not commonly used in small treatment plants because of the additional maintenance requirements. In package plants, treatment chemicals are generally injected directly into the raw water pipe. Rapid mixing is typically provided by a static mixer (an immobile mixing device built into the pipe) or chemicals may be injected before a raw water pump so that mixing is provided by the pump itself.

Most small treatments also use hydraulic mixing for flocculation. Fig. 8 shows a typical baffled flocculation channel. Gently local mixing is achieved by forcing the water to flow around the turn at the end of each section of the channel. In package plants, the same effect be achieved using sections of pipes.

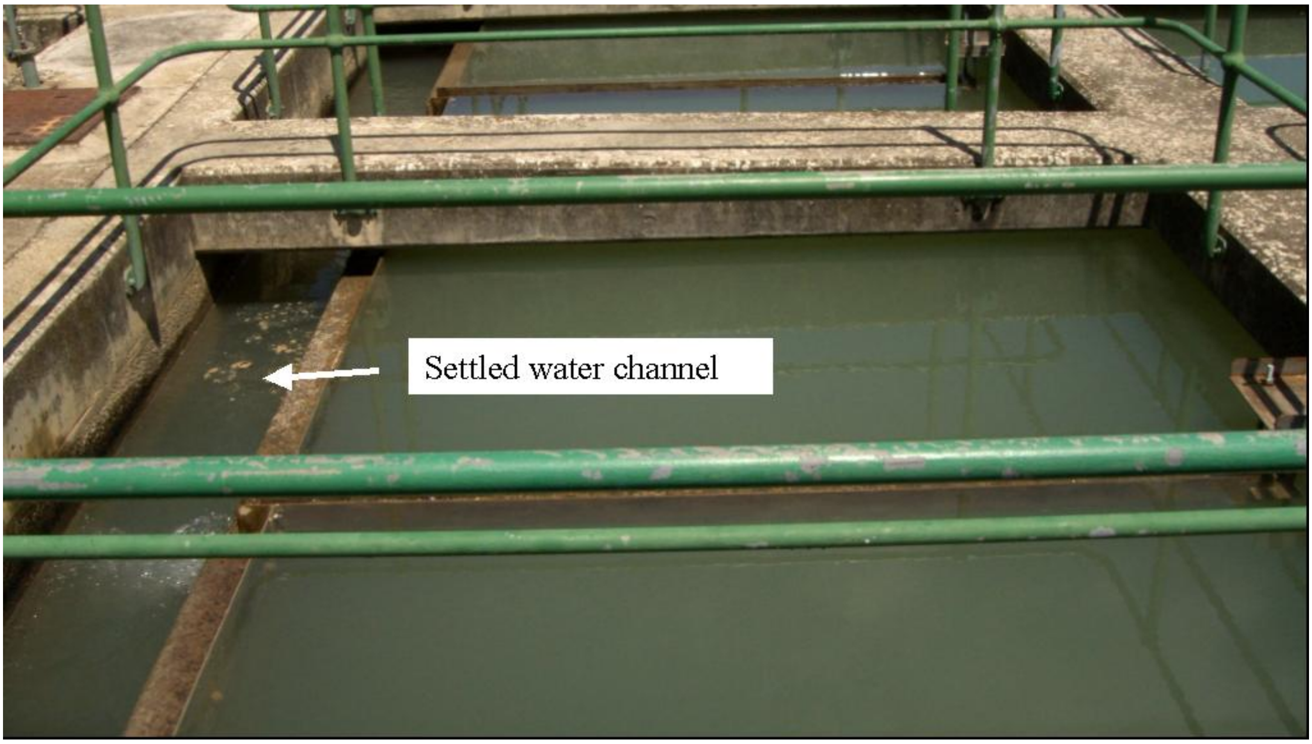
Flocculation channels and pipes are not required in all treatment plants. Some settling tanks, such as floc blanket clarifiers are designed so that most flocculation occurs in the settling tank itself. However, some small treatment plants do not have adequate flocculation in either the flocculation channels or settling tanks and settling performance suffers as a result. Assessing the adequacy of both rapid mixing for flash mixing and slow mixing for flocculation generally has to be carried out by personnel with some background in **water treatment design**.

Inadequate mixing for coagulation and flocculation may result in poor floc formation and settling performance. However, several other factors also affect floc formation. Assessing the adequacy of mixing requires some background in design.

Fig.**8** Flocculation channel.

3.2.5 Sedimentation

In conventional treatment, sedimentation is the process in which most of the original contaminants that were in the raw water are removed. Sedimentation occurs in tanks or basins known as **settling tanks**, **settlers** or **clarifiers**. Floc formed in the coagulation and flocculation stages sink to the bottom of these tanks while the settled water overflows into the **settled water launders**. The settled floc forms a sludge layer at the bottom of the tank which is periodically removed by **desludging.**.



(a) Small horizontal settling tank

(b) Horizontal settling tank with collection launders extending into the main body of the tank

(c) Radial flow clarifier with travelling bridge.

Fig. 9 Horizontal and radial flow clarifiers.

3.2.5.1 Types of settling tanks

There are many different designs of settling tanks or clarifiers but they can generally be classified as either horizontal flow, radial flow or up flow (sludge blanket). Fig. 8. shows examples of horizontal and radial flow clarifiers.

Horizontal flow clarifiers are usually large rectangular concrete basins (Fig. 8(a) and (b)). Flow enters at one end and overflows into the clarified water launders at the other. Well designed horizontal settlers usually have launders extending back into the body the tank to increase the length of the weir over which the settled water flows.

In radial flow clarifiers, the flocculated water is introduced through a central feedwell and flows outwards to clarified water launders around the edges of the tank. This kind of clarifier is usually circular but can also be square. Radial flow clarifiers may be large concrete tanks but smaller package plant type units are increasingly used for upgrading existing plants. The larger radial flow clarifiers often have rotating travelling bridge systems which either scrape sludge into sludge hoppers in the floor of the tank or suction it up. Fig.(c) shows a radial flow clarifier with a travelling bridge.

In upflow or sludge blanket clarifiers, the flocculated water is introduced at the bottom of the tank and flows upwards through the sludge layer which in this case is called a **sludge blanket**. Passing the feed through the sludge blanket increases the efficiency of floc removal. However, the problem with this type of clarifier is that the sludge blanket is easily lost if it is not operated and desludged carefully and this leads to a reduction in performance. Sludge blanket clarifiers are not commonly used in rural treatment plants.

3.2.5.2 Factors affecting the efficiency of sedimentation

The most important factor affecting sedimentation is **coagulation** efficiency. If the wrong coagulant dose is applied or rapid mixing of the chemicals is inadequate then the floc formed will not settle well. The **flocculation** stage is also very important: the larger the floc formed, the better they will settle. It is therefore important to ensure that the floc is not broken up between the flocculation channels and settling tanks. **It is never acceptable to pump water from the flocculation channels to the clarifiers** as this will destroy the floc. Consequently, settling tanks must always be situated below the flocculation channels and not above them. Where flocculation takes place inside a pressurised pipe, the clarifiers may be located above the section where flocculation occurs

> Flocculation **channels** should always be located above the settling tanks so the flocculated water can flow under gravity. Passing flocculated water through a pump will break up the floc.

provided that there is sufficient pressure to lift the flocculated water to the clarifier inlet without further pumping.

The efficiency of sedimentation is also strongly influenced by both the flow rate and the degree of mixing in the clarifiers. The slower the flow through the clarifier, the easier it is for floc to settle out. Conventional clarifiers are generally designed to a handle a maximum **surface loading rate** of 1 m/h. The surface loading rate is the flow through the tank in m^3/h (cubic metres per hour) divided by the surface area of the tank in m^2. Operators need to ensure that the flow is split evenly between equally sized clarifiers.

Mixing and short-circuiting (some water travels through the clarifier much faster than the rest of the flow) results in floc carrying over into the clarified water and therefore needs to be minimized. Some degree of mixing and short-circuiting occurs in all basins but it can be made worse as result of windy conditions and density currents. Density currents can occur at high raw water turbidities and when the temperature of the flocculated water is different to that of the water in the clarifier (Thompson *et al*, 2004). Reducing mixing and short-circuiting is primarily a design issue. The clarifier inlet and clarified water collection system must be designed to ensure the flow distribution is as even as possible. Baffles are also typically used to reduce short-circuiting. In addition, the operators need to check the flow into the settled water launders is evenly distributed along their length and that the weirs are kept clear of debris and floc deposits.

The growth of bacterial slimes and algae (furry green coatings) on clarifier walls is a common problem, especially in summer. Algae and bacteria cause taste and odour problems and may clog the weirs or the filters if they detach. Pre-chlorination may help to prevent biological activities and the walls can also be treated to with mixture of copper sulphate and lime (10 g of each per litre of water) painted onto the walls (Thompson *et al*, 2004).

Efficient operation of the settling tanks requires regular **desludging**. Excessive build up of sludge will reduce the volume in which settling can occur and the sludge may become more difficult to remove the longer it is left in the tank. The sludge can also become biologically active which can lead to taste and odour problems and in some cases, the release of iron and manganese back into the water.

Some clarifiers have automatic desludging systems but most clarifiers in small rural treatment plants have to be desludged manually. More frequent desludging is required when the raw water turbidity increases. Even with regular desludging, sludge deposits tend to accumulate on the sides of clarifiers without mechanical scraping systems. These clarifiers have to be periodically drained and cleaned out. Every treatment plant should therefore have at least settling tanks so that one can keep operating when the other is taken off-line for maintenance.

3.2.6 Filtration

Filtration is the final step in turbidity removal in conventional treatment. Water is passed through a layer of sand or other granular material such as anthracite and dirt or floc particles are removed by sticking to the grains. Filtration is the most difficult step for operators to get right and it is nearly impossible to meet turbidity standards when filters are not working properly. Consequently, filter problems are a common cause of poor treated water quality in rural water supplies. There are many different filter designs currently been used in small treatment plants and all have limitations of which operators and supervisors are often not aware. Filters can be classified as rapid filters (filters which have to be backwashed), slow sand filters (filters which have to be scraped) and pre-coat filters (filtration occurs through a thin layer of e.g. diatomaceous earth coated onto collector tubes). Pre-coat filters are not commonly used and will not be discussed here. This section discusses the most common types of filters in use and some important operating issues which impact their long-term performance. For more information on both rapid and slow sand filters see Section 2B of *Quality of Domestic Water Supplies Volume 4: Treatment Guide* (DWAF *et al*., 2002).

3.2.6.1 Rapid filtration

Typical examples of rapid filters used in small treatment plants include conventional filters, pressure filters and valveless or self-backwashing filters. The common characteristic of rapid filters is that once they have clogged up, they are cleaned by backwashing. Backwashing involves sending a flow of water and sometime also air up through the clogged media to dislodge the deposited floc. Filters should be backwashed as soon as any of the following occur:

(a) The filter reaches its maximum headloss (maximum pressure or degree of clogging. If the filter is not backwashed, the filtration rate will start to decrease).
(b) The filtered water turbidity starts to increase, even though coagulation, flocculation and sedimentation seem to be working well (discussed in Section 3.2.6.2.1).
(c) The maximum filter run time is exceeded (discussed in Section 3.2.6.1.3).

The most common types of rapid filters used in rural treatment plants are conventional filters, pressure filters and valveless filters. Examples of each type of filter are shown in Fig. 10.

Conventional gravity filters consist of a sand bed in a concrete tank with nozzles or orifices in the floor which allow the filtered water to pass through. These filter are expensive to construct and tend to be used mainly in larger treatment works while pressure filters and valveless filters are popular in smaller plants. The sand bed in a pressure filter is located inside a pressurised tank.

(a) Conventional rapid filters.

(b) Pressure filters.

(c) Valveless filter.

Fig. 10 Common types of rapid filters.

Clarified water is pumped into the filter by the filter pump. The filter pump usually provides sufficient pressure to also pump the filtered water into an elevated finished water storage reservoir. The filter pump is also used for backwashing. Valveless filters are designed to operate under gravity and to be able to backwash themselves automatically when a certain headloss (degree of clogging of the filter sand) is reached. They are called "valveless" filters because no valves have to be opened or closed for the filter to backwash.

Rapid filters have a number of limitations which need to be understood if they are to be used effectively and if appropriate actions are to be taken when the they develop problems. Various factors which affect filter performance are discussed next.

3.2.6.1.1 Factors affecting the efficiency of filtration.

As in the case of clarifiers, the efficiency of turbidity removal in filters depends very strongly on the effectiveness of coagulation. It also depends on the flow through the filter and on there being an even flow distribution. Scouring of the surface of the filter bed by the filter influent must be avoided.

3.2.6.1.2 Variations in filtrate turbidity during the filter run

During normal filter operation, the filtrate turbidity does not remain constant but varies with time. At the beginning of the run, there are usually two to three hours of relatively poor filtrate turbidity. While this is normal, the operator should try to ensure that the filtered water turbidity remains less than 1 NTU. High filtrate turbidities after backwashing can indicate:

(a) Coagulation is inadequate.
(b) Backwash was stopped to soon. Backwash should be continued until the turbidity of the dirty backwash water drops to 10 NTU.
(c) The filter bed was not adequately cleaned because backwash is inadequate (discussed further in the next section).

After the first few hours, if the filter is working properly, the filtrate turbidity should improve. However, if the filter is run for too long, the filtrate turbidity may start to get worse again. This is known as **terminal filter breakthrough**. The filter should be backwashed as soon as terminal breakthrough is observed and preferably before.

3.2.6.1.3 Adequacy of backwash

The most challenging part of the operation of rapid filters is ensuring that the filter media (sand or other granular material) is adequately cleaned during backwashing. Floc which remains attached to the filter grains after backwashing tends to accumulate and form solid masses known as mudballs. Inadequately cleaned areas of filters also tend to shrink during filtration resulting in cracks n the filter bed through which dirty water can pass without being properly filtered. The deterioration of the filter media can go unnoticed for some time, especially in valveless and pressure filters where the operator cannot see the filter bed. However, filter performance will eventually be affected. Typical signs of filter media problems include:

- The filter clogs up very quickly even though the settled water turbidity is low
- The filtered water turbidity is poor throughout the filter run even though coagulation, flocculation and sedimentation appear to be adequate.

Once filter has developed these problems, the filter media usually has to be replaced. It is now widely accepted that it is not possible to clean filters properly with water backwash alone. Some kind of auxiliary backwash system is required to prevent dirty filter problems developing. In South Africa, the most common form of auxiliary backwash involves blowing compressed air through the filter (air scour). However, this is not necessarily a suitable option for small rural treatment plants. There is a danger of seriously damaging the filter floor or blowing the sand out in the washwater if the air is not applied correctly. Furthermore, air scour systems not only add a significant cost the plant but also need regular maintenance to f unction properly.

Consequently, many filters in small treatment plants are installed without auxiliary backwash facilities. This includes all valveless filters and some pressure filters. These filters will typically develop problems within one to two years of clean filter media being installed. Consequently, municipalities must be prepared to change or chemically clean the filter media at least every two years and probably every year.

> Plants with rapid filters without auxiliary backwash will have to replace or chemically clean the filter media every 1 to 2 years.

Other factors which negatively affect backwash efficiency include overdosing coagulant/flocculant, allowing filters to run for too long without backwashing and uneven and/or inadequate backwash flow. The longer filters run without backwashing, the more difficult it is to remove the floc deposits (Brouckaert, 2004).

Filters with auxiliary backwash should be backwashed at least once every 48 hours. Filters without auxiliary backwash should be backwashed at least once a day.

Filters which have air scour backwash should be backwashed after 48 hours at most while filters without air scour should be backwashed at least once a day. Backwashing in conventional and pressure filters is usually initiated by the operator. Backwash in valveless filters is initiated by the filter clogging up, but can also be manually initiated. Operators should to be trained to initiate backwash manually if necessary when the filters are installed. Operators need to keep track of when the filters are backwashing automatically and make sure that backwash occurs at least once a day.

Filters should be designed to ensure that the backwash flow is appropriate for the size and weight of the filter grains and is evenly distributed across the filter floor. Poor backwash design will lead to poor backwash efficiency. However, backwash flow problems can also develop over time. Filter nozzles and backwash pipes can become clogged causing the backwash flow in some or all areas of the filter to drop. The development of large mudballs and clogged regions also contributions to uneven backwash flow. In conventional filters, the operator can easily see evidence of poor flow distribution during backwash (including air distribution) however, he will not be able to see what is going on inside a pressure or valveless filter. He should, however, always report any apparent drop in the overall backwash flow observed at the point where the dirty water is discharged.

Whenever the filter media is replaced, the filter nozzles and pipes should be inspected for signs of damage or blockage. Any work done on filters which involves removing the sand and exposing the filter floor should only be done by experts in filter refurbishment because of the risk of damaging the nozzles.

3.2.6.1.4 Filter media size and depth

The performance of filters is also strongly dependent on both the depth of the filter bed and the size of the filter media. If the sand is replaced, the replacement sand must be exactly the same size as the original sand and the filter must be filled to the original design depth. Note that the bed depth can change during operation as a result of number of factors including mudablling which tends to cause the bed height to increase (Brouckaert *et al*, 2003) and media losses which tends to cause it to decrease). The design media size and depth should be given in the plant operating manual or may obtained from the company which installed or upgraded the filter.

If the bed height is too short, poor filtered water turbidities may result. If too much sand is added, it may be washed out during backwashing. It may also result in air binding of the filters if there is insufficient water level above the top of the bed. Air binding involves the formation of air bubbles in the filter which cause it to clog up more quickly than it should. It is more likely to occur if the water level above the filter is too low. For filters fed by gravity, the water depth above the bed should not be less than 0.5 m. Air binding does not happen in pressure filters because high pressure causes dissolved gases which form air bubbles to stay in solution.

3.2.6.2 Slow sand filtration

3.2.6.2.1 Principle of operation

Slow sand filters differ from rapid filters in several key respects: The filtration rate is much lower in slow sand filters (0.1 m/h compared to 5 to 10 m/h) and the sand is smaller (0.3 mm in size compared to 0.5 to 1 mm in size for rapid filters. In rapid filters, floc penetrates deep into the filter bed and consequently the whole bed has to be backwashed. In slow sand filters, floc, micro-organisms and dirt particles are mainly removed in a thin layer which forms at the top of the filter. When the filter clogs up, this layer can simply be scraped off. Note this layer, known as the *schmutzedecke* is biologically active, and plays an important role in the removal of pathogens by slow sand filters. Consequently, there should not be any chlorine in the influent to slow sand filters. Filters typically operate for several weeks or months between cleanings, depending on the characteristics of the water being filtered. The sand removed during scraping may be cleaned and replaced or discarded and replaced with fresh sand.

3.2.6.2.2 Advantages and disadvantages of slow sand filters

Slow sand filters have a number of advantages which make them attractive for use in small treatment plants:

(a) The filters are simply to operate. They can be operated successfully by workers or community members with minimal training.
(b) The design of slow sand filters is very simple. They have no backwash pumps and there are few things which can go wrong with them. They are therefore cheaper to operate and maintain than rapid filters..
(c) They can be effective in removing pathogens even without the use of coagulant. By contrast, the removal of pathogens in rapid filters is strongly dependent on effective coagulation.

Slow sand filters have traditionally been operated without any chemical pre-treatment. However, this option is only suitable for very high quality raw waters because turbidity removal is generally poor when coagulant is not used. In South Africa, a number of small treatment plants use slow sand filtration instead of rapid filtration following conventional coagulation, flocculation and sedimentation. Disadvantages of slow sand filters include the following:

(a) As a result of much lower filtration rates, slow sand filters have to be much bigger than rapid filters to treat the same amount of water. Consequently, the initial cost of slow sand filters tends to be higher than rapid filters

(b) When slow sand filters are used on their own (without coagulation, flocculation and sedimentation), they cannot achieve the same turbidity removal as conventional treatment and can clog up too quickly when the raw water turbidity increases.

(c) Operators do not like cleaning the filters and the dirty filter sand manually.

Municipalities currently using slow sand filters should consider their options carefully before replacing them with rapid filters. Some may be tempted by the convenience of having filters which can be backwashed as opposed to the tedious manual process of cleaning slow sand filters. However, they are often not aware of the many operating and maintenance problems which they are likely to encounter with rapid filters.

Major advantages of slow sand filtration for small treatment plants

- Simplicity of operation.
- Low operating costs.
- Effective removal of bacteria when the *schmutzedecke* develops.

3.2.7 Stabilisation

Chemical stabilisation is an important part of conventional treatment but is unfortunately neglected in many small treatment plants in South Africa. The negative effects of not providing chemical stabilisation may not be observed immediately and some municipalities appear to believe that they can cut costs by leaving it out of their treatment process (Hinsch, 2003). This section explains what chemical stabilisation is and why it is necessary both to reduce operating costs and improve the quality of the water provided to consumers.

3.2.7.1 Why chemical stabilisation is important

The chemical stability of water refers to its tendency to either form chemical scales on surfaces in water pipelines and fixtures or to corrode materials used in the construction of the distribution system (DWAF *et al.*, 2002c). Both excessive scale formation and corrosion have serious economic consequences for water service providers and consumers. Excessive scaling reduces the capacity of pipes and can damage kettles and geysers. Associated costs include:

- Increased pumping costs.
- Cost of cleaning or replacing pipes.
- Cost of replacing equipment and appliances.

> Corrosive waters can seriously damage metallic and asbestos-cement pipes, pumps, valves and flow meters, metallic plumbing fixtures and concrete. Failure to stabilise finished water will lead to increased pumping and maintenance costs and may lead to catastrophic system failures. No Water Services Provider can afford to ignore the need for adequate corrosion control.

Corrosion can damage metal and asbestos-cement pipes, fittings and even concrete structures such as reservoirs (Schock, 1990; Kawamura, 1991). This leads to leaks, significantly increased water losses and increased maintenance requirements. Corrosion also has a negative impact on the microbial quality of the water. Corrosion products (chemicals released into the water or deposits formed on the pipes as a result of corrosion) consume chlorine and therefore make it difficult to maintain an adequate chlorine residual. Biofilms (bacteria growing on the pipe walls) find it easier to grow on corroded surfaces than on clean smooth surfaces. Biofilms consume chlorine, can cause taste and odour problems, may harbour dangerous pathogens, increase the number of bacteria in the water at the point of delivery and can even increase the rate corrosion. Increased costs associated with corrosion include:

- Increased pumping costs due to corrosion products.
- Water losses and lost water pressure due to leaks.
- Replacing corroded pipes.
- Repairing damage to concrete structures.
- Water damage to dwellings and businesses and the necessity of replacing corroded fittings and water heaters.
- Dealing with consumer complaints about “coloured water” (due to corrosion products), stained laundry and plumbing fixtures as well as unpleasant tasting water.
- Increased chlorine dosing requirements.

PVC piping, which is widely used in the distribution systems of small treatment plants in South Africa, is fortunately resistant to corrosion. However, since every distribution system includes concrete and metallic elements, it is imperative that **all** Water Services Providers take steps to minimize corrosion in their systems.

3.2.7.2 Calculating and adjusting the chemical stability of water

The chemistry of both corrosion and scale formation are quite complicated but the tendency of the water to form scale tends to increase with increasing pH and hardness (calcium and magnesium concentration) while the corrosiveness of the water tends to increase with decreasing pH and decreasing hardness. Waters with total hardness (sum of calcium and magnesium ions) less than 75 mg/L as $CaCO_3$ are classified as soft whereas waters with total hardness greater than 75 mg/L are classified as hard (Benefield and Morgan, 1990).

Chemical stabilisation involves adding certain chemicals to water to prevent both excessive amounts scale formation and corrosion. This is usually achieved by adjusting the pH to ensure that the finished water is slightly over-saturated with calcium carbonate. Water which is over-saturated with calcium carbonate tends to form a small amount of calcium carbonate scale on the surfaces of pipes and fixtures. While a large amount of scale is undesirable, a thin film of calcium carbonate tends to protect metal pipes and fixtures from corrosion. Ensuring that the water is over-saturated with calcium carbonate also prevents corrosion of cement –asbestos pipes and concrete structures such as storage reservoirs.

The tendency of water to form calcium carbonate scale can be expressed as its calcium **carbonate precipitation potential** (**CCPP**). A **finished water** calcium carbonate precipitation potential of at least 4 mg/L is recommended while the total **total hardness** should remain in the range 50 – 100 mg/L as $CaCO_3$ (Thompson *et al*, 2004). Water with a negative potential to form calcium carbonate scale (i.e. water which tends to dissolve calcium carbonate) is treated with a chemical which tends to **increase pH**. The most commonly used chemical for increasing pH is **lime**. However, many plants are switching to **soda ash** (Na_2CO_3) because it is easier to handle. If on the other hand the CCPP value of the water is too high, then **carbon dioxide gas** is added to the water to reduce the pH.

The following information is required to calculate the CCPP of water and determine its potential to corrode various materials (Murphy, 2002):

- On-site pH
- On-site temperature
- Electrical conductivity (EC)
- Alkalinity
- Magnesium concentration

- Calcium concentration
- Calcium hardness
- Chloride concentration
- Sulphate concentration

Most small treatment plants and municipalities do not have the facilities to measure all of these parameters in-house and consequently the analysis for water stability would probably be done by an external laboratory on a weekly or monthly basis (Note: it is important that pH and temperature are measured on site). The calculation of CCPP is also quite complicated and is usually performed using a spreadsheet or computer software, such as **STASOFT** (Morrison and Loewenthal, 2000). STASOFT can be purchased from the South African Water Research Commission (WRC). Some background in chemistry and familiarity with computers is helpful.

In practice, the calculations would be used to determine an acceptable range of **final water** pHs and expected doses of the pH adjustment chemical(s). The operators would then adjust the chemical doses to get the final water pH in the target range. Note that if alum or ferric chloride is used for coagulation, the amount of lime or soda ash required will generally increase with increasing coagulant dose.

An alternate and widely used indicator of the corrosive tendency of finished water is the **Langelier Index** (LI). The LI of water is the actual pH of the water minus the pH of the same water at which CCPP would be 0. Since the solubility (amount which can dissolve in water) of calcium carbonate tends to decrease with increasing pH, a positive value of LI usually corresponds to a positive value of CCPP while a negative value of LI corresponds to a negative value of CCPP. A value of LI ~ 0.2 is generally recommended (Kawamura, 1991). LI has several limitations including that it does not always correctly predict whether CaCO3 will precipitate or not and it also does not predict how much will precipitate (Schlock, 1990). Therefore it is preferable to use CCPP rather than LI.

3.3 OPERATION OF PIPED WATER DISTRIBUTION SYSTEMS

Once treated water leaves the chlorine contact tank or finished water reservoir, it typically spends several hours to several days in the distribution system. The distribution system consists of all the pipes, storage reservoirs and pumping stations between the treatment plant and the taps or community standpipes where consumers obtain their water (point of delivery). Depending on the quality of the finished water, the state of the distribution system and the length time that water remains in the distribution, the quality of the water at the point of delivery may be substantially worse than the quality of the finished water at the treatment plant.

Chlorine residual is one of the primary indicators used to assess the microbial quality of water and the adequacy of treatment. The chlorine residual in the treated water helps to prevent the growth and proliferation of microorganisms and provides some protection against re-contamination. However, free chlorine disappears over time and will eventually disappear completely if the water is not used quickly enough. Factors which cause the chlorine to disappear more quickly include high finished water turbidities, high dissolved organics concentrations (including colour), corrosion, the presence of biofilms and other organic or inorganic deposits in pipes and the contamination of treated water with untreated water as a result of leaks, backflow and cross-connections.

This section discusses the impact of various aspects of the operation of the distribution system on water quality. Distribution system management is also discussed in *Quality of Domestic Water Supplies Volume 5: Management Guide* (DWAF *et al.*, 2002d). Section 4 of this reference provides guidelines on responding to specific problems that may arise in the treated water supply. However, for a comprehensive review of the management of piped water distribution systems, see *Safe Piped Water* (Ainsworth, 2004) published by the World Health Organisation (WHO).

3.3.1 Preventing the development of biofilms in the distribution network

Biofilms are coatings of living bacteria which become established on the walls of pipes and reservoirs in the distribution system. Biofilms negatively impact water quality in several ways:

- They may cause taste and odour problems.
- They may harbour dangerous pathogens.
- Individual cells or clumps of bacteria break off from the walls and increase bacterial counts (specifically heterotrophic plate counts) in the water at the point of delivery.
- Biofilms consume chlorine, reducing the chlorine residual.
- They may increase the rate of corrosion of the surfaces they are attached to.

One of the main reasons for trying to maintain a chlorine residual in the distribution system is to prevent biofilm growth in the first place. However, biofilms may still develop if:

- **Chlorine is not consistently applied**. For example, if there is no chlorine or inadequate chlorine for several weeks, then biofilms will become established. Once they are established, restoring the chlorine dose to recommended levels usually will not get rid of the biofilms.

- **If there are significant levels of turbidity and biodegradable organic material in the finished water**. Turbidity shields bacteria from chlorine and bacteria feed on biodegradable material. The presence of both turbidity and organics will also reduce the chlorine residual.
- **Pipes are corroded or coated with organic or inorganic deposits**. Biofilms establish themselves more easily on rough corroded surfaces than smooth clean surfaces.

In order to prevent biofilm development it is important to:

- **Reduce turbidity, organic matter and bacteria in the finished water** to the lowest levels possible.
- **Maintain a consistent and adequate chlorine residual** in the finished water and throughout the distribution system.
- **Minimise corrosion** in the distribution system by ensuring that the finished water is adequately stabilised.
- **Minimise the potential for untreated water to seep into the reticulation system** (discussed further in Section 3.3.3).
- **Monitor heterotrophic plate counts** in both the finished water and at various points in the distribution to determine where biofilms may be developing.

Once biofilms have become established they usually have to be removed by shock dosing of disinfectant and/or high velocity flushing or swabbing of the pipes. Methods and strategies for cleaning pipe networks are discussed in Chapter 4 of *Safe Piped Water* (Ainsworth, 2004).

3.3.2 Storage reservoir design and operation

Most towns have several domestic water storage reservoirs which serve different zones in the supply area. Water is pumped to reservoirs located above the treatment works while reservoirs located below the plant may be fed by gravity. Reservoirs may be operated with either variable or constant level. **Level indicators** are usually used to determine when the flow to the reservoir needs to be either increased or decreased. In many cases, automatic level control systems are used: the level sensor on a reservoir sends signals to the pumps feeding the reservoir to turn them on or off. When the reservoir level drops to the minimum allowed value, the pumps are turned on and when the level reaches the allowed maximum, the pumps are turned off.

Reservoirs which are fed under gravity (water flowing downhill with no pumping required) from other reservoirs are often operated at constant level. A **float valve** on the inlet opens when the reservoir level starts to drop and closes when the reservoir level starts to rise. This simple scheme prevents the lower reservoir overflowing when the flow at the outlet drops.

Off-site storage reservoirs provide additional storage capacity for:

- **Meeting peak flow requirements (balancing capacity).** They allow the treatment works to operate at a relatively constant rate even though the water demand in the supply area varies from hour to hour.
- **Having a sufficient supply of water on hand for fighting fires.**
- **Providing residents with an uninterrupted supply of water** during both scheduled (for maintenance or construction) and unscheduled (emergencies and system failures) down time at the treatment works.
- **Providing additional chlorine contact time** if the contact time at the treatment works is insufficient.

Elevated reservoirs are used to increase the pressure in the distribution system so that consumers getting a sufficiently strong flow at the point of delivery. Unfortunately, storage reservoirs also significantly increase the amount of time that water remains in the distribution system and this can negatively affect water quality. The chlorine residual even in very clean water gradually disappears and will eventually drop to zero. The longer the water remains in storage reservoirs or stagnant areas of the pipe network, the more time bacteria have to recover from the disinfection process and start increasing in numbers again.

Particular attention needs to be paid to storage reservoirs and areas of the distribution system where demand is low. Some towns and villages have a only a few days total storage capacity at most while others have storage tanks designed with future demand in mind. These tanks may be much larger than the area's current need and can have very long **retention times** if operated closed to 100 % full (See Section 3.2.2.3 for the calculation of retention time). As a result the chlorine residual in the water may disappear before the water reaches consumers and there is an increased chance of bacterial re-growth. Problems may also arise when there is a chain of reservoirs with one feeding into another as shown in Fig. 11 It may be difficult to maintain an adequate residual in supply zone 4 without having unpleasantly high levels of chlorine in zones 1 and 2.

Other factors which affect the quality of water stored in reservoirs include the degree of mixing in the reservoirs and their general sanitary state. Section 3.2.2.3 discussed the importance of minimising the amount of mixing in tanks and reservoirs used for providing chlorine contact time. The opposite is true for reservoirs which are used only for storage i.e. those reservoirs which do not have chlorine addition at the inlet. In this case, the greater the degree of mixing and the shorter the effective contact time, the better the water quality. Small length to width ratios are preferred and baffles are generally not recommended (Ainsworth, 2004).

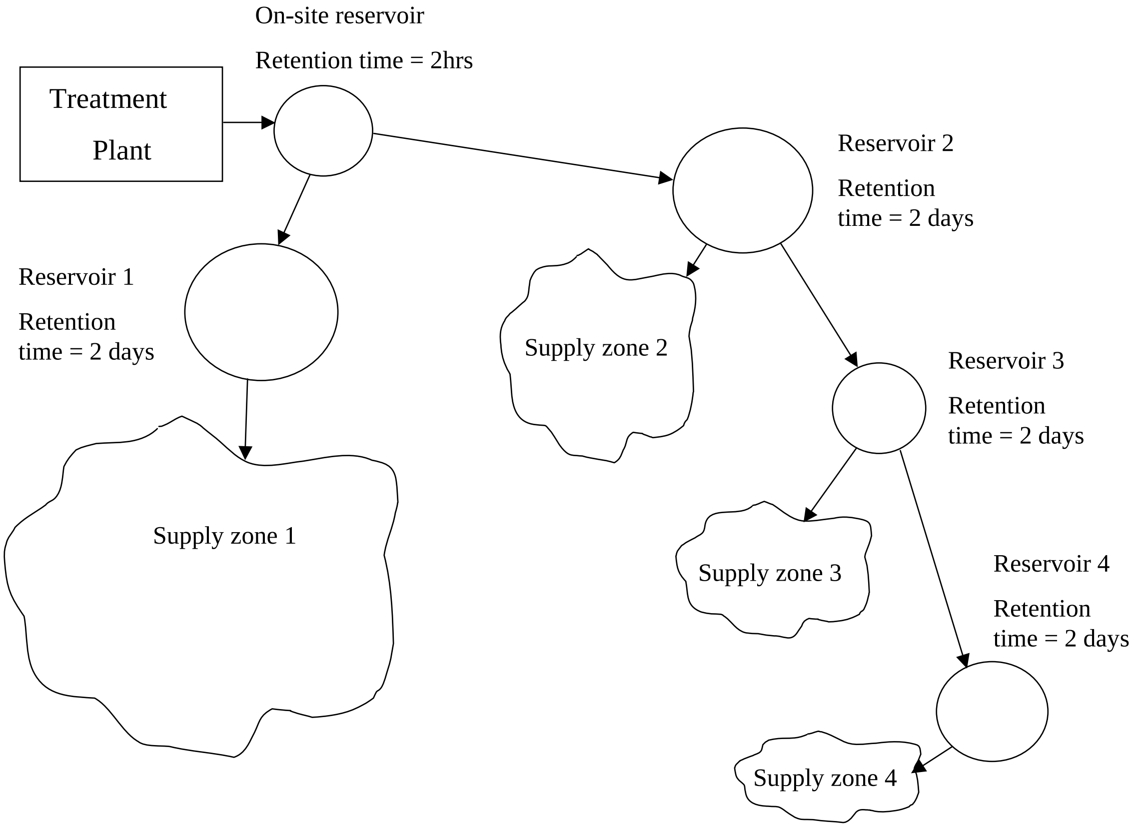


Fig. 11 Example of a distribution system with several off-site storage reservoirs.

Treated water storage reservoirs must be covered and secured to prevent contamination of the stored water. Reservoirs should be drained and cleaned every 1 to 5 years depending on the rate of accumulation of sediment in the reservoirs.

Maintaining the sanitary condition of reservoirs is extremely important (Ainsworth, 2004). All reservoirs holding treated water need to be covered and secured to prevent contamination by humans, animals and litter. All access hatches should be kept locked except for inspections or sampling and reservoirs should be fenced off. Vents should be designed to prevent animals and foreign objects entering the reservoir. A suitable design is a U-shaped pipe or duct with a mesh covered opening facing downwards. In addition, reservoirs should be drained and cleaned out with pressure hoses or approved chemical treatments every 1 to 5 years. This is because sediments which tend to settle out in the reservoir will tend to consume chlorine, making it difficult to maintain an adequate residual. The required frequency of cleaning will depend on the efficiency of turbidity removal at the treatment works, water quality at points downstream of the reservoir and visual evidence of damage or contamination of the reservoir. It is extremely important that personnel tasked in cleaning reservoirs are properly trained in sanitary procedures. Details are given in Tarbet, Thomas and Brown (1993).

If it is not possible to maintain chlorine residuals within acceptable levels in all parts of the supply area then the following options may be considered:

1. **Reducing the operating level.** Reducing the operating levels of reservoirs reduces the average retention time and therefore the loss of chlorine residual. For reservoirs operated with varying level, this means lowering the minimum level to provide no more than two days average retention time at average daily flow. The average daily flow is the average volume of water flowing out of the reservoir in one day. This number may vary seasonally. For reservoirs operated at constant level, the operating level must be lowered. Where the inlet valve is operated by a float, the float arm can simply be lengthened so that the valve closes at a lower operating level. Whatever arrangement is made, it must be easy to change back if the average demand increases and the average operating level needs to be increased again.

2. **Introducing booster chlorination.** Booster chlorination involves dosing additional chlorine at points in the distribution where long retention times are a problem. This makes it possible to maintain adequate chlorine residuals at the farthest points in the distribution system without excessively high chlorine levels in the water delivered to consumers closer to the plant. The most convenient point to deliver booster chlorination is the inlet of storage reservoirs. HTH will usually be the most practical option for off-site chlorination. If a dosing pump is to be used, there must a suitable power source and the dosing system must be protected from the weather. Other options including floating swimming pool chlorinators and manual dosing by municipal workers. Manual dosing should be at least at least once a day. Both manual dosing and floating chlorinators should be kept as close to the reservoir inlet as possible to ensure that the chlorine is mixed with as much of the flow as possible. When booster chlorination is used, it is important to ensure that workers can visit the reservoir regularly to replenish the chemicals. Furthermore, the chlorine residual needs to measured at various points below the reservoir to ensure the system is working as intended.

3. **Introduce chloramination.** Chloramination produces a longer lasting disinfectant residual than chlorination and therefore is a potential option for distribution systems with long retention times. However, there is a risk of nitrites formation in stagnant areas (LeChevallier and Au, 2004). Furthermore, the successful application of chloramination requires a high level of operator skills and the maintenance of high safety standards (Thompson, 2003). Consequently, it is not suitable for use in most small treatment plants under present conditions.

3.3.3 Minimising the risk of contamination in pipe networks

Apart from inadequate disinfection at the treatment plant or contamination of reservoirs, there are several other ways that microbes can enter pipes in the distributions system. These include contaminated water seeping into leaky pipes when the pressure in the distribution system drops, cross-connections, backflow and failure to maintain hygienic conditions during construction and repair of pipe networks (Ainsworth, 2004). The chlorine residual in the treated water will generally be insufficient to kill off microbes entering the pipe network via any of the above routes, but the sudden disappearance of the residual may be an indication that contamination has occurred. Therefore routine monitoring of chlorine residual and microbial quality at various points in the distribution system is important for detecting possible contamination.

Leaking pipes and intermittent (not continuous) water supply pose a major risk to the microbial safety of water. While the pressure in the distribution system is high, water tends to leak out of the pipes. Although this is wasteful, there is little risk of contaminants entering the pipes against the flow. However, if the water supply is shut off for any reason then the pressure in the pipes will drop. Consequently, dirty water from outside the pipes may seep in through the leaky pipe walls. In order to avoid contamination by this route, it is important to:

- Minimise disruptions in pressure and water supply.
- Minimise leaks.

Water services providers should any case seek to minimise leaks because the wasted water represents an increase in operating costs without an increase in revenues. Strategies for reducing leakage include:

1. Installing meters at various points of the distribution system to determine where significant water losses are occurring.
2. Repairing leaks promptly when they occur.

3. Maintain the operating pressure throughout the distribution system below 900 kPa or if feasible, below 600 kPa to reduce the risk of pipe bursts.
4. Using appropriate materials and construction methods in the pipe network.
5. Stabilising the treated water to minimize corrosion.

Current regulations already specifically require Water Services Authorities and Providers to implement the first three points (DWAF, 2002b). The last four points also apply to sewers and wastewater lines because leaking wastewater poses a threat to any drinking water lines it comes in contact with.

The risk can be reduced by locating water pipes a safe distance from sewer lines wherever possible. For, example regions in the United States recommend that water and sewer mains should be separated by at least 3 m horizontally and 45.7 cm vertically (Great Lakes, 1997). It is also undesirable to have water lines passing through stagnant pools of water e.g. in flooded drains (Ainsworth, 2004).

A **cross-connections** is any connection between the piped domestic water supply and any potential source of contamination. Cross-connections are most likely to occur on private property (residential and commercial) where the Water Services Provider has less control over the plumbing arrangements (Ainsworth, 2004). However, since they may affect the safety of water supply supplied to other consumers in the vicinity, they are very much the Water Services Provider's concern.

The most dangerous type of cross-connection is **accidental connections between potable water and wastewater pipes**. In order to prevent this from occurring:

- The Water Services Provider and Water Services Authority must keep up to date maps of all domestic water, sewer and industrial wastewater lines.
- Potable water and wastewater lines should be easy to tell apart e.g. different colour pipes could be used.
- Connections should be made only by properly trained, authorised personnel.
- All illegal connections should be removed as soon as they are discovered.

Other types of cross-connections can potentially contaminate the piped water supply as a result of **backflow**. Backflow may occur if the pressure in the distribution system drops or if a high back pressure is applied at the point of delivery. Backflow events have been identified as the most common cause of waterborne disease outbreaks in the United States (Dyksen, 1997; Craun, 1981). Examples of potential sources of cross-connection due to backflow include beverage dispensers, hose pipe sprayers, water jetting equipment and fire sprinkling systems (Ainsworth, 2004). Strategies for preventing backflow include:

- Installing backflow prevention devices where hazards are identified.
- Minimising disruptions to the water supply.
- Educating consumers about the dangers of cross-connections.
- Implementing a cross-connection management programme.

For more information on cross-connection control see Chapter 3 of *Safe Piped Water* (Ainsworth, 2004). For detailed guidelines see the *Australian and New Zealand Standard AS/NZS 3500.1.2:1 National plumbing and drainage code. Part 1.2: water supply — acceptable solutions.* AS/NZS (1998) or *Manual M14: Recommended practice for backflow protection and cross connection control* (AWWA, 1990). South Africa does not currently have national guidelines on cross-connection control. However, backflow prevention is discussed in Annex F of SANS 10252-1 (SABS 0252-1), *Water supply and drainage for buildings: Part 1: Water supply installations for buildings* (SABS, 2004a). South African regulations (*Government Gazette, Vol. 432 No. 22355, 8 June 2001*) do however require that all consumer installations other than meters comply SANS 10252/SABS 0252 (SABS, 2004a) and SANS 10254/SABS 254 (SABS, 2004b).

There is also a significant risk of contamination of pipes during construction and maintenance. While every precaution should be taken to minimise contamination of pipework (see Chapter 5 of *Safe Piped Water* (Ainsworth, 2004) for details), it is inevitable that some dirt will get into the lines. Therefore lines should be disinfected and thoroughly flushed until all the dirt has been washed out. Pipes can be disinfected by placing powdered HTH in the lines before sealing them (Ainsworth, 2004). Local users should be warned that the disinfectant may cause taste and odour problems and discolouration of the water for a period of time (DWAF *et al.*, 2002d).

Strategies to prevent contamination of pipe networks:

- Minimise flow disruptions.
- Minimise leaks and pipe bursts.
- Locate water pipes away from sewer mains and areas where stagnant pools of water collect.
- Prevent cross-connections and backflow.
- Adopt hygienic work practices and disinfect lines after installation or repair.
- Monitor chlorine residual and microbial quality at point of delivery to identify potential problem areas.

3.4 PROCESS CONTROL

Water treatment plant operators are all aware that the characteristics of the raw water they are treating changes from time to time. The quality of **borehole water** tends to change the least while the quality water extracted directly from **rivers** tends to change the most. The raw water can be more or less dirty and it may be more or less difficult to form a floc which settles easily. Even the change in temperature from winter to summer can affect how difficult it is to treat the water. (It is harder to form floc in cold water). Furthermore, there are variations in water demand which may require changes in raw water flow rate. Consequently, operators need to make adjustments to the operation of the plant from time to time in order to meet changing treatment requirements. They also need to check that the adjustments that they are making are having the desired effect

The efficient production of safe drinking water requires the implementation of proper **process control procedures**. Process control involves **measuring** the performance of the various treatment processes (including storage and distribution) and **adjusting** the operation of these processes to achieve the desired performance. The most important process control measures involve the dosing of treatment chemicals. For process control to be effective, an appropriate system for measuring treatment effectiveness needs to be in place. Such a system will have three key components:

i) What parameters (turbidity, pH, etc.) need to be monitored and what procedures and equipment are required for sampling and analysis (measurement).

ii) At which stages of the treatment will samples be collected/measurements be made.

iii) What is the **frequency** of sampling (how often are samples collected and analysed).

Process control requires that a further two components be specified:

iv) Acceptable **ranges of values** for the measurements made must be defined

v) **Procedures** for adjusting the treatment processes to meet required performance standards must be established.

The number of different operational parameters monitored for process control will depend on the size and complexity of the plant, the treatment objectives and the skill of the operators. Every treatment plant should be equipped to measure at least **turbidity**, **pH**, **free chlorine, filter run time, flow rate** (See Section 3.2.3) and/or **hours of operation**. These are all easy to measure if the right equipment is available and all have an impact on the efficiency of treatment. In addition, operators need to be able to carry out the **jar test** to select the **optimum coagulant dose** and should record all dosing rates. The **operating levels**, **flows** into and out of and **hours of pumping** for all storage tanks and reservoirs in the distribution system should also be recorded.

A vital part of monitoring and process control is **record keeping**. All measurements must be recorded on **logsheets** along with the time and date they were measured and any comments. All **process control decisions** and adjustments (including time and date) should also be recorded. This is vital for correctly interpreting the results and for improving process control procedures in the future.

Monitoring for process control should be carried out both at the treatment plant and at various points in the distribution system. Monitoring on the plant should be undertaken by the operators as part of their daily routine. Monitoring and process control in the distribution system is more complicated because there are many more possible sampling points, there are few operating variables which can be adjusted and it is difficult to tell what is going on in the pipes and at the bottom of reservoirs. Process control actions also take much longer to have a measurable effect therefore past experience is important in making the correct decisions.

The Water Service Provider should set up a system for monitoring at least **pH**, **turbidity** and **chlorine residual** in tap water from around the distribution system. The area supplied by the treatment plant should be divided into different zones based on an **up to date map of the distribution system** and **at least one** sampling site should be selected in each zone. There should be at least on site for each **storage reservoir** and **main line** and one for **each type delivery point** in a given zone (inside tap, yard tap or public standpipe). Sampling should be carried out all sites **monthly** but not necessarily all on the same day. Monitoring data collected by the WSP should be compared with data collected by any external monitoring groups (for example data collected on behalf of the Water Service Authority as required by national regulations) however, it is not necessary for all the same sampling sites to be used in both cases.

The following sections describe how the process control monitoring data will be used to make process control decisions.

3.4.1 Turbidity

Turbidity is used to assess the efficiency of the **coagulation**, **flocculation**, **sedimentation** and **filtration** processes. It is also required to access the quality of water at the point of delivery and can provide an indication of various processes in the distribution system which can negatively impact water quality. These include sedimentation in the reservoirs and pipelines, biofilm development and corrosion. Turbidity should be measured at the following points: raw water, settled water, filtered water, finished water, point-of-use. It is **not** necessary to measure the turbidity of the flocculated water. If there are more than one settling tank and/or filter, the settled or filtered water from each individual unit should be measured if possible. This is particularly important in the case of filters since they perform differently at different times in their cycle (See Section 3.2.6). Both slow and rapid filters tend to produce higher than average turbidities just after backwashing/scraping while the filtered turbidity from a rapid filter may also start to get worse towards the end of its cycle. In this case, the filter should be backwashed as soon as the worsening quality is observed.

Table 9(a) lists the points in the treatment plant where turbidity should be measured, the frequency of sampling and the recommended control limits. Raw water here refers to the raw water inlet before coagulation. Note that in the case of turbidity, operators should try to keep improving the turbidity of the filtered and finished water, even if it is already good. This is because the lower the turbidity, the more efficient disinfection becomes and the smaller the chance that any pathogens will get into the final water. Table 9(b) provides a list of possible causes of poor turbidities at each stage of the treatment process and corrective actions.

TABLE 9(a) TURBIDITY MONITORING					
Sampling point	Frequency	Person	Target Ranges (NTU)		
			Ideal	Good	Acceptable
Raw water	At least once per shift, preferably once every two hours. More often when raw water turbidity high or turbidity removal targets not met	Operator/ supervisor	-	-	-
Settled water*			< 2	< 5	< 10
Filtered water			< 0.1	< 0.5	< 1.0
Finished water (after on-site reservoir)**			< 0.1	< 0.5	< 1.0
Distribution system *** At least one sample per zone and for each type of delivery point.	Monthly or whenever a complaint is received from the area.	Supervisor	< 0.1	< 1	< 10

* In addition to meeting the target turbidity values, the settled water turbidity must be significantly less than the raw water turbidity. For example, if the raw water turbidity is 2.5 NTU and the settled water turbidity is 1.9 NTU then there is clearly a problem with coagulant dosing and/or the sedimentation process.

** The filtered and finished water indicates that sediment is settling out in the finished water reservoir. This is a problem because the layer of sludge which develops in the reservoir will exert a high chlorine demand.

*** The turbidity of tap water samples is often higher than that of filtered and finished water. This is not necessarily a problem, but a sudden and excessive increase in turbidity in tap water samples not related to treatment plant performance should be investigated further. A significant decrease in turbidity between the treatment plant and consumers' taps suggest that excess turbidity is settling out in storage reservoirs. See previous comment.

TABLE 9(b) PROBABLE CAUSES OF TURBIDITY PROBLEMS AND CORRECTIVE ACTIONS *		
Sample	Possible cause	Control action
Raw	Heavy rains.	Usually operators have no direct control over raw water quality but some plants have the option of switching between sources. For river abstraction, stopping abstraction for short periods during storms and floods may be considered in order to avoid the worst quality raw water (DWAF *et al*, 2002d). When significant changes in raw water turbidity are observed, the operator must be prepared to make appropriate adjustments to chemical doses. See Sections 3.2.2.7 and 3.2.4.2.
Settled water	The most likely cause is incorrect coagulant dose.	The jar test should be used to find the correct dose.
	Very high raw water turbidity.	See comments for raw water.
	Plant flow rate is too high.	Adjust down if possible and extend hours operation if necessary. The settling tanks may be operating above their design capacity and may require upgrading.
	Settling tank requires desludging.	Desludge.
	Excessive mixing in settling tanks due to wind or thermal currents.	See Section 3.2.5. Design modifications may be required. Increase filter backwash frequency and chlorine dose while problem persists
	Sludge blanket has been lost due to excessive desludging or other reasons.	Dose bentonite if facilities available. Increase filter backwashing and chlorine dose until new sludge blanket develops.

* If there are problems with the settled water turbidity, then problems with filtered water and finished water should also be expected. First the probable causes of poor settling should be addressed, and then if the problems with filtered water turbidity persist, these should be addressed separately.

TABLE 9(b) CONT. PROBABLE CAUSES OF TURBIDITY PROBLEMS AND CORRECTIVE ACTIONS		
Filtered water	Post-precipitation. This can occur when alum, lime or ferric chloride is overdosed.	Conduct the jar test to determine the optimum dose.
	A filter has been taken off-line for backwashing or has just returned to service after backwashing.	Keep monitoring filtered water turbidity and temporarily increase chlorine dose until turbidity improves. Also check whether backwashing is being stopped too quickly. The turbidity of the dirty backwash water should drop to 10 NTU before backwash is stopped.
	Mudballing and filter cracking.	Replace or chemically clean filter media as soon as possible. Investigate whether filter backwash is too weak (See Section 3.2.6). In the mean time increase the chlorine dose until the problem is fixed.
	A slow sand filter has been returned to service after being scraped.	Raise the chlorine dose in the filtered water until the turbidity is within an acceptable limit.
Finished water or off-site storage reservoir	Scouring of sludge accumulated in storage/contact tank.	Drain and scour reservoir to remove sludge.
	Dirty water leaking in from an external source.	Repair leak. Clean and disinfect tank/reservoir.

3.4.2 pH

pH is a critical control parameter because it impacts the efficiency of three key processes, namely coagulation, disinfection and stabilisation. The pH control strategy has to take into account the requirements of all three processes. Many small treatment plants are not setting sufficiently tight control limits for pH. Supervisors should note that the ideal pH range of 6.0 – 9.0 specified in *SABS-241* does not correspond to appropriate control limits for conventional treatment plants. For example, pH 6 water may be corrosive while disinfection efficiency will be deceased at pH 9.

The pH of the flocculated water has to fall in the acceptable range for the coagulant used (see section 3.2.4). The optimum pH for coagulation can be determined from the jar test (Section 3.2.4.1). If there are no further chemical additions between flocculation and filtration then the pH should not vary much between the flocculated and filtered water. An increase in pH between the flocculated and settled water when lime is used for pH adjustment suggests that the lime was not completely dissolved at the flocculated water dosing point. When alum is used, a drop in pH between the settled and filtered water combined with poor filtered water turbidity indicates overdosing of alum and **post-precipitation**. Other factors which could cause variations in measured pH include instrument problems (instrument drift), disruptions in dosing and biological activity in the treatment units. The optimum pH range for stabilisation has to be determined from the calculation of calcium carbonate precipitation (Section 3.2.7). As a general rule, the pH of the finished water should be not more than 8.0 for disinfection to be adequate but not so low that the water is corrosive. A lower limit of pH 6.5 is recommended.

TABLE 10

pH MONITORING

Sampling point	Frequency	Person	Target Ranges (NTU)		
			Ideal	Good	Acceptable
Raw water	At least once per shift, preferably once every two hours. Flocculated water pH should be checked more often when coagulant and lime/soda ash doses being adjusted.	Operator/ supervisor.	-	-	-
Flocculated water			Determined from jar test.	6.0 – 7.4 (alum*) 5.0 – 8.0 (ferric) For other coagulants, check with manufacturer/supplier.	
Settled water					
Filtered water					
Finished water	At least once per shift, preferably once every two hours.		Based on disinfection efficiency and corrosion control requirements for specific system .	6.5 – 8.0 **	
Point of use (distribution system) ***	Monthly. Daily if problem detected or reported by public.	Supervisor and/or monitoring agency.	6.0-9.0	5.0 – 9.5	4.0 – 10.0

* This pH range is required both to ensure good coagulation and to prevent high aluminium residuals in the finished water (DWAF *et a*l., 2002c)

** This pH range is recommended for ensuring adequate disinfection efficiency and for reducing the risk of corrosion in the distribution system

***The control limits for pH at the point of use are those specified by SABS-241. A large change in pH between the finished water and point of use indicates possible problems with corrosion, scaling and/or biological activity in the distribution system.

3.4.3 Free chlorine residual

Free chlorine residual is the primary indicator of **microbial safety** used in process control. Although it is extremely important to monitor the actual microbial quality of the water microbial analysis takes hours or days to yield results, by which time it is too late to prevent poor quality water reaching consumers. By contrast, chlorine can be measured almost instantaneously and any necessary adjustments to operation can be made within minutes.

One of the most important steps in water treatment is ensuring there is an adequate chlorine residual in the finished water. However, the Water Services Provider must also ensure that sufficient free chlorine remains in the water at the point of delivery. Establishing **control limits** for chlorine residual is more difficult than for turbidity or pH because it depends on the size of the distribution system, the state of the pipes and reservoirs and the length of time that water is being stored at various points. This is why routine monitoring of chlorine residual throughout the system is required to determine the effect of the chlorine dose at the plant on the quality of the water received by consumers in various areas of the supply zone. In addition to ensuring that all the requirements for adequate disinfection are met in the finished water (See Section 3.2.2.4) the **supervisor** needs to ensure that the chlorine residual is between 0.1 mg/L and 1 mg/L at all points in the distribution system. It may be quite difficult to meet these requirements at all points simultaneously. Slightly higher chlorine residuals may be permitted at public standpipes. This is because

- These delivery points are always contaminated with microbes from the people collecting water there and from the animals usually roaming free in the vicinity.
- The containers used to collected the water are usually not properly cleaned and disinfected
- The water is generally stored in the containers for a period of time before being used.

Sampling points and required ranges of chlorine residual are summarised in Table 11(a). Monitoring chlorine residual at the point of delivery is an important way of detecting a variety of problems within the distribution system. The most common reason for an insufficient chlorine residual at the tap is inadequate chlorine dose at the plant. However, there are a number of reasons why the chlorine residual may be absent at the tap in certain parts of the supply area even when chlorine dosing appears to be adequate. Possible causes of inadequate chlorine residuals and corrective actions are summarised in Table 11(b).

Every time an inadequate chlorine residual is detected in a tap water sample, the cause needs to be investigated and the situation in that particular area needs to be **monitored on a daily**

basis until the chlorine residual is restored. In the mean time, **local residents and businesses should be warned** of the potential threat to the safety of their water and advised to take precautions.

TABLE 11(a) CHLORINE RESIDUAL MONITORING					
Sampling point	Frequency	Person	Target Ranges (mg/L)		
			Ideal	Good	Acceptable
Finished water (after on-site reservoir)	At least once per shift, preferably once every two hours. More often when raw water turbidity high or turbidity removal targets not met	Operator/ supervisor	At least 0.5 mg/L at pH less than 8.0 and turbidity less than 1 NTU after at least 30 minutes effective contact time (See Sections 3.2.2.3 and 3.2.2.7)		
Distribution system*. At least one sampling point in each zone and for each type of delivery point.	Monthly. Daily if problem detected or reported by public.		0.3 – 0.6	0.2 – 0.3 or 0.6 – 0.8	0.1 – 0.2 or 0.8 – 1.0**

* Reference: *Quality of Domestic Water Supplies Volume 1: Assessment Guide* (DWAF *et al.*, 1998)

** A slightly higher limit is acceptable if the water is not used immediately.

TABLE 11(b) PROBABLE CAUSES OF CHLORINE RESIDUAL PROBLEMS AND CORRECTIVE ACTIONS *		
Sample	Possible cause	Control action
Finished water	Chlorine dose inadequate	Increase dose
	Filtered water turbidity too high	See Table 9(b)
	Accumulated sediment in finished water reservoir consumes chlorine. Another clue would be a drop in turbidity between the filtered and finished water.	Clean reservoir. Improve turbidity removal
Point of delivery	Chlorine dose at plant inadequate	Check plant chlorine dose. Note that it takes several hours or days for water to travel from the treatment works to point of delivery in certain areas of the distribution system. There may have been a dosing disruption a few days earlier although the current dose is correct. **Check the plant operating records** and keep monitoring the situation.
	High turbidity in the filtered and finished water results in rapid disappearance of the chlorine residual	See Table 9(b)
	Sediment deposited in storage reservoirs exerts a high chlorine demand. (Another clue would be a decrease in turbidity after the reservoir).	Clean reservoir. Ensure reservoir properly covered and secured and to prevent small animals, leaves, debris and rubbish getting in. Improve turbidity removal at plant (Table9(b))

TABLE 11(b) CONT. PROBABLE CAUSES OF CHLORINE RESIDUAL PROBLEMS AND CORRECTIVE ACTIONS		
Sample	Possible cause	Control action
Point of delivery	**The growth of biofilms in pipes and slimes in reservoirs**. This may be accompanied by taste and odour problems at the point of delivery. This is usually the result of inadequate chlorine dosing, corrosion and aging the pipes.	Maintain effective chlorine dosing. Implement corrosion control. Some sections of pipe may need to be replaced in severe cases. Once biofilms are established, shock dosing with chlorine or chloramines, high pressure flushing or mechanical cleaning should be considered.
	Consumption of chlorine by corrosion products. This may be accompanied by other evidence of corrosion such as rusty water at the point of delivery	Implement corrosion control. Some sections of pipe may need to be replaced in severe cases. High pressure flushing or mechanical cleaning can be considered.
	Contamination of the piped water due to leaks or cross-connections with sewage and wastewater lines	Repair all leaks promptly (water or wastewater). Be particularly careful with water lines passing through flooded areas. Keep up to date maps of all water and sewer lines and records of all repairs to lines. Implement a cross-connection prevention programme. Removal all illegal connections and educate public about the danger of cross-connections.
	Contamination of the storage reservoirs due to leaks or small animals or birds or rubbish getting into them.	Cover and secure all reservoirs to prevent any foreign materials entering them. All access hatches should be sealed and locked.
	Stagnant areas within the distribution system, especially storage reservoirs with much more capacity than required	Possible solutions include operating reservoirs at lower levels (no more than 1 week average retention time). Booster chlorination may be considered. (See Section 3.3.2).

3.4.4 Other control parameters

In addition to turbidity, pH and free chlorine residual, several other operating parameters need to be **monitored**, **recorded** and **adjusted** when required. These are listed in Table 12.

TABLE 12

OTHER PROCESS CONTROL PARAMETERS

Operating Parameter	Frequency	Comments
Flow rate (raw, filtered, finished, recycle)	At least once per shift and every time the flow rate is changed.	**Flows should be changed gradually** rather than abruptly. Both the **instantaneous flow** and **daily average flow** must be recorded. The instantaneous flow is used to calculate required dose rates. The average daily flows are used to calculate water losses and balancing requirements,
Hours of operation	Daily	If the plant or any part of it does not operate continuously, then the hours of operation must be recorded. If the plant is shut down and started up manually, then the operator must record the **shutdown** and **start up times**. If shutdown and start up is automatic then the operator should record the number of hours on the **pump hour meters**.
Reservoir levels	Daily and whenever the flow rate is changed manually.	Reservoir levels are required to calculate the chlorine contact time and flow balancing requirements (Section 2.3.3).
Desludging of settling tanks	Depends on plant design and raw water characteristics.	If settling tanks are desludged manually then the operator must record **which tank is desludged, the time and date, the number of minutes the sludge valve is open and any comments about the quality and appearance of the sludge**. This information can be used to determine whether the desludging procedure needs to be adjusted.

TABLE 12 CONT. OTHER PROCESS CONTROL PARAMETERS		
Operating Parameter	Frequency	Comments
Filter run time (rapid filters) and filter backwash	At least once a day if no auxiliary backwash (air) otherwise at least once every 48 hours. These time limits apply whether the plant operates continuously or not.	Filters should be backwashed if the turbidity breakthrough occurs, the maximum pressure drop /headloss is achieved or if the maximum run time is reached. The **time of each backwash for each filter** should be recorded. This is to assist in the interpretation of filtered water turbidity data. The **duration of backwash** (number of minutes) should also be recorded along with any comments about the appearance of the washwater. If possible the operator should take a sample of the washwater **at the end of backwash** and check that the turbidity has dropped to about 10 NTU. If the turbidity is much higher the length of backwash should be increased. If the turbidity is lower than 10 NTU, the length of backwash may be decreased.
Jar test	Once a day or when the raw water turbidity changes.	Records of all jar test results should be kept along with the **time** and **date** of each test. This will assist in the analysis of trends in coagulant demand and consumption.
Chemical dose rates	Once per shift and whenever adjusted.	The **times** and **dates** of all dose rates adjustments must be recorded. All **calibration checks** should also be recorded.
Calcium carbonate precipitation potential (CCPP)	Monthly	The calculation of CCPP is required to determine the optimum pH range for stabilisation. Since the raw water characteristics change over time, the stabilisation requirements must be continuously reviewed.
Off-site storage reservoir levels and pumping hours.	Weekly	These should be recorded weekly by the supervisor or the plumbing department in order to monitor reservoir retention times.

In addition, plants which have problems with **iron, manganese** and/or **colour** will have to introduce process control strategies for these parameters. Iron and manganese are common problems in borehole water and may also occur in dam water at certain times of year. Colour here refers to dissolved organic compounds in the water which give it a brownish appearance even when all particles have been removed. This is a common problem in the Western Cape. It is **not** the same as the muddy colour resulting from ordinary dirt particles in most other raw waters. Colour is an important consideration in disnfection efficiency because it consumes chlorine. Colour has to be removed before a stable chlorine residual can be established.

Iron, manganese and colour can all be measured using simple colorimetric methods similar to that used for chlorine. However, the actual removal of colour, iron and manganese are considered advanced treatment methods and are beyond the scope of these guidelines. Expert help is required for modifying or adding treatment processes to remove these contaminants and for establishing process control measures. For basic information on colour, iron and manganese removal, see *Quality of Domestic Water Supplies Volume 4: Treatment Guide* (DWAF *et al.*, 2002c).

3.4.5 Equipment required for process control

In order to implement process control measures, operators need to have the right equipment and instruments. The minimum requirements for equipment and instrumentation are listed below.

Equipment required for process control

- Turbidity meter.
- pH meter.
- Chlorine meter or chlorine comparator.
- Flow meters.
- Standard jar test apparatus.
- Stop watch.
- Measuring cylinders or dosing tanks with calibrated sight glasses to measure dosing rates for dosing pumps.
- Kitchen scale to measure dry chemical dose rates if dry feeders are used.
- Chlorine gas flow meter if chlorine gas is used.
- Clip board.
- Log sheets.
- Documented process control procedures.

4

ACHIEVING EFFECTIVE DISINFECTION – MANAGEMENT ISSUES

The sustainable production of safe drinking water requires **supportive** and **pro-active** (acting before rather than after problems arise) management strategies. This section discusses various management strategies for improving the quality of drinking water and areas in which management in Water Services Institutions needs to improve. **Section 4.1** discusses the implementation of **Drinking-water Quality Management** plans which have had some success in improving water quality in the Free State and Western Cape (Mackintosh et al, 2004a,b).

Sections 4.2 discusses the responsibilities of the operating staff and various levels of municipal management in ensuring that the water supplied to consumers is of an acceptable quality or consumers are warned if the water is not safe to drink. Within the Water Services Provider, the treatment plant operators and their supervisors make daily decisions which affect the quality of the water produced and supplied to consumers. They are also generally the first to notice problems with equipment which could jeopardise operations. However, **ultimate responsibility** for the safety of the water supply lies with the top levels of municipal management (Mackintosh *et al.,* 2004b). In order to ensure that the Water Service Provider is able to comply with all Compulsory National Standards (Section 2.2), management must ensure that the operating staff (operators and supervisors) have adequate training and resources to run the treatment plants, effective process control measures are in place, facilities and infrastructure are adequately maintained and operating and maintenance costs are budgeted for. Management must also constantly review performance data to ensure standards are being met. A critical part of effective management is insisting that detailed and accurate records of performance data, operational procedures and both routine and non-routine maintenance are kept.

Section 4.3 discusses three important strategies for maintaining the safety of the treated water supply. These are **developing emergency response strategies**, **ensuring treatment chemicals are delivered in time** and ensuring that **equipment is properly maintained**. **Section 4.4** discusses the importance of **good communications between management and the operating staff** while **Section 4.5** discusses the importance of **communication between the municipality and the local community** on water quality issues.

Many Municipalities (District and Local) currently lack technical capacity in several key areas, in particular those relating to water quality monitoring and treatment plant and distribution system optimisation. In the short term, partnerships with various governmental and nongovernmental organisations can assist municipalities in both monitoring and improving the quality of water produced. However, the majority of these partnerships should be seen as capacity building exercises rather than permanent arrangements. Training of both operators and managers is crucial to ensuring that municipalities become more independent and self-sufficient in the near future. It is also important that municipal management takes an active part in both determining what its specific training needs are and co-ordinating the efforts are the various organisations trying to assist them. **Section 4.6** discusses the role of partnerships, training and capacity building in helping municipalities achieve sustainable improvements in the quality of drinking water supply.

Finally **Section 4.7** discusses the importance of **external monitoring** for **protecting** and **regulating** the quality of water supplied to consumers.

4.1 DRINKING WATER QUALITY MANAGEMENT PLANS

The sustainable, efficient and effective production of safe drinking water which complies with all relevant national standards requires a holistic and pro-active approach to the entire process of water treatment and distribution. Under current regulations Water Services Authorities are required to monitor and report on the quality of drinking water supplied to all consumers in the area under their jurisdiction. However, monitoring alone will not result in any improvements in water quality. The causes of poor drinking water quality need to be determined and appropriate actions taken to resolve the problems. Mackintosh *et al.* (1999; 2004) describe a simple methodology for achieving progressive and sustainable improvements in rural water treatment schemes which they refer to as Drinking-water Quality Management (DWQM) procedures. The methodology is appropriate for both water treatment schemes operated by municipalities and community operated schemes. The development and implementation of DWQM involves four main steps:

1. Initial data collection on a water scheme. This includes relevant information on water sources, vulnerability of sources, water treatment requirements and existing treatment procedures, the drinking-water distribution network, drinking-water quality records and present drinking-water quality management procedures.

2. Collection of additional water quality data to fill in gaps in existing data. Special attention is given to sampling raw water sources, post-water treatment works, network dead-ends, high occupancy buildings, hospitals and schools, areas perceived to be problematic and any regions using untreated water.

3. Defining roles and responsibilities for operators, managers and community members. Emphasis is placed on skills training, capacity building, technical support, planning and facilitation of project implementation and increasing community participation.

4. Design and implementation of a monthly drinking water quality monitoring programme based on the findings of steps one and two, and considering the outcome of step three. This includes training operators and local community members to collect the required samples according to standard techniques, the review and dissemination of water quality data to all stakeholders and taking appropriate action when the water quality fails to comply with required standards. This includes issuing "boil order" alerts to the community if the water quality is determined to pose a significant health risk.

Water Services Authorities which have sufficient experienced and qualified personnel can work with Water Services Providers under their jurisdiction to develop appropriate Drinking-water Quality Management plans. Where the WSA lacks capacity to carry out the required monitoring, co-operative government requirements specify that Provincial and National Government must ensure that monitoring takes place. Assistance with training, capacity building and planning may be provided by a number of different organisations.

Mackintosh *et al.*, (2004a,b) describe a particularly successful example of co-operation between local and provincial government in setting up the Free State Water Quality Management Initiative. The Free State Department of Local Government and Housing conducts a monthly Consultative Audit of drinking water and treated wastewater across all Free State communities. The results of water quality analysis are reported back to local government. Since the inception of the programme, there has been a 45 % reduction in the number of samples collected from surface water based systems which exceed 5 total coliforms/100 mL and a 30 % reduction in the number of samples in which faecal coliforms were detected.

The following sections discuss specific management issues which need to be addressed in the operation of water treatment schemes under municipal control.

4.2 CLARIFYING ROLES AND RESPONSIBILITIES

For any organisation to function effectively and efficiently, there needs to be a clear framework clarifying roles and responsibilities for all the aspects of its operation. Equally important is the need for the municipal management structures at all levels to support this framework by providing adequate resources to fulfil these various roles. This is particularly critical in the case of water services providers because failure to follow proper procedures or to deal with operational problems as quickly as possible can result in treatment failures which endanger public health. A common reason for poor water quality in rural municipalities is that serious operational and maintenance problems are not dealt with in a timely fashion. This is often due to misunderstandings about who is responsible for dealing with various situations, and in many cases, how serious these situations are. Management must ensure that:

1) First, it understands what is required to produce safe water efficiently;
2) All employees know what their own particular responsibilities are and are able to perform them;
3) All employees also understand what the roles and the responsibilities of the people working above and below them are;
4) All employees, including managers, know who to report problems to and where they can ask for help;
5) All employees know what constitutes an emergency situation (a treatment failure which poses a serious risk to public health).
6) All employees know what they are required to do in an emergency situation.
7) No critical tasks, such as routine maintenance, have been overlooked.

. In addition, management should make every effort to hire and retain competent and motivated staff. Figure 13 shows a typical organogram for a local municipality acting as a Water Services Provider.

The actual titles of positions will vary from municipality to municipality depending on the size and structure of the organization, the size of the treatment plants and number of people required to run them, and the skills levels of the operators and their supervisors. In particular there is a large overlap in the functions typically assigned to operators and supervisors. What is important however, is that employees at each level understand clearly what their responsibilities are. The following sections outline the typical responsibilities of operators, supervisors and municipal management.

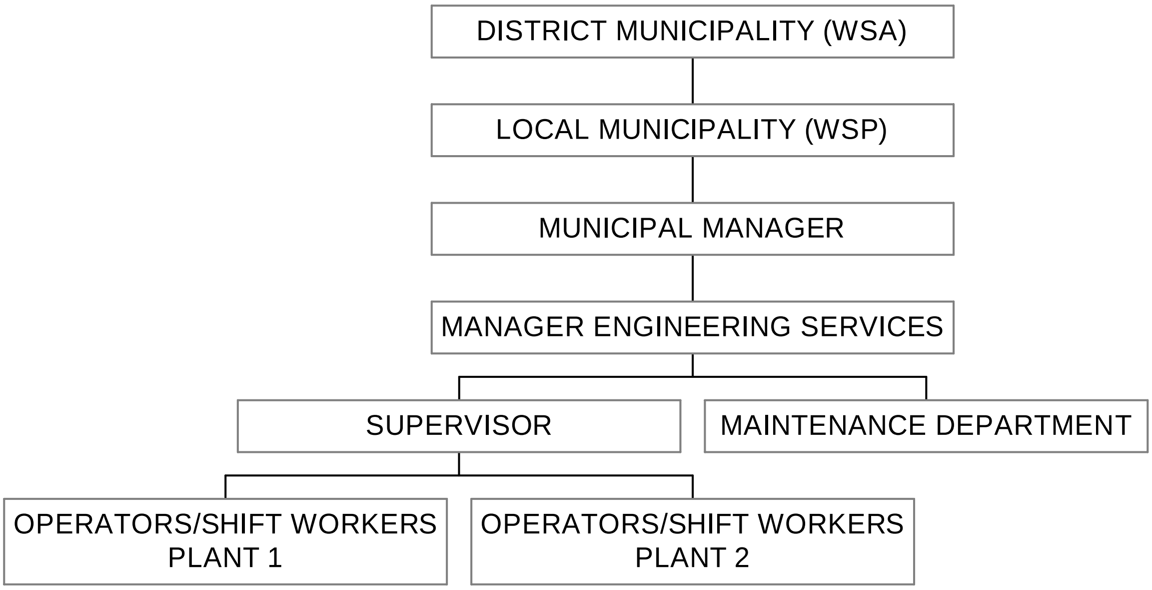


Fig. 12 Typical organogram for a Water Services Provider

4.2.1 Operators

For the purposes of these guidelines, **operators** are employees who remain at the treatment plant most or all of the time and are responsible for most or all of the tasks required for routine operation (e.g. making up chemical stocks and backwashing filters). Operator skill and training levels vary widely as do their responsibilities. Some simply take instructions from the supervisor or overseer or from a senior operator whereas others mostly work independently. In some cases, a single operator may be responsible for running more than one treatment plant, usually with the assistance of one or more shift worker. Education and training levels vary from on-the-job training only, to some formal training to some post-matric education and technical certification.

4.2.2 Supervisors

Operators report to **supervisors** who are usually responsible for overseeing the operation of more than one plant and are also responsible for the procurement of chemical supplies, new equipment and repairs to existing. Supervisor are usually based at the municipal offices and spend a few hours a week at most at any given plant. In some cases, monitoring and process control (Section 3.4) is the sole responsibility of the supervisor. However, this is not an ideal situation. Since process control measurements should be made as frequently as is practical, both the measurements and the process control adjustments should be the responsibility of the operators since they spend more time at the plant. The supervisor should review their data and check the plant performance herself daily for inexperienced operators and weekly for experienced operators.

The importance of good co-operation between the maintenance or plumbing and water treatment departments cannot be overstated. The water treatment supervisor must work closely with the maintenance department to ensure that all maintenance issues relating to water treatment and distribution are promptly dealt with. The supervisor should also make sure that the maintenance department is always involved when any new equipment is installed.

4.2.3 Water or engineering services manager

The water treatment supervisor or supervisors usually report to the water services manager if there is one, or more usually to the engineering services manager or town engineer. Water treatment is usually not the top priority of the engineering department; nonetheless the engineering services manager is responsible for ensuring that

:

1) water treatment has sufficient, appropriately trained, motivated staff
2) the staff have the resources they need to properly execute their duties
3) proposed plant upgrades are appropriate and meet all treatment needs
4) all requirements to provide training are met by suppliers and contractors
5) systems are in place for process control and routine maintenance
6) compulsory national standards are being met in the water supplied to consumers
7) consumer complaints and queries are efficiently dealt with
8) monitoring data collected by external agencies, particularly microbial data is shared with the supervisors and operators

4.2.4 Municipal manager

Ultimate responsibility for the safety of the treated water supply lies with the municipal manager. In addition to ensuring that water services are functioning properly, the municipal manager must set up a system whereby the public can be rapidly informed if the drinking water supply is determined to pose a threat to health and of what measures consumers need to take to avoid potential exposure to water born diseases. Communicating with the public is discussed further in Section 4.5. Options for emergency home treatment of water are discussed in Section 3B of *Quality of Domestic Water Supplies Volume 4: Treatment* (DWAF *et al.*, 2002c).

4.3 IMPORTANT STRATEGIES FOR MAINTAINING THE SAFETY OF THE TREATED WATER SUPPLY IN RURAL AREAS

4.3.1 Developing emergency response strategies

Particular attention needs to be given to defining roles and responsibilities in emergency situations. Emergency situations include those where **the supply of water is affected** e.g. major pipelines are ruptured or pumps are damaged as well as those where only **the safety of the water is affected**. A typical example of the latter is the failure of the chlorination system. In municipalities, there seems to be an attitude that these sorts are situations can be dealt with whenever it is convenient for the staff involved while the potentially serious threat to public can simply be ignored. In fact, the law requires that they are dealt with as a matter of extreme urgency **and** that the public also be informed (Section 2.2).

Water services authorities and water services suppliers must draw up emergency response plans for foreseeable events such as natural disasters, major equipment failures and human actions such as strikes and sabotage (Chapter 4, WHO, 2004). In situations with a high risk of waterborne disease outbreaks, the assistance of provincial and national government may be required. Emergency response plans must be developed with consultation with all relevant authorities and be consistent with all local and national emergency response arrangements.

Good **communication** between operators, maintenance personnel and management is especially important during emergency situations. The operators will usually be the first to pick up problems with the raw water supply or with the treatment process and must have a means of rapidly informing the relevant authorities. They must also know what immediate steps they can take, for example, temporarily shutting down the plant. Management must act quickly and decisively to resolve the problem.

Emergency response plans must always include a **communications plan** to inform the public of the situation. The municipal manager is responsible for alerting the public if the treated water is determined to be unfit for human consumption (See Section 2.2). Municipal management should also inform the public when scheduled activities such as plant upgrades may temporarily affect the reliability of supply and the quality of the water. Communication with the public is discussed further in Section 4.5. For a more detailed discussion of emergency response plans, see Chapter 4 of *Guidelines for Drinking-water Quality* (WHO, 2004).

4.3.2 Ensuring adequate chemical supplies

The plant supervisor or other municipal official directly responsible for overseeing the routine operation of the plant is responsible for ensuring that **the plant always has adequate stocks of water treatment chemicals** (coagulant/flocculant, pH adjustment chemical, disinfectant). The plant operators are responsible for ensuring that the superintendent is aware of the rate of consumption of the chemicals and when fresh stocks will be needed. Any disruption to coagulant or disinfectant dosing (whether due to equipment failure or chemicals running out) constitutes an emergency situation which must be dealt with as outlined in Section 4.3.1. In many cases it may be possible to produce at least Class II quality water without a pH adjustment chemical (lime, soda ash, carbon dioxide or acid). Therefore, one of these chemicals running out does not necessarily constitute an emergency. However, the replenishment of the chemical must be treated with utmost urgency and the plant performance must be closely monitored (sampling at least every 2 h) until dosing is restored.

Chemical stocks must be replenished at least **1 week** before they are needed. The ordering of new chemical stocks should preferably be automatic, that is, the water service provider should arrange with the supplier(s) to have the treatment chemicals delivered without fail at regular intervals. Otherwise, each order must be initiated sufficiently far in advance to ensure that the chemicals will arrive in time. The minimum frequency of delivery will depend on the rate of consumption of chemicals and the available storage space. In order to ensure regular and timely delivery, the water service provider must: (a) buy only from reputable suppliers and (b) ensure suppliers are always paid on time. Adequate funds for the purchase of treatment chemicals must be earmarked in the municipal budget, taking into account possible increases in transport costs over the budget period. All municipal employees involved in the processing of orders must be aware of the importance of having the chemicals arrive at the plant on time, must follow up on orders and must face significant penalties if they allow avoidable disruptions in chemical dosing due to their own negligence.

> All municipal employees involved in the procurement of treatment chemicals must be aware that it is critically important that they **arrive at the plant** on time. Proper planning and budgeting is required to avoid disruptions.

The operators must record the daily usage of chemicals e.g. they should record the date on which each bag of alum/drum of polyelectrolyte/drum of HTH is finished. The supervisor must review these records in planning and budgeting for purchasing chemical supplies taking into account seasonal variations in coagulant and chlorine demand.

4.3.3 Maintenance

An acceptable quality of treated water cannot be sustained if the facilities for abstracting, treating and distributing the water are not adequately maintained. Water Service Authorities are required to submit details of their maintenance plans as part of their water development plans, however, maintenance of pumps and water treatment equipment is generally given very low priority in small treatment plants. In the authors' experience, equipment failure is one of the major contributors to poor water quality. Furthermore, there is a lack of urgency when dealing with equipment failures provided that the quantity of water which can be supplied is not affected. Consequently, vital equipment such as flowmeters, dosing pumps and chlorinators may not function correctly or at all for months or even years before action is taken. There appear to be several reasons for this problem:

- **Lack of interest** by both municipal management and the public in the quality of water provided. (By contrast, broken pipelines which result in disruption of the water supply are dealt with much more quickly).
- **Operators are not trained or do not have the tools** to perform routine maintenance and minor repairs.
- **The maintenance department may not have the skills** to repair specialised equipment.
- The maintenance department is located some distance from the treatment plant and **personnel often do not have transport.**
- There are **insufficient maintenance personnel**.
- There are **insufficient funds** budgeted for maintenance and the repair and replacement of faulty equipment.
- **The process for approving the purchase of replacement parts or paying for repairs** by external agencies is too slow.

The relationship between Water Service Authorities and local service providers can make the problem worse in some cases. In a recent survey of small treatment plants in the Eastern Cape, some plant supervisors complained that it took days or weeks to get approval for vital repairs from the Water Service Authority. They felt that WSA officials based at a the District Municipality head offices were not particularly interested in the problems of Water Services Providers located several hundred kilometres away. It therefore appears that the first step to solving this problem is getting municipal and district municipality management to realise that:

- Maintenance of all parts of the treatment and distribution system is a critical part of providing effective, efficient and sustainable water services.
- Scheduling routine maintenance and addressing equipment problems as soon as they arise is cheaper in the long run than neglecting maintenance.

1) maintenance of all parts of the treatment and distribution system is a critical part of their obligation to provide effective, efficient and sustainable water services.
2) scheduling routine maintenance and addressing equipment problems as soon as they arise is cheaper in the long run than ignoring evident problems until a catastrophic failure occurs..

In addition to drawing up and implementing routine maintenance programs, water services institutions must streamline the procedures for getting faulty equipment replaced or repaired. As soon as a problem is noticed, **the operators must immediately alert the plant supervisor** who should in turn notify both the **maintenance department** and the **water or engineering services manager**. The supervisor should make a judgement on how urgent the problem is and must follow up to ensure that the problem is dealt with within an appropriate time frame. Where outside assistance is required or replacement parts have to be purchased, the supervisor must be able to obtain authorisation within a matter of hours and not days.

It is also important that **records of all maintenance activities** are kept, both routine and non-routine. Copies of these records should be available at both the treatment plant and the municipal offices. This will assist in planning and scheduling routine maintenance, budgeting for both routine and non-routine maintenance and developing procedures for dealing with equipment failures. Monitoring and surveillance (Section 4.7) should include checking that these records are accurate, complete and up to date.

4.4 Communication between operating staff and management

In some municipalities, communication between operating staff and management is generally very good, however, in many others, this is an area which needs to be improved. Operators complain that working condition are poor, their concerns about equipment and operating problems are ignored, they are discouraged from reporting bad results, they receive no feedback about treatment plant performance and are not informed about or involved in managements decisions which affect water treatment.

The operating staff at water treatment plants play a vital role in protecting public health and ensuring municipality resources are used efficiently and effectively. Furthermore, the success of any attempt to improve plant operation requires the full commitment and co-operation of the operators, especially since they will usually be required to undertake additional duties. All decisions and strategies should be discussed with the operators and they should be encouraged to take a personal interest and pride in any improvements achieved. It is equally important that management demonstrates that it also committed to improving the performance of water treatment plants through both fulfilling the responsibilities listed in Section 4.2 and creating an institutional environment where operators feel that their work is important and valued.

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> For more discussion on important management concepts for water service providers, see Section 6 of *Quality of Domestic Water Supplies Volume 5: Management Guide* (DWAF, 2002).

4.5 COMMUNICATION BETWEEN THE MUNICIPALITIES AND THE PUBLIC ON WATER QUALITY ISSUES

Good communication between municipalities and consumers is an essential part of providing effective water services. Municipalities are already used to interacting with the public on issues of **water supply** and **access to services**. However more attention to issues relating to **water quality** is required. Several different types of interactions are involved:

4.5.1 Public education

An informed public is a better partner in ensuring the sustainable delivery of water services and preventing outbreaks of waterborne diseases. Effective communication and public education helps to increase community awareness and knowledge of drinking-water quality issues and helps consumers to understand and contribute to decisions about the service provided by a drinking water supplier. An informed public is also more likely to accept land use constraints imposed in catchment areas. (WHO, 2004). The revised definition of a basic water supply (Annexure 3: Definitions in the Strategic Framework for Water Services, DWAF 2003) includes the communication of good water-use, hygiene and related practices. District Municipalities, whether they are WSAs or not, have primary responsibility for health and hygiene education related to water and sanitation services (Section 3.6.4 in Strategic Framework for Water Services, DWAF, 2003). For more details on the responsibilities of various spheres of government as well as consumers regarding water supply, see DWAF's *Quality of Domestic Water Supplies Volume 5: Management Guide* (DWAF *et al.*, 2002c).

4.5.2 Consumer complaints

While it is extremely important for municipalities to monitor the quality of water supplied to consumers, for practical and economic reasons, routine sampling will be limited to a few sites and a few samples per month. Therefore, routine sampling can easily miss problems in some areas of the distribution system and deterioration of water quality due to transient (lasting for a short time) events. Consumers however are collectively exposed to water quality at all points of the distribution system on a daily basis. Therefore, consumer complaints about the taste, smell and appearance of the water delivered are an important tool for detecting problems in the distribution system and should be encouraged rather than discouraged.

According to the *Strategic Framework for Water Services* (DWAF, 2003), it is the responsibility of water services authorities to establish mechanisms for facilitating, listening to and responding to the consumer and citizen feedback on the quality for services provided. However, it is important that consumers interact directly with the **local Water Services Provider**. All consumer complaints should be logged along with the date, time and location in the distribution system and reported to the engineering services department or water treatment supervisor. Up to date maps of the distribution system should be kept at the water services provider offices. The location, type and date of the complaint can be marked on the maps to help identify problem areas (areas in which several similar complaints are reported) and focus investigations to determine the source of the problem.

4.5.3 Alerting consumers about poor water quality

The Constitution of South Africa defines access to safe drinking water as a basic human right. While a healthy adult population may become adapted to a certain level of microbial contamination of their drinking water, young children and babies, elderly people, the sick (particularly HIV infected individuals) and visitors to the area are always at risk. If a Water Services Provider is for any reason unable to supply water that complies with Class II standards for potable water (See Section 2.3), then the provisions of the Water Services Act (1997) require that it inform DWAF, the relevant provincial department of health and all consumers. Information supplied to consumers must include the nature of the problem, the risks associate with the problem, what the Water Services Provider and Water Services Authority are doing to resolve the problem and what consumers can do to protect themselves from waterborne diseases. Information on home treatment of water in emergency situations is provided in Section3B of *Quality of Domestic Water Supplies Volume 4: Treatment Guide* (DWAF *et al.*, 2002c).

Possible means of communication include announcements on local radio broadcasts and in local newspapers, notices posted in public places like taxi ranks, schools, clinics and municipal offices, and municipal representatives or community workers going door to door where necessary. While the public have a fundamental right to know if their drinking water is unsafe, informing consumers about potential risks to their health must be handled sensitively to avoid spreading panic, confusion and misinformation among the public and potentially driving them to even less safe sources of water. Furthermore, there are health risks associated with issuing a “boil water” alert so this option should only be exercised if the microbial quality of the water is determined to pose a significant health risk (WHO, 2004).

Broad based communication of water quality and awareness information to restore public confidence in drinking water should be a significant area of communication activity in the aftermath of a major incident.

4.6 TRAINING, CAPACITY BUILDING AND PARTNERSHIPS

A major barrier to the production of safe drinking water in many areas of South Africa is the inadequate qualifications and training of many operators and supervisors at small treatment plants. This is particularly a problem in newly established municipalities which did not previously have water services. In a recent survey of plants in the Eastern Cape, the authors found that newly commissioned plants without properly trained operators typically performed much worse than older plants with inadequate facilities but experienced and motivated operators and/or supervisors.

The Department of Water Affairs and Forestry is currently developing regulations which specify minimum qualifications for treatment plant operators and supervisors based on the size and complexity of treatment works (Boyd, 2004). However, the reality is that attracting and retaining technically qualified personnel is a major problem in most municipalities outside of the major urban centres. Two practical ways of addressing this problem are as follows:

1) Upgrading the training of the personnel already involved in running these treatment facilities.
2) Developing partnerships between municipalities and external agencies and institutions which can provide technical support and mentorship..

To a large extent this is already happening. There are already a range of organizations involved in training and mentorship, including NGO's, consulting firms, educational and research institutions, suppliers of treatment chemicals, established water boards and various departments of national and provincial government. This section highlights a few areas in which these initiatives can be made more effective.

4.6.1 Specific areas in which technical assistance is often required

While many operators have a good working knowledge of their treatment works and an instinctive feel for how to deal with various operating problems, they often struggle with record keeping and anything that requires computational skills. Also many are not fluent in English, the language in which most manuals and technical guidelines are written. Consequently, it is important that training courses and capacity building activities are tailored to their specific needs and skills levels. A substantial amount of time and effort needs to be devoted to **dosing calculations** and **process control**. To assist operators it can be helpful to generate tables which summarise dosing calculations. For example, required alum dose rates can be tabulated as a function of raw water flowrate and optimum dose determined from the jar test (See Momba *et al*., 2005 for examples). However, follow up training is required to ensure that these kinds of tools are being used correctly and that operators are able to obtain all of the information required to use them.

Technical aspects of treatment plant operation and management where operators and supervisors may require technical assistance are listed below. Technical assistance may take the form of training to perform specific tasks e.g. jar tests, guidance or collaboration on the development and documentation of operating procedures and co-operative arrangements e.g. the calibration of instruments is checked during routine monitoring by the Water Services Authority.

- Calibrating dosing equipment (Section 3.4)
- Checking dosing equipment calibration (Section 3.2.4.2)
- Calculating dosing rates (Section 3.2.31.)
- Conducting jar tests and using the results to adjust chemical doses (Section 3.2.4.1)
- Adjusting chlorine doses to achieve desired residual in finished water (meeting the chlorine demand) (Section 3.2.2.2)
- Evaluating filter backwash (Section 3.2.6.1.3)
- Measuring flow rate (Section 3.2.3.1)
- Flow rate adjustment (Section 3.2.3.2)
- Calculating balancing capacity (Section 3.2.3.2)
- Calculating reservoir detention times and effective chlorine contact times (Section 3.2.2.3)
- Determining dosing requirements for chemical stabilisation (Section 3.2.7)
- Use of instruments (pH, turbidity, chlorine) (Section 3.4)
- Taking care of instruments (Section 3.4)
- Calibrating and checking the performance of instruments (Section 3.4)
- Sample collection and handling techniques (Section 4.1)
- Developing and writing up procedures for all aspects of plant operation e.g. making up dosing solutions, desludging settling tanks, cleaning filters, cleaning reservoirs, etc.

- Developing and writing up process control strategies. Tables 9 to 12 in Section 3.4 can be used as a starting point but they need to be adapted for individual treatment works (Section 3.4)
- Record keeping
- Interpretation of data
- Troubleshooting (investigating and solving problems)
- Reporting problems and failures
- Developing operating manuals for older plants
- Translation of procedures and safety materials into the local language for staff who are not fluent in English
- Gaining access to guidelines and educational materials published by DWAF and the South African Water Research Commission
- Developing log sheets and sampling programmes for specific plants
- Basic maintenance

Organisations involved in capacity building exercises must work together with the operating staff and responsible municipal officials to determine the most practical ways to ensure that none of these important aspects of treatment plant operation are neglected.

4.6.2 Importance of on-site training

Most operators of rural treatment plants and many of their supervisors need to upgrade their training in order to achieve the necessary improvements in performance to produce water that is consistently safe to drink. Formal training in a classroom environment does have some benefits: it is cheaper to have many learners in one location and operators will benefit from the exposure to new ideas and the opportunity of meeting their peers. However, operators with low levels of formal education may find the presentation of the course material difficult to follow. Furthermore, operators may not understand how to implement certain procedures in their own plants if they do not correspond exactly to the examples studied in class. In many cases, operators may return to plants which do not have the instruments and equipment necessary to practice their newly acquired skills and will quickly forget their training if they do not have the opportunity to use it.

For training to be effective, it is therefore very important for trainers to understand the conditions and constraints at each treatment plant and to tailor the training to the needs and skills of individual operators. This is best achieved through on-site training courses. The advantages of on-site training include:

1) Trainers have a better idea of the challenges faced by operators at particular plants and be better able to assess their competence. The authors have often found that when questioning operators about the operation of their plant, they give inaccurate or misleading answers simply because they cannot relate the question to their own practical experience of the plant.
2) Trainers can ensure that the acquisition of theoretical knowledge of water treatment operations goes together with direct implementation of that knowledge for the specific conditions at each plant
3) Operators are given hands on training with equipment that they are familiar with.
4) The benefits of treatment plant optimisation can be demonstrated for the operating staff and municipal officials

On-site training should always involve plant supervisors and other municipal officials should also be encouraged to attend. On-site training must emphasise why each step in water treatment is important for the sustainable production and delivery of safe drinking water and how to check the performance at each stage. Illustrated training materials should be developed in colour format with translations in local languages in order to be useful to operators with a wide range of education levels.

4.6.3 Role of universities and technikons

Universities and technikons can play an important role in capacity building at small treatment plants, particularly when students team up with experienced professionals from either academia or industry. Students and academic research groups can be used to strengthen capacity building and partnerships with municipalities in a number of specific ways:

- Students can be used to
    - increase contact time with operators to reinforce skills learned in formal training programmes.
    - assist the operators with calculations and data analysis.
    - assist the operators in developing and documenting operating procedures.
    - translate training materials, manuals and safety information into local languages.
- Tertiary institutions also can provide municipalities with indirect access to a number of important resources which they may not have otherwise
    - laboratory facilities.

- internet and other information sources.
- extensive local and international contacts within the water sector and research community.
- information on national and global trends.

Students and university research programmes are often funded by external agencies such as the Water Research Commission, National Research Foundation and even international funding agencies so the assistance provided to municipalities and to other agencies working with them may be free of charge.

Students also benefit tremendously from this arrangement because they get hands-on experience, hopefully under the guidance of experienced professionals. In many cases, young graduates and diplomates are being placed in positions of enormous responsibility in local and district municipalities with little prior experience. Students who have participated in the type of partnership envisaged here would bring all the advantages of appropriate academic background, relevant experience and an established network of contacts to any position in which they are employed in the water sector.

4.6.4 Pro-active attitude of municipal management

For a partnership or mentorship programme to be effective the municipality involved must believe this is important and relevant to its needs and obligations. In the experience of the authors, the people closest to the plant operation, that is the operators and supervisors, are usually enthusiastic about upgrading their own training and improving plant operations. However, the efficiency of treatment plants and the quality of the water supplied to consumer are typically low on the list of priorities of municipal management. Not only does management pay little attention to what is going on at the purification works, but they are often reluctant to spend money on critical equipment and repairs.

For example, during an on-site operator training course at Alice Water Treatment Plant, Momba *et al* (2004b) found that the coagulant dosing pump, filters and chlorine dosing system all had such serious problems that it was impossible to demonstrate the skills being taught at the plant-scale. During a recent survey of small treatment plants in Eastern Cape, the authors also met operators who had taken off-site training courses and were aware of the need for process monitoring and control but did not have any of the equipment needed to implement it.

It is important that municipal management not only provides the necessary resources for improving the efficiency of water treatment but that it also takes an active interest in the process. Municipalities cannot simply be passive recipients of technical assistance, but need to ensure that specific goals are being met and maximum use of available resources is being made. Areas which require particular attention include the following:

(a) **Municipalities must ensure that capacity building is actually taking place** and that employees are acquiring the skills that they need to run the plants efficiently. For example, operators need to be given the training and resources to make appropriate adjustments to chemical doses whenever required. They should not be dependent on a consultant who only visits the plant once a month.

(b) **Management must ensure that there is a training component in every contract to supply equipment or chemicals, to upgrade any part of existing treatment works or to build new ones.** Installing new equipment is more likely to have a negative than positive impact on treated water quality if no one in the municipality understands how to operate or maintain it (See also Section 4.3.2 on maintenance).

(c) Management at both and district and local level must ensure that all water quality monitoring data is shared with plant operators and supervisors as soon as it is available (See Section 4.1 and 4.7). This is particularly important for microbial quality data since individual treatment plants rarely have the facilities or skills to perform these analyses themselves. Many plant operators and supervisors complain that various groups are collecting monthly samples from plants, usually on behalf of the Water Services Authority, however, they never receive feedback on the results and consequently do not know if their performance is adequate or not.

4.7 IMPORTANCE OF SURVEILLANCE AND TREATMENT PLANT AUDITS

> Surveillance by external agencies does not remove or replace the responsibility of water services providers to monitor their own operations and to ensure that the water produced meets all required standards.

In addition to routine operational monitoring, international experience has shown that it is extremely important to have an external agency periodically checking the quality of the water being provided and the performance of the Water Services Provider in general (WHO, 2004). Surveillance by an external agency contributes to the protection of public health by promoting improvement of the water quality, quantity, accessibility, coverage, affordability and continuity of water supplies (known as service indicators). Drinking-water surveillance is also used to ensure that any transgressions which occur are appropriately investigated and resolved. It is important to note, however, that surveillance by external agencies does not remove or replace the responsibility of Water Services Providers to monitor their own operations and to ensure that the water produced meets all required standards.

The surveillance agency must have, or have access to, legal expertise as well as expertise on drinking water and water quality (WHO, 2004). The surveillance agency should be independent of and have the power to penalise service providers which fail to comply with compulsory standards or to meet contractual obligations in terms of provision of services. The surveillance agency should be empowered by law to compel water suppliers to recommend the boiling of water or other preventative measures when microbial contamination which could threaten public health is detected. However, the relationship between the surveillance agency and the service provider should be primarily collaborative with the emphasis on setting realistic goals to ensure the **progressive** improvement of service provision. Punitive action should only be taken as a final resort.

Surveillance has two important components:

(a) Direct assessment of the quality of the water supplied
(b) Review of all aspects of treatment and distribution of water supplied including inspection of facilties, review of operating records and procedures, process control measures and management strategies.

Direct assessment is important for providing an independent check on water quality which can be compared to the water services provider's own monitoring data. However, it provides only a indication of water quality at the particular time that samples are collected and may miss occurrences of poor water quality which the water services provider may or not report. Furthermore, water quality analysis alone does not necessarily provide any information on why a particular water quality problem has occurred and what can be done to correct it. A comprehensive review of the condition of facilities, operating procedures and records on the other hand will show whether the conditions and procedures required for the sustainable production of safe water are in place.

In the South Africa, the role of regulating and monitoring Water Service Providers is assigned to the Water Service Authorities. All WSA's should have developed and implemented programmes for sampling the quality of potable water provided to consumers in their areas of jurisdiction by 2003. Detailed guidelines on water quality sampling and analysis are provided in *Quality of Domestic Water Supplies Volume 2: Sampling Guide and Volume 3: Analysis Guide* (DWAF, 2002). Where local government structures lack the resources to carry out the required monitoring, co-operative government requirements specify that Provincial and National Government must ensure that monitoring takes place Mackintosh *et al.*, (2004a).

The performance of the Water Service Authorities is in turn monitored by provincial and national government, primarily through the annual water services audit which WSA's are required to submit (See Section 2.2). The water services audit must include information on the quantity of water services supplied, extension of services to the unserved, level of service provided, level of cost recovery achieved, progress with meter installations, water quality sampling and testing, progress on water conservation and demand management measures (DWAF, 2002b). While the Water Services Act places general requirements on water services institutions to operate treatment plants in an effective, efficient and sustainable manner and to make appropriate investments in infrastructure including maintenance, there is currently no regulatory requirement for WSAs to undertake comprehensive reviews of operating procedures and conditions of facilities as part of its monitoring programmes. However, this may change in the future as regulations become tighter and expectations of Water Services Providers are raised.

5

STRATEGIES FOR ENSURING SAFE DRINKING WATER

This section provides a summary of recommendations for Water Services Authorities and Providers to ensure the microbial safety of treated water supplied to consumers in rural municipalities. The key to ensuring clean, safe and reliable drinking water is to implement **multiple barriers** which control microbiological pathogens and chemical contaminants that may enter the water supply system. This includes adopting sound management practices and continuously reviewing both the state of the water treatment and distribution infrastructure and the quality of the water produced.

Source Water Protection

- Restrict access by humans and animals to raw water source close to abstraction point.
- Educate public about water quality issues and water resource management.
- Work with Catchment Management Agencies to protect water resources.

Treatment Plant Operation

- Install flow meters on the raw water, filtered water, finished water and recycle flow.
- Avoid large or rapid variations in plant flow rate. Operate plant continuously (24 h/d) if possible.
- Use the jar test to optimise coagulation and flocculation.
- Install baffles and wind breaks if necessary to minimize mixing in settling tanks.
- Closely monitor filter and filter backwash performance. Expect to change filter media every 1-2 years if filter performance deteriorates.
- Monitor disinfectant residual, pH and effective contact time to ensure adequate disinfection.
- Implement chemical stabilisation to prevent excessive scaling or corrosion in the distribution system.
- Introduce process control measures for turbidity removal, pH adjustment and disinfection.
- Install back-up dosing systems for coagulation and disinfection.
- Attend to all maintenance issues promptly to avoid catastrophic system failures.
- Develop procedures for responding to adverse conditions and emergency situations.
- Keep up to date records of all performance data, operating decisions and maintenance activities.

Distribution System

- Avoid interruptions in supply to minimise risk of untreated water seeping into the distribution system
- Monitor disinfectant residual and microbial quality in each zone of the supply area to identify problem areas
- Cover and secure all service reservoirs to prevent contamination of the treated water. Reservoirs must be drained and cleaned every 1 – 5 years depending on the treated water quality.
- Install flow meters on all service reservoirs in order to monitor retention time. Where excessively long retention times result in low chlorine residuals, lower operating levels or introduce booster chlorination.
- Introduce measures to prevent cross-connections between domestic water and sewer lines.

Management Issues

- Become familiar with the regulatory requirements for the quality of potable water.
- Introduce a Drinking-water Quality Management Plan.
- Ensure that the responsibilities of all personnel are clearly defined and documented for both routine operation and emergency situations.
- Implement measures to ensure treatment chemicals are always ordered and delivered to the treatment plant on time.
- Ensure maintenance issues are always promptly attended to.
- Ensure operators have adequate training and resources to perform their duties, particularly when new equipment is installed.

The recommendations provided in this section are all measures which need to be implemented as soon as possible i.e. within the next few years. All of the recommendations are consistent with constitutional requirements for local government to provide efficient, effective, sustainable and safe water services. However, they should be only considered a first step. International experience has shown that water providers need to constantly review and improve their operating and management practices as new technologies and new threats to water quality emerge and as regulations become stricter. Once the basics are in place, Water Services Institutions need to look for new ways to improve the efficiency and effectiveness of their operations and the safety of the water supply. The World Helath Organisation (WHO, 2004) advocates the development and implementation of comprehensive Water Safety Plans which go beyond the guidelines presented here. On-going professional development programmes for both operators and managers are an essential part of meeting future challenges and achieving higher standards of performance.

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