APPLYING AN ABBREVIATED HAZARD ANALYSIS AND CRITICAL CONTROL POINT PROGRAMME TO EVALUATE THE EFFECTIVENESS OF TWO POTABLE WATER TREATMENT SYSTEMS TO REMOVE HEALTH-RELATED CONTAMINANTS

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BLOEMFONTEIN
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DECLARATION OF INDEPENDENT WORK

I, **CORíNNE JAGALS**, Identity Number [redacted] and Student Number [redacted], do hereby declare that this research project, submitted to the Central University of Technology, Free State for the degree **MAGISTER TECHNOLOGIAE: ENVIRONMENTAL HEALTH**, is my own independent work.

This work has not been submitted before to any institution by myself or, to the best of my knowledge, any other person in fulfilment of requirements for the attainment of any qualification.

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SIGNATURE OF CANDIDATE

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- To my Father in heaven, for protecting me, keeping me safe and most of all sane.
- To the two most important people in my life -
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SUMMARY

The abbreviated HACCP (Hazard Analysis and Critical Control Point) programme applied in this study comprised mostly of a health-related microbiological hazard analysis together with the use of critical performance limit targets (CPLTs) to assess the effectiveness of treatment system components at two drinking water treatment facilities.

The hazard analysis was based on the occurrence of total coliforms and faecal coliforms, both of which are health-related microbiological indicator organism groups. Turbidity was used to assess the effectiveness of the treatment components to produce quality of drinking water that would comply with national water quality guidelines. Turbidity testing was also included in this study to augment microbiological hazard analyses with the understanding that if turbidity levels were reduced to sufficient levels, microorganisms would also be reduced – an approach which could have offered the treatment facility manager a quick test option in lieu of microbiological testing.

The raw river water used for drinking water treatment at both treatment facilities complied with the raw water extraction guidelines proposed for this study. The same was observed of the treated end-product, namely treated potable water. The end product complied with national health-related drinking water guidelines, which indicated that the designs of the selected treatment facilities were well planned and managed. To determine the effectiveness of the treatment components (known as critical control points (CCPs)), a set of critical performance limit targets (CPLTs) was compiled for this study since such targets were not available at the treatment facilities. The premise was that if the CCP complied with the CPLT, the process was effective and thus functioning properly.

Most of the health-related indicator results complied with the target CPLTs. When comparing *sedimentation* from both treatment facilities, it appeared that this process within the Mazelspoort treatment facility functioned more effectively in reducing the health-related indicator levels than the sedimentation process at the Rustfontein treatment facility. The CPLT for sedimentation is 90% removal for the

microbiological indicators and 85% removal for turbidity. Sedimentation at the Rustfontein treatment facility could not reduce any of the indicators used in this study to comply with the CPLTs. It reduced only 87% of the total coliforms, 89% of the faecal coliforms and 45% of turbidity received from the raw water extraction point. The filters at the Rustfontein treatment facility under-achieved in the reduction of the indicator organisms, while the filters at Mazelspoort seemed to perform effectively with only occasional under-achievement in the reduction of faecal coliforms. The filters at the Rustfontein treatment facility failed to reduce the numbers of total coliforms to the required CPLT. They only reduced 41% (CPLT of 99%) of the total coliform load received from sedimentation, placing pressure on the chlorination stage to reduce the remaining organisms. Chlorination reduced the numbers of all the indicators to acceptable limits. Although some critical control points at these treatment facilities could face difficulties in controlling these health-related risks, these facilities could be perceived as effective in treating the raw river water to a high quality potable water to be distributed to the public.

Weak correlations were found between the occurrence of the health-related indicator organisms and turbidity. The assumption could therefore be made that turbidity should not be used as a solitary indicator of process effectiveness. Additional microbiological and possibly additional chemical quality tests should be considered as monitoring procedures to manage a water treatment facility effectively.

OPSOMMING

Die verkorte *HACCP (Hazard Analysis and Critical Control Point)*-program wat in die studie toegepas is, bestaan hoofsaaklik uit 'n gesondheidsverwante mikrobiologiese risiko-analise, sowel as die gebruik van kritieke prestasiebeperkingsmikpunte (KPBM) om die effektiwiteit van suiweringstelselkomponente by twee drinkwatersuiweringswerke te bepaal.

Die risiko-analise is gebaseer op die voorkoms van totale kolivorme en fekale kolivorme, waarvan beide gesondheidsverwante mikrobiologiese indikatororganisme groepe is. Turbiditeit is gebruik om die effektiwiteit te bepaal van die suiweringskomponente om drinkwatergehalte, wat voldoen aan nasionale watergehalteriglyne, te vervaardig. Turbiditeitstoetse is ook in die studie gebruik vir die toevoeging tot mikrobiologiese risiko-analise met dien verstande dat indien turbiditeitsvlakke verminder word na voldoende vlakke, die mikrobiologiese vlakke ook sal verminder. Die benadering kan lei tot 'n vinnige toetsingsopsie in plaas van mikrobiologiese toetse wat die bestuurder van die suiweringswerke kan gebruik.

Die rou rivierwater wat gebruik is vir drinkwatersuiwering by beide die suiweringswerke het voldoen aan die rouwateronttrekkingsriglyne wat deur die studie voorgestel is. Dieselfde kon gesien word by die eindproduk, naamlik gesuiwerde drinkwater. Die eindproduk het voldoen aan die nasionale gesondheidsverwante drinkwaterriglyne wat daarop wys dat die ontwerp van die geselekteerde suiweringswerke goed beplan en bestuur is.

Om die effektiwiteit van die suiweringskomponente (ook bekend as kritieke beheerpunte (KBP)) te bepaal, is daar 'n stel kritieke prestasiebeperkingsmikpunte (KPBM) saamgestel aangesien sodanige mikpunte nie geredelik beskikbaar was by die suiweringswerke nie. Die doel is dat indien die KBP aan die KPM voldoen, die proses beskou sal kan word as effektief en dat dit dus behoorlik funksioneer.

Die meeste van die gesondheidsverwante indikatorresultate het voldoen aan die KPM. As *besinking* van beide suiwerings vergelyk word, dan wil dit voorkom asof die proses by die Mazelspoort-suiweringswerke meer effektief is om die gesondheidsverwante indikatorvlakke te verminder, as die proses by die

Rustfontein-suiweringswerke. Die KPBM vir besinking is 90% vermindering van mikrobiologiese indikatore en 85% vir die vermindering van turbiditeit. Besinking by die Rustfontein-suiweringswerke kon nie enige van die indikatore wat in die studie gebruik is verminder sodat dit voldoen aan die KPBM nie. Dit kon slegs 87% van die totale kolivorme, 89% van die fekale kolivorme en 45% van die turbiditeit wat ontvang is van die rouwateruittrekpunt verminder.

Die filters by die Rustfontein-suiweringwerke het onderpresteer wat betref die vermindering van indikatororganismes, terwyl dit blyk dat die filters by die Mazelspoort-suiweringwerke beter presteer het, met slegs toevallige onderprestasie in die vermindering van fekale kolivorme. Die filters by die Rustfontein-suiweringswerke het nie daarin geslaag om die vlakke van totale kolivorme te verminder na die vereiste KPBM nie. Dit kon slegs 41% (KPBM van 99%) van die totale kolivormelas, wat verkry is van sedimentasie, verminder. Meer druk word dus op die ontsmettingsfase geplaas om die oortollige organismes te verminder. Ontsmetting kon die vlakke verminder na aanvaarbare beperkings. Hoewel sommige van die kritieke beheerpunte by die suiweringswerke probleme getrotseer het om die gesondheidsverwante risiko's te beheer, kan die werke gesien word as effektief in die suiwering van rou rivierwater na 'n hoëgehaltedrinkwater wat versprei kan word aan gebruikers.

Swak korrelasies is gevind tussen die voorkoming van die gesondheidsverwante indikatororganismes en turbiditeit. Die afleiding kan dus gemaak word dat turbiditeit nie alleen gebruik kan word om die effektiwiteit van prosesse te bepaal nie. Bykomende mikrobiologiese en moontlike bykomende chemiese gehaltetoetse moet ook oorweeg word as moniteringsprosedures om watersuiweringswerke effektief te bestuur.

ABBREVIATIONS

/ mℓ	per millilitre
ANOVA	Analysis of Variance
CCP	Critical control points
CFU	Colony forming unit
CCPT	Critical control point target
CPL	Critical performance limit
CPLT	Critical performance limit target
CR	Cumulative reduction
DWTF	Drinking water treatment facility
FC	Faecal coliforms
HA	Hazard analysis
HACCP	Hazard Analysis and Critical Control Point
HRMWQ	Health-related microbiological water quality
HRWQ	Health-related water quality
mℓ	Millilitre
MPN	Most probable number
ND	Not detected
NTU	Nephelometric turbidity units
ORT	Overall reduction target
RM	Reasonable maximum
RPS	Reduction per stage
SOP	Standard operation procedure
TBY	Turbidity
TC	Total coliforms
WSP	Water service plan

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CHAPTER 1: INTRODUCTION and LITERATURE REVIEW

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1.1 BACKGROUND

In recent years, developed countries with conventional water treatment systems and proper distribution systems have still been experiencing waterborne disease outbreaks associated with failures within treatment processes. Bouchier (1998) reports that 25 known outbreaks of *cryptosporidiosis* have been associated with the consumption of public drinking water supplies in the United Kingdom since 1988. This is extraordinary in a society where drinking water is regularly monitored and strictly controlled.

In the South African context, the Health Act (South Africa. Health Act, 1977) requires from municipalities to ensure safe drinking water for the communities they serve. According to Potgieter (2002), it seems as though there are still many areas where, although treated piped water is available, monitoring of the health-related microbiological quality of the water on a routine basis does not exist. Smaller municipalities simply do not have sufficient resources (finance, laboratory facilities and skilled staff) to monitor effectively. Generally, these rely on the design and function of drinking water treatment facilities to reduce contaminant levels in water to protect human health.

This is risky practice, which may lead to the release of microbiologically unsafe water to consumers. This may be because the multiple contaminant barriers that form part of treatment facility design may fail. Multiple contaminant barriers are treatment system components such as sedimentation, filtration and disinfection that, in sequence, reduce contaminant levels in resource water, and are important design factors that prevent complete treatment failure should a single component break down (World Health Organisation (WHO), 2000).

For instance, what would happen if chlorination, which, in the context of health protection and seen as the important final treatment stage, failed to reduce potential health-related risks to acceptable limits? It is not always certain to what extent the breakdown of a particular treatment component could influence the final product.

Effective monitoring of the quality of treated water that exits the treatment systems is generally meant to detect evidence of contamination. However, information regarding especially microbiological contamination is often received too late for corrective action prior to significant volumes of unfit water being distributed.

All of the above point towards a need for preventive measures and corrective actions early in drinking water treatment processes (Hellier, 2002). Applying a hazard analysis and critical control point (HACCP) programme at treatment facilities might answer this need. An HACCP programme applied in a water treatment system would focus on managing health-related water quality throughout the process rather than relying mainly on single components to "carry" other ailing components in the system, for instance relying on end-point treatment such as chlorination (in the case of microbiological contaminant removal) (WHO, 1996c) should sedimentation not be up to standard. Using HACCP, managers at potable water treatment facilities could monitor treatment processes to determine at what points (referred to as critical control points (CCPs)), microbiological hazards might occur that could affect the safety of the potable water product.

Although well established within the food industry, there are some important differences in the application of the HACCP process in the water industry that could make the full HACCP process too elaborate or out of context for application in a water treatment process (Hellier, 2002), making it too costly in terms of benefits gained from the expense incurred (Couper and Walker, 1997).

The study piloted an abbreviated (simplified) HACCP approach at two selected potable water treatment facilities (Rustfontein and Mazelspoort) on the Modder River in the Middle Modder River catchment (Chapter 2, Figure 2.2). The rationale was to see whether applying some form of HACCP programme could add value towards improving health-related water quality management at the two facilities.

1.2 TREATED WATER IS SIGNIFICANT FOR PROTECTING HEALTH

Human life can exist for many days without food but the absence of water for only a few days will have fatal consequences. Water plays an essential role in supporting life; consequently, the availability of water is often a critical sociological issue

(Nazaroff and Alvarez-Cohen, 2001). While essential for life and important for a good quality of life, water is unfortunately also a known carrier of human disease and can pose serious health risks to people if the health-related microbiological quality is not good (Galal-Gorchev, 1993).

The WHO estimated that nearly half of the populations in developing countries suffer from health problems associated with the use of insufficient or contaminated water (Galal-Gorchev, 1993). In South Africa, communicable water-related diseases, especially diarrhoea, are some of the most widespread health problems related to consumption of contaminated water. Waterborne diseases of concern are those caused by a microbiological agent of disease. The transmission and prevention of water-related infections are therefore largely dependent on management of microbiological water quality (Genthe and Seager, 1996).

High health-burden diseases such as diarrhoea, cholera and dysentery are most often associated with water of inferior microbiological quality (Briggs, Corvalan and Nurminen, 1996; Genthe and Rodda, 1999; WHO, 1997), making it a high priority, especially in developing countries (including South Africa) to supply treated, microbiologically safe water to all of their people. In these countries, supplying people with treated water comes at a high cost. The health-related quality of the supply water has to be carefully managed not to add to the already high health-burdens of their economies, while minimising the risk of disease and death (Couper and Walker, 1997).

As far back as 1977, the United Nations Conference in Mar del Plata resolved that "all people, whatever their stage of development and social and economic conditions, have the right to have access to drinking water in quantities and quality equal to their basic needs" (Lloyd and Helmer, 1991). This huge societal sentiment is also reflected in the South African Constitution (South Africa. Government Gazette, 1996) of which Section 27 (1b) states that everyone has the right to have access to sufficient water. The Water Services Act (South Africa. Water Services Act, 1997) similarly states that water service institutions such as municipalities, water service providers, water boards and water service committees should provide access to a basic water supply. This implies the prescribed minimum standard of water supply services necessary for the reliable supply of a sufficient quantity and

quality of water to households, including informal households, to support life and personal hygiene (South Africa. Water Services Act, 1997). Although waterborne infectious diseases are largely under control in the industrialised countries, outbreaks related to microbiologically contaminated water continue to occur when water sources are inadequately protected against faecal pollution before treatment or when water treatment systems are poorly operated and maintained (Craun *et al.*, 1994).

It is not only in developing countries where a poorly treated water supply may endanger the health of the consumer. An epidemiological study in Montreal, Canada, estimated that 35% of unreported diarrhoea from a suburban population was associated with the consumption of conventionally treated and filtered municipal tap water, but of which the raw water was pumped from a river contaminated with human sewage (Payment, Richardson, Siemiatycki, Dewar, Edwardes and Franco, 1991a; Payment, Franco, Richardson and Siemiatycki, 1991b).

Microorganisms are found everywhere in our environment and a variety of these may be transmitted by water (South Africa. Department of Water Affairs and Forestry (DWAF), 1996; Bernè and Richard, 1991). While the vast majority of microorganism species do not cause disease (Parrot, Ross and Woodard, 1996), a number of them do cause disease in humans. These are referred to as pathogens (Lloyd and Helmer, 1991; Cartwright, 1998; United States Environmental Protection Agency (USEPA), 2000). Pathogens in water that is to be prepared for drinking water should ideally be completely removed or inactivated by the treatment processes applied at the water treatment facility (Payment, 1990). Pathogen removal during drinking water treatment is therefore an all-important aspect of water quality control, which implies that assessment of the microbiological quality of treatment water is of great significance (Tebbutt, 1998).

Proper management of the health-related microbiological quality of water produced by water treatment processes must be a high priority for water utilities and municipalities. To achieve this, water treatment consists of two major aspects: an effective treatment system and proper monitoring of the functioning of components of the system that produces the safe water.

1.3 MONITORING WATER TREATMENT COMPONENTS

All water made available to consumers through a supply system should be treated even if individuals directly consume only a small fraction of it (Berne and Richard, 1991). If water is not properly treated, consumers are at risk of contracting waterborne diseases. The provision of a safe supply of potable water depends upon the use of protected high-quality groundwater or the treatment of surface waters through a properly selected and operated series of treatments capable of reducing pathogens and other contaminants to negligible levels not injurious to health (USEPA, 1999).

A potable water treatment system designed to produce drinking water of high microbiological quality must always produce water to strict quality criteria such as those proposed by the WHO (1996b). To achieve this, treatment systems provide multiple barriers to the transmission of microbiological infection (WHO, 1996a;b) through water from the raw resource to the consumer. A typical multiple barrier series generally includes at least three unit treatment processes in series i.e. sedimentation, filtration and disinfection (WHO, 1997).

This has proven a successful method of treating polluted surface water by progressively removing pathogens and other contaminants (notably turbidity) from the intake to the delivery stage. With proper application and use of water treatment and supply technology, public water suppliers can eliminate disease outbreaks. Waterborne disease outbreaks are often characterised by the following principle treatment problems (Troyan and Hansen, 1989; WHO, 2001):

- water supply systems either do not have the required water treatment facilities or existing water treatment facilities are inadequate;
- proper operation of existing facilities may be interrupted due to lack of adequate system reliability, mechanical failure, unanticipated emergencies or operator error;
- equipment improperly installed and / or poorly maintained;
- inadequate monitoring;
- filtration processes inadequate; and
- sources of high contamination found upstream but near the treatment facility.

Water quality managers therefore need effective early-warning systems to prevent these aspects from occurring and causing contaminated water to be released into drinking water distribution systems. Microbiological monitoring within a HACCP framework provides a sensitive indication of the extent to which source protection, treatment and distribution are effective barriers to the transmission of infectious agents of waterborne disease (WHO, 1996b).

The universe of microorganisms, even for pathogens, is extremely large and each species has its own characteristics, including degrees of resistance to specific disinfection technologies. As a result, ranges of different treatment technologies are required to remove or reduce a specific microorganism contamination challenge. Not all facilities can achieve this effectively (Cartwright, 1998).

With the potential for treatment failures or poor efficiency, the utilisation of surface waters polluted with wastewaters and other polluted urban discharges containing large numbers of pathogenic microorganisms always constitutes a high risk of releasing pathogens into a drinking water supply. Transient failures or reductions in efficiency of treatment processes are recognised as potential means of pathogens entering distribution systems. Without a proper monitoring system, this can be a significant hazard to the health of consumers.

It is in this context that a HACCP programme can add value in standardising the control of health-related microbiological quality of water produced by treatment facilities before delivery to distribution systems. Authors such as Davidson and Deere (1999) advocated the use of HACCP in Australian drinking water supplies, but it was Havelaar (1994), cited in Dewettinck, Van Houtte, Geenens, Van Hege and Verstraete (2001), who first described the application of HACCP in drinking water supply to control the major causes of microbiological hazards in drinking water supply. These were considered to be from ❶ pollution of raw water sources, ❷ inadequate management of treatment, ❸ recontamination of storage and distribution facilities for treated water and ❹ growth of pathogens in raw and treated water.

This study focused on using HACCP to assess the ability of two selected treatment facilities to effectively convert polluted raw water sources to safe drinking water before distribution.

1.4 WHAT IS HACCP (Hazard Analysis and Critical Control Points)?

The HACCP concept originated in the early 1960s from the Pillsbury Company working together with the National Aeronautic and Space Administration (NASA) and the United States of America (USA) Army laboratories. It was based on the engineering concept of failure, mode and effect analysis, which looked at what could potentially go wrong at each stage in an operation and putting effective control mechanisms in place. This was adapted to a microbiological safety system in the early days of the USA manned space programme to ensure the safety of food for the astronauts by minimising the risk of a food poisoning outbreak in space. During this time, food safety and food quality systems in the food industry were generally based on end-product testing; limitations on sampling and testing, however, made it difficult to ensure food safety. It became clear that there was a need for something different, a practical and preventative approach that would give a high level of food safety assurance (Mortimore and Wallace, 2001). HACCP provided this approach, which then rapidly became a part of risk and quality control management in the food industry.

1.4.1 GENERAL APPLICATION OF HACCP

HACCP is a systemic approach that enables early detection and control of hazards at critical points in foodstuff processing. If the process is well managed, it should detect soon enough whether a threat (the hazard) to the process and end-product is developing and will then provide for effective interventions to minimise any risk to the health of the consumer (Dewettinck *et al.,* 2001).

HACCP is often thought of as being complicated, requiring substantial resources and expertise associated with large companies/utilities. While several specialist skills are required to use the HACCP principles effectively, there are certain basic skills needed: ❶ a detailed knowledge of what is required to produce the product; ❷ raw materials; ❸ the manufacturing process; and ❹ an understanding of whether any situation that may cause a health risk to the consumer is likely to occur in the process and product (Mortimore and Wallace, 2001). HACCP is applicable not only to the food industry, but also to other processes requiring an end-product safe for consumption, such as potable water.

1.4.2 PRELIMINARY STEPS AND PRINCIPLES OF HACCP

The HACCP Guidelines "Codex Alimentarius" (WHO, 1996c; Mortimore and Wallace, 2001), means *food code*. It details five preliminary steps and seven principles for implementing HACCP. This study applied only some of these steps and principles (indicated in blue).

Five HACCP Steps

1 Assemble an HACCP team

2 Describe the product

3 Identify its intended use

4 Construct a flow diagram and

5 Confirm the flow diagram on-site

Seven HACCP principles

1 Conduct a hazard analysis

2 Determine/identify Critical Control Points (CCPs)

3 Establish critical performance criteria with critical limits for each control point

4 Establish a system to monitor performance of the CCPs

5 Establish the corrective action to take when monitoring indicates that a particular CCP is not under control

6 Establish procedures for verification to confirm that the HACCP system is working effectively

7 Establish documentation concerning all procedures and records appropriate to these principles and their application.

The whole process of actually using the HACCP principles could be divided into four key stages as seen Figure 1.1 (adapted and converted from Mortimore and Wallace, 2001). This study was not about developing a full HACCP plan (all five steps and seven principles) for water treatment facilities but aimed at using some of its key components (Figure 1.1, Stage 2) to examine whether optimal health-related water quality management could benefit during water treatment. Should this prove to be the case, this provisional process would then be taken further, in future studies of

this nature, into developing full HACCP systems for treatment utilities that apply all the HACCP principles.

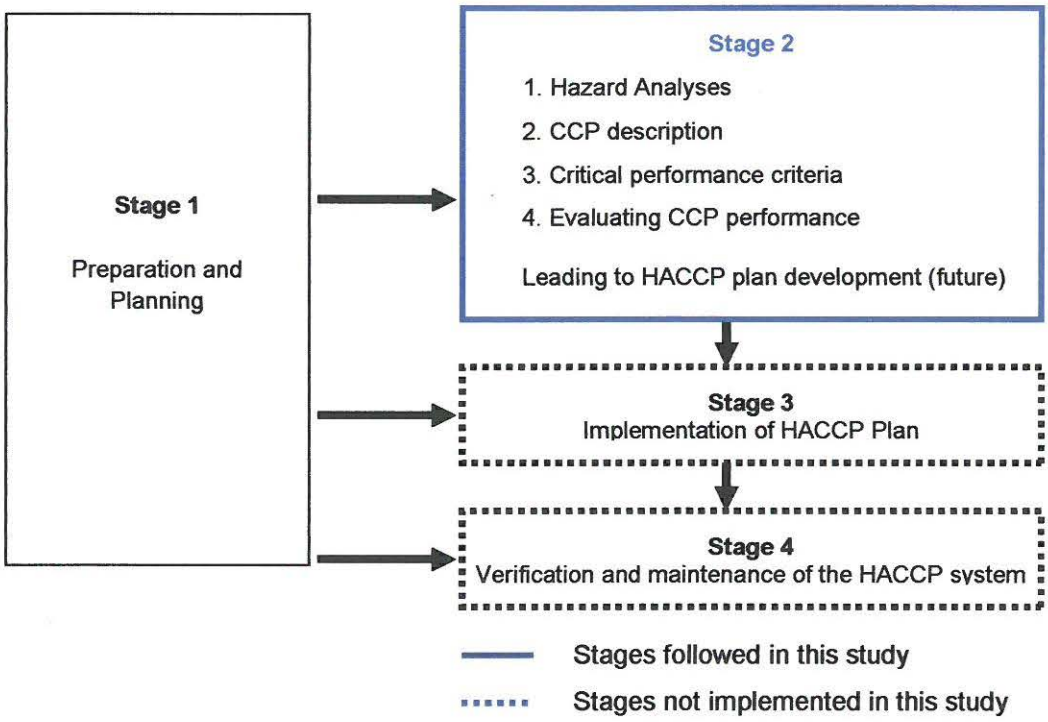

FIGURE 1.1: A summary of the HACCP system overview (abbreviated)

1.5 HACCP PRINCIPLES APPLIED IN THIS STUDY

Chapter Two: Methodology discusses details of the abbreviated HACCP programme. A review of the key HACCP principles that formed the core of this study follows.

1.5.1 HAZARD ANALYSIS

Hazard Analysis (HA) of a process is where an HACCP team systematically analyses each raw material and each step of the process to identify and assess potential hazards and their control mechanisms (Mortimore and Wallace, 2001).

The basic Hazard Analysis step for this study is comprised of two phases:

❶ Deciding on what water quality indicators to use to measure the performance of various system components (later referred to as critical control points (CCPs)). This was based on common practice in the treatment industry and literature review.

❷ Measuring the performance of each CCP to reduce the levels of these indicators to prerequisite levels.

Hazards are considered significant if they are likely to cause harm to the consumer. The controls to be applied to these hazards are specific for each and can be either process steps or activities. Hazards may be:

- biological (e.g. microbial pathogens, which present the greatest risk to consumers);
- chemical (e.g. pesticides or herbicides, which might be carcinogenic and/or cause allergic reactions in consumers); or
- physical (likely to cause injury or health risk to consumer, although in the context of water quality, parameters such as turbidity should be considered) (Genthe and Rodda, 1999; Mortimore and Wallace, 2001).

The HA step for this study focused on health-related microbiological water quality because in developing countries, this water quality aspect is considered more critical in terms of human health risk than, for instance risks posed by chemical water pollution (Anderson, 2001; Jagals and Steyn, 2002).

Microbiological criteria have meaningful roles in HACCP but are generally not considered an effective means of monitoring CCPs because of the lengthy time required to obtain results from microbiological quality testing (United States Department of Agriculture (USDA), 1997). In most instances, monitoring of CCPs can best be accomplished by using physical and chemical tests. Nevertheless, for water treatment systems, health-related microbiological data are essential for applying HACCP because the relationships between the occurrence of microorganisms and other criteria that can be "quick tested" (e.g. turbidity) are not clearly understood (Chapra, 1997, Tchobanoglous and Schroeder, 1987).

This means that using quick testing might not be effective as a means of microbiological Hazard Analysis. Nevertheless, of the rapid testing methods, turbidity is reported to be associated with microbiological water quality (Water Research Commission (WRC), 1998). Turbidity testing was therefore included in this study to augment the microbiological hazard analysis with the understanding

that if turbidity levels were reduced to sufficient levels, microorganism numbers would also be reduced – an approach which can offer the treatment facility manager a quick test option in lieu of microbiological testing.

1.5.1.1 Indicators of microbiological water quality

This study primarily based the hazard analysis on health-related microbiological water quality (HRMWQ). The HRMWQ concept refers to the occurrence of microbiological pathogens in water (American Water Works Association (AWWA), 1991). Analysing water for its health-related quality implies testing the water for the occurrence of pathogens or some proxy organism that indicates their occurrence. The most effective means of HRMWQ assessment is to test directly for microbiological pathogen species in water. This is, however, not always possible. Direct tests for all pathogens related to waterborne diseases are complex, time consuming and expensive, especially for developing countries, which often have only limited financial and skilled human resources (Genthe and Kfir, 1995). In these countries (and in many other countries), data on the health-related quality of water are often generated by affordable alternative methods such as microbiological indicators of water quality e.g. coliform bacteria.

The use of bacterial indicator organisms to assess the microbiological quality of water is well established and has been practised for almost a century (International Association for Water Pollution Research and Control (IAWPRC), 1991; Grabow, 1996). Since waterborne diseases in general are associated with water contaminated by faeces of either human or animal origin, the primary objective for using indicator organisms and methods commonly related to their examination is to indicate the degree of water contaminated by faecal wastes (Grabow, 1996; Standard Methods, 1998).

Microbiological indicators are relatively easy and inexpensive to detect and generally not dangerous to analysts (Grabow, 1996). The numbers of indicator organisms detected in a water body are indicative of the potential level of actual pathogens present (Parrot *et al.,* 1996). For instance, the levels of coliform occurrence in drinking water also indicate the likelihood of clinical infections occurring in consumers (WRC, 1998).

Since coliforms are detected in water contaminated by sewage or recent contact with faeces, they form the core of indicator organisms in water testing. The premise was that if no coliforms were detected in the test samples, the water was generally presumed to be uncontaminated by disease-causing organisms.

Total coliforms and faecal coliforms were the two coliform indicator groups used in this study. The choice of these indicators was based on considerations of simplicity and reliability of the test methods as well as on aspects such as cost, availability of laboratory facilities, culture media and suitably skilled personnel. Most importantly, well-established health-related South African water quality guidelines are also available (WRC, 1998; DWAF, 1996).

1.5.1.1.1 Total coliforms

Total coliforms (TC) are the most common indicators to test for when specifically measuring the effectiveness of treatment processes to remove microbial pathogens from water (DWAF, 1996; WHO, 1997; Standard Methods, 1998; WRC, 1998).
The total coliform bacteria group is mainly comprised of a vaguely defined group of facultative anaerobic, gram-negative, non-spore-forming, rod-shaped bacteria that ferment lactose and produce acid and gas within an incubation time of 24 – 48 hours at 35 – 37°C (Grabow, 1996; Standard Methods, 1998).

Among the "classic" indicators of faecal pollution, total coliforms belong traditionally to the genera of *Citrobacter, Enterobacter* (now *Panteo*), *Escherichia* and *Klebsiella* (Baudisova, 1997). Development of methods for enumerating these coliform bacteria in water as indicators of water quality started in the early 1900s to assess water quality with regard to public health (Edberg, Allen and Smith, 1994; Eckner, 1998). The indicator group remained the cornerstone of the national water regulations in the United States (USEPA, 1975) and is used by many in the water supply industry as a criterion of operational quality-related water treatment and supply parameters (WRC, 1998; Troyan and Hansen, 1989).

TCs should NOT be detectable in treated water supplies. The South African and WHO guidelines allow for 5 (DWAF, 1996) and 10 (WHO, 1997; WRC 1998) TC per 100 mℓ before any significant health effects are expected in consumers drinking water containing more than these levels of total coliforms. If detected in treated

water however, these organisms represent inadequate treatment, post-treatment contamination and/or aftergrowth (like biofilm formation) or an excessive concentration of nutrients (DWAF, 1996; WRC, 1998). It was also for these reasons that total coliforms were included in this study.

1.5.1.1.2 Faecal coliforms

Faecal coliforms (FC) are a sub-set of the total coliform group that, according to the South African Water Quality Guidelines (DWAF,1996), as well as the Assessment Guide (WRC, 1998) indicate the possible presence of disease-causing organisms such as bacteria, viruses or parasites responsible for the transmission of infectious diseases such as gastroenteritis, salmonellosis, dysentery, cholera and typhoid fever. In other words, where TCs indicate inadequate treatment, post treatment contamination and aftergrowth, FCs (if present) indicate a greater likelihood of the water being contaminated with pathogens.

FCs are used to measure the sanitary quality of the water supply for drinking, recreational, industrial and agricultural purposes. When these indicators are present in drinking water supplies, it is considered *prima facie* evidence of a health hazard whether or not the hazard will manifest in overt cases of disease. In other words, its occurrence in water is considered strongly indicative of a health hazard (Environment Australia, 2000). Conversely, water is generally considered free of disease-causing organisms if no faecal coliforms are present in drinking water (Payment, Franco and Siemiatycki, 1993).

1.5.1.2 Turbidity testing

The lengthy time required to obtain results from microbiological testing in the application of HACCP is generally considered a shortcoming in effectively monitoring CCPs (USDA, 1997). Effective application of HACCP requires more rapid testing since water quality managers can react quicker. Measuring for turbidity provided such a test for the purpose of this study. Turbidity (TBY) in water is caused by solid materials carried in suspension. These solid particles, mainly produced by erosion of the land surface, have been found to constitute the major part of the suspended material in most natural waters (WHO, 1996b).

Turbidity has been adopted as an easy and reasonably accurate measure of overall water quality (USEPA, 1999). Turbidity has a significant effect on the microbiological quality of water. Disease-causing microorganisms in water are often associated with suspended matter and not only with sewage or industrial wastes. Particulate matter in water can protect bacteria and viruses against treatment removal since these organisms can adhere to particles and slip through processes unchallenged (AWWA, 1991).

Turbidity testing quantifies the concentration of such suspended matter in water. It can therefore be concluded that low turbidity in water indicates a low pathogen potential and therefore also a low probability for transmission of infectious diseases (DWAF, 1996). While the USEPA (1999) does not consider turbidity as a direct indicator of health risk, studies show a strong relationship between removal of turbidity and removal of microbial pathogens. The removal of turbidity from resource water can be considered a suitable indicator of a treatment facility's capacity to reduce excessive bacteria and thereby to control a microbiological hazard. Water quality guidelines in South Africa (DWAF, 1996; WRC, 1998) apply health risk criteria associated with turbidity levels in water intended for domestic use.

1.5.2 CRITICAL CONTROL POINTS

Control points in water treatment systems are the components where hazards are controlled by reducing or eliminating the transfer of pathogens or other health-related hazards from the one point to the other and eventually to the end users through the treated product. To ensure appropriate prioritisation, some of these points are singled out as the most significant and are considered as "critical" - hence the phrase *Critical* Control Points (CCPs) (WHO, 2001).

After an extensive literature review and investigation of the various treatment components at the selected treatment facilities, the following processes were identified as CCPs: ❶ raw resource (river) water, ❷ post-sedimentation ❸ post-filtration and ❹ post-chlorination.

1.5.2.1 Raw resource water as a CCP

Raw resource water is not essentially a CCP in terms of control, since the treatment facility manager often has very little control over its quality. It was nevertheless decided for this study to include the raw resource as a CCP because, despite having little control over the raw resource water that they have to treat, treatment facility managers have a critical role to play in the management of the upstream catchment. It is a generally accepted principle that the fewer contaminants raw waters have, the better the treatment system will cope with the contaminant load and the risk of contaminant release into the distribution network in the case of accidental or other types of system failure will be lessened (DWAF, 2002; Chapra, 1997).

Including the raw water as a CCP in a HACCP programme provides a means to early warning for preparing the treatment system during periods of intermittent pollution peaks e.g. after rainstorms, when heavily polluted run-off could be expected. It also provides assessment data as to the efficiency of the catchment management system operating in the catchment since it is at the treatment facility where the quality of the surface water in the resource is most often measured.

1.5.2.2 Treatment components as CCPs

1.5.2.2.1 Sedimentation

Sedimentation is a separation technique most often used to reduce the levels of suspended solids and colloids in raw water during conventional treatment (Bernè and Richard, 1991) and is generally found at the beginning of the process. Sedimentation is critical for effective treatment, since it is regarded as most effective in removing viruses as well as spores of protozoan parasites (e.g. of *Giardia* and *Cryptosporidium*), and spore-forming bacteria (e.g. *Clostridia*) (WHO; 2001).

The mechanism that makes sedimentation so effective is adherence to or entrapment of very small particles such as viruses and spores in the settling flocs. Thus, by removing the bulk of the suspended matter (which will include microorganisms) during sedimentation, the filtering and disinfection processes become more effective.

Sedimentation is the unit operation that removes suspended particulate matter from the treatment water by settling by gravity. Sedimentation requires treatment waters to flow through some form or configuration of sedimentation tank at a velocity low enough to permit the particles to settle out from the treatment water (usually to the bottom of the structure) from where it is removed to some form of evaporation pond system, or in older systems, returned to the river whence it came.

In conventional water treatment systems, sedimentation follows the coagulation/ flocculation processes, and is considered by several authors as the end-point of the coagulation/flocculation processes (Tchobanoglous and Schroeder, 1987; Smith, Renner, Hegg and Bender, 1991; Berne and Richard, 1991). It is for this reason that only sedimentation was selected at this stage of the process.

1.5.2.2.2 Filtration

Filtration systems are regarded as effective for the removal of turbidity and microbial contaminants (Smith *et al.,* 1991). The performance of each filter type depends on the quality of the influent and proper design and operation (Smith *et al.,* 1991). Conventional treatment accommodates filtration systems best because of flocculation and sedimentation, which reduces turbidity before the water is filtered (Smith *et al.,* 1991).

Water treatment systems accomplish filtration by passing water through a fine granular medium such as sand. As the water passes through the sand layer, particles are captured in capillaries that naturally form between the sand granules, as well as adhering to the granules. The sand itself is supported by under-drain systems, generally consisting of horizontal networks of perforated pipes placed in a layer of graded gravel - the relatively coarse grains at the bottom and finer grains towards the top of the filter bed so that water flow is not restricted and sand does not escape from the filter. As filters function, the capillaries clog with trapped particles, which means the filters must be cleaned periodically, using a process known as backwashing (Nazaroff and Alvarez-Cohen, 2001).

Filtration is looked upon as a "polishing" phase which provides a high quality finish, especially for the aesthetical appearance of the water (Tchobanoglous and Schroeder, 1987; DWAF, 1996) as well as for enhancing the chlorination process.

1.5.2.2.3 *Disinfection by chlorination*

Disinfection is the final stage of treatment before the drinking water is distributed and is meant to inactivate or remove all pathogenic microorganisms from the water to such an extent that even with a limited number of microorganisms that may still be in the water (disinfection does not mean sterilisation), the end-product should still be safe to use (Bernè and Richard, 1991; Tchobanoglous and Schroeder, 1987). Because of chlorine's high oxidising and residual properties, it is a convenient, effective and economical method of disinfecting of large volumes of water (Cartwright, 1998).

Chlorination has its limitations. While it is quite effective in reducing the numbers of bacterial pathogens that cause e.g. cholera and typhoid fever, it is not as effective against protozoan cysts and spores, viruses and endo-spores of spore-forming bacteria. These organisms and organism-components are best removed by a combination of multi-barriers (Cartwright, 1998), which would include chlorination. Chlorination is most efficient when turbidity has already been removed, which means that substances capable of protecting pathogens from disinfection have been removed as far as possible (WHO, 1996a).

It is increasingly being recognised that a safe drinking water supply should not be based on a single barrier such as chemical disinfection but that a multiple barrier approach is required to effectively eliminate and/or inactivate the various types of hazardous microorganisms (Havelaar, 1994) and to obtain a high level of reliability (Dewettinck *et al.*, 2001).

1.5.3 CRITICAL PERFORMANCE LIMIT TARGETS

Critical performance criteria are boundaries of safety (benchmarks) designed to gauge the performance of CCPs (Food Safety and Inspection Services (FSIS), 1996). A critical performance limit (CPL) will usually be an upper value (or target) of the reading or observation of the particular criterion. For this study, reasonable maximums (RM) of the indicator counts and turbidity measurements were critical performance limit targets (CPLTs) against which the performance of the particular CCP was measured. This study compiled CPLTs from national and international water quality guidelines (Chapter 2 and Appendix C).

The CPLTs established the degree of treatment necessary to cope with the varying quality of the raw waters and for defining targets of performance for bacterial removal. The primary aim of the study CPLTs were to provide compliance levels for each CCP. In complying with its CPLT, such a system component contributes to the protection of public health (Ryan, O'Toole, Bannister and Deere, 2001).

The assumption was that if the CPLT were complied to, health risks posed by the final treated water would be at a minimum even if some of the processes were to fail during treatment.

1.5.4 MEASURING CCP PERFORMANCE AGAINST THE CPLTs

Measuring CCP performance against the CPLTs during this study was structured in a programme that systematically and carefully collected and analysed samples, observations and *in situ* measurements with the aim of providing information and knowledge about the performance of each CCP. For such a monitoring programme to be effective, it should be designed to measure and report on, or provide understanding about, a particular situation or set of issues (Environment Australia, 2000). Monitoring in the HACCP context is the measurement or observation of the CCPs to confirm that they are functioning properly (Mortimore and Wallace, 2001). In the context of this study, measuring CCP performance against the CPLTs determined whether the treatment facilities were actually functioning adequately and effectively to produce a high quality of drinking water.

1.6 SUMMARISING THE STUDY PARAMETERS

1.6.1 PROBLEM STATEMENT

In-process health-related water quality monitoring generally does not form a regular part of the management of the potable water treatment facilities, especially those investigated for this study. This implies that the application of a health-related microbiological water quality safety-plan, based on HACCP principles, does not form part of management systems at the target treatment facilities. It was, therefore, uncertain whether microbiological hazards, which previous studies had shown to exist in the raw water upstream from the facilities, are sufficiently reduced at critical points in each process to ensure that water of suitable health-related quality is allowed into the receiving distribution systems.

1.6.2 AIM OF THE STUDY

The aim of this study was to apply four of seven HACCP principles at two potable water treatment facilities on the Modder River to assess whether selected critical control points were sufficient barriers to reduce microbiological hazards in the final product (safe potable water delivered to distribution networks).

1.6.3 STUDY OBJECTIVES

By implementing the four HACCP principles at the two treatment facilities, the following objectives were to be met:

- Identify critical control points within the two treatment facilities.
- Develop and apply a hazard analysis protocol for each facility based on coliform and turbidity assessments.
- Develop critical performance level targets (CPLTs) to measure CCP effectiveness.
- Apply a monitoring programme to assess the effectiveness of the CCPs based on the critical performance criteria, to reduce hazardous microbiological as well as turbidity levels.

1.6.4 SCOPE OF STUDY

Treatment facility performances are time-dependent. This implies that when point sampling is done in terms of engineering performance management, plant performance would be important and therefore time-dependency needs to be considered when designing the sampling regime.

However, these are design issues which is not the within the scope of this study since this did not follow an engineering approach. The part of the HACCP plan where this performance measurement would have been applicable is part of the fourth study objective and therefore a minority component.

1.6.5 POTENTIAL APPLICATION OF THE RESULTS OF THE STUDY

The methodology used in, as well as the results from, this study can be applied in later developments of an HACCP plan for the two treatment facilities, and can also serve as a template for other treatment systems as well.

CHAPTER 2: METHODOLOGY

CHAPTER 2: METHODOLOGY

The components constituting the abbreviated HACCP programme are shown in Figure 2.1, which also presents an overview of the methodology followed in this study. Section 2.1 presents details of the study area and the treatment facilities, as well as the flow charts and brief descriptions of the targeted treatment facilities and the sampling points. The latter two reflect the two HACCP steps described in Chapter 1, Section 1.4.2. Section 2.2 describes the analysis of the water samples, Section 2.3 shows the procedure followed to identify the critical control points (CCPs) and the compilation of the critical performance level targets (CPLTs) for the various CCPs and Section 2.4 describes the CPLT measurement and quantification process.

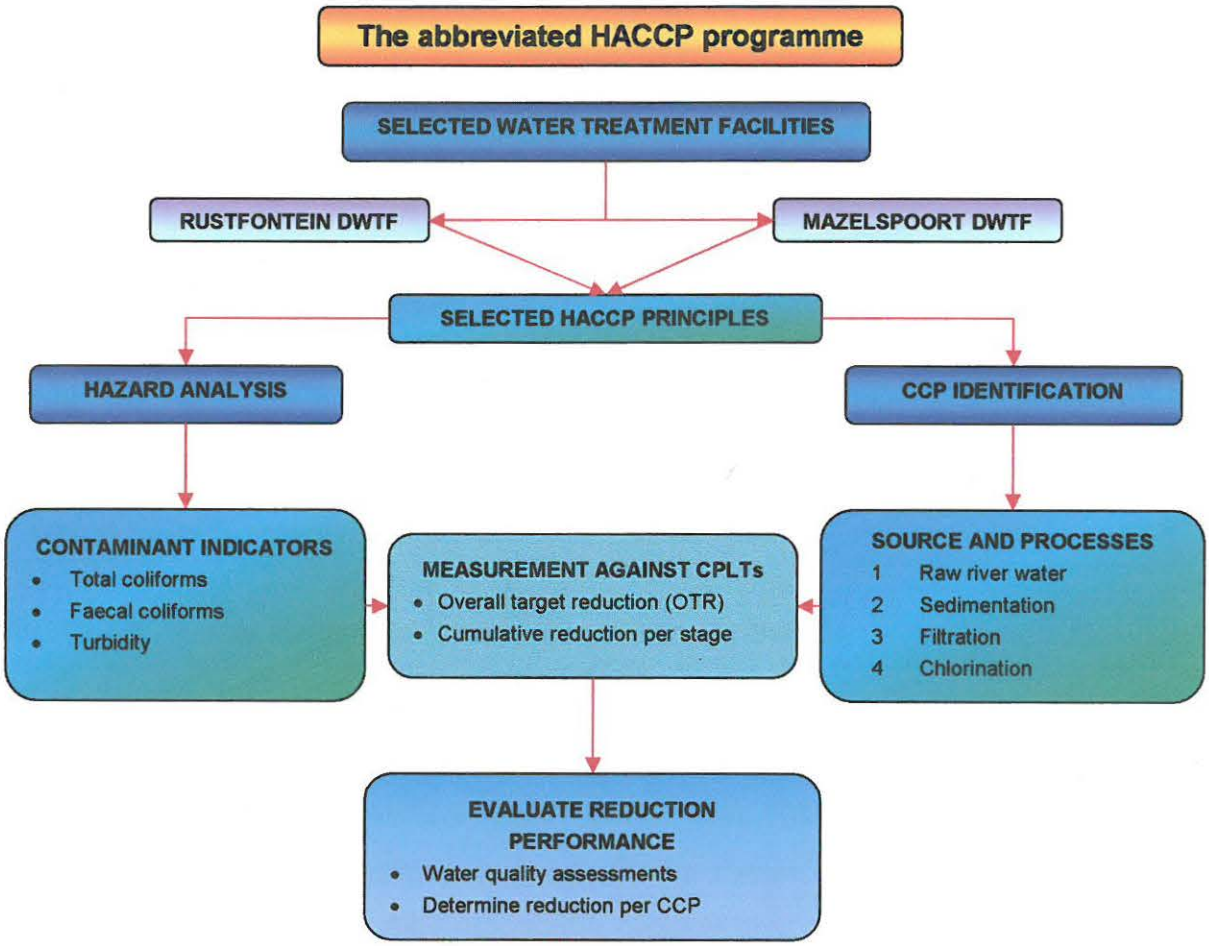

FIGURE 2.1: Study design of the abbreviated HACCP programme

2.1 THE STUDY AREA AND TREATMENT FACILITIES

Rustfontein and Mazelspoort are two potable water treatment facilities in the Mangaung local municipality area (Figure 2.2). These facilities supply treated water to approximately 590,000 consumers in the Bloemfontein, Botshabelo and Thaba 'Nchu areas (Central Statistics Services (CSS), 1997). The water treatment facilities are located on the outskirts of these urban areas and were therefore close at hand for the research team to collect water samples and analyse these in good time.

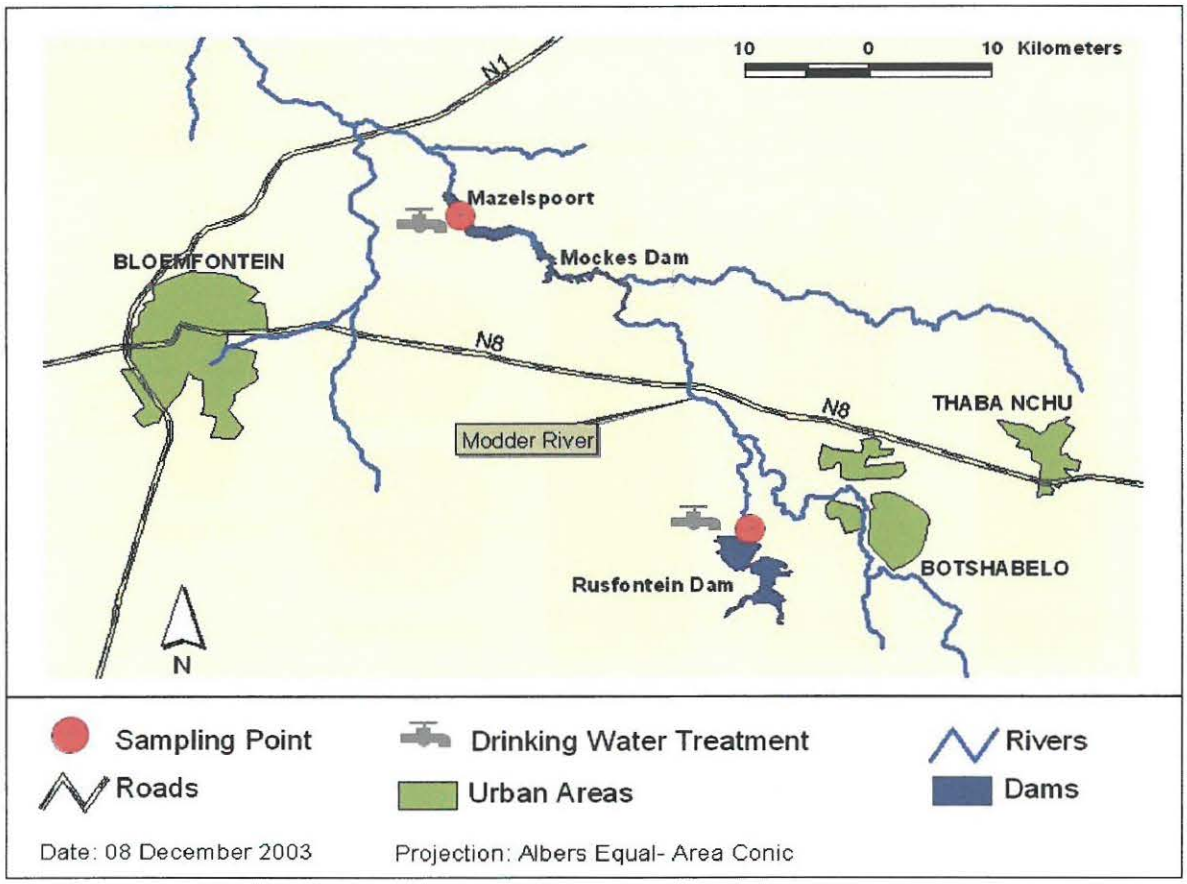

FIGURE 2.2: Middle Modder River sub-catchment and study sites

2.1.1 RUSTFONTEIN TREATMENT FACILITY

The Rustfontein facility is relatively new, built in 1997-1998 in the upper reaches of the Modder River. The facility belongs to Bloem Water, the regional water utility. The health-related water quality monitoring protocol that is currently applied at the facility covers only the raw (intake) water and the final product. The facility supplies treated water on demand to the major cities in the local municipal area of Mangaung, i.e., Botshabelo, Thaba 'Nchu and Bloemfontein (Figure 2.2).

Resource water treated at the Rustfontein facility is withdrawn from the Rustfontein impoundment in the Modder River. The health-related water quality of this impoundment was described as unpolluted river water by Jagals (2000), which means that the water in the resource is not impacted by urban pollution since human activity in the upstream area that could lead to faecal pollution in the catchment to the impoundment, is minimal. Figure 2.3 shows a diagrammatic layout of the facility configuration.

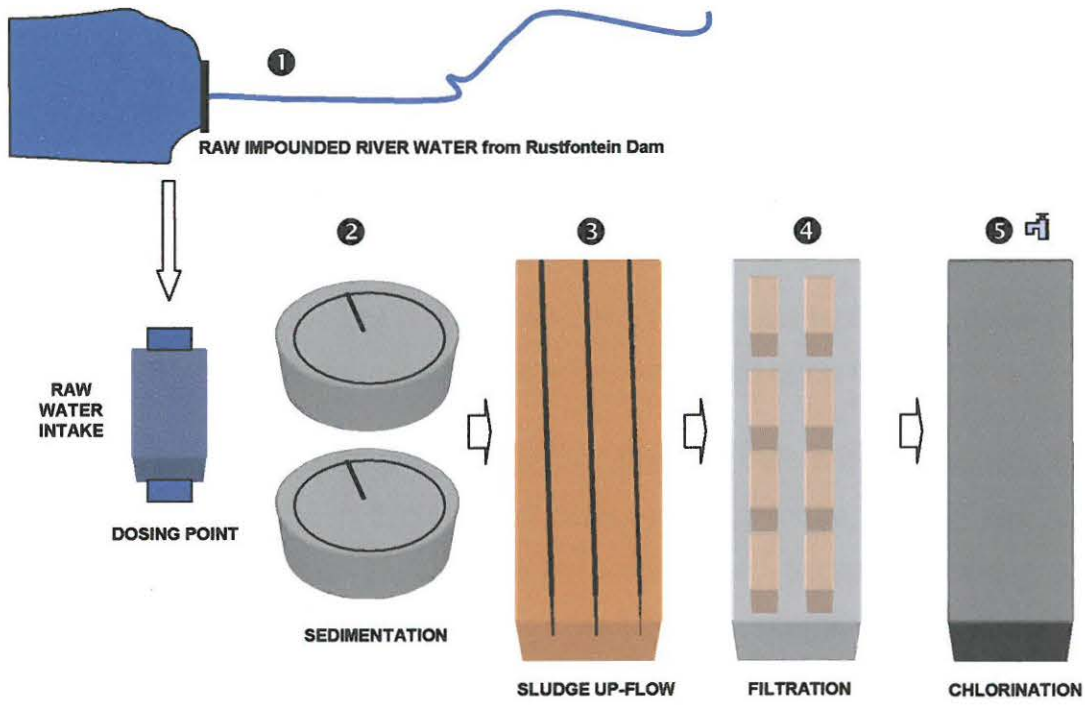

FIGURE 2.3: Diagrammatic layout of the Rustfontein potable water treatment facility

The following section briefly describes the processes and sampling points:

❶ Impounded river water (Sample 1: Raw intake) is pumped from the Rustfontein dam to the chemical dosing point at the head of the works. The water is dosed and rapidly mixed with flocculants consisting of lime and polymer electrolytes.

❷ The water with coagulating flocs gravitates into primary circular sedimentation basins through central stilling wells where the flocculation process continues. Gravity separates the liquid (water) and solids (flocculated particles), with the bulk of the flocs settling at the bottom of the basins from where these are periodically removed. Only limited levels of flocculated particles were observed to escape from the tanks with the overflowing water.

❸ The overflow water flows in pipes to sludge up-flow basins (also described as the secondary sedimentation step of this process) and enters from below. The remaining floc is trapped in a "sludge blanket" that is kept in suspension some distance from the bottom. The trapped floc is removed from the swelling sludge blanket to evaporation ponds. The "clear" water (water without floc) overflows to rapid sand-filter beds.

Note on ❷ & ❸: Although the treatment facility has primary as well as secondary sedimentation, both are included in one CCP namely *sedimentation*. Samples (Sample 2: Sedimentation) were taken from the overflow water from both sedimentation basins. The results from the two processes were combined to show the effectiveness of sedimentation as a whole at this facility.

❹ In the uncovered rapid sand-filters, the water filters through a sand bed to "polish" the water before it enters the chlorine contact tanks. Samples (Sample 3: Post filtration) were collected after the water had been filtered.

❺ The filtered water is dosed with gas chlorine just before it enters a contact tank where it is retained in a quiescent state for the chlorine to react and disinfect before being pumped for distribution in the cities. Samples (Sample 4: Post-chlorination) were collected at the first outlet (tap) after the chlorination stage.

2.1.2 MAZELSPOORT TREATMENT FACILITY

Mazelspoort has been functioning since the late 1800s. The local municipality manages this facility which provides treated water to the people who live in the city of Bloemfontein (Figure 2.2). The existing health-related water quality monitoring protocol covers the raw water as well as the final product.

The resource water extracted from the Modder River to the Mazelspoort facility was described by Jagals (2000) as polluted river water because the water was often severely polluted by discharges from upstream urban areas and poorly managed wastewater treatment facilities from Botshabelo and Thaba 'Nchu. Sources of pollution of this water body are generally land-deposited human faecal materials that flush into the watercourse in urban run-off (e.g. after rainstorms). This is because of limited or inadequate sanitary facilities and from faecal material from domestic and farm animals kept in the urban areas (Jagals, Grabow and De Villiers, 1995; Jagals,

1997; 2000). Jagals (2000) also reported a variety of recreational activities (full contact and intermediate contact) taking place in these waters. Figure 2.4 shows a diagrammatic layout of the facility configuration.

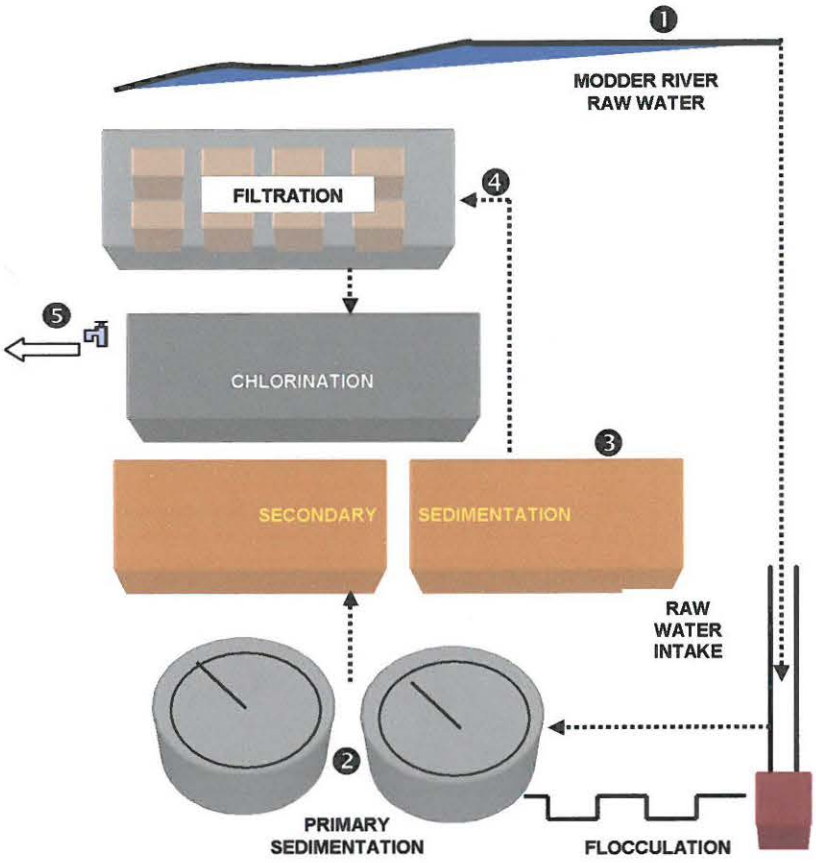

FIGURE 2.4: Diagrammatic layout of the Mazelspoort potable water treatment facility

The sampling points in Figure 2.4 can be described as follows:

❶ Raw resource water is extracted from the Mazelspoort barrage in the Modder River and pumped to the chemical dosing point at the head of the works. Samples (Sample 1: Raw intake) were collected from the resource water.

❷ The raw water is chemically dosed with chlorine and flocculants (lime and polymer electrolytes). The dosed water is rapidly mixed and flows through a flocculation canal that allows the coagulation and flocculation to advance. The mixture flows to a sedimentation process, where gravity separates the liquid and solid phases.

❸ Mazelspoort also applies secondary sedimentation to remove remaining floc from the water received from the primary sedimentation tanks. The water moves at a slow pace through a dam-like structure and the "clean" water flows to the filter chambers. Both processes are dealt with as one CCP namely *sedimentation*. Samples (Sample 2: Sedimentation) were taken from the overflow water from both sedimentation basins. The results from the two processes were combined to show the effectiveness of sedimentation as a whole.

❹ Water flows from the secondary sedimentation tank to the covered rapid sand filters in the filtration chambers. The semi-treated raw water is then filtered through a multimedia (different sizes of sand granules) sand filter bed. Samples of the post-filtration water (Sample 3) were collected.

❺ The filtered water is dosed with gas chlorine before entering the contact tank where it is retained in a quiescent state for the chlorine to react and disinfect before being pumped to the reservoirs in the city of Bloemfontein. Samples were taken after disinfection of the water (Sample 4: Post-chlorination).

2.2 MICROBIOLOGICAL HAZARD ANALYSIS

The microbiological indicator organism groups total coliforms (TC) and faecal coliforms (FC) as well as the physical water quality parameter turbidity (TBY) were used to gauge potential microbiological hazards and to assess the effectiveness of the selected potable water treatment systems in reducing these organisms and turbidity levels in the raw intake water to acceptable guideline levels as described in the Assessment Guide for Domestic Water Quality (WRC, 1998) and the South African Water Quality Guidelines (DWAF, 1996). Appendix A details the physical sampling and analysis protocol. The study was conducted over a period of 8 months with a total of 16 sampling sessions. In each facility, samples were taken at the treatment components identified as critical control points (CCPs; Section 1.5.2).

2.2.1 CONTAMINANT ASSESSMENT (See Appendix A; Section 3.5)

2.2.1.1 Total coliforms (See Appendix A; Section 3.5.1)

Total coliforms indicate the general sanitary quality of drinking water related to the efficacy of treatment to reduce levels of organic waste contaminants (Grabow,

1996). These indicators were detected in the water samples on the culture media Chromocult® Coliformen Agar (Merck, 1996), using membrane filtration (Appendix A; Section 3.4) according to Standard Methods (1998). Presumptive total coliform numbers were expressed as organisms per 100 mℓ according to the South African Water Quality Guidelines (DWAF, 1996) and the Assessment Guide for domestic water quality (WRC, 1998).

2.2.1.2 Faecal coliforms (See Appendix A; Section 3.5.2)

Faecal coliform bacteria are recommended by the WHO (1996a) as an indicator of the efficiency of water treatment processes in removing enteric pathogens and faecal bacteria, as well as for grading the quality of source waters in order to select the intensity of treatment needed (WHO, 1996a). Faecal coliforms were cultured on MFc Agar (Biolab®) using the membrane filtering technique (Standard Methods, 1998). After incubation, colonies were counted as faecal coliforms and expressed as organisms per 100 mℓ, according to the South African Water Quality Guidelines (DWAF, 1996) as well as the Assessment Guide (WRC, 1998).

2.2.1.3 Colony verification (See Appendix A; Section 4)

Total and faecal coliform colonies were verified with analytical profile indices (API 20E multi-test galleries, bioMérieux, 2001). This was done to determine the percentage of true-positive colonies (Dionisio and Borrego, 1995; Jagals, 2000; Griesel, 2001; Nala, 2002).

2.2.1.4 Turbidity (See Appendix A; Section 5)

Turbidity can be used to measure the performance of individual treatment processes as well as the performance of an overall water treatment system (USEPA, 1999). A HACH 2100 turbidity meter was used to measure turbidity levels in the same water samples used for microbiological analyses and the measurements were recorded as Nephelometric Turbidity Units (NTUs).

2.2.2 STATISTICAL DATA ANALYSES (APPENDIX B)

Data were entered into Microsoft Excel® XP spreadsheets. Microbiological data were transformed into logarithmic (Log_{10}) numbers to remove excessive variance in an effort to establish normality of the data (Helsel and Hirsch, 1995).

The data were statistically analysed for range, geometric mean (mean of logs) and the reasonable maximum set at the 90th percentile. The statistical programme SigmaStat V2 (1997) was used to test for the minimum sample size, normality, statistical significant differences using analysis of variance (ANOVA) as well as testing for correlations. Sigmaplot 8.02 (2002) was used to plot the data into box plots and line-and-scatter graphs.

2.3 CRITICAL CONTROL POINTS (CCPs)

A CCP decision tree adapted from Mortimore and Wallace (2001) identified CCPs for each treatment facility (Figure 2.5). The tree consisted of a number of questions that were applied to identify each hazard. CCPs identified for this study were ❶ sedimentation, ❷ rapid sand filtration and ❸ chlorine disinfection. The raw river water CCP was selected on the basis described in Section 1.5.2.1.

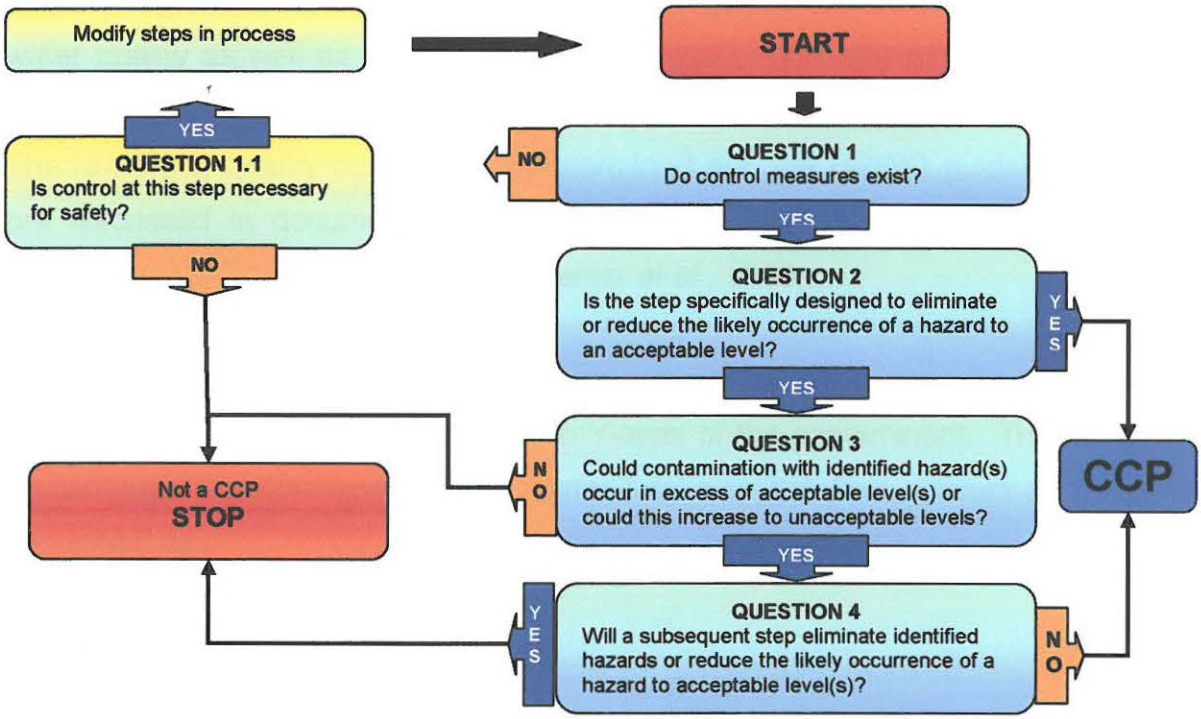

FIGURE 2.5: CCP decision tree

2.3.1 CRITICAL PERFORMANCE LIMIT TARGETS

Performance guidelines for critical performance limits were not available in documented format and certainly not at either of the two facilities.

To measure the performance of each CCP during this study, critical performance limits targets (CPLTs) were compiled in sets of guidelines for each of the CCPs (Tables 2.1–2.6). The performance measurement approach was tailored according to the work of Poda *et al.* (1994) and comprised two stages, i.e.❶ the overall target reduction CPLs and ❷ CPLTs for cumulative reduction (CR) per stage.

Two statistical approaches were applied to measure the system performance of each facility.

❶ To obtain an overall impression, the mean performance over the study period was measured with the geometric mean (the mean of the logs).

❷ To assess the reasonable maximum capability, performance was measured at the 90th percentile.

2.3.1.1 Overall reduction target (ORT)

Overall target reduction CPLs are based on targets that are functions of the raw water quality as well as health-related water quality (HRWQ) requirements for the treated drinking water (proposed in Table 2.3). Both are independent variables. The raw water quality cannot be predetermined and the HRWQ guidelines for this are discussed in documentation such as the *Tools for Microbial Water Quality Assessment of South African Rivers* (Venter *et al.,* 1996).

The very simple principle is that raw water containing X-level of contaminant has to be cleaned up to contain not more than Y-level of the contaminant. This implies a percentage reduction from the raw water intake to the final product and can be expressed as:

$$ORT = 100 - (y / x) * 100$$

Where: ORT is the overall reduction target (in percentage) required,

y = level of contaminant in the final product required by HRWQ guidelines and

x = level of contaminant in the raw water (geometric mean and/or 90th percentile).

2.3.1.2 CPLTs for cumulative reduction (CR) per stage

This consisted of applying percentage reduction criteria for each CCP. For example, the sedimentation process will be expected to remove 90% of the indicator bacteria from the water that will next be put through the filters at the facility. The

water from the filters will be expected to have e.g. 99% of the indicator organisms removed. The actual indicator reduction at each CCP is assessed and then measured against these CPLT percentages.

A percentage reduction from the one CCP to the next is expressed as:

$$CR = (x-y) / x * 100$$

Where: CR is the cumulative reduction target (in percentage),

x = geomean and/or 90^{th} percentile of the contaminant value from previous CCP and

y = geomean and/or 90^{th} percentile level of contaminant at the current CCP.

If the actual reduction percentage is on par or exceeds the CPLT, the CCP performed as required. If it did not meet the expectations it means that the excess contaminants have moved on to the next process, putting the whole treatment system at risk of not attaining the overall target reduction. Management interventions should then be implemented.

Percentage target compliance per CCP is expressed as:

$$C = CR - CCPT$$

Where: C = is the percentage compliance,

CR = cumulative reduction target (in percentage) and

CCPT = critical control point target (in percentage).

2.3.2 CPLTS APPLIED IN STUDY

2.3.2.1 Raw (untreated) resource water

As discussed in section 1.5.2.1, raw water is strictly speaking not a CCP, but is nevertheless, for the purposes of this study, linked to a CPLT. While raw water would not actually "perform" at a given contaminant level, Table 2.1 shows that there is wide acceptance of the principle that raw water should have at least some quality criteria to strive for in order to minimise the risk of distribution system contamination in the event of systems failure.

Table 2.1: Proposed health-related microbiological quality of raw water for drinking water abstraction

Country	Contaminant	Organism numbers	Type of limit
South Africa	Total coliforms[2] Faecal coliforms[3]	20,000 / 100 mℓ 2,000 / 100 mℓ	Maximum for raw water
European Economic Community, 1980	Total coliforms[1] Faecal coliforms[1]	5,000 / 100 mℓ 2,000 / 100 mℓ	Guideline value
United States of America USEPA, 1973	Faecal coliforms[2]	2,000 / 100 mℓ	Geometric mean in raw water
United Kingdom UK Drinking Water Supply Regulations, 1989 *Based on EC directives	Faecal coliforms[2]	20 / 100 mℓ 2,000 / 100 mℓ	90th percentile limit for simple physical treatment 90th percentile limit for conventional treatment

[1] Tebbutt, 1998. Guidelines for normal full physical and chemical treatment with disinfection

[2] Venter *et al.*, 1996. Guidelines for conventional water treatment

[3] DWAF, 2002. Guidelines for conventional treatment

Turbidity was not included in Table 2.1 above, since literature does not provide reasonable direction towards proposing an acceptable raw water quality. The USEPA (1999) gives an indication of what the turbidity levels should be when compared to the origin of turbidity. For example, low turbidity streams and rivers (less than 20 NTU) are those which are usually located in the upper reaches of an undeveloped (by anthropogenic measures) watershed. In general, larger reservoirs or lakes have lower turbidity levels. For example, the Great Lakes of America usually have turbidity levels below 100 NTU, whereas rivers can have turbidities reaching over 1,000 NTU.

Table 2.2 presents the study CPLTs compiled from the values in Table 2.1. These are intended to serve as guidelines, with which raw water for potable treatment should be consistent in order to effectively treat such potable water quality.

Table 2.2: Proposed critical performance limit guidelines for raw water applied in this study

Indicator	CPLT for indicator numbers / levels
Total coliforms (Venter *et al.*, 1996)	20,000 / 100 mℓ
Faecal coliforms (DWAF, 2002)	2,000 /100 mℓ
Turbidity	None

2.3.2.2 Drinking (treated) water quality guidelines

The various national and international potable water quality guidelines that measure the health risks indicated by total coliforms, faecal coliforms and turbidity are shown

in Appendix C. It is generally to these types of guideline criteria that water quality managers would strive to comply with the quality of water after conventional treatment. Table 2.3 presents a summary of the guidelines in Table C1 and C2 (Appendix C). These were for treated drinking water used specifically for this study.

Table 2.3: Treated drinking water guidelines used for this study

Guideline limit	Health risk
TOTAL COLIFORMS	
0 - 10 / 100 mℓ	Insignificant change of infection (WRC, 1998)
10 - 100 / 100 mℓ	Clinical infections unlikely in healthy adults, but may occur in some sensitive groups (WRC, 1998)
5 – 100 / 100 mℓ	Indicative of inadequate treatment, post treatment contamination or growth in the distribution system (DWAF, 1996)
FAECAL COLIFORMS	
0 / 100 mℓ	No detectable change of infection (DWAF, 1996; WRC, 1998)
0 - 1 / 100 mℓ	Insignificant change of infection (WRC, 1998)
TURBIDITY	
< 0.1 NTU	No effects (WRC, 1998)
0.1 – 1 NTU	Slight risk of potential health effects (WRC, 1998)
1 – 5 NTU	No turbidity visible and a slight chance of adverse aesthetic effects and infectious disease transmission exists (DWAF, 1996)

2.3.2.3 CPLTs for the in-process CCPs

2.3.2.3.1 Sedimentation

Finding guidelines that could be converted into reduction criteria for sedimentation proved problematic, especially for turbidity. USEPA (1999) guidelines offer a wide removal range (Table 2.4). For the purposes of this study and future HACCP programmes this range was narrowed down (Table 2.7). The WHO (2000) provides an end-point value which, depending on the level of TBY in the raw water, would also prove to be too wide a target range. The WHO (2000) guidelines do provide clear criteria for microbe (bacteria) removal.

Table 2.4: Literature propositions on reduction effectiveness of the sedimentation process

Organisation	Contaminant	Suggested reduction
USEPA, 1999	Turbidity	50 – 90 % reduction
WHO, 2000	Microbes	<90% reduction
	Turbidity	To < 5 NTU

Tebbutt (1998) provides an indication of removal efficiency of sedimentation processes by stating that a raw water sample with a turbidity of 30 NTU should usually be improved to about 5 NTU after coagulation, flocculation and

sedimentation. This constituted 85% TBY reduction effectiveness which provided some guidance on this criterion. Table 2.7 indicates the percentage turbidity reduction for sedimentation set for this study.

2.3.2.3.2 Filtration

According to the Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions (USEPA, 1999), filtered water should never exceed 1 NTU at any time. The Surface Water Treatment Rule (SWTR) of the USEPA, on the other hand, requires that filters achieve turbidities of less than 0.5 NTU in 95% of the finished water samples and never exceed 5 NTU (Smith *et al.*, 1991). Table 2.5 indicates the percentage reduction guidelines set for this study for the reduction of indicators by the filters.

Table 2.5: International literature suggestions on reduction of effectiveness of the filtration process

Organisation / authors	Contaminant	Suggested reduction
Tebbutt, 1998	Total coliforms	90 % reduction
	Turbidity	< 1 NTU
WHO, 1996	Thermotolerant coliform bacteria	80 % reduction
	Turbidity	> 80 % reduction
WHO, 1996	Bacteria	98-99% reduction
WHO, 2000	Microbes	< 90% reduction
	Turbidity	< 1 NTU
USEPA, 1999	Turbidity	< 0.5 NTU in 95% of finished water samples
Australian Drinking Water Guidelines, 1996	Faecal coliforms	> 80% reduction

2.3.2.3.3 Chlorination

There are various treated water guideline sets available nationally and internationally. However, these guidelines indicate the quality of the end–product which inadvertently gives an appropriate indication of the critical performance limit target of this CCP. Table 2.6 indicates the percentage reduction guidelines set for this study.

Table 2.6: Critical performance limits for chlorination applied in this study

Indicator	Percentage reduction
Total coliforms (WHO, 2000)	99.99 %
Faecal coliforms (WHO, 2000)	99.99 %
Turbidity (WHO, 2000)	< 1 NTU

2.3.4 SUMMARY OF CRITICAL PERFORMANCE LIMIT TARGETS

Table 2.7: A guide for critical performance limits applied in this study

Indicator	Raw water extraction	Sedimentation (in % reduction)	Filtration (in % reduction)	Chlorination / Treated water (in % reduction)	
Total coliforms	20,000/100 mℓ (Venter *et al.*, 1996)	90 % (WHO, 2000)	99 % (WHO, 2000)	99.99 % (WHO, 2000)	0-5 / 100 mℓ (DWAF, 1996)
Faecal coliforms	2,000 / 100 mℓ (DWAF, 2002)	90 % (WHO, 2000)	99 % (WHO, 1996)	99.99 % (WHO, 2000)	0 / 100 mℓ (DWAF, 1996)
Turbidity	None	85 % (USEPA, 1999)	< 1 NTU (WHO, 2000)	< 1 NTU (WHO, 2000)	1 NTU (DWAF, 1996)

2.4 MEASURING CCP PERFORMANCE AGAINST THE CPLTs

The Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions (USEPA, 1999), states that turbidity can be used to measure the performance of individual treatment processes as well as the performance of an overall water treatment system. As discussed in Section 1.5.1.2, turbidity relates strongly to microbiological pathogens. Results from microbiological hazard analyses and the turbidity levels were compared and plotted in figures, using scatter plots with regression analyses for a visual summary of the test results. It was assumed that although microbiological indicator organisms might occur in larger numbers than turbidity in the same water sample, their occurrence would positively co-vary i.e. when the levels of turbidity decrease, so will the levels of the microbiological indicator group. This is referred to as positive linearity and should indicate strongly in the direction of r = 1 (Jagals, 2000). Associations were also calculated to assess whether the indicators increased or decreased in the same samples. If the indicators correlated, then the assumption could be made that turbidity might be used in the place of microbiological indicator organisms to determine effectiveness of treatment facilities to supply a high quality of drinking water.

CHAPTER 3: RESULTS AND DISCUSSION

CHAPTER 3: RESULTS AND DISCUSSION

This chapter presents results of the two treatment systems (Rustfontein and Mazelspoort), and discusses whether the two systems succeeded in reducing the health-related microbiological hazards that might have existed in the raw intake water, to acceptable limits. It also discusses the role of each CCP in these reductions.

Figure 3.1 shows the layout of the hazard analyses results discussed in this chapter.

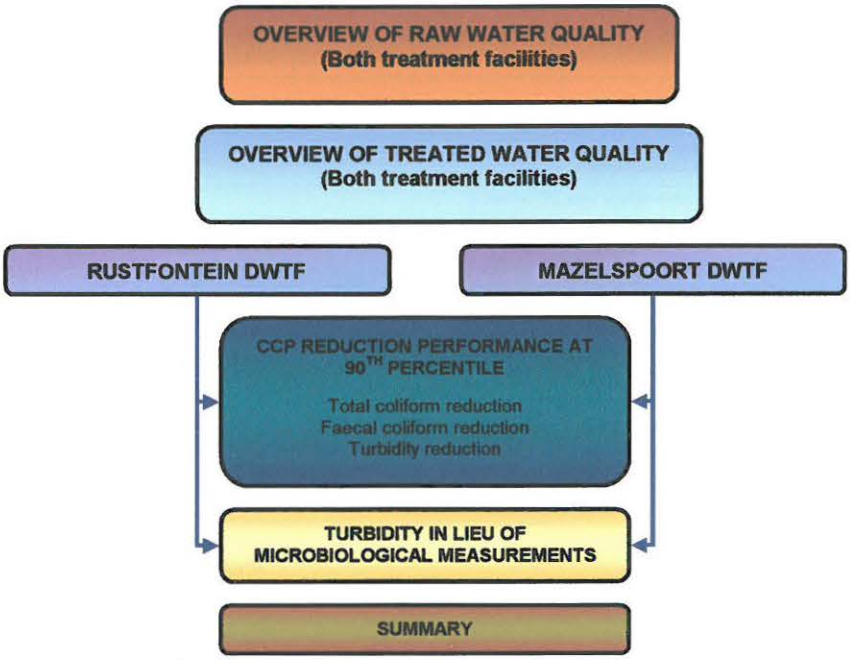

FIGURE 3.1: Layout of hazard analyses results

3.1 THE RAW WATER QUALITY

Appendix E presents the data of the raw water quality measurements at both treatment facilities. Figure 3.2 shows that, at the 90th percentile (the upper horizontal whisker-cap of each boxplot as illustrated in Appendix B), the health-related microbiological quality of the raw water extracted from both of the surface resources were well within the guideline values construed in Table 2.7 (Chapter 2). It is important to remember that no value was proposed for turbidity in raw water. Water from the Rustfontein impoundment generally appeared to have been of a better microbiological quality than that of the water from the Mazelspoort impoundment.

This was due to polluted urban run-off from substantial urban settlements upstream from Mazelspoort (Jagals, 1997; 2000).

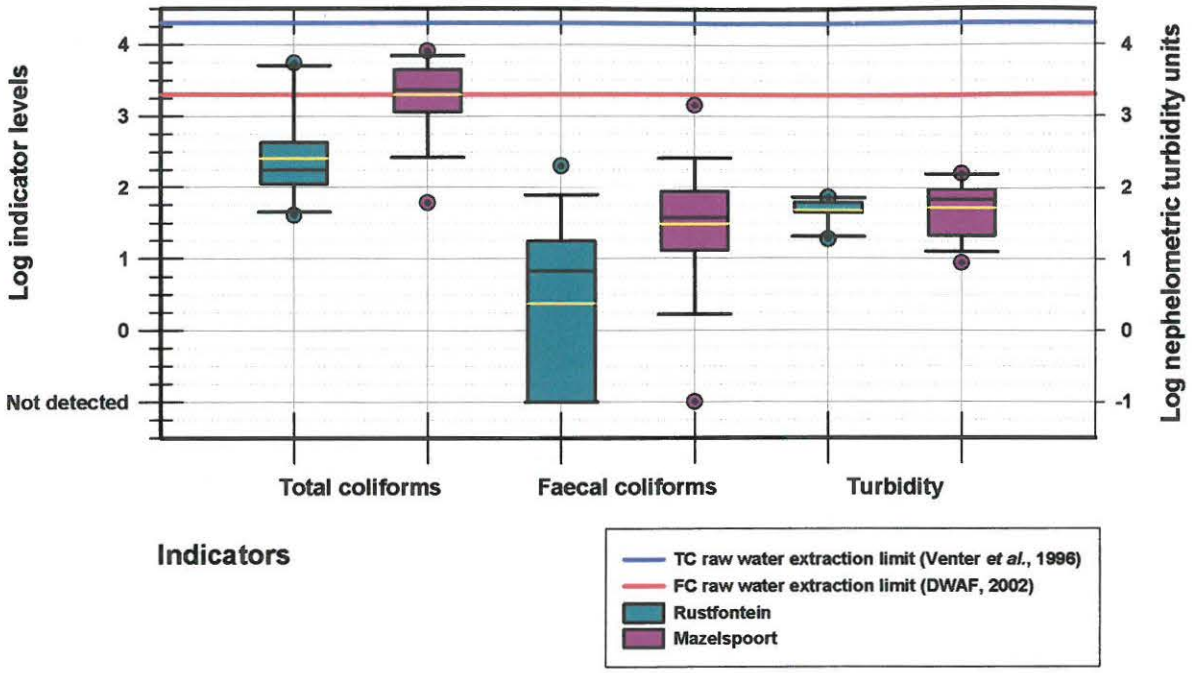

FIGURE 3.2: Indicator levels in raw water intakes at Rustfontein and Mazelspoort water treatment facilities

3.1.1 TOTAL COLIFORMS

Total coliforms ranged between 40 and 5,470 TC/100 mℓ at the Rustfontein impoundment and between 60 to 8,070 TC/100 mℓ in the Mazelspoort impoundment. These numbers were relatively low when compared with studies done by Jagals (2000) as well as with other studies elsewhere in the world.

Quintero-Betancourt and De Ledesma (2000) reported total coliform numbers ranging from 100 to 26,000 CFU/100 mℓ in the raw water used for extraction at a drinking water treatment facility of Maracaibo City in Venezuela. From Egypt, El-Taweel and Shaban (2001) reported total coliform numbers in raw extraction waters from the Nile River ranging from 1,900 to 25,000 organisms per 100 mℓ. Studies done in Canada by Payment, Gamache and Paquette (1989) showed total coliform numbers in water extracted from rivers of up to 490,667 CFU/100 mℓ. High numbers of TC were also detected in raw waters extracted for drinking water treatment in Chile, where total coliform numbers ranged from 100 to 92,000 TC/100 mℓ (Martins, Castillo and Dutka, 1997).

According to the United States Geological Survey (USGS) national field manual for the collection of water quality data, the ranges of total coliforms typically found in surface water in the United States of America (USA), varied from *not detected* (<1) to 80,000 colonies/100 mℓ, while faecally contaminated surface waters ranged from 1,200 to > 4,000,000 TC/100 mℓ (USGS, 1997).

A factor that probably played a role in the lower counts obtained in this study was the time of the year that the study was done, which was during the late summer, winter and early spring. Jagals (2000) had shown that total coliform counts in samples taken from these resources during high summer, especially after heavy thundershowers following dry periods, generally contributed to higher numbers of indicator organisms than the annual averages, ranging from Log 1 – Log 6/100 mℓ. Nevertheless, the study period was characterised by generous (and somewhat unseasonable) rains that would have flushed pollutants into the resources.

The winter counts of the work by Jagals (2000) tended to reflect the levels reported in these results. The TC numbers can therefore be seen as a reflection of the general occurrence levels of total coliforms in the resource waters during the time the study was done but with considerably higher numbers expected during the high summer period. For this study, these numbers were well within the maximum resource water limit of 20,000 TC/100 mℓ (Table 2.7, Chapter 2) proposed by Venter *et al.* (1996), which indicated that the general hygienic quality of raw waters extracted from the Rustfontein and Mazelspoort impoundments during the period of this study were of a quality suitable for treatment in conventional treatment facilities such as the two systems investigated.

3.1.2 FAECAL COLIFORMS

While the total coliforms indicated that resource waters in the study area were of good hygienic quality, faecal pollution did occur. Faecal coliforms ranged from *not detected* (<1) to 200 FC/100 mℓ at Rustfontein and from *not detected* (<1) to 1,400 FC/100 mℓ at Mazelspoort. The faecal coliform numbers appeared to be relatively similar to results obtained in other studies done in the same study area (Jagals, 2000) as well as in other parts of the world. Nevertheless, Jagals (2002) reported considerably higher counts during storm flush, especially in the Mazelspoort catchment.

Faecal coliform numbers reported by Quintero-Betancourt and De Ledesma (2000) ranged between 1 and 30 CFU/100mℓ. Previous studies in the area (Jagals, 1997; 2000) showed faecal coliform numbers which ranged from *not detected* (<1) to 1,600 FC/100 mℓ at the Rustfontein impoundment and numbers of *not detected* (<1) to 58,000 FC/100 mℓ at Mazelspoort. Water extracted from the Nile River in Egypt to be used for conventional treatment had faecal coliform numbers that ranged from 58 to 750 MPN/100 mℓ (El-Taweel and Shaban, 2001).

Payment *et al.* (1989) detected faecal coliforms in raw river samples collected from a river in Canada in numbers of between 9,267 CFU/100 mℓ and 21,133 CFU/100 mℓ. The USGS (1997) suggested that surface waters in the USA would typically have faecal coliforms in the range of *not detected* (<1) to 5,000 FC/100 mℓ but under severe pollution circumstances, water that is faecally contaminated would have FCs ranging from 200 to > 2,000,000 FC/100 mℓ. The FC numbers reflected the general levels of the faecal coliforms that occur in the resource waters to be well within the maximum resource water limit of 2,000 FC/100 mℓ proposed in Table 2.7, Chapter 2. This indicated that even though raw water showed signs of faecal pollution, conventional treatment facilities should be able to treat such water effectively if properly designed, maintained and operated.

3.1.3 TURBIDITY

The mean levels measured for Rustfontein and Mazelspoort impoundments were 50 NTU and 69 NTU, respectively. Quintero-Betancourt and De Ledesma (2000) measured mean turbidity levels of 6.4 NTU within a narrow range of ± 2.3 NTU in the Venezuelan resource waters. Mean turbidity levels of 8 NTU were measured in resource waters in areas in Canada (Payment *et al.*, 1989).

However, the levels of turbidity measured in this study could be compared to the turbidity levels of rivers in the United States, which according to the USEPA (1999), have turbidity levels of below 100 NTU for lakes (dams) and > 1,000 NTU for rivers. Overall, the turbidity in the raw water of the Rustfontein and Mazelspoort impoundments appeared to be of an acceptable quality for drinking water treatment.

3.1.4 SUMMARY

Despite being within the guideline values in Table 2.7 (Chapter 2), the following were evident:

- Considerably higher indicator concentrations could be expected during high summer especially during storm flush after prolonged dry periods.
- Should any one or more of the processes within each treatment facility fail, the quality of the water delivered to the receiving distribution systems could potentially contain bacterial contaminants hazardous to the health of human users, even at the relatively lower levels.
- The Mazelspoort facility had to cope with a considerably larger microbiological contaminant load than the Rustfontein facility.

3.2 TREATED WATER QUALITY

The results on the indicator levels of treated water quality at the two treatment facilities are given in Appendix E. Figure 3.3 shows that, at the 90th percentile, the health-related microbiological quality of the treated water delivered from both facilities was generally within guideline limits proposed by the South African Water Quality Guidelines (DWAF, 1996) and the Assessment Guide for Quality of Domestic Water Supplies (WRC, 1998), except for Mazelspoort where total coliforms as well as turbidity intermittently exceeded guideline values.

Comparing the results of the treated water from both treatment facilities to national health-related water quality guidelines, the following was observed (at the 90th percentile):

- Total coliform numbers were below the *insignificant risk* limit of 5 TC/100 mℓ as proposed by the South African Water Quality guidelines (DWAF, 1996) and Assessment guide (WRC, 1998), except for at Mazelspoort, for which the outliers at the 95th percentile (in the graph) indicated potential post-treatment contamination. This implied that while both treatment facilities generally reduced the levels of total coliforms in the respective raw waters to acceptable health-related quality levels, excessive numbers of total coliforms did intermittently enter the drinking-water distribution system supplied by the Mazelspoort facility.

- No faecal coliforms were detected in the water after treatment. This indicated that the treatment processes effectively rendered these indicator organisms inculturable – therefore assumed not active.
- Turbidity levels in the final water from the Mazelspoort facility were significantly higher ($P \leq 0.001$) than those in the Rustfontein final water. The turbidity in approximately 40% of the final water samples from Mazelspoort exceeded the maximum guideline limit of 5 NTU (DWAF, 1996), which implied that turbidity may often be visible and objectionable to users, while some chance existed of disease transmission by micro-organisms associated with particulate matter, particularly for agents with a low infective dose such as viruses and protozoan parasites.

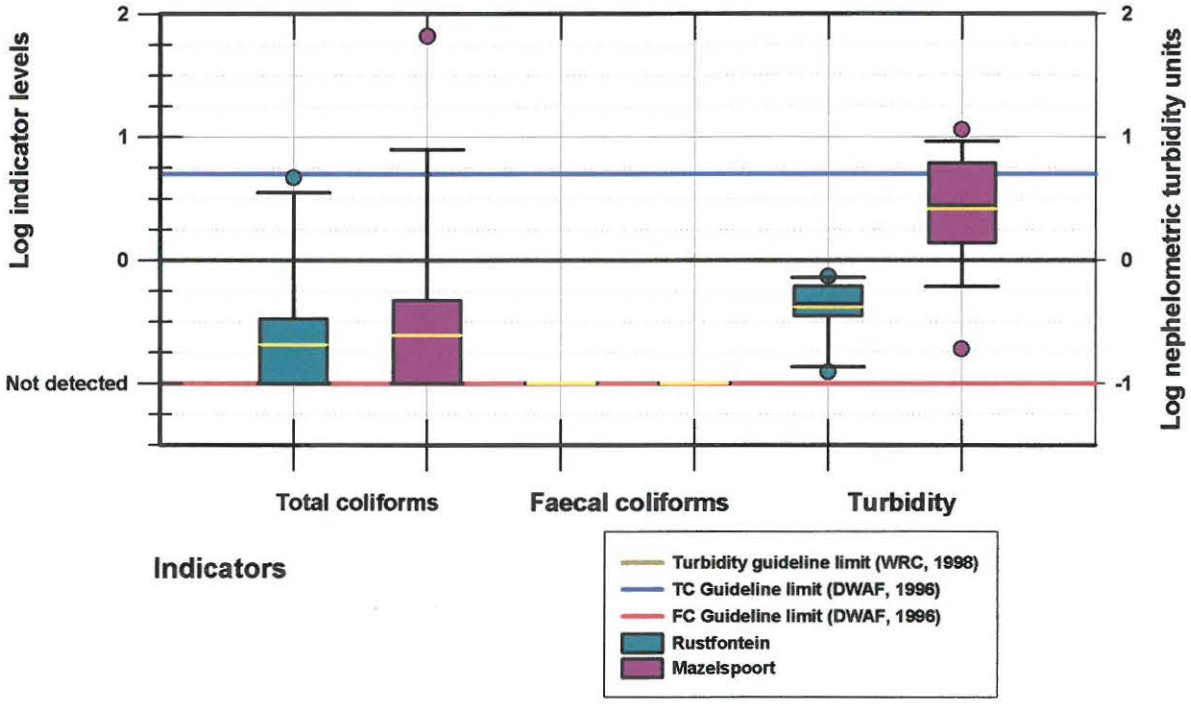

FIGURE 3.3: Indicator levels in <u>treated water</u> from Rustfontein and Mazelspoort water treatment facilities

Studies done (El-Taweel and Shaban, 2001) on water treatment facilities in Egypt found no total coliforms or faecal coliforms in the treated water. Martins *et al.* (1997) indicated in their study that most of the drinking water samples had no faecal coliforms, however, positive total coliform samples were detected were TC numbers ranged from *not detected* (<2) to 1,600 TC/100 mℓ. Quintero-Betancourt and De Ledesma (2000) reported that 45% of the samples examined from the finished water at the drinking water treatment plant of Maracaibo (Venezuela) were positive for the

presence of total coliforms (range of *not detected* (<1) to 100 CFU/100 mℓ). Nine percent (9%) of the samples examined in their study had faecal coliform densities of up to 0.4 CFU/100 mℓ. These authors were concerned about the presence of coliform bacteria as well as the high turbidity levels (6 NTU) found in the finished water, which is an indication that the TC, FC and turbidity levels might have co-occurred.

The following sections discuss the contributions of the respective treatment units (critical control points (CCPs)) within in the treatment facilities to reduce levels of microbial and particulate contaminants in water from the resource to produce water fit for human consumption.

3.3 CCP PERFORMANCE AT THE RUSTFONTEIN FACILITY (90th Percentile)

Tables 3.1 – 3.3 (Sections 3.1 – 3.3 below) summarise CCP performance measured against the values construed in Table 2.7 (Chapter 2). The computation sheets for these tables are in Appendix E. Figure 3.4 summarises the cumulative effect (in percentage) of the reduction achieved for all three contaminant indicators at the 90th percentile.

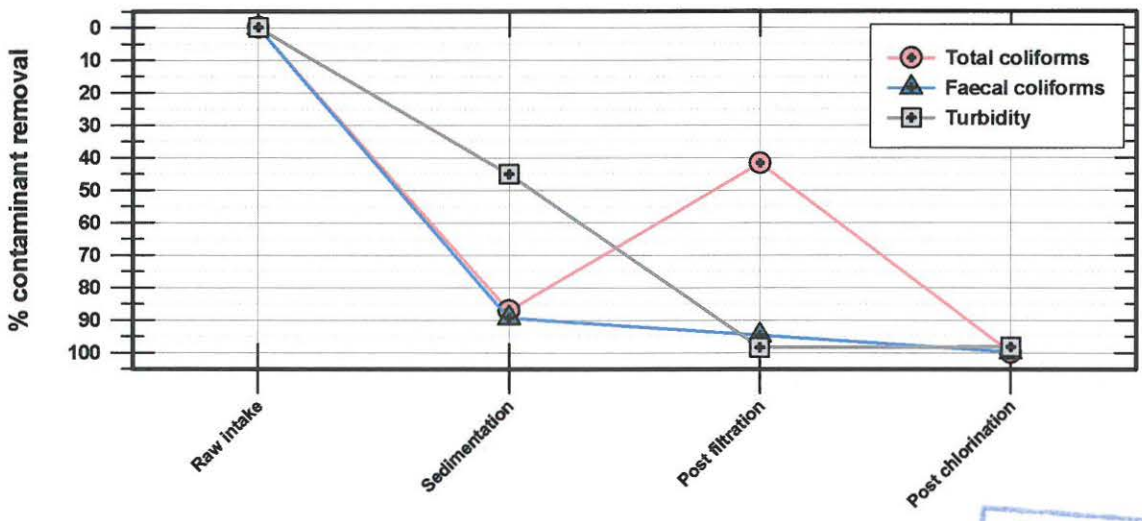

FIGURE 3.4: Contaminant reduction at each critical control point within the Rustfontein water treatment facility

3.3.1 TOTAL COLIFORM REDUCTION

Table 3.1 shows that total coliforms in 90% of the raw water samples from the Rustfontein impoundment were at and below 4,750 TC/100 mℓ. These numbers had to be reduced to 5 total coliforms per 100 mℓ or less. This implied that the minimum aggregate percentage reduction could be set at a CPLT of 99.89% at the 90th percentile.

Table 3.1: CCP reduction rates for total coliforms at the Rustfontein water treatment facility.

Guideline value	Overall reduction target (%)	Organisms per 100 mℓ	% Reduction per stage (RPS)	Cumulative reduction (CR) (%)	CPLT* in %	Compliance % of target: 0 = compliance -X = underachieve X = overachieve
5 organisms per 100 mℓ	Geomean: 98.06 90th percentile: 99.89					
Raw intake water	Geomean	258				
	90th percentile	4,750				
Sedimentation	Geomean	35	86.59	86.59	90.00	-3.41
	90th percentile	612	87.12	87.12		-2.88
Post filtration	Geomean	20	42.21	92.25	99.00	-6.75
	90th percentile	2,816	-360.13	40.72		-58.28
Post chlorination	Geomean	0.21	98.95	99.92	98.06	1.86
	90th percentile	3	99.88	99.93	99.89	0.04

* Critical performance limit target

The total coliform reduction at the 90th percentile is given in Figure 3.5. It appears that the majority of total coliforms in the raw water were removed by the sedimentation component.

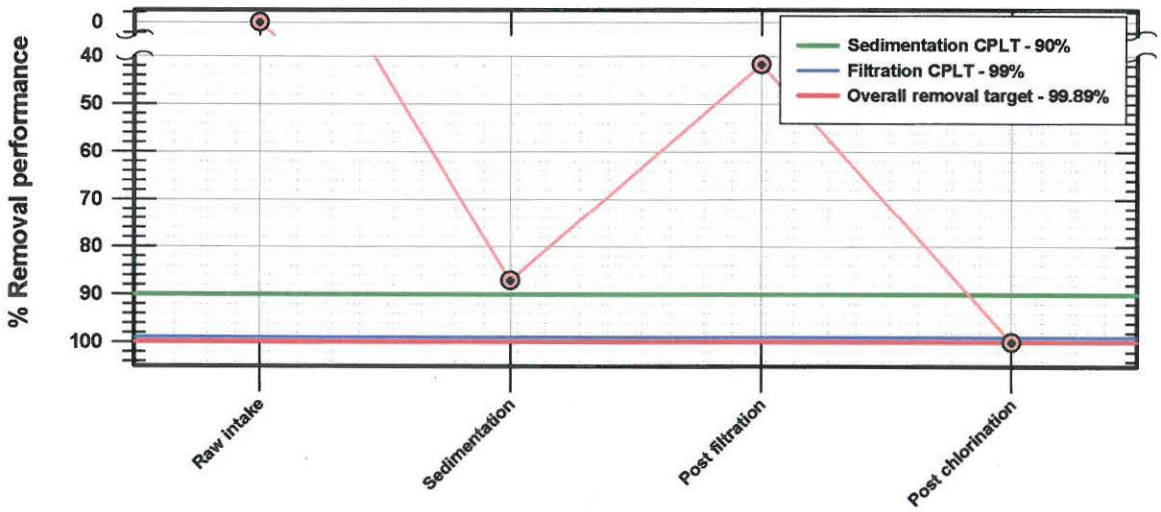

FIGURE 3.5: Total coliform reduction (at the 90th percentile) at critical control points within the Rustfontein water treatment facility

This CCP reduced the numbers in the raw water from 4,750 to 612 TC/100 mℓ, thus reducing by 87% (Table 3.1) the total coliform load from the raw water. The critical performance level target (CPLT) for sedimentation was set at 90% (Chapter 2, Table 2.7), which indicated that although the sedimentation process succeeded in significantly reducing the total coliforms (P = < 0.001), it could not meet the proposed target guideline. The filtration process somehow re-contaminated the water with total coliforms (but not statistically significantly at P = 0.495).

According to the WHO (1996b), 99% of total coliform numbers should be removed from the raw water after the filtration process in conventional treatment. This means that the filters at this facility were to remove an additional 9% of the total coliforms if the sedimentation process was on target. Since the sedimentation process showed an approximately 3% underachievement (Table 3.1), this meant that the filters had to remove 9% + 3% = 12% of the load. As it turned out, this could not be achieved. The total coliform results after filtration (2,816 TC/100 mℓ), show that organisms numbers increased by 78% during the filtration process. Nevertheless, though the filters did not perform effectively, the chlorine disinfection component was effective in removing 99.88% of the total coliforms received from the filtered water. A cumulative reduction (from all the treatment processes - sedimentation, filtration and chlorination) of 99.93% was achieved, which was more than the required overall reduction target of 99.89%.

3.3.1.1 CCP total coliform reduction performance to protect health

Figure 3.6 illustrates the extent to which each CCP altered the geometric mean TC numbers (yellow line) compared to the 90th percentile. The results for the filtration process show that the TC numbers often increased above the geometric mean, which shows that the treatment waters were intermittently re-contaminated to the point where the excessive TC numbers (2,816 TC/100 mℓ at the 90th percentile) indicated poor process function (DWAF, 1996). From a health risk perspective, this constituted a process failure. The probable reason for the increase in TC numbers was bacterial build-up in the filters. The persistence of coliform species such as *Klebsiella* spp. as well as non-coliform species such as *Aeromonas* spp. (e.g. *A. hydrophila)* in sand filters is well recorded (Kühn *et al.*, 1997; Foundation of Water Research (FWR), 1994, American Water Works Association Research Foundation (AWWARF), 2001).

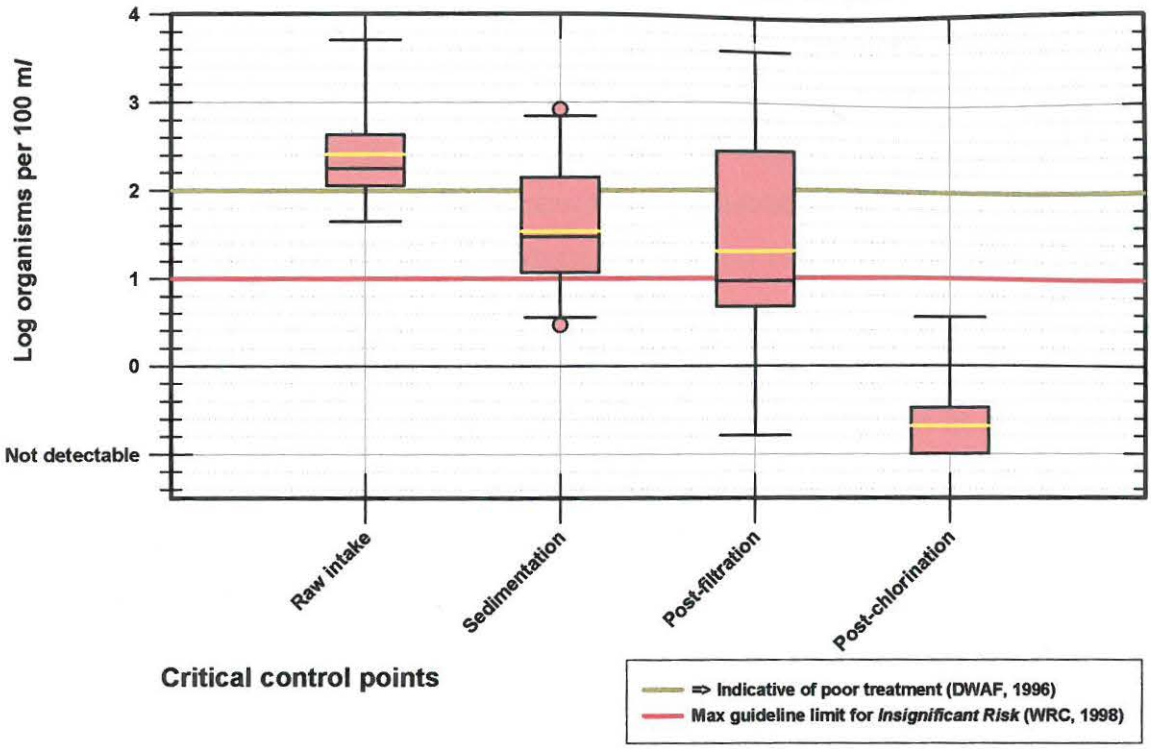

FIGURE 3.6: Total coliforms measured at critical control points within the Rustfontein water treatment facility

Aeromonas spp. are detectable on the Chromocult Coliformen® agar despite being non-coliform (Jagals, 2000). This does not imply that these two species were the only ones that could have caused the increase in the numbers in the filters. Analytical profile indices (Appendix A; Section 4) done on the colonies detected during this study had shown that *Aeromonas* spp. were constantly being detected as false positives along with the other coliforms. This discussion therefore uses these as examples since the scope of this study did not include a detailed assessment of all the bacterial groups that may potentially cause the increase in numbers. The two species are however, quite pertinent (FWR, 1994). *Aeromonas* spp. and *Klebsiella* spp. have the ability to colonise in sand filters, distribution network pipes and storage reservoirs if protected within biofilms. The majority of the sub-species within these species are non-pathogenic. However, pathogenic sub-strains do exist, which illustrate the need for controlling the occurrence of all viable bacteria in treatment water (Kühn *et al.*, 1997; FWR, 1994, AWWARF, 2001).

Another possible reason for the total coliform build-up in the filters might be due to algae blooms observed in the filter beds. According to Toranzos and Mcfeters (1997) some members of the coliform group can originate from non-enteric

environments such as epilithic algal-mat communities in pristine streams. Algae blooms were observed during sampling and plant operators reported that the occurrence of algae has been problematic for months prior to the study. This further implies that the chlorine disinfection process has to be relied upon quite substantially to ensure that TC numbers are reduced to below the water quality guideline limits. Where the CCP reduction criterion required only a further 0.89% reduction for this stage after 99% reduction at the filter stage, (Table 3.1), the chlorine process had to cope with up to nearly 60% of the original coliform load at the 90th percentile of the 16 samples analysed. This implies that at any given time, should the chlorination process fail, up to Log 3 (approximately 60% of the original 4,750 = 2,800 TC/100 mℓ) and other opportunistic pathogens could be expected to enter the distribution system. However, it is generally accepted that total coliform detections are symptomatic tests for facility effectiveness. With regards to health implications, effectiveness of faecal coliform reduction in the next section will provide a more realistic picture of the health risk caused by the CCP failure.

3.3.2 FAECAL COLIFORM REDUCTION

The values given in Table 3.2 shows that faecal coliforms in 90% of the raw water samples from the Rustfontein impoundment were at and below 47 FC/100 mℓ. These numbers had to be reduced completely in the water i.e. 100% reduction. This meant that the minimum aggregate percentage reduction could be set at a CPLT of 99.79% at the 90th percentile.

Table 3.2: CCP reduction rates for faecal coliforms at the Rustfontein water treatment facility

Guideline value	Overall reduction target (%)	Organisms per 100 mℓ	% Reduction per stage (RPS)	Cumulative reduction (CR) (%)	CPLT* in %	Compliance % of target: 0 = compliance -X = underachieve X = overachieve
No organisms detectable per 100 mℓ	Geomean: 95.00 90th percentile: 99.79					
Raw intake water	Geomean	2				
	90th percentile	47				
Sedimentation	Geomean	1	51.50	51.50	90.00	-38.50
	90th percentile	5	89.36	89.36		-0.64
Post filtration	Geomean	0.39	59.79	80.50	99.00	-18.50
	90th percentile	3	40.00	93.62		-5.38
Post chlorination	Geomean	None detected	100.00	100	95.00	5
	90th percentile	None detected	100.00	100	99.79	0.21

*CPLT = Critical performance limit target

The sedimentation process reduced the faecal coliform numbers by 89% (Table 3.2) compared to its CPLT of 90%. The filters reduced the organism numbers received from the sedimentation component by another 40% (reduction per stage (RPS), Table 3.2). A cumulative (sedimentation and filtration) reduction percentage of 94% (CPLT of 99%) was achieved, in other words a 5% under-achievement. As with TC reduction, chlorine disinfection effectively reduced faecal coliform numbers by 100%.

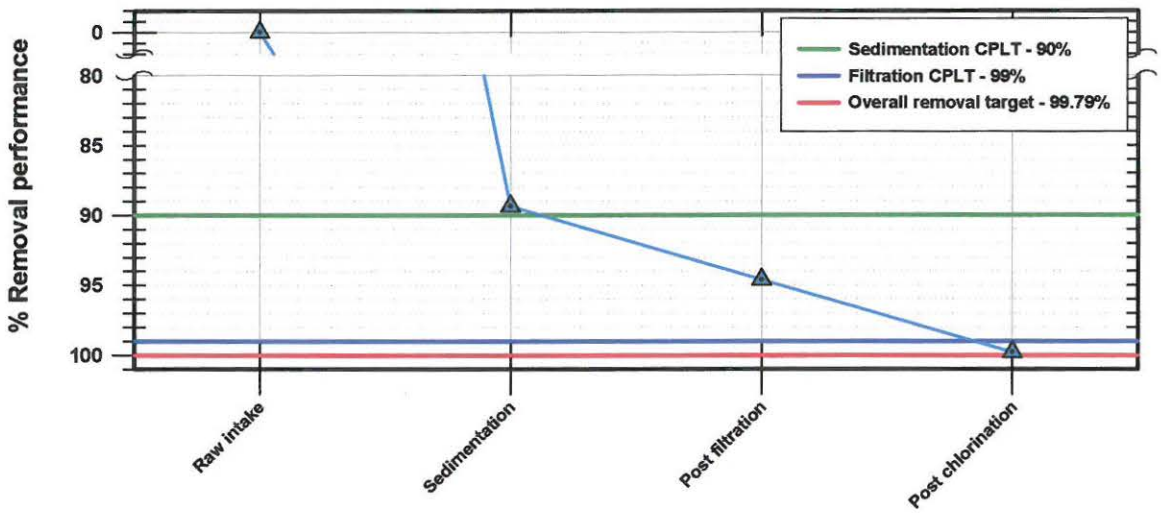

FIGURE 3.7: Faecal coliform reduction (at the 90th percentile) at critical control points within the Rustfontein water treatment facility

3.3.2.1 CCP faecal coliform reduction performance to protect health

While the entire treatment process appeared to effectively reduce the faecal coliform numbers in the raw water to within the South African water quality guidelines (WRC, 1998; DWAF, 1996) for safe water, the results indicated that a health risk would occur should the chlorine process fail.

Ideally one would want the faecal coliforms not to exceed 1 FC/100 mℓ at the 90th percentile after filtration (one FC is the maximum level of *Insignificant Risk* of expected health effects proposed by the Assessment Guide (WRC, 1998)). If this criterion were pursued in the case of the Rustfontein treatment facility, approximately 25% of the filtered water (the 75th percentile lies on the risk limit shown in Figure 3.8) would have contained faecal coliform numbers in excess of the maximum limit of 1 FC/100 mℓ, proposed for an *Insignificant Risk* (WRC, 1998).

In case of a chlorination process failure at any time, taking into consideration the poor performance of the filters and sedimentation, approximately 2 FC/100 mℓ would have been released into the distribution system, which is above the guideline limit for *Insignificant Risk* (WRC, 1998).

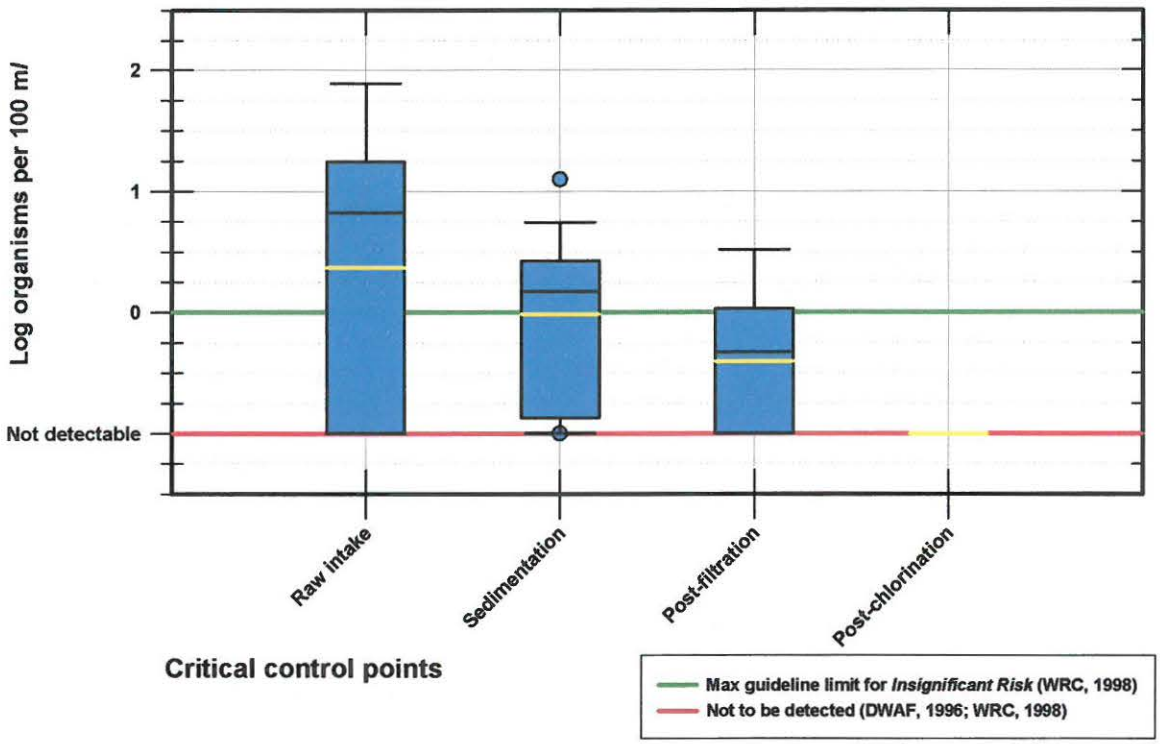

FIGURE 3.8: Faecal coliforms measured at critical control points within the Rustfontein water treatment facility

3.3.3 TURBIDITY REDUCTION

Table 3.3 shows that turbidity in 90% of the raw water samples from the Rustfontein impoundment were at and below 69 NTU. To achieve a NTU of 0.1 (WRC, 1998), 99.86% of the turbidity had to be removed after the filtration process since the disinfection process was not deemed a CCP for the reduction of turbidity.

The CPLT for sedimentation to reduce turbidity at Rustfontein was set at 85% reduction, which could not be complied with. Sedimentation reduced the turbidity levels in the raw water by 45% with a 40% under-achievement (Table 3.3). Cumulatively, the filters reduced the turbidity levels by 99.23% (set target of 99.86%).

Table 3.3: CCP reduction rates for turbidity at the Rustfontein water treatment facility

Guideline value	Overall reduction target (%)	Turbidity levels	% Reduction per stage (RPS)	Cumulative reduction (CR) (%)	CPLT* in %	Compliance % of target: 0 = compliance -X = underachieve X = overachieve
NTU 0.1	Geomean: 99.79 90th percentile: 99.86					
Raw intake water	Geomean	47.28				
	90th percentile	69				
Sedimentation	Geomean	8.11	82.84	82.84	85.00	-2.16
	90th percentile	38	44.93	44.93		-40.07
Post filtration	Geomean	0.35	95.68	99.26	99.79	-0.53
	90th percentile	0.53	98.61	99.23	99.86	-0.62
Post chlorination	Geomean	0.42	-20.00	99.11	99.79	-0.68
	90th percentile	0.68	-28.30	99.01	99.86	-0.84

*CPLT = Critical performance limit target

The slight increase during the chlorination process (from 0.53 NTU at filtration to 0.68 NTU at post chlorination) was not statistically significant (P = 0.278). The chlorination-disinfection process is not seen as a process that should contribute to reduction of turbidity. In fact, turbidity should be removed to a high degree *before* disinfection to ensure no interference of the chlorination process (WHO, 1993).

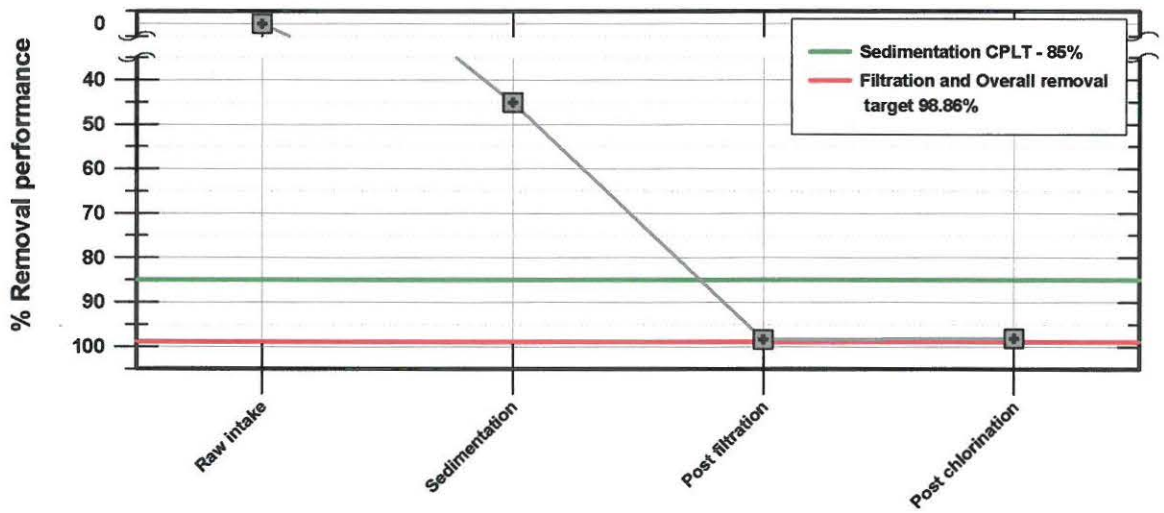

FIGURE 3.9: Turbidity reduction (at the 90th percentile) at critical control points within the Rustfontein water treatment facility

3.3.3.1 CCP reduction of turbidity to protect health

Figure 3.10 illustrates the extent to which each CCP reduced the turbidity at the geometric mean (yellow line) as well as at the 90th percentile levels. The results indicated that the filtration process could not reduce the turbidity levels to achieve

the optimum quality guideline value of ≤ 0.1 NTU (*no health effects expected*) proposed by the Assessment Guide for Domestic Water Quality (WRC, 1998). The probable cause of this is the high levels of turbidity in the overflow from the sedimentation process, of which more than 50% of the samples exceeded 5 NTU, the level at which the water would have been visibly turbid, with definite potential for expected health effects (DWAF, 1996) should the filtration process fail and these waters pumped into the distribution system.

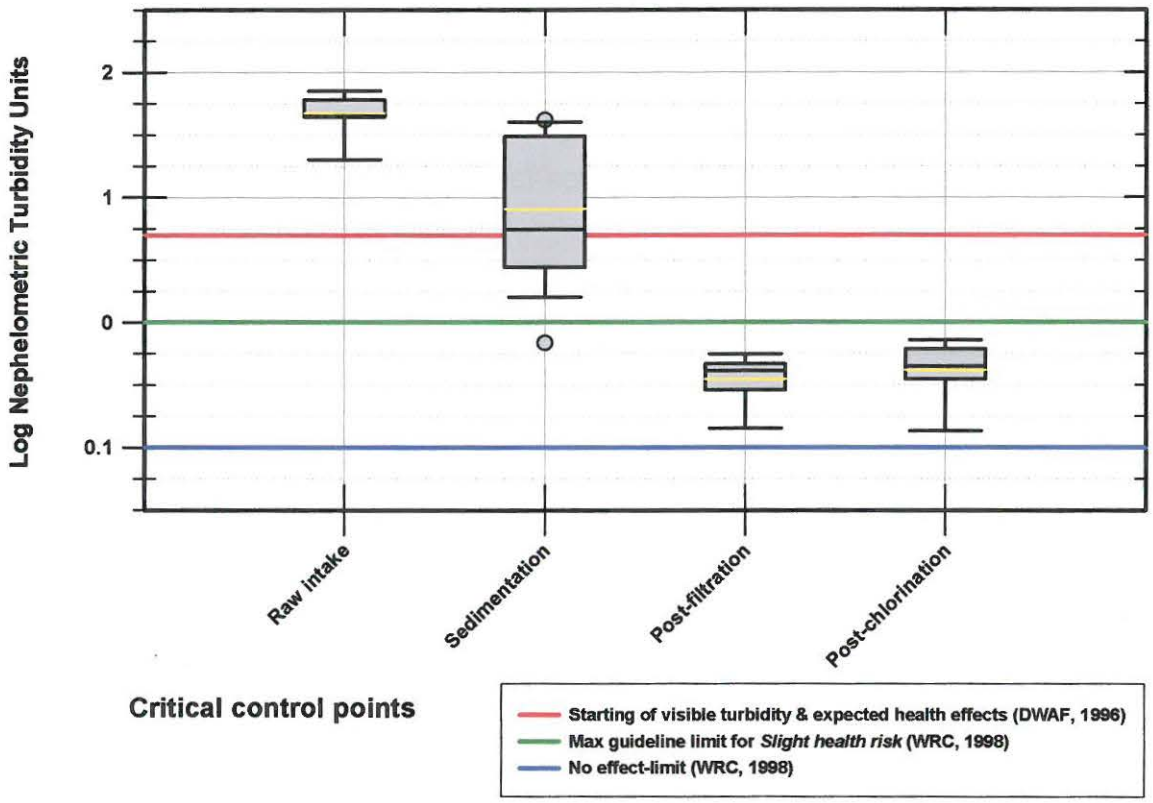

FIGURE 3.10: Turbidity levels measured at critical control points within the Rustfontein water treatment facility

The performance of the filters at Rustfontein would nevertheless have complied with the Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions (USEPA, 1999), which states that filtered water should never exceed 1 NTU at any time.

More importantly however, is that from a risk point of view this still implies that should the filtration process fail, water would be released containing up to 14.84 NTU at the 90th percentile, which is well above the critical 5 NTU level (DWAF, 1996). The fact that the treatment waters, after the filtration process, still failed to

meet the prime criterion of 0.1 NTU can probably in part be attributed to excessive biofilm release as indicated by the levels of total coliforms.

3.4 CCP PERFORMANCE AT THE MAZELSPOORT FACILITY (90th Percentile)

As with Rustfontein treatment facility, the CCP performance of Mazelspoort was measured against the values construed in Table 2.7 (Chapter 2) and are summarised in Tables 3.4 – 3.6 (Sections 4.1 – 4.3 below). The computation sheets for these tables are in Appendix E.

Figure 3.11 shows the cumulative effect (in percentage) of the reduction achieved for all three contaminant indicators.

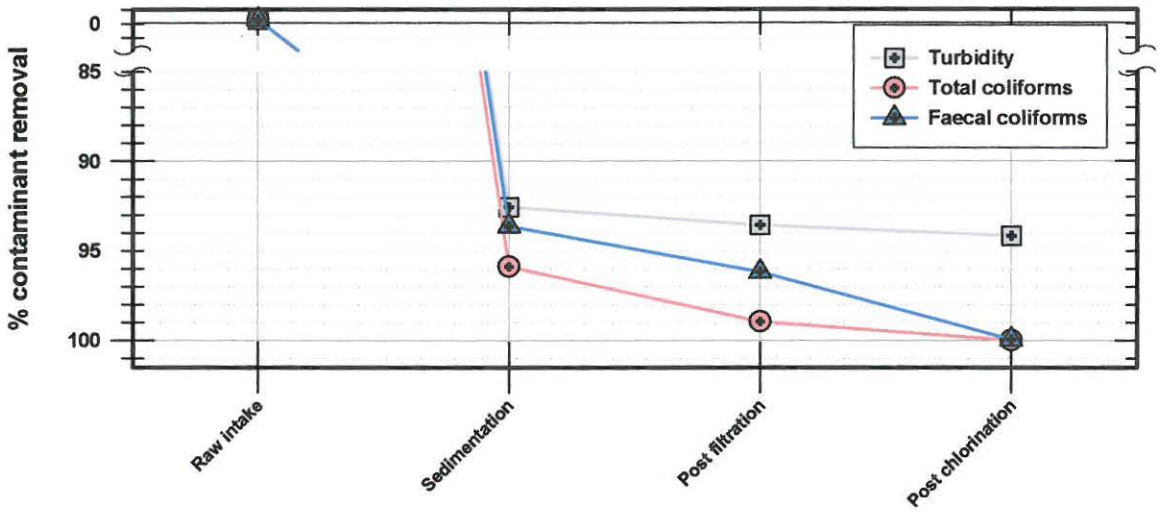

FIGURE 3.11: Contaminant reduction at each critical control point within the Mazelspoort water treatment facility

3.4.1 TOTAL COLIFORM REDUCTION

Table 3.4 shows the total coliform numbers detected in the samples from the Mazelspoort impoundment and indicates that 90% of the raw water samples were at and below 6,534 TC/100 mℓ. These numbers had to be reduced to 5 total coliforms per 100 mℓ or less. Thus, a minimum aggregate percentage reduction could be set at a CPLT of 99.92% at the 90th percentile.

Table 3.4: CCP reduction rates for total coliforms at the Mazelspoort water treatment facility

Guideline value	Overall reduction target (%)	Organisms per 100 mℓ	% Reduction per stage (RPS)	Cumulative reduction (CR) (%)	CPLT* in %	Compliance % of target: 0 = compliance -X = underachieve X = overachieve
5 organisms per 100 mℓ	Geomean: 97.48 90th percentile: 99.92					
Raw intake water	Geomean	1,991				
	90th percentile	6,534				
Sedimentation	Geomean	20	99.00	99.00	90.00	9.00
	90th percentile	269	95.88	95.88		5.88
Post filtration	Geomean	10	50.00	99.50	99.00	0.50
	90th percentile	64	76.21	99.02		0.02
Post chlorination	Geomean	0.25	97.54	99.99	97.48	2.51
	90th percentile	4	93.44	99.94	99.92	0.01

*CPLT = Critical performance limit target

From Figure 3.12 it appears that the majority of total coliforms in the raw water were removed by the sedimentation component which reduced the numbers in the raw water from 6,534 to 269 TC/100 mℓ (Table 3.4), thus reducing 96% (CPLT of 90%) of the total coliform load from the raw resource water. This indicates that this CCP succeeded in significantly reducing the total coliforms taken in with the raw water (P = <0.001).

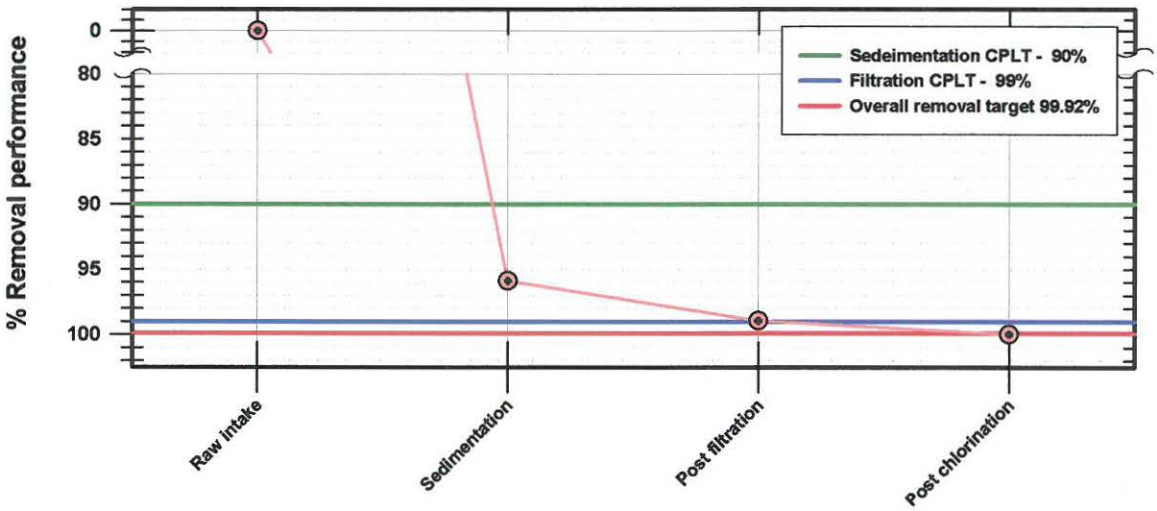

FIGURE 3.12: Total coliform reduction (at the 90th percentile) at critical control points within the Mazelspoort water treatment facility

The filters at Mazelspoort reduced the numbers of TC from the sedimentation component by a further 76% (RPS, Table 3.4). A cumulative reduction between sedimentation and filtration reduced 99.02% of the TC load (CPLT of 99%). The disinfection stage successfully reduced FC by a cumulative 99.94% (ORT of 99.92%).

3.4.1.1 CCP total coliform reduction performance to protect health

Figure 3.13 illustrates the extent to which each CCP sequentially reduced the geometric mean TC numbers (yellow line) and at the 90th percentile.

Even though sedimentation reduced the numbers of total coliforms received from the raw water intake, about 60% of the total coliforms exceeded the *insignificant risk* levels (WRC, 1998), and these numbers, at the 90th percentile, were above the *poor treatment* guideline level of 100 TC/100 mℓ as proposed by the South African Water Quality Guidelines (DWAF, 1996). Some TC numbers found in the post filtration water were also above the *insignificant risk* guideline levels (WRC, 1998). Disinfection successfully reduced these numbers to "safe" levels.

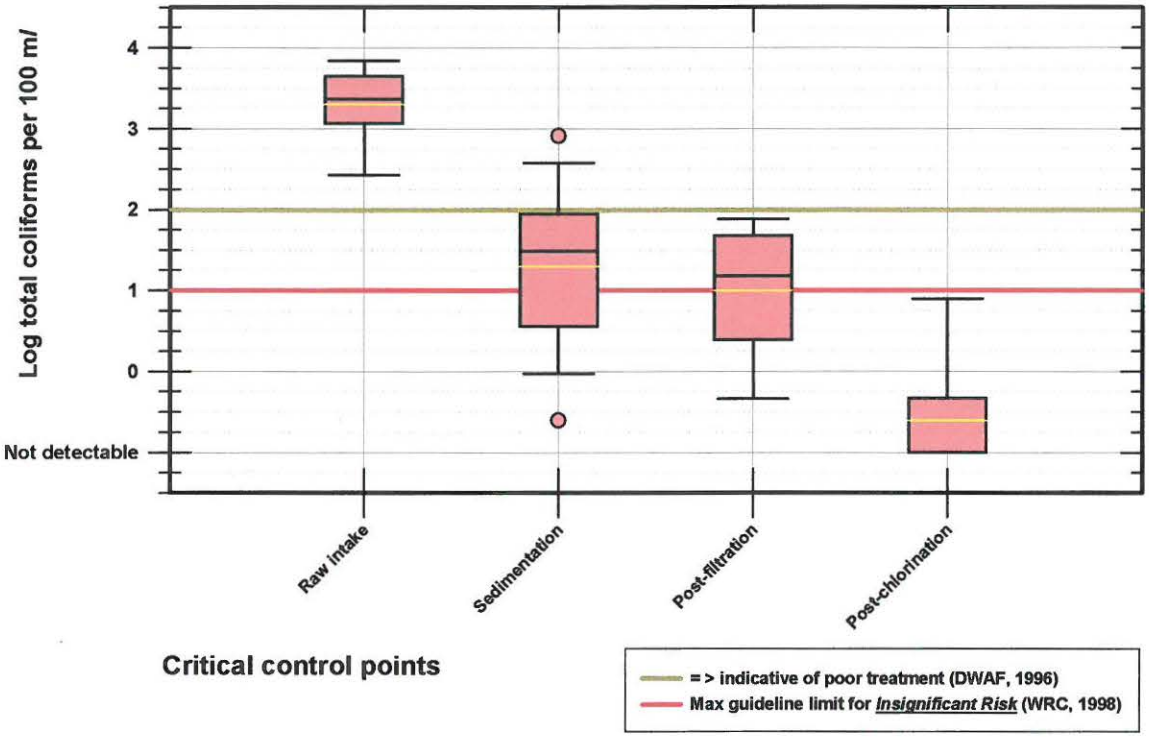

FIGURE 3.13: Total coliforms measured at critical control points within the Mazelspoort water treatment facility

3.4.2 FAECAL COLIFORM REDUCTION

Table 3.5 and Figure 3.14 show that the faecal coliform numbers (at the 90th percentile) in the raw river water from the Mazelspoort impoundment were at and below 157 FC/100 mℓ, which had to be further reduced before distribution of the water. This implied that the minimum aggregate percentage reduction could be set at a CPLT of 99.94% at the 90th percentile.

Table 3.5: CCP reduction rates for faecal coliforms at the Mazelspoort water treatment facility

Guideline value	Overall reduction target (%)	Organisms per 100 mℓ	% Reduction per stage (RPS)	Cumulative reduction (CR) (%)	CPLT* in %	Compliance % of target: 0 = compliance -X = underachieve X = overachieve
No organisms detectable per 100 mℓ	Geomean: 99.67 90th percentile: 99.94					
Raw intake water	Geomean	30				
	90th percentile	157				
Sedimentation	Geomean	0.56	98.13	98.13	90.00	8.13
	90th percentile	10	93.63	93.63		3.63
Post filtration	Geomean	0.49	12.53	98.37	99.00	-0.63
	90th percentile	6	40.00	96.18		-2.82
Post chlorination	Geomean	None detected	100	100	99.67	0.33
	90th percentile	None detected	100	100	99.94	0.06

*CPLT = Critical performance limit target

The sedimentation process reduced 94% of the faecal coliform numbers (CPLT of 90%). The filters managed to reduce the organism numbers by a further 40% (Table 3.5), reducing the raw resource water FC load by a cumulative 96%, but the filters still under-achieved by 3%.

Even though filtration could not manage to perform optimally, chlorination was effective in reducing the faecal coliform numbers by 100%, thus indicating that the treated water is "safe" for potable use.

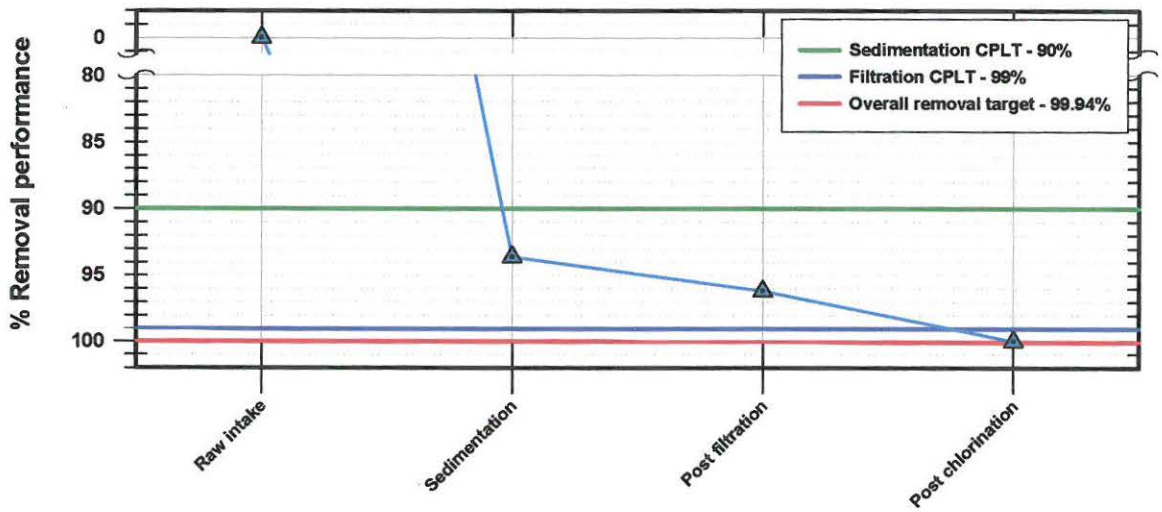

FIGURE 3.14: Faecal coliform reduction (at the 90th percentile) at critical control points within the Mazelspoort water treatment facility

3.4.2.1 CCP faecal coliform reduction performance to protect health

The entire treatment facility at Mazelspoort appeared to effectively reduce the faecal coliform numbers in the raw water to within the national guidelines (WRC, 1998) for safe water, but the results suggested a health risk should the chlorine process fail to remove these organisms completely. Figure 3.15 illustrates the extent to which each CCP reduced faecal coliform numbers at the geometric mean (yellow line) as well as at the 90th percentile levels.

Sedimentation seemed to reduce the majority of the faecal coliform load, but filtration could not achieve the critical performance level target. Approximately 12% of the faecal coliform numbers in the filtered water were above the *insignificant risk* guideline limit (WRC, 1998). Even though this would not pose a major health threat, it was up to chlorination to reduce the faecal coliform numbers by 100%. The filters could not reduce the faecal coliform numbers by the required 99% but could only achieve 96%, leaving the chlorination stage to reduce an additional 3% FC load. If chlorination failed at any time, approximately 5 FC/100 mℓ could be released into the distribution system, which is above the maximum guideline limit (1 FC/100 mℓ) for insignificant risk, and clinical infections could occur in some sensitive groups (WRC, 1998).

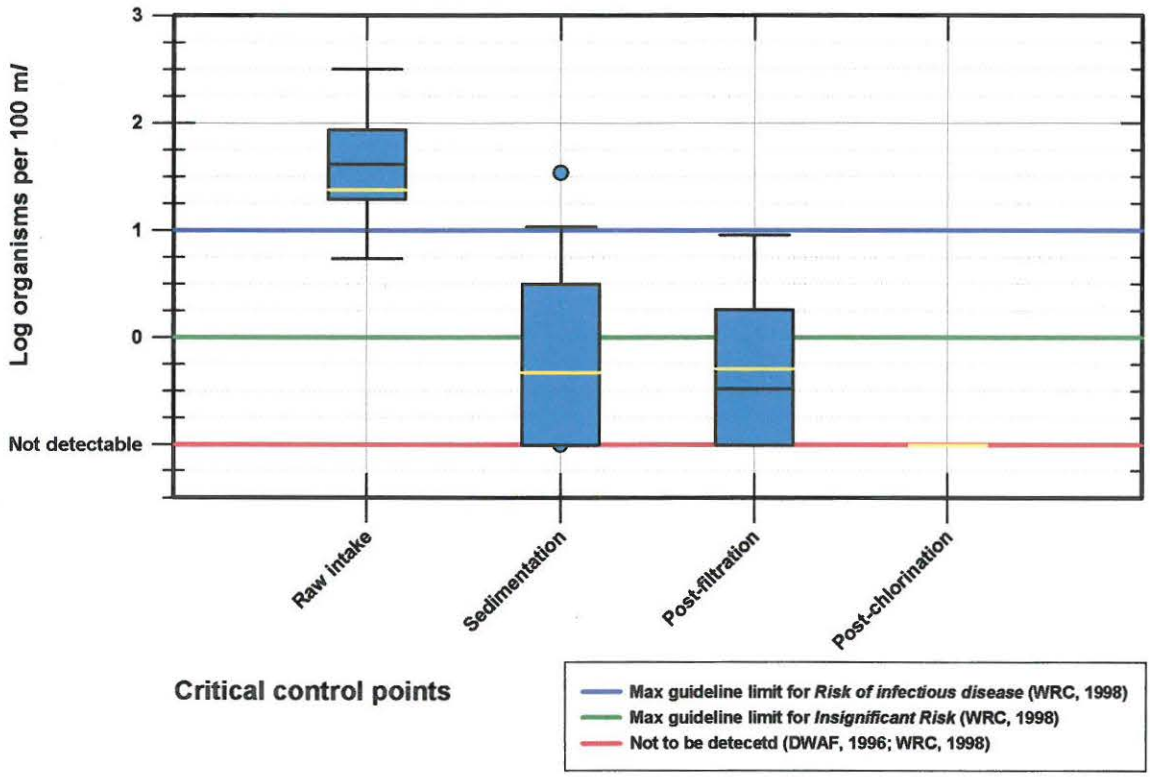

FIGURE 3.15: Faecal coliforms measured at critical control points within the Mazelspoort water treatment facility

3.4.3 TURBIDITY REDUCTION

Table 3.6 as well as Figure 3.16 show the reduction rates achieved for turbidity. Ninety percent (90%) of the raw samples from the Mazelspoort impoundment were at and below 149 NTU.

Table 3.6: CCP reduction rates for turbidity at the Mazelspoort water treatment facility

Guideline value	Overall reduction target (%)	Turbidity levels	% Reduction per stage (RPS)	Cumulative reduction (CR) (%)	CPLT* in %	Compliance % of target: 0 = compliance -X = underachieve X = overachieve
NTU 0.1	Geomean: 99.81 90th percentile: 99.93					
Raw intake water	Geomean	52.00				
	90th percentile	149.40				
Sedimentation	Geomean	3.61	93.06	93.06	85.00	8.06
	90th percentile	11.10	92.57	92.57		7.57
Post filtration	Geomean	2.29	36.57	95.60	99.81	-4.21
	90th percentile	9.64	13.19	93.55	99.93	-6.38
Post chlorination	Geomean	2.61	-13.97	94.98	99.81	-4.83
	90th percentile	8.73	9.38	94.16	99.93	-5.78

*CPLT = Critical performance limit target

Figure 3.16 shows that sedimentation at this treatment facility was the most effective treatment component to reduce the levels of turbidity. It reduced the turbidity levels of raw water by 93% (CPLT of 85%). The filters failed to reduce the turbidity levels to their CPLT of 99.93%. This could cumulatively (together with sedimentation) reduce turbidity levels by 94%. The turbidity levels increased slightly after chlorination, but this was not statistically significant (P = 0.368).

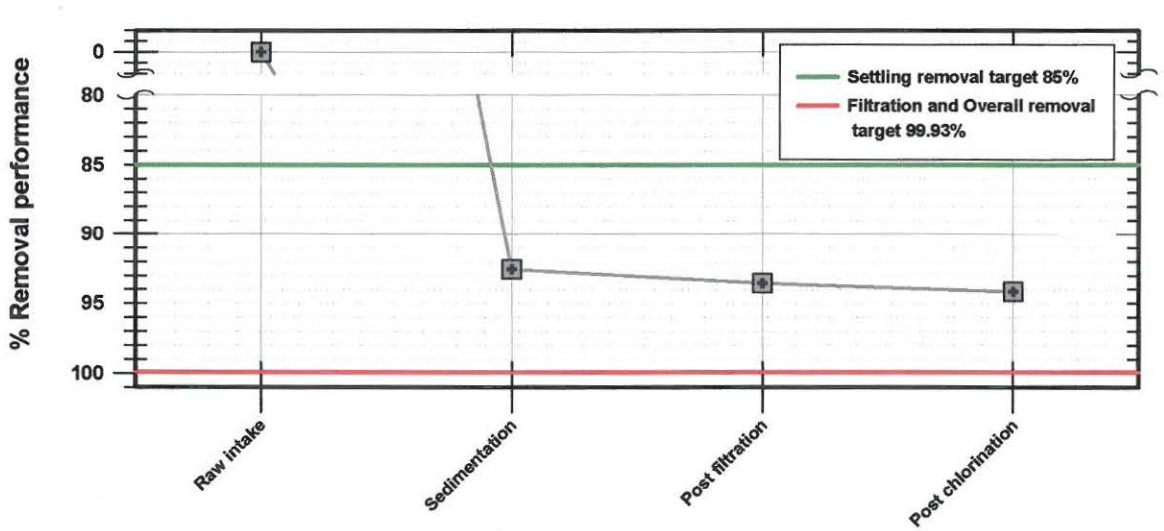

FIGURE 3.16: Turbidity reduction (at the 90th percentile) at critical control points within the Mazelspoort water treatment facility

3.4.3.1 CCP reduction of turbidity to protect health

Figure 3.16 illustrates the extent to which each CCP reduced the turbidity at the geometric mean (yellow line) as well as at the 90th percentile levels.

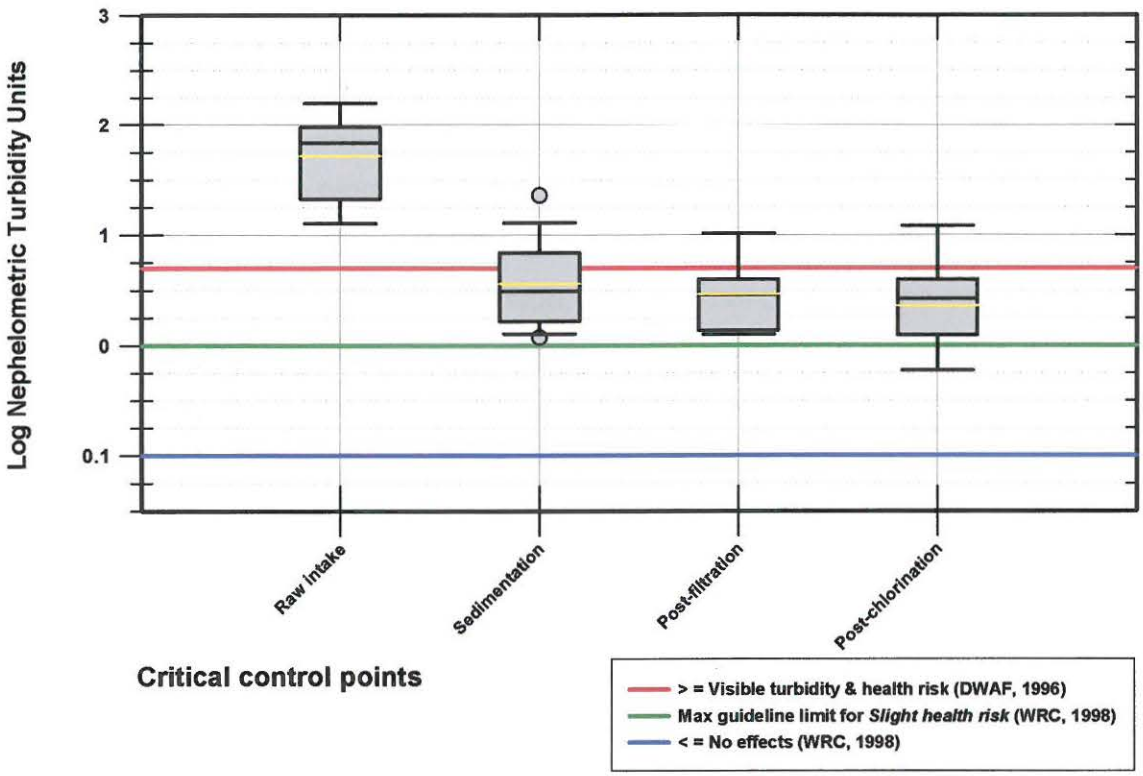

FIGURE 3.17: Turbidity levels measured at critical control points within the Mazelspoort water treatment facility

Although the levels of turbidity decreased as the water passed through the various treatment components, the results nevertheless indicated that the facility could not reduce the levels to below the maximum guideline limit for *slight health risk* of 1 NTU as well as the *no effects expected* quality guideline value of 0.1 NTU proposed by the Assessment Guide for Domestic Water Quality (WRC, 1998). The turbidity levels increased from the secondary sedimentation process from 8.57 NTU at the 90th percentile to 9.64 NTU in the post filtration samples. From a risk point of view, should the filtration process fail, water would be released to the chlorination phase containing 9.68 NTU at the 90th percentile, which is above the critical 5 NTU level (DWAF, 1996).

If few or no coliforms were detected in the treated water samples, what then is the cause then of the high turbidity measurements? The high turbidity measurements might be due to the high turbidity levels in the raw water which seemed to be

reduced by the sedimentation stage, but do not continue to decrease as the water passes the filtration component. High turbidity levels measured in this study might be due to breakdown products of dead microorganisms or, according to an article by Health Canada (1995), the presence of turbidity could have interfered with the quantisation of bacteria. Bacteria are enumerated by incubating bacterial cells on nutritive media for a fixed period of time and counting the number of visible colonies that form during the incubation period. It is assumed that each colony represents one cell; however, a single colony could result from a particle containing many bacterial cells adsorbed on its surface. Fewer cells than were actually present would then be recorded (Health Canada, 1995). This could be the case in this study where membrane filtrations were used in the enumeration of the indicator bacteria. Further research should be done on the effects of turbidity on the enumeration techniques of health-related microbiological indicator organisms.

3.5 TURBIDITY IN LIEU OF MICROBIOLOGICAL MEASUREMENTS

According to Logsdon and Lippy (1982), studies have indicated that bacteriological count reductions were achieved with decreasing turbidity and practically complete reduction of algae and coliform bacteria with a 0.1 NTU effluent. Haas, Meyer and Paller (1983) noted that increasing values of turbidity were associated with increasing concentrations of microorganisms. The results from the selected health-related microbiological indicators used in this study were compared with turbidity levels to determine whether an association between these organisms and turbidity could be detected in the samples from the different critical control points and if any, whether these associations were strong enough to conclude whether turbidity measurements could replace microbiological measurements as a routing rapid assessment tool.

3.5.1 RUSTFONTEIN WATER TREATMENT FACILITY

3.5.1.1 Turbidity and indicator organisms in raw water

There were no significant relationships ($P > 0.050$) between turbidity and the indicator organisms (or any TBY/TC or TBY/FC pair) in the raw extraction water from the Rustfontein impoundment. While the linear correlation coefficient ($r = 0.68$) showed a marked association for TBY/TC in Figure 3.17, this was a negative

association – i.e. increasing TC numbers correlated with decreasing TBY levels, which in the context of what the test is supposed to achieve, a non-sensical association. It is evident that TBY testing would not have been a suitable gross-indicator of the indicator organism numbers in the raw extraction water from the Rustfontein impoundment during the period of this study.

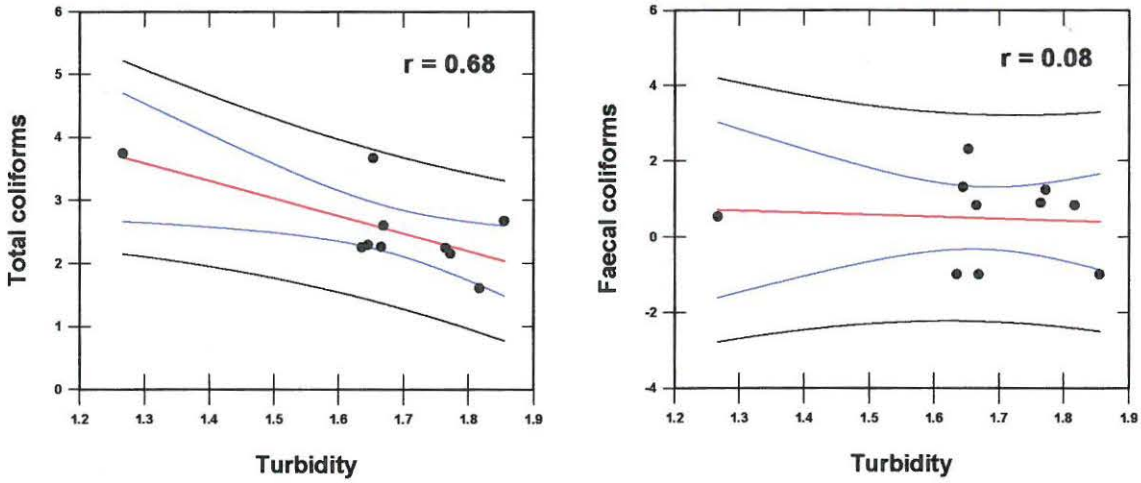

FIGURE 3.18: Correlations between turbidity and total as well as faecal coliforms in raw extraction water within the Rustfontein water treatment facility

3.5.1.2 Turbidity and indicator organisms in settled water

There were no significant relationships ($P > 0.050$) between any TBY/TC and any TBY/FC pair in the waters sampled directly after the sedimentation CCP. The TBY/TC correlation coefficient was $r = 0.02$, indicating a very weak correlation between total coliforms and turbidity in water after sedimentation (Figure 3.18). For TBY/FC, the correlation coefficient ($r = 0.23$) indicated a very weak correlation between faecal coliforms and turbidity in the sedimentation water in the same water samples.

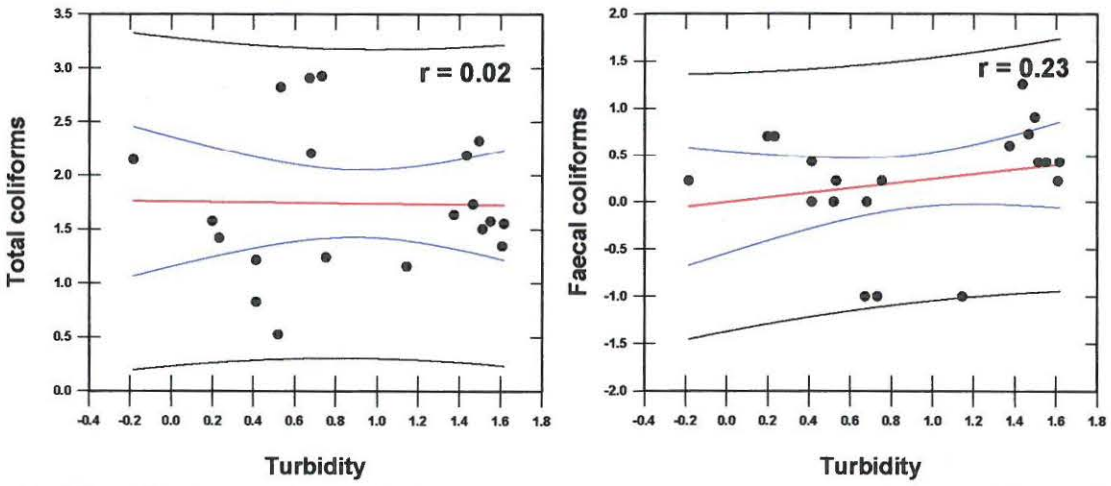

FIGURE 3.19: Correlations between turbidity and total as well as faecal coliforms in settled water within the Rustfontein water treatment facility

3.5.1.3 Turbidity and indicator organisms in filtered water

The TBY/TC pairs had a P value of 0.029, which indicated a relationship. However, the negative correlation coefficient (r = 0.77) shown in Figure 3.20, indicated that when one variable tended to decrease, the other tended to increase. There were no significant relationships between any TBY/FC pair (P > 0.050) in the waters sampled directly after the filtration CCP. The weak correlation coefficient (r = 0.06) shown in Figure 3.20 confirms this. For example, some samples contained substantial levels of turbidity while no faecal coliforms were detected in these same samples.

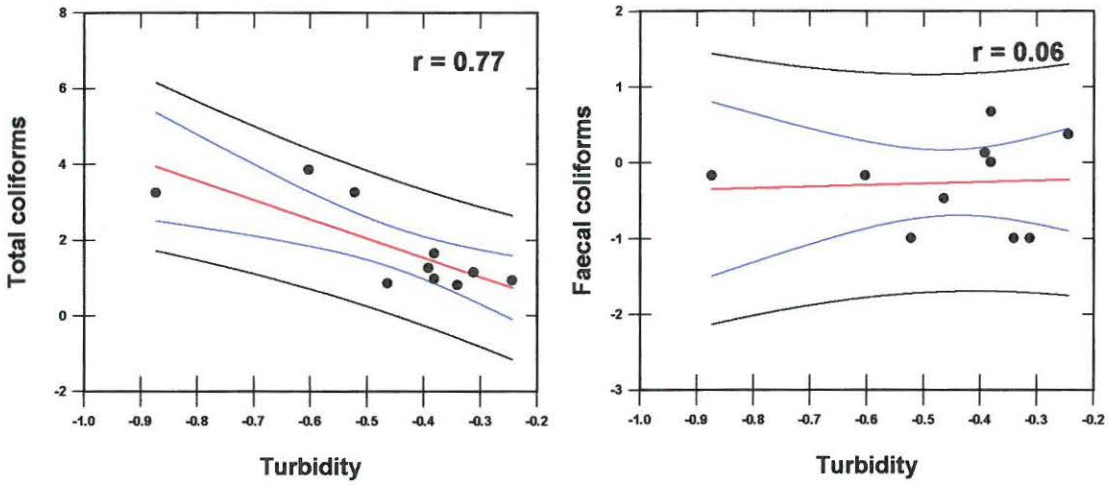

FIGURE 3.20: Correlations between turbidity and total as well as faecal coliforms in filtered water within the Rustfontein water treatment facility

3.5.1.4 Turbidity and indicator organisms in treated water

There was no significant relationship (P > 0.050) between turbidity and total coliforms in the disinfected water at the Rustfontein water treatment facility. The positive linear correlation coefficient (r = 0.29) indicated a weak correlation between total coliforms and turbidity in treated water (Figure 3.21). The weak association was again characterised by several results of the <1 total coliforms in the samples where turbidity yielded higher levels in the same samples. There was a statistically significant relationship (P = < 0.001) between the TBY/FC variables. The linear correlation coefficient of r = 0 indicated a non-existent co-variance between faecal coliforms and turbidity in treated water.

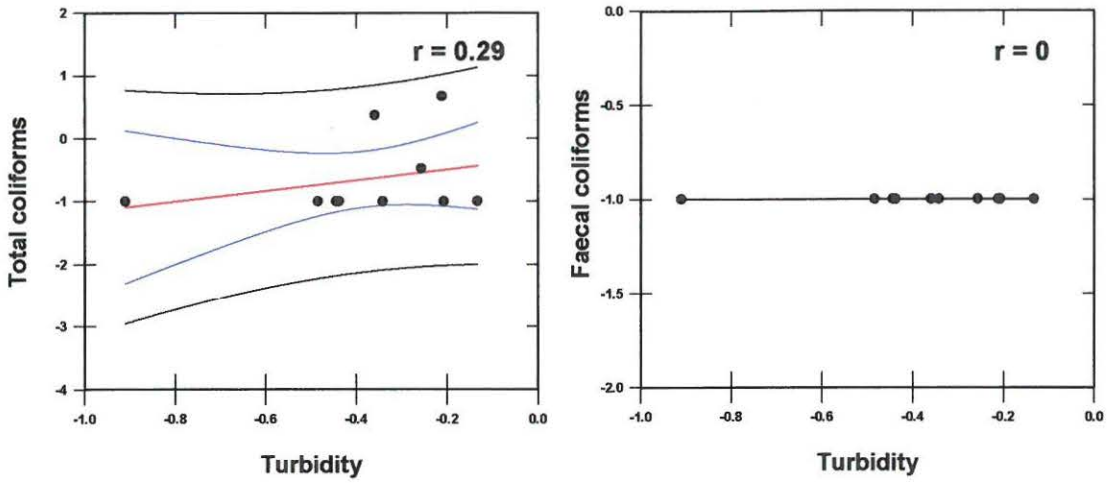

FIGURE 3.21: Correlations between turbidity and total as well as faecal coliforms in treated water within the Rustfontein water treatment facility

3.5.2 MAZELSPOORT WATER TREATMENT FACILITY

3.5.2.1 Turbidity and indicator organisms in raw water

There was no significant relationship ($P > 0.050$) between TBY/TC pairs in the raw water from the Mazelspoort impoundment. The linear correlation coefficient ($r = 0.19$) indicated a very weak correlation between total coliforms and turbidity in raw water. There was also not a significant relationship ($P > 0.050$) between the TBY/FC pairs. The linear correlation coefficient ($r = 0.36$) indicated a weak correlation between faecal coliforms and turbidity in raw water.

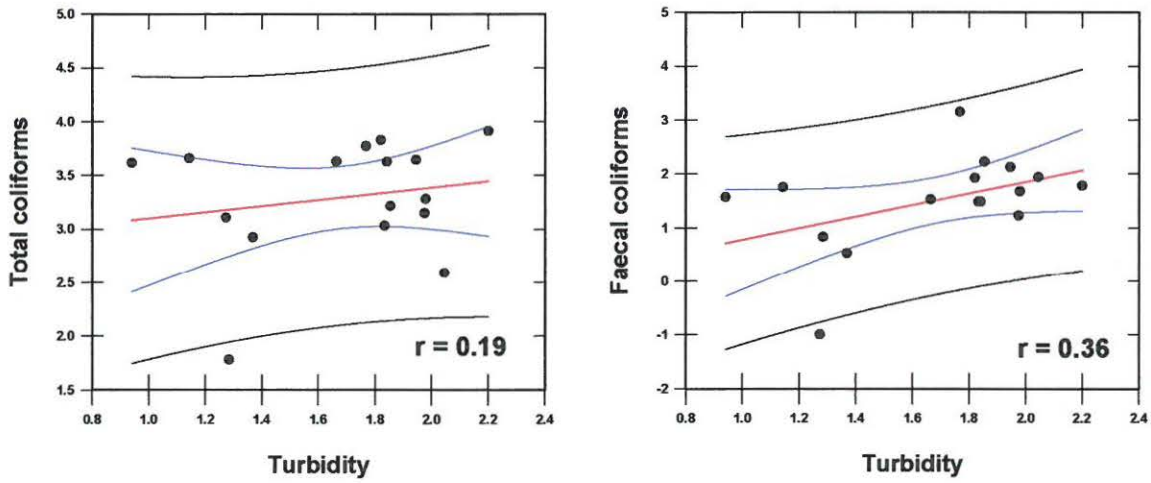

FIGURE 3.22: Correlations between turbidity and total as well as faecal coliforms in raw extraction water within the Mazelspoort water treatment facility

3.5.2.2. Turbidity and indicator organisms in settled water

No significant relationship (P > 0.050) existed between the two variables. The linear correlation coefficient (r = 0.06) indicates an extremely weak correlation between total coliforms and turbidity in the overflow water from the sedimentation tanks. There was also no significant relationship (P > 0.050) between the TBY/FC pairs. The linear correlation coefficient was r = 0.2, which indicated a weak association of co-variance between faecal coliforms and turbidity in settled water. The weak association could be caused by the number of non-detectable (<1) readings of faecal coliforms from the same samples that produced levels of turbidity. However, the relationship between turbidity and faecal coliforms was stronger than the relationship between turbidity and total coliforms.

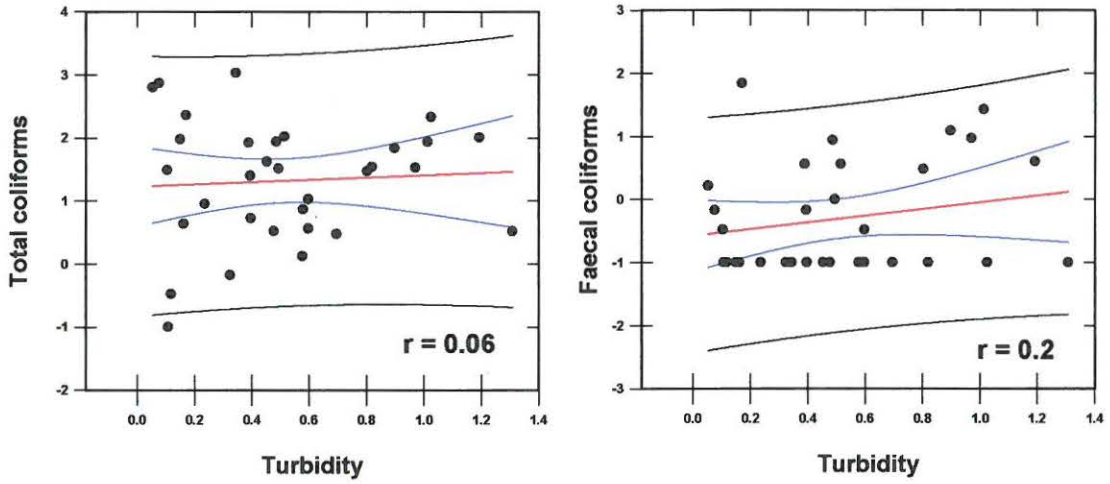

FIGURE 3.23: Correlations between turbidity and total as well as faecal coliforms in settled water within the Mazelspoort water treatment facility

3.5.2.3 Turbidity and indicator organisms in filtered water

No significant relationship (P > 0.050) existed between the TBY/TC pairs of the post-filtration samples. The linear correlation coefficient (r = 0.18) indicated a very weak correlation between total coliforms and turbidity in filtered water.

There was also not a significant relationship (P > 0.050) between the TBY/FC pairs. The linear correlation coefficient (r = 0.24) indicated a weak correlation between faecal coliforms and turbidity in filtered water, which again was stronger than the relationship between turbidity and total coliforms.

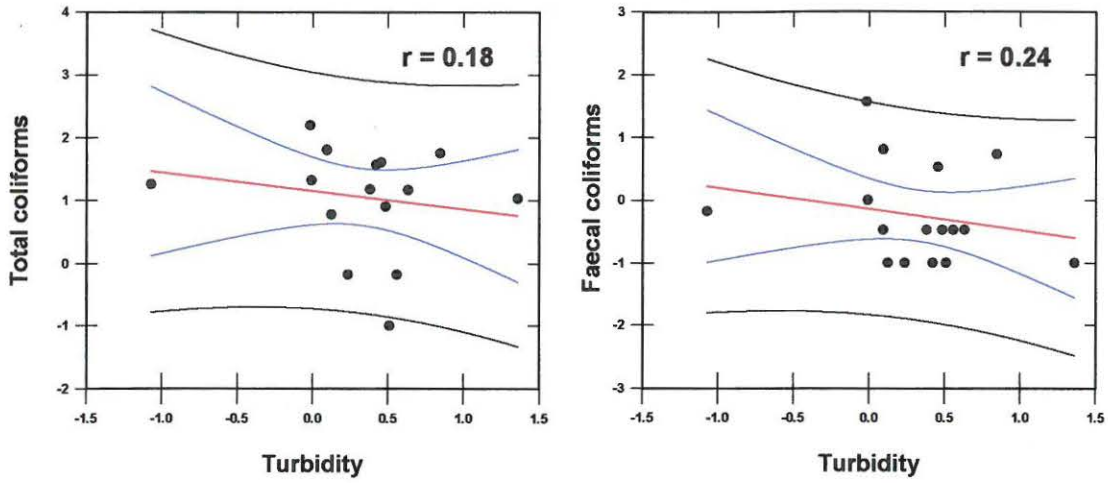

FIGURE 3.24: Correlations between turbidity and total as well as faecal coliforms in filtered water within the Mazelspoort water treatment facility

3.5.2.4 Turbidity and indicator organisms in treated water

No significant relationship ($P > 0.050$) existed between turbidity and total coliforms. The linear correlation coefficient was $r = 0.23$ which indicated co-variance between total coliforms and turbidity in treated water. There was no significant relationship ($P > 0.050$) between the two variables and also no correlation (linear correlation coefficient $r = 0$) at all between faecal coliforms and turbidity in treated water. The non-existent association was clearly caused by the number of <1 faecal coliform readings. More simply stated, some samples contained substantial turbidity levels with virtually no faecal coliforms in the same sample.

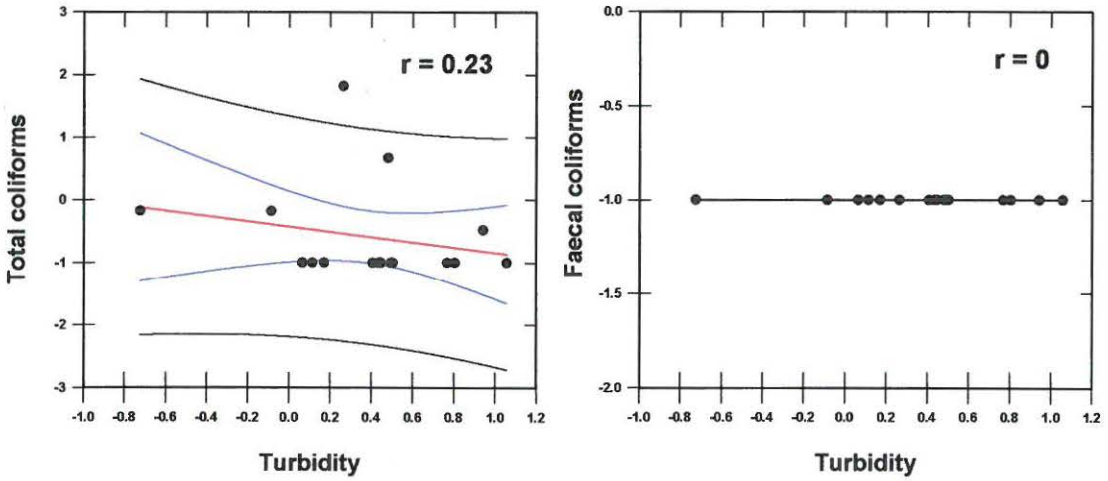

FIGURE 3.25: Correlations between turbidity and total as well as faecal coliforms in treated water within the Mazelspoort water treatment facility

3.5.3 GENERAL DISCUSSION: TURBIDITY IN LIEU OF MICROBIOLOGICAL MEASUREMENTS

There was a weak correlation between the occurrence of the health-related indicator organisms and turbidity. The assumption may be made that turbidity should not routinely be used as a solitary indicator of process effectiveness. Additional microbiological tests should be included in the monitoring procedures to ensure risk free water from these water treatment facilities on a continuous basis.

In most cases the microbiological indicators were detected in the same water samples in which turbidity was evident, but with most of the samples showing weak associations. The only strong relationship was between total coliforms and turbidity in the filtered water samples from the Rustfontein treatment facility. This might indicate that regular testing of turbidity at this process at Rustfontein might prevent a complete breakdown of the effectiveness of this treatment facility. Testing could assist in early assessment of high numbers of total coliforms which should be controlled before they reach the chlorination stage.

The weak relationships between turbidity and the health-related microbiological indicators at the rest of the CCPs were peculiar, since strong relationships between the reduction of turbidity and bacteria have been reported in other studies. According to the USEPA (1999), low filtered water turbidity can be correlated with low bacterial counts and low incidences of viral disease. Positive correlations between reduction of pathogens and turbidity have also been observed in several studies. In fact, in every study to date where pathogens and turbidity occur in the source water, pathogen reduction coincides with turbidity/particle reduction (Fox, 1995).

The weak associations found in this study could be due to an insufficient sample size for the measurement of correlations between bacteria and turbidity. A larger data base, with an additional feature such as seasonal variance, might strengthen the correlation figures. Thus, taking to account the results from this study, the assumption could be made that turbidity should not be used as a solitary indicator of process effectiveness. A wider range of microbiological and chemical tests should be considered as monitoring procedures to manage a water treatment facility effectively.

3.6 SUMMARY

The raw river water used for drinking water treatment at both treatment facilities complied with the proposed guidelines for raw water extraction for drinking water treatment as proposed by Venter *et al.* (1996) as well as DWAF (2002). The same may be said of the treated end-product namely, treated potable water, which complied with national health-related drinking water guidelines (DWAF, 1996; WRC, 1998). This generally indicated that the designs of the selected treatment facilities were effective and well managed under normal circumstances.

The question was, what if any of the processes malfunctioned? One of the main purposes of this study was to assess the reduction effectiveness of each CCP at the treatment facilities by following a health-related hazard analysis protocol and comparing the health-related indicator results with critical performance limits chosen for this study. Conclusions could then be drawn regarding the effectiveness of each CCP to ensure the highest quality of water being distributed.

When the sedimentation processes of both treatment facilities were compared, it appeared that the sedimentation components at Mazelspoort functioned more effectively in reducing all the selected indicators than sedimentation at the Rustfontein treatment facility. The results of all the indicators assessed at Mazelspoort complied with the CPLT. The sedimentation components at Rustfontein failed to reduce any of the indicators to the required CPLT. It seems that the filters at the Rustfontein treatment facility could cause a breakdown in the effectiveness of the treatment facility due to the high under-achieved reduction percentages of the health-related microbiological indicator organisms. At Mazelspoort, the filters seemed to perform effectively with occasional under-achievement in the reduction of faecal coliforms. Chlorination at both treatment facilities reduced the numbers of all the selected indicators to acceptable limits. Although some CCPs at these treatment facilities have certain difficulties in reducing the health-related risks, these facilities could be perceived as effective in treating the raw river water to enable a high quality potable water to be distributed to the consumers. Nonetheless, it still remains to be seen how both of the facilities would perform if the health-related microbiological water quality of the raw waters were less favourable than was the case during this study. Even with the low levels of indicators in the raw water, health risks were indicated.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

At both facilities the inconsistent performances of the critical control points (CCPs) suggested potential break downs in the effectiveness of the entire treatment facility, creating health risks to water consumers in the distribution area. Continuous monitoring of CCPs at the targeted drinking water treatment facilities, using health-related microbiological indicators and turbidity, could lower such risk. No monitoring and control plans in the form of HACCP plans are in operation at these particular facilities. The relevant water supply managers and facility operators would be well-advised to consider including HACCP plans at the treatment facilities as part of their water quality management programme.

4.1 FUTURE APPLICATION OF AN HACCP PLAN

As discussed in Chapter 2, the purpose of this study was not to develop a full HACCP programme, but to apply a selected number of HACCP principles (❶ conduct a hazard analysis; ❷ determine/identify CCPs; ❸ establish critical performance criteria with critical limits for each control point and ❹ establish a system to monitor the CCPs) to investigate whether the actual health-related treatment effectiveness of the two drinking water treatment facilities could be better assessed.

The abbreviated HACCP approach applied in this study has definitively improved understanding of how well each of the components within the treatment facilities functions to reduce microbiological hazards in the treatment water. What was NOT clarified in this study were the reasons for the under and over-achievements of the CCPs. It would appear however, that human understanding of the risk of system failures and its consequences were important elements. This could be addressed by a comprehensive HACCP plan (Water Safety Plans is the concept the water industry now seems to be embracing (Medema, 2003)) based on the HACCP steps as envisaged in Chapter 1. The interviews and discussions with the various role players in this study provided a grass-roots level perspective of how typical facilities should operate. In a full HACCP plan, the management of these facilities would be more operationally involved and emergency planning more prevalent.

The basic steps applied in this study were therefore intended to be a pilot model for the development of a comprehensive Water Safety Plan (WSP). The following are recommendations for special consideration and inclusion in the WSP:

❶ A wider range of hazards (microbiological, physical and chemical) should be identified and included in the hazard analysis step. This would increase effectiveness of monitoring of the system.

❷ Critical performance limits should be established for each facility according to end-user requirement, raw water qualities, system design and management (resource) capabilities. In this regard collaboration with consulting engineers and environmental/public health specialists are important considerations to provide answers on the functions of treatment components as well as to establish how and when the need for corrective actions should trigger management to intervene.

❸ Water quality managers and operators at treatment facilities should be trained on the application of regular monitoring procedures of water quality and to react operationally to results indicating potential/actual system failure.

❹ The importance of a WSP should be workshopped and communicated with stakeholders such as the consumer, consulting engineers, environmental/ public health specialists, water supply managers and facility operators. A WSP will only succeed if it is backed by a management that fully understands the concept.

4.2 FUTURE RESEARCH INTO TREATMENT SYSTEM OPERATIONS

Resources have precluded aspects such as seasonal sampling and analyses, a larger sample size, as well as inclusion of more CCPs such as the coagulation and flocculation steps. Though the sample size was sufficient to satisfy statistical requirements, it eventually became clear that the aspects mentioned below, while outside the scope of the study, could have had an impact on the results obtained from the study. It is recommended that these aspects be included in future research of this nature or in an operational comprehensive WSP.

4.2.1 COAGULATION CHEMISTRY

Inadequate mixing of chemicals or their addition at inappropriate points within the treatment facility can limit performance (USEPA, 1999). The following aspects relating to coagulation chemicals should be considered by systems but were not investigated in this study:

- Are chemicals being dosed properly, paying special attention to pH? Are chemicals being added in the correct sequence? This is very important, as certain chemicals could interfere with others.
- Do Standard Operating Procedures (SOPs) exist for coagulation controls? Systems should develop SOPs, and should establish a testing method that is suited to the facility and personnel.
- Is the best coagulant being used for the situation? Changing coagulant chemicals or adding coagulant aids may improve the settling ability of the flocculated water and in turn optimise performance. Coagulants should also be changed seasonally.
- Do operators have the ability to respond to varying water quality by adjusting coagulation controls to ensure optimum performance? Systems analyses within an HACCP plan should provide operators with such learning opportunities so that they can react to various conditions with understanding and confidence.
- Are the chemicals utilised before the expiration or use-by dates recommended by the manufacturer?
- Is the coagulation system operating properly i.e. is adequate dispersion taking place; are coagulants being added at the proper points?

4.2.2 RETENTION TIMES IN COAGULATION AND FLOCCULATION

It was uncertain what the retention times (i.e. residence times) were for the waters in this study to develop sufficient coagulation-flocculation. According to Smith *et al.* (1991) the retention time, together with the design configuration of the flocculation basin determine the size of the floc. Sections 4.2.3 and 4.2.4 were treatment components investigated in this study. The shortcomings will be described according to specific treatment facility.

4.2.3 SEDIMENTATION

- Is sludge collection and removal adequate? Inadequate sludge collection and removal can cause particles to become re-suspended in water or upset circulation – in other words, the sludge blanket should be disrupted as little as possible. At Rustfontein, the sludge blanket at the upflow clarifier was reported to set loose floc in the overflow often, causing trapped bacteria to be released to the filters.

- Is the floc the correct size and density? Poorly formed floc is characterised by small or loosely held particles that do not settle properly and are carried out of the settling basin. This could be the result of inadequate rapid mixing, improper coagulant dosages, or improper flocculation.

  As mentioned above, sedimentation at Rustfontein takes place in a sludge upflow clarifier. By means of observation, flocs could still be seen at the intake or overflow point where the "cleaner" water (water with less floc) enters the pipeline to be distributed to the filters. A consideration in this study was to determine whether these observed flocs could have an impact on the quality of the settled water. It was also not clear why these flocs did not settle. It was observed at least twice during this study that the pipes in the sludge upflow clarifier were broken due to rust or improper design of the clarifier. The facility had to be shut down temporarily on a short time basis to empty the clarifier in order to repair the pipes, placing more pressure on the primary settlers, which were shown not to achieve required removal rates.

  At Mazelspoort, the overflow water from the sedimentation basins was observed as "clean", thus the assumption could be made that proper flocculation had taken place. A possible reason for this could be that at this facility a separate component specifically for flocculation is included in the design.

- Are basins located outside and subject to windy conditions? Wind can create currents in open basins that can cause short-circuiting or disturbances to the floc.

  At both treatment facilities, the sedimentation basins are located outside and therefore subject to windy conditions. The role of windy conditions in the

effectiveness of flocculation was not considered in this study. It could, however, be assumed that the windy conditions at Mazelspoort for instance, did not interfere with flocculation taking place in the sedimentation basins because the majority of flocculation takes place in the flocculation channel before the water reaches the sedimentation basin.

- Are basins subject to algal growth? A problem that occurs in open, outdoor basins is the growth of algae and slime on the basin walls.

  At both treatment facilities, algae growth was observed in the sedimentation basins. Rustfontein has a greater problem of algae growth than Mazelspoort because of the higher quantity of algae in the impoundment from which the raw intake water is extracted. Pre-chlorination of raw water takes place at Mazelspoort to eliminate the algae and other contaminants which could interfere with other treatment components. The raw water at Rustfontein is not pre-chlorinated.

4.2.4 FILTERS

- Is the correct filter media being used? Issues such as size, uniformity coefficient and depth need to be evaluated. Biofilm formation on filter media could cause pathogenic bacteria entrapment that can be released at unpredictable future dates.

  The issues mentioned were not investigated in this study. Through discussions with the facility operators, it could be determined that water engineers had been consulted in the past regarding the correct filter media being used.

- Is the rate of filter backwash appropriate? Filters can be either under-washed or over-washed. Utilities need to determine the appropriate flow that will clean the filter and prevent mudballs or tunnelling.

  Backwashing of filters takes place at both treatment facilities. The issue of the appropriate rates was not investigated.

- Are criteria set for initiating backwash? Systems should establish criteria such as time, headloss, turbidity or particle counts for initiating backwash procedures.

Backwashing criteria also exist at both treatment facilities. Each facility works according to different criteria. Time was the main criterion at both treatment facilities, and was determined when the facilities were designed. Thus, backwashing took place on a fixed time-frame e.g. per X hours or X cycles. It was not clear whether turbidity was measured in order to revise the backwashing cycle if necessary.

- How are filters brought back on-line? Filters should be brought back on line slowly to allow media to settle after backwashing.

  Because backwashing was not investigated in this study, it was only observed once at Mazelspoort. It was clear that the filters at this facility were brought back online slowly. This was not observed at Rustfontein.

- When a filter is backwashed, more water is diverted to the remaining filters, causing them to be overloaded during backwash. During the backwash, flow going to the remaining filters may need to be cut back to ensure that the filters are not overloaded or "bumped" with a hydraulic surge causing particles to pass through.

4.3 PROPOSED MONITORING PROGRAMME FOR THE TREATMENT FACILITIES INVESTIGATED

The fourth principle of an HACCP programme is the establishment of a system to monitor the CCPs. One of the outcomes of this study was that turbidity could not be used as a solitary indicator of the effectiveness of CCPs. A monitoring programme for drinking water treatment facilities could be divided into two categories namely, system performance (which concentrates mainly on the distribution system) and operational monitoring (which monitors the processes and equipment which is used to protect and enhance water quality). Monitoring requirements will differ from facility to facility in terms of water quality characteristics to be measured, sampling location and frequency of sampling. A monitoring programme should preferably be designed by personnel who have experience in water quality assessment. An example of a monitoring programme is presented in Appendix D.

Both treatment facilities could benefit by applying a Water Safety Plan to ensure early detection of potential process failure and a continuous delivery of an acceptable end-product, namely safe potable water.

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APPENDIX A

SAMPLING AND ANALYSES PROTOCOL

1 SAMPLING

Samples were taken in 800 mℓ sterile Whirlpacks® from the various sampling points (Chapter 2, section 2.1.1 and 2.1.2) and placed in cooler bags (7°C–10°C) for transportation to the water analysis laboratory. The samples were analysed within 6 hours of collection.

2 ORGANISM ENUMERATION EQUIPMENT

2.1 MEMBRANE FILTRATION

2.1.1 Equipment

Equipment and procedures for bacteriological analysis by membrane filtration were based on generally accepted methods (South Africa Bureau of Standards (SABS), 1984 & 1987; Millipore Corporation, 1992; Standard Methods, 1998).

2.1.1.1 Filter and vacuum assembly

The filter and vacuum assembly consisted of:

- 4 x Millipore® 3-place PVC manifolds
- 12 x 47 mm diameter Millipore® glass filter holder sub-assembly, comprising of:
  - ⇨ glass funnels of ± 250 mℓ capacity,
  - ⇨ fritted glass base support for filter membrane and
  - ⇨ clamps to secure funnel on base after loading filter membrane.
- 2 x EDWARDS® 1.5 Two-stage 220/240 V 50/60 Hz vacuum/pressure pumps.
- Two sets of glass 1 litre vacuum filter flasks for receiving filtered samples and acting as moisture traps before each vacuum pump.
- The assembly is connected by means of silicone rubber tubing.

2.1.1.2 Membrane filters

Sterile Millipore® HA-type 0.45 µm pore size membranes were used. The membranes were 47 mm in diameter, white and grid-marked.

2.1.1.3 Pipettes

Pipetting for 1 mℓ and smaller volumes was done with Finnpipette® adjustable pipettes, with sterile disposable tips. Errors in calibration were checked so as not to exceed 2.5%. Larger volumes were dispensed with standard graduated glass pipettes.

2.1.1.4 Balances

A Sartorius Basic balance was used for weighing the various powered media in the preparation of the media plates.

2.1.1.5 Incubation

Labcon and Scientific incubators with forced circulation were used. The incubators were monitored constantly to maintain a constant and uniform temperature at all times. Temperatures varied within 0.5°C accuracy - especially within stacks of incubated plates.

2.1.1.6 Oven

A Labcon economy oven was used to dry-sterilise the analysis equipment.

2.1.1.7 Refrigerator

A refrigerator was used to store samples, plates and reagents at temperatures of 1 – 4.4 °C.

3 PREPARATION AND PROCEDURES

3.1 STERILISING

Equipment was steam-sterilised in an autoclave at 121°C / 15 psi for 20 minutes after each completed filtration session of all samples. Each glass funnel assembly was separately wrapped in tinfoil and steam-sterilised before each session of filter plating. Dry-sterilisation of equipment was done in an oven at 180°C for 10 min. Dry-sterilisation was done between each sample filtration session. Forceps were

immersed in alcohol and flamed before filter handling between batches.

3.2 PHOSPHATE BUFFER

Stock phosphate buffer solution and stock magnesium chloride solution were prepared according to Standard Methods (1998). Working solutions of buffer were made up by adding 1.25 mℓ of phosphate (34 g KH_2PO_4 / ℓ distilled water) buffer and 5 mℓ of magnesium chloride solution (81.1 g $MgCl_26H_20$ / ℓ distilled water) to 1 litre of reagent grade water and autoclaved to sterilise.

3.3 DILUTIONS

All samples were filtered in triplicate (3 filters) per dilution. Dilutions were made up to ideally achieve counts of between 20 to 60 colonies per plate (Standard Methods; 1998).

Dilution procedures in the laboratory should ideally be adapted to minimise variations while diluting from the sample. Undiluted sample applications varied between 1 mℓ and 100 mℓ. These applications were single extractions by pipette or decanted into sterile 100 mℓ measuring cylinders from the raw sample, after the sample had been vigorously shaken. The procedure for preparing a dilution series was as follows:

- A volume of 90 mℓ sterile phosphate buffer was prepared per sample.
- Samples were vigorously shaken to mix the contents homogeneously.
- 10 x 1 mℓ extractions, from various areas and depths in the sample, were aseptically transferred from the sample to the prepared volume of phosphate buffer, to prepare a 100 mℓ of 10^{-1} diluted sample.
- 1 mℓ of 10^{-1} dilution was aseptically transferred to a 9 mℓ volume of sterile phosphate buffer to provide a 10^{-2} dilution.
- Subsequent dilutions were made up in a similar manner.

For clear water, volumes of between 10 mℓ and 100 mℓ sample were pipetted. For turbid samples dilutions of up to 10^{-4} were prepared and 1 mℓ of undiluted sample or sample dilute was pipetted onto the filters.

3.4 THE MEMBRANE FILTRATION TECHNIQUE (USEPA, 1978; SABS, 1984 & 1987; Millipore Corporation, 1992; Standard Methods, 1998).

1. Four sets of Millipore® 3-place vacuum manifolds, complete with filter holds sub-assemblies were used. Filter plating of the same sample was done in decreasing dilution order to avoid contamination.
2. Sterile phosphate buffer (Section 3.2) was used for diluting samples and rinsing funnels after filtration (Millipore Corporation, 1992).
3. Pre-sterilised membrane filters were used. Membranes were loaded with a sterile forceps, grid side up, onto the fritted glass support base of the funnel holder, and the funnel clamped onto the filter base.
4. The sample was then re-mixed by vigorously shaking the bottle for several seconds.
5. 20-30 mℓ of sterile phosphate buffer (Section 3.2) was poured into the funnel and a volume of sample was pipetted into the buffer.
6. Vacuum was applied while slowly swirling the manifold unit to ensure uniform suspension of the sample in the volume of buffer during filtering.
7. The funnel walls were rinsed repeatedly (3 times) with approximately 30 mℓ of sterile buffer. Buffer was drawn into a syringe and ejected through a sterile 0.22 µm Sterivex® (Millipore®) filter to avoid contamination.
8. Vacuum was broken and the membrane lifted with a sterile forceps and put grid side up, onto the selective media in petri dishes, ensuring no trapped air under the membrane.
9. The dishes were marked, inverted and incubated.
10. The incubation temperatures and times for each indicator organism group are described in Section 3.5.

3.5 CONTAMINANT ASSESSMENT

3.5.1 Enumeration of total coliforms by means of Chromocult Coliformen® Agar

Total coliforms were enumerated on Chromocult Coliformen® Agar (Merck®) (*for the simultaneous detection of coliforms and* E. coli *in water samples*) using the membrane filter technique (Section 3.4).

3.5.1.1 Procedure for Chromocult Coliformen® Agar (Merck®, 1996)

26.5 g of the powder was suspended in 1 litre of distilled water. The mixture was heated in a flowing water bath while gently being stirred until the powder was totally dissolved. The medium was cooled to 40-50°C and Cefsulodin solution (10 mg Cefsulodin in 2 mℓ of distilled water) was added to the 1 litre of medium by gently shaking to homogenise.

The liquid was poured into 90 mm petri dishes, 5 mm deep. This medium does not require autoclaving. Fresh plates were stored in the dark, sealed inside plastic bags (for moisture retention) at < 8°C. Unused plates were discarded after 6 months.

Incubation: The plates were inverted and incubated at 37°C for 24 hours.

Identification: Colonies appear in various shades of salmon to red (Merck®, 1996).

Confirmation: API® 20E (bioMérieux®).

3.5.2 Enumeration of faecal coliforms by means of M-FC agar

Faecal coliforms were enumerated with the membrane filter technique (Section 3.4) using M-FC Agar.

3.5.2.1 Procedure for M-FC agar (Biolab®)

52 g of the powder was suspended in 1 litre of distilled water. The mixture was boiled until the powder was totally dissolved. The liquid was poured 5 mm deep into 90 mm petri dishes. This medium does not require autoclaving. Unused plates were discarded after 3 months. The plates were inverted and incubated in at 44.5°C for 24 hours.

3.6 COUNTING

After incubation for appropriate periods of time, colonies were counted according to the definitions for each group of organisms. To achieve reliable statistical quantification the final count per 100 mℓ per sample was calculated as follows (Standard Methods, 1998):

$$\frac{\frac{[(\text{Plate 1} + \text{plate 2} + \text{plate 3}) / 3]}{\text{Sample size}}}{\text{Sample dilution}} \times 100$$

The above-mentioned formula was programmed in an MS Excel® spreadsheet. The analyst enters:

① the counts from each of the 3 plates (membranes)

② sample size (maximum 1 mℓ for diluted samples) as well as

③ the dilutions expressed as 0.1; 0.01; etc. (minimum 1 mℓ for undiluted samples).

Counts are expressed as number of organisms per 100 mℓ.

4 COLONY VERIFICATION

The actual selectivity/specificity of the various selective growth media has been found in many reports to be inconsistent (Dionisio and Borrego, 1995; Figueras, Inza, Polo, Feliu and Guarro, 1996). To establish the accuracy of detected indicator levels, as well as the selectivity of the various media for detecting the selected indicators, a verification programme was designed and followed according to Standard Methods (1998). Representative selections of colonies were made of various bacterial pollution-indicator organisms detected in water samples from the target catchment. Standard Methods (1998) recommends that at least 10 colonies be picked randomly per month, from known positive samples, and verified.

4.1 THE PRINCIPLE OF IDENTIFICATION SYSTEM GALLERIES

Selections were made from the plates where the particular dilution yielded growth of between 20 and 80 colonies. Of this, a constant percentage exceeding 10% of the identified coloured colonies was selected and processed for transfer to the various types of confirmation galleries. The identification system (API 20E) consisted of strips with a characteristic number of micro-tubes containing dehydrated substrates. These substrates support specific enzymatic activity for fermentation of sugars.

Each micro-tube is inoculated with a dense bacterial suspension made up of the original selected colony, which at the same time reconstitutes the substrates. Metabolic end-products are produced during incubation, which produce spontaneous colour changes or revealed colours afterwards by the addition of reagents.

4.2 PREPARATION OF COLONIES FOR VERIFICATION

Selections were made only from colonies that could be counted as the actual indicator on the various selective growth media. These counts were based on various colour-related identifications (counting the specific coloured colonies) as prescribed by relevant authoritative manuals such as Standard Methods (1998) or guidelines from manufacturers (bioMérieux®, 2001). Between 12% and 40% of all the colonies cultured on the various media, were randomly selected. Before verification began with multi-test identification system galleries (API®, bioMérieux®), the coloured selected colonies were first stripped of any colouration that facilitated the selectivity of the growth medium. This was to eliminate all possible interference with the functions of the Identification System Galleries.

Coliform colonies were picked from the membranes with inoculum needles, streaked out on the same selective medium and incubated at the prescribed temperature. This was to obtain pure single colonies (without the membrane) with the same colour that had originally been used to identify the specific colony as being from the relevant coliform group. In fact this could be seen as further affirmation of the original selection of the colony, as alien particles trapped on the membrane could sometimes lead to colouration of the membrane, making the colour identification of the colony difficult. Single colonies on the selective media were then streaked out and grown on Plate Count Agar (Standard Methods, 1998) to strip the colonies of their colour. This part of the process was the last step in which the colonies were touched with the metal eye of an inoculum needle. Picking the isolated colony from the Plate Count Agar to be used for identification on the API strip was done with sterile swabs to exclude possible interference from the metal eye of an inoculum needle with the oxidase test. The various reactions are then coded and read into a Reading Table. The identification is obtained from an Identification Table or a computerised Analytical Profile Index.

4.3 IDENTIFICATION PROCEDURE

4.3.1 Chromocult Coliformen® and M-FC agar

Red colonies exhibiting the typical *salmon to red* (total coliform on Chromocult Coliformen® Agar) and *shades of blue* (faecal coliforms on M-FC agar) colour reactions were selected. The colony morphology was carefully noted, together with

the colour, size, shape, composition, and margin appearance. These would be colonies that the analyst would count as the coloured coliform colonies on a given specific growth media. A note was made of the number of colonies counted from every particular plate (membrane), as well as the number taken for verification by the API® 20E identification system.

4.3.2 API® 20E multi-test galleries (bioMérieux®)

API® 20E is a standardised identification system for *Enterobacteriaceae* and other non-fastidious Gram-negative rods. The system uses 12 and 20 miniaturised biochemical tests (respectively) in strips, and a related database. These systems can be used to identify a substantial number of species, which include the most important species used in this study.

4.3.2.1 Preparation of the inoculum

Homogeneous bacterial suspensions of the selected (and purified) colonies were made according to the prescriptions contained in the manual provided with the commercial identification kit (bioMérieux®).

4.3.2.2 Inoculation and reading of the strips

The micro-tubes on the prepared strips were filled according to prescription and incubated for 18-24 hours at 35 - 37°C. After the incubation time, the spontaneous colour reactions from each strip were recorded. Reagents were then added to the prescribed tubes and the colour reaction recorded. All these recordings were done on result sheets provided with the identification kit.

4.3.2.3 Identification

The pattern of each of the reactions obtained was hand-coded, on the result sheets, into a numerical profile. These numerical profiles were then read into the ANALYTICAL PROFILE INDEX as a number. The Index provides the name of the species that matches the code.

4.4 QUALITY CONTROL (QC)

Several QC tests were done on the various batches of strips acquired. The stock cultures used were obtained from local medical commercial pathological

laboratories. The reference organisms used were *Klebsiella pneumoniae pneumoniae, Proteus vulgaris* and *Pseudomonas aeruginosa.*

5 TURBIDITY MEASUREMENT

Turbidity is described in the *Standard Methods for the Examination of Water and Wastewater* Method 2130B (EPA Method 180.1) for turbidity measurement as, "an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample" (Standard Methods, 1998).

5.1 SAMPLE VOLUME

Samples are typically introduced into benchtop turbidity meter instruments through a transparent sample cell made of glass. These samples cells, or cuvettes, are usually about 30 mℓ in capacity.

5.2 THE BENCHTOP TURBIDITY METER

The HACH Model 2100 N laboratory turbidity meter was used in this study to assess the levels of turbidity in the water samples. This instrument is designed for measurement of turbidity from 0 to 4,000 NTU (Nephelometric Turbidity Units) with automatic range selection and decimal point placement (HACH Company, 1993).

5.3 PROCEDURE FOR TURBIDITY MEASUREMENT

The sample cells were filled with approximately 30 mℓ of the water sample and a thin bead of silicone oil from the top to the bottom of each cell was applied – just enough to coat with a thin layer of oil. An oiling cloth was used to spread the oil uniformly. Excess oil was wiped off. The sample cell was placed in the instruments cell compartment and the cell cover was closed. A turbidity measurement appeared on the LCD display and recorded on a spreadsheet to be used for result interpretation.

6 QUALITY CONTROL

6.1 WASHING AND STERILISING

All plastic and glassware used in this study was cleaned with a suitable detergent in hot water and thoroughly rinsed to remove all traces of soap and washing compounds.

All equipment was rinsed several times in distilled water before use.

Sterilisation was done at 121°C for 15 minutes. The autoclave was monitored on a regular basis by the manufacturers.

6.2 STORAGE OF CULTURE MEDIA

All dehydrated powder media was stored in tightly closed bottles in the dark at less than 30°C and low humidity. Purchased media was used within six months. Caution was taken not to use discoloured or caked media. Media plates were used within one week.

APPENDIX B

STATISTICAL ANALYSES

1 CHARACTERISTICS OF DATA FOR THIS STUDY

Microbiological water resources data generally have substantial variations, which cause these data not to be normally distributed around the mean for the set (Standard Methods, 1998). The data for this study had characteristics not unlike those described for water resources by Helsel and Hirsch (1995) as well as Jagals (2000). The following were the characteristics:

- A lower boundary of zero (0) – no negative values are possible. Several samples had shown zero counts for the microbiological indicators – which implied that the indicator was not cultured, suggesting that they were removed or had not occurred. This had to be manipulated to compensate for the fact that 0 cannot be log-transformed. The manipulation technique is described later on.
- Presence of outliers, observations considerably higher or lower than most of the data. This occurs infrequently but regularly. Outliers on the high side are more common in water resources.
- Positive skewness, due to items 1 and 2 above. Skewness can be expected when outlying values occur only in one direction.
- Non-normal distribution of data due to items 1 – 3 above. Many statistical tests assume that data follow a normal distribution while water data often do not.
- Consecutive observations of the different indicators co-occurred under similar circumstances but tended not to correlate.

The following sections describe how data analyses were approached in context of these characteristics.

2 DATA DISTRIBUTION

2.1 NORMALITY OF DATA

The data sets of both total and faecal coliforms in this study varied widely in their distributions around their respective means. Such wide distributions are often not

normally distributed around the means (Helsel and Hirsch, 1995). Application of most statistical techniques in the field of water resource management generally assumes that data sets have symmetrical distributions such as the normal (Gaussian) curve (Pearson and Turton, 1993). However, microbiological water-quality data distributions are often not symmetrical. Bacterial counts in clearer waters such as those measured in this study often have a skewed distribution (non-parametrical data) (Standard Methods, 1998) because of more low counts than high counts. For this study, the data sets generally showed non-normality where negative skewness was encountered because of the low.

Problems can occur with the reliability of data interpretation where statistical procedures such as parametric tests, which assume normality, are directly employed (Helsel and Hirsch, 1995) on data that do not follow a symmetrical distribution about the mean (the Gaussian curve). The data sets for this study required non-parametrical testing. Non-parametrical kinds are more robust than parametrical tests, and can be effectively applied even in instances where a data set might have a normal distribution (Glantz, 1997, Helsel and Hirsch, 1995). For this study, non-parametrical tests were used throughout to analyse the data.

2.2 DATA TRANSFORMATION

Even when using non-parametrical analyses of data, the analysts should strive to work with data that has as little variance as possible (Helsel and Hirsch, 1995). To produce data that would display closer-to-normal distribution characteristics, transformations of data could be used (Standard Methods; 1998). Transformations are used to make data more symmetric, linear or more consistent in variance (Helsel and Hirsch, 1995). For this study, data were transformed to their logarithms (ladders of power), which generally produced less-varying data. The log-transformed data often did not achieve normality despite the transformation.

2.3 OUTLIERS

Outliers are observations whose values are quite different from others in the data set (Helsel and Hirsch, 1995). While analysts often discard outliers, this procedure was not followed in this study. Outliers represented real events in the sampling and analysis routines such as higher activity pollution in the particular water type at the

particular time. When outliers did occur during this study, the following was investigated:

- possible recording errors such as erroneous entering into calculation programmes
- copying, decimal points or other obvious errors
- comparing the outlying tendency with the other indicators enumerated from the same sample, to see if a similar event occurred

Where no errors were detected, the outliers where kept in the data sets.

3 BOX PLOTS

According to Helsel and Hirsch (1995), box plots provide the clearest visual summaries of the following:

- The interquartile range (variation or spread of the data) is the boundaries forming the box height. This indicates the spread of data between the 25th and the 75th percentile. The closer the data are clustered to the median within the interquartile range, the less varied (more stable) the data set is.
- The skewness (also referred to as the quartile skew) is represented by the relative size of the box halves. The further the median line is from the middle of the box, the less normally (non-parametric) the data are distributed around the mean.
- The cap-whiskers on the lines protruding above and below the 75th and the 25th percentiles represent the 10th and 90th percentile boundaries. The circle symbols beyond the caps and whiskers indicate outliers.

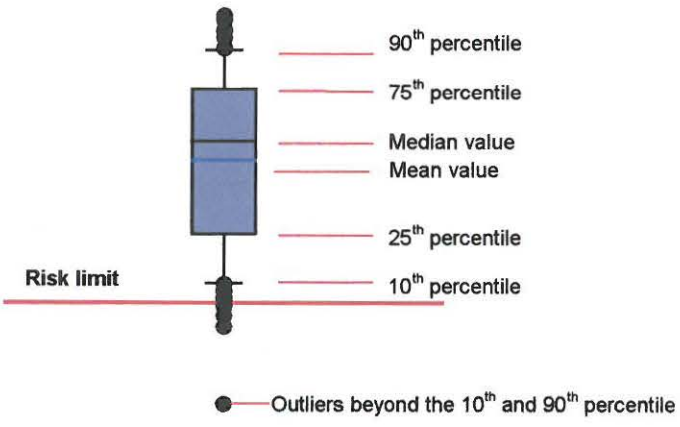

Figure B1: An example of a box plot

4 STATISTICAL TESTS

The following statistical procedures were used in this study:

4.1 THE 90TH PERCENTILE

The 90th percentile is that value in a data set below which 90% of the data lies. It is defined as a function that could establish a threshold of acceptance (Microsoft® Excel, 2002). Percentiles are used to monitor compliance with water quality standards (Helsel and Hirsch, 1995). Simply stated, the South African Water Quality Guidelines (DWAF, 1996) require not more than 5 total coliforms per 100 mℓ for health protection. This is definitely not the central (average) value required, because in any given data set, approximately half the data values would be above the guideline value. In the water and health industry, it is hardly possible for 100% of the samples to comply. It is reasonable to allow for a certain percentage of the samples NOT to comply, since there are several things that could cause this, such as analyst errors with random but negligible occurrences of total coliforms above the limit. We must, however, be strict with drinking water quality. Therefore, we would allow for 5% non-compliance – meaning a 95th percentile threshold. 95% of the data we have collected from a drinking water outlet must be below the 5 TC per 100 mℓ or else the water quality from this point is deemed in non-compliance and some intervention has to be activated.

This means that for any data set of which a percentage of the data has to be within a given set of parameters to show compliance, to a health parameter, for instance, the discipline in which that assessment is done usually decides on a reasonable maximum (in percentage or at a percentile) which the data should not exceed. If more data exceed than the established reasonable maximum (RM) then the data did not satisfy the need or did not comply.

For this study, the 90th percentile was used as the RM. In other words 90% of the data had to be below the 90th percentile level. If the data set at its 90th percentile had exceeded the guideline or standard, the data, and therefore the performance, of the CCP did not comply. For instance, the mean and some percentile of data in a set should not exceed a standard imposed on a particular contaminant where an excessive amount would imply an acute risk of the population taking ill when ingesting the medium (Glantz, 1997).

The UK Drinking Water Supply Regulations, 1989, based on EC directives (Venter *et al.*, 1996) suggests that the 90th percentile limit would be a practical level against which to test the results of water quality monitoring for any given contaminant for conventional treatment.

4.2 MEAN (OR AVERAGE)

The arithmetic mean is the sum of all the data in a set, divided by the sample size. If data is normally distributed, the mean is at the centre of the distribution. The mean was used in this study to determine the central value for all log-transformed data.

It is common practice to use the mean value of a data set to see where the average (central) measurement would probably be in a data set. In data that vary considerably, the mean most suited for a realistic central value is the geometric mean (Standard Methods, 1998). The geometric mean is calculated by log-transforming the data, calculating its average (mean) and powering the log-value back (anti-log) to the natural value. This eliminates much of the variance, creating more "normally" distributed data, although the data may not necessarily be symmetrical yet. The geometric mean is therefore nothing more than the arithmetic mean of the logarithms of data in a set. This study used log-transformed data for graph plotting and the geometric mean for reporting in tables.

4.3 MEASUREMENTS OF ZERO (0)

Log-transforming a data reading of 0 is not possible. Technically speaking, microbiological counts of less than one are a statistical artefact, since less than one organism means no organism. The log of the value 1 is Log_0. Natural values showing a zero were replaced by 0.1 and then log-transformed, which returned a -1 value. After the averaging and anti-log step, the 0.1 was again deducted, negligibly influencing the outcome. This enabled realistic depiction of the zero values, especially on the graphs. Since organism numbers of zero (0) cannot be shown on the log y-axes of the graphs as zero (since this would actually depict the value of 1), the zero value is depicted as ND (not detected) at the –1 level in graphs.

While this approach is not widely advocated, use of this technique in analysing microbiological water quality data is not uncommon (Standard methods, 1998).

It provides a means of including zero data (which is essential) and not discarding these because the geometric mean cannot be calculated.

5 MINIMUM SAMPLE SIZE

For this study, the statistical programme SigmaStat Version 2.0 (1997) was used to calculate the sample size needed for statistical significance. The outcome was at least 15 samples per sample point.

The minimum samples sizes for statistical significance were determined before each series of experiments commenced at the various levels and approaches of this study. The data in the sets used for this study were non-parametric estimates. In water resource measurements, these estimates generally "consider the important and frequently observed effects of seasonality or trend and so may never provide estimates sufficiently accurate to be anything more than a crude guide" (Helsel and Hirsch, 1995).

Another important factor that requires careful consideration of the sample size is the availability of resources. Nevertheless, one should determine approximately how big the sample size has to be – crude or not - in order to detect an effect or difference at a specified level of statistical difference or power. All else being equal, the larger the sample size, the greater the power of the relevant test applied (Helsel and Hirsch, 1995; SigmaStat, 1997).

6 COMPARING DATA

The classic technique for comparing data sets is to analyse the sets for variance (ANOVA) (Wadsworth, 1990; Helsel and Hirsch, 1995). ANOVA is usually a parametric test but has variations that can be applied non-parametrically. For this study, the data not passing the normality test were by far in the majority, despite data transformation. Non-parametric testing for variance was employed throughout the study. Where parametric testing, such as the traditional Student *t*- test, loses power to detect differences in non-normal data, non-parametric testing displays considerable power in non-normal, as well as normal, data testing and display (Wadsworth, 1990; Helsel and Hirsch, 1995).

The Mann-Whitney Rank Sum Test is a non-parametric test used to test for differences between two data sets that are greater than what can be attributed to random sampling variation. This test ranks all the observations (data) from smallest to largest without regard to which group each observation comes from. If there is no difference between the two groups, the mean ranks should be approximately the same. If they differ by a large margin, one can assume that the lower ranks will tend to be in one group and the higher ranks in the other; the conclusion will be that the samples were drawn from different populations (i.e. that there is a statistically significant difference) (Glantz, 1997; Helsel and Hirsch, 1995).

7 REGRESSION AND CORRELATION

Correlation and regression measures the strength of association between two continuous variables (Wadsworth, 1990; Glantz, 1997). To visualise the shape and describe the behaviour of data, scientists and engineers most often use regression (Wadsworth, 1990; Helsel and Hirsch, 1995; Glantz, 1997).

7.1 REGRESSION ANALYSIS

Regression procedures use the values of one or more independent variables to predict the value of a dependent variable. For this study, regression analyses were used to estimate (predict) values of one variable (coliforms) based on the knowledge of another variable (turbidity).

Independent variables are the known, or predictor (explanatory) variables – for this study these were the turbidity results. These were plotted as X-axis values. When the independent variables are plotted, they result in corresponding values for the dependent (response) variables, most often assigned to the Y-axis (Wadsworth, 1990; Glantz, 1997). For this study, the coliforms were the dependent variables.

To display whether there were dependences between the two continuous variables, e.g. turbidity (as the independent variable on the X-axis) and the coliforms (as the dependent variable on the Y-axis), linear regression was applied. The computer programme SigmaPlot® 8.02 (2002) was used for this function.

The Simple Linear Regression procedure was used. Simple Linear Regression assumes an association between the independent and dependent variables that, when graphed on a Cartesian co-ordinate system, produce a straight line. Linear Regression finds the straight line that most closely describes, or predicts, the value of the dependent variable, given the observed value of the independent variable.

7.2 CORRELATION

Correlation procedures measure the strength of association between two variables, which can be used as a gauge of the certainty of prediction. Unlike regression, it is not necessary to define one variable as the independent variable and one as the dependent variable. Correlation measures observed co-variation (Helsel and Hirsch, 1995).

The correlation coefficient *r* is a number that varies between –1 and +1. A correlation of –1 indicates there is a perfect negative relationship between the two variables, with one always decreasing as the other increases. A correlation of +1 indicates there is a perfect positive relationship between the two variables, with both always increasing together. A correlation of 0 indicates no relationship between the two variables.

Correlation was used for this study to see whether the coliforms (dependent variable) increased as the turbidity (independent variable) increased (correlation), or whether their patterns of variation were totally unrelated (weak or no correlation).

For this study, the non-parametric Spearman Rank Order Correlation was used to measure the strength of association between pairs of variables without specifying which variable is dependent or independent but for data sets not normally distributed with constant variance.

7.3 STRENGTH OF ASSOCIATION

Traditionally, a correlation of >0 is expressed at various levels of strength of association. Water quality literature is generally vague about what constitutes a "strong" relationship (how close *r* should be to 1). To simply reject the H_0 because there is some relationship proven does not tell practitioners whether the correlation

barely exists (e.g. $r = 0.001$) or is close to being totally related (e.g. $r = 0.99$). Helsel and Hirsch (1995), as well as Lifshitz and Joshi (1998), express a correlation coefficient of 0.9 and above as "strong".

It was necessary for this study to describe the strengths of relationships based on the correlation coefficient. It was decided to use the expressions of Jagals (2000) to describe strengths of association in this study:

① *Very strong association* when $r = >0.9<1$. The independent variable predicts the dependant variable (as with $H_0 = 1$).

② *Strong association* when $r = >0.75<0.9$. There is a definite tendency. The independent variable predicts the dependant variable under certain circumstances that must be explained in the relevant chapter.

③ *An association* when $r = >0.5<0.76$. There is some tendency. The independent variable could predict the dependant variable but the findings should be treated with caution. The association could be accepted only after intense debate but should generally not be seen as a positive relationship between the variables.

④ *Poor association* when $r = >0<0.5$. The independent variable could not predict the dependant variable.

APPENDIX C

HEALTH-RELATED WATER QUALITY GUIDELINES

Table C1: Various national and international guidelines for *microbiological* drinking water quality

Country	Guideline value	Description
TOTAL COLIFORMS		
South Africa South African Water Quality Guidelines, DWAF,1996	0 – 5 / 100 mℓ	Negligible risk of microbial infection
	5 – 100 / 100 mℓ	• Indicative of inadequate treatment, post treatment contamination or growth in the distribution system • Risk of infectious disease transmission with continuous exposure and slight risk with occasional exposure
South Africa Assessment guide for Quality of Domestic Water Supplies WRC, 1998	0 / 100 mℓ	No detectable chance of infection
	0-10 / 100 mℓ	Insignificant change of infection
	10-100 / 100 mℓ	Clinical infections unlikely in healthy adults, but may occur in some sensitive groups
World Health Organisation WHO, 1996	0.01 / 100 mℓ	Guideline[1]
	0 / 100 mℓ	Treated water entering distribution system[2]
Australia Australian Drinking Water Guidelines, 1996	0 / 100 mℓ	Guideline limit
France, 1989[1]	0.01 / 100 mℓ	
United Kingdom UK drinking Water Supply Regulations, 1989	0 / 100 mℓ	Maximum value[1]
United States USEPA, 1999	<1 / 100 mℓ	Maximum contaminant level
FAECAL COLIFORMS		
South Africa South African Water Quality Guidelines, DWAF,1996	0 / 100 mℓ	Negligible risk of infection
	0 – 10 / 100 mℓ	• Slight risk of microbial infection with continuous exposure • Slight risk with occasional exposure
South Africa Assessment guide for Quality of Domestic Water Supplies, WRC, 1998	0 / 100 mℓ	No detectable change of infection
	0 - 1 / 100 mℓ	Insignificant change of infection
	1-10 / 100 mℓ	Clinical infections unlikely in healthy adults, but may occur in some sensitive groups
World Health Organisation WHO, 1996	0 / 100 mℓ	Guideline
Australia Australian Drinking Water Guidelines, 1996	0 / 100 mℓ	Guideline limit
France, 1989[1]	0 / 100 mℓ	
United Kingdom[1] UK drinking Water Supply Regulations, 1989	0 / 100 mℓ	Maximum value

[1] Tebbutt, 1998. UK drinking water supply regulations (1989).

[2] Genthe and Kfir, 1995.

Table C2: Various national and international guidelines for *turbidity* in drinking water

Country	Guideline value	Description
TURBIDITY		
South Africa South African Water Quality Guidelines, DWAF, 1996	0 NTU	• No turbidity visible • No adverse aesthetic effects regarding taste or odour • No risk of transmission of infectious microorganisms
	1 – 5 NTU	• No turbidity visible • A slight chance of adverse aesthetic effects and infectious disease transmission exists
	5 – 10 NTU	• Turbidity visible and may be objectionable to users • Some chance of transmission of disease by microorganisms associated with particulate matter, particularly for agents with low infective dose such as viruses and protozoan parasites
South Africa Assessment guide for Quality of Domestic Water Supplies, WRC, 1998	<0.1 NTU 0.1 – 1 NTU 1 – 20 NTU	No effects Slight risk of potential health effects Possibility of secondary health effects
United States USEPA, 1999	1 – 5 NTU	Maximum contaminant level
World Health Organisation WHO, 2000	< 1 NTU	Guideline
Australia Australian Drinking Water Guidelines, 1996	5 NTU > 1 NTU < 1 NTU	Just noticeable in a glass May shield some microorganisms from disinfection Desirable for effective disinfection

APPENDIX D

PROPOSED MONITORING PROGRAMME FOR TARGETED TREATMENT FACILITIES

1 HEALTH-RELATED WATER QUALITY (HRWQ) MONITORING PROGRAMME

1.1 HEALTH-RELATED INDICATORS

The microbiological quality of drinking water should be monitored by testing for at least two indicators organisms namely: faecal coliforms (FC) (alternatively *E. coli*) and total coliforms (TC).

Indicator organism: Faecal coliforms (alternatively *E. coli*)

Guideline: No sample should contain any FC numbers (or *E. coli*) per 100 mℓ of sample (DWAF, 1996)

Action: If any faecal coliforms (or *E. coli*) are detected, then irrespective of the number of organisms, both the following steps should be taken immediately:

❶ Another sample (also called a repeat sample) should be taken from the same site and tested for the presence of faecal coliforms (or *E. coli*) and total coliforms.

- If the repeat sample is negative for both faecal coliforms and total coliforms, then routine sampling can resume, but only after step ❷ below has been completed.
- If the repeat sample were positive for either faecal coliforms or total coliforms, then increased disinfection and a full sanitary survey (Section 2, below) should be implemented immediately

❷ Disinfection should be increased and/or investigation should be undertaken to determine the possible sources of contamination.

Indicator organism: Total coliforms

Guideline: Not more than 5 TC numbers per 100 mℓ should be detected (DWAF, 1996).

Action: If total coliforms are detected in any sample, then irrespective of the number of organisms, the following action should be taken immediately:

Another sample (also called a repeat sample) should be taken from the same site and tested for the presence of both total coliforms and faecal coliforms (or *E. coli*).

- If the repeat sample is negative for both total coliforms and faecal coliforms, then routine sampling can resume and no further action is required unless local knowledge of a system dictates an increased response.
- If the repeat sample were positive for either total coliforms or faecal coliforms, then corrective action such as increasing disinfection dosage and a full sanitary survey should undertaken immediately

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Systems that use conventional treatment must conduct continuous monitoring of turbidity for each individual filter:

Indicator: Turbidity

Guideline: Turbidity level of representative samples of a system's filtered water (measured every four hours) must be less than or equal to 0.3 NTU in at least 95% of the measurements taken each month. The turbidity level of representative samples of a system's filtered water must not exceed 1 NTU at any time (USEPA, 1999)

Turbidity of treated water should not exceed 0.1 NTU (WRC, 1998).

Action: Turbidity measurements must be performed on representative samples of the system's filtered water every four hours (or more frequently) that the system serves water to the public.

Systems must also record the results of individual filter monitoring every 15 minutes. If the individual filter is not providing water which contributes to the combined filter effluent, (i.e. it is not operating, is filtering to waste, or recycled) the system does not need to record or monitor the turbidity for that specific filter.

1.2 MONITORING FREQUENCY

Samples that are representative of the quality of water supplied should be collected and analysed for indicator organisms at the following frequency.

Table D1: Recommended sampling frequency for microbiological monitoring of treated water supply

Population served	Minimum frequency*
> 100,000	6 samples per week, plus 1 additional sample per month for each 10,000 above 100,000
5,000 – 100,000	1 sample per week, plus 1 additional sample per month for each 5,000 above 5,000
1,000 – 5,000	1 sample per week (52 samples per year)

*During rainy season, sampling should be carried out more frequently.

Turbidity measurements must be performed on representative samples of the system's filtered water every four hours (or more frequently) that the system serves water to the public. Systems should also record the results of individual filter monitoring every 15 minutes.

The above-mentioned part of the monitoring programme was adapted from the Australian Drinking Water Guidelines (National Health and Medical Research Council, 1996) for the microbiological assessment and the Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions (USEPA, 1999) was used as a source for the compilation of the programme for turbidity testing.

1.3 PERFORMANCE ASSESSMENT

For samples representative of the quality of water supplied to consumers, performance can be regarded as satisfactory if over the preceding 12 months at least the minimum number of routine samples (as set out in table D1) has been tested for indicator organisms and at least 98% of the scheduled samples contain no faecal coliforms and at least 95% contain no total coliforms. It is also proposed that for all health-related characteristics, a reasonable objective is to be confident that the 95th percentile of results over the preceding 12 months is less than the guideline value.

Critical performance criteria such as those applied in this study could be used to assess the performance of each treatment process. Sampling points should be

chosen to be representative of the entire water treatment cycle and could include raw resource water, coagulation-flocculation, sedimentation, filtration and chlorination. The proposed guideline set is:

Table D2: Proposed critical performance limit guideline set

Indicator	Raw water extraction	Sedimentation in removal %	Filtration in removal %	Chlorination / Treated water in removal %	
Total coliforms	20,000 / 100 mℓ (Venter *et al.*, 1996)	90 % (WHO, 2000	99 % (WHO, 2000)	99.99 % (WHO, 2000)	0-10 / 100 mℓ (WRC, 1998)
Faecal coliforms	2,000 / 100 mℓ (DWAF, 2002)	90 % (WHO, 2000)	99 % (WHO, 1996)	99.99 % (WHO, 2000)	0 / 100 mℓ (DWAF, 1996)
Turbidity	None	85 % (USEPA, 1999)	< 1 NTU (WHO, 2000)	< 1 NTU (WHO, 2000)	1 NTU (DWAF, 1996)

2 SANITARY SURVEY

A monitoring programme should start with a sanitary survey to acquire an overall perspective of the treatment facility and all the factors which could influence the effectiveness thereof. Such a survey could also form an integral part of catchment management of the resource water. This survey could consist of the elements listed below:

2.1 ON-SITE REVIEW OF THE WATER RESOURCE

A survey of the resource water to be extracted for drinking water treatment needs to be conducted on a systematic basis. This is essential for resource water quality control management and may be conducted by the facility alone or in cooperation with the local authority. Such a survey should be designed to identify all areas of concern within the supply system, including the entire contributory watershed and should be conducted by a qualified sanitary engineer or watershed inspector.

Natural factors which could influence resource water quality should be investigated and noted such as *climatic changes* (e.g. rainfall patterns, seasonal changes, temperature), *watershed characteristics* (topography, vegetative cover, wild animals), *geology* (e.g. groundwater characteristics) and *microbiological growth* (e.g. various species, quantity of species etc.). Point sources and non-point sources should also be considered. Point sources should include *wastewater discharges*

(e.g. determine the quantity of facilities upstream which discharge effluents into resource water) and *industries* (e.g. determine the quantity of industries upstream which could potentially influence the quality of the resources water). Non-point sources include *agricultural run-off* (e.g. determine the number of farms which are located near the impoundment as well as the usage of pesticides etc.), *livestock* (observe the various types of livestock consuming the water source), *urban and surface runoff* (e.g. investigate local reports on the potential health-related water quality of urban and surface run-off) and *land development* (note the rate at which the land next to the source water is developed and also the type of development).

Factors such as the potential resource water users should also be determined, such as recreational users (boating, swimming), agricultural users (water extraction for irrigation and water for animals) and domestic users (communities established along water banks).

2.2 SOURCE PROTECTION PROGRAMME

If the outcomes from a sanitary survey indicate that the resource water contributes to the majority of the water contamination, then it is advisable that a source protection programme should be compiled and implemented. Such a programme may include information and technology transformation (education) to resource water users and controlling of livestock next to water banks. A good quality of source water makes the delivery of a high quality drinking water immune from most potential failures in treatment processes and in the distribution systems.

2.3 FACILITIES

2.3.1 Equipment used at the facility

The survey should assess the potential for contamination of the supply through inventory of all significant installations, activities and other possible sources of contamination and of pollutants of concern and their avenues of movement.

2.3.2 Operation and maintenance of a water treatment facility

The survey should also include the operation and maintenance procedures at a treatment facility. Such a survey could identify the key problem areas in the procedures. Routine preventative measures should be in place at the treatment

facility as well as the distribution system. These routine measures could detect problem areas such as accumulation of algae in the filter chambers etc. Operators and maintenance personnel need to be trained in the operation and maintenance of a treatment facility and these personnel should also attend courses on new developments in the water treatment arena. The skills covered in these training sessions could include record-keeping, requirements for repair, proper control of treatment and maintenance of the distribution system.

3 OTHER FACTORS TO CONSIDER IN A MONITORING PROGRAMME

3.1 PROTOCOLS FOR FREQUENCY OF SAMPLING

The determining factor for the frequency of water quality examination for the hygienic control of water supplies as well as for the location of the sampling points should be that a proper control of the health-related quality of the water is enabled. Sampling points should be chosen to be representative of the entire water treatment cycle and could include raw resource water, pumping stations, treatment facility (including system components such as coagulation-flocculation, sedimentation, filtration and chlorination), reservoirs and distribution systems. Frequency will depend on the quality of the sources, the treatment of water, the risk of contamination, the history of water supply and the size of population served. When water requires chlorination before entering the distribution systems, a constant daily check on both the bacterial quality and chlorine residuals should be performed. It would be advisable that treatment facilities should be capable of performing water quality analysis on a daily basis to sustain the level of efficiency. According to USEPA (1999), resource water should be monitored according to the following:

Table D3: Recommended samples taken from source water for water treatment

Population served	Samples per week*
< 500	1
501 to 3,300	2
3,301 to 10,000	3
10,001 to 25,000	4
> 25,000	5

*** Must be taken on separate days**

3.2 METHODOLOGY OF ANALYSIS

According to the Assessment Guide for Quality of Water Supplies (WRC, 1998), substances such as electrical conductivity, pH, turbidity, faecal coliforms and free available chlorine should be frequently tested at all the selected sampling points. Other substances indicated in Table D4 could be assessed if resources are available.

Table D4: Proposed substances for the evaluation of performance efficiency

Substance	Resource	Treatment facility	Point of use
MICROBIOLOGICAL			
Faecal coliforms	■	■	■
Total coliforms	■	■	■
PHYSICAL			
Turbidity	■	■	■
CHEMICAL			
Electrical conductivity	■	■	■
pH	■	■	■
Free available chlorine		■	■
Nitrate	■	■	■
Fluoride	■	■	■
Sulphate	■	■	■
Chloride	■	■	■
Cadmium	■	■	■
Copper	■	■	■
Manganese	■	■	■
Zinc	■	■	■
Iron	■	■	■
Potassium	■	■	■
Sodium	■	■	■
Total hardness	■	■	■

■ Critical, should always be included in assessment

■ Important, should be included in assessment

■ Useful, often provides more information about the quality of water

It is important to use a reliable laboratory to analyse the samples. Water treatment facilities with on-site analytical laboratories should ensure that the laboratory personnel are well-trained in the analysis of water quality parameters. It is advisable that these laboratories participate in the health-related water quality proficiency scheme which is nationally available. These proficiency schemes would

give an indication of the capacity and skills of these laboratories to ensure a high standard and accuracy of analysis. Management of water treatment facilities should standardise on methods or techniques to be used when analysing water samples. Health-related microbiological, chemical and physical parameters should be assessed. These methods should be evaluated and the most suitable method should be used. While evaluating these methods, factors such as cost-effectiveness, capacity and skills of laboratory personnel, equipment and time should also be considered. Specialised methods such as the detection of *E. coli* and pathogens require additional training of laboratory personnel and might not be cost-effective.

It is custom for most water quality laboratories at treatment facilities to follow the basic total and faecal coliform protocol, because it is inexpensive, simple and quick to carry out, but it would be an advantage for effective management if other microbiological indicators such as *E. coli* (specific indicator of faecal pollution), faecal streptococci (more persistent in water than *E. coli* and might be a better mirror of the presence of certain pathogens which also die off slowly, such as viruses) and *Clostridium perfringens* (spore-former and highly persistent). Indicators of general water quality such as heterotrophic plate count could be a useful indicator for operational performance. This test reflects the number of bacteria in a water supply that are able to grow and produce viable colonies on the growth medium used for the test under specific conditions (e.g. incubation time and temperature). Not all bacteria in water will grow under these test conditions (National Health and Medical Research Council, 1996). The assessment of bacteriophages could also be included to indicate the possible survival of viral pathogens. These tests would unfortunately not be done at a laboratory, and equipment would be basic, and personnel would have only basic training. Samples might need to be sent to a laboratory which specialises in testing of bacteriophages.

3.3 ESTABLISH BASELINE DATA TO INDICATE BOTH SHORT AND LONG TERM TRENDS

It could be to the advantage of a treatment facility if all of the above-mentioned substances could be tested for. This could form a baseline data set for short and long term planning and management of treatment facilities. It could also act as a baseline for performance effectiveness over time to determine the need for further

improvements of the treatment barriers. It would however not be economically feasible to test these for parameters on an ongoing basis. It is not clear what such a baseline data set should cover and what the sampling size should be. Monitoring programmes and resources should be directed to those parameters which require frequent monitoring. It would be advisable that further studies should be done on the size of a baseline data set. A recommendation is that all the parameters be tested for and the parameters which exceed the national water quality guidelines should be tested for more frequently.

3.4 RECORDS

Records on monitoring procedures should be kept at all times. The evaluation of such records would be included in a full HACCP plan. These records may indicate the regular programme of sampling and analysis, the performance of treatment processes and the quality of drinking water delivered to consumers. If such records are not kept up to date, monitoring might not be sufficient and episodes of serious health-related contamination might go undetected.

APPENDIX E

HAZARD ANALYSES DATA

1 RUSTFONTEIN TREATMENT FACILITY

Total coliforms per 100 ml					
#	Log Raw intake	Log Sedimentation		Log Post Filtr	Log Post Chlor
		Log Prim Sed	Log Sec Sed		
1	3.66	2.92	2.90	3.25	0.37
2	3.74	2.20	2.14	3.24	-1.00
3	2.67	2.18	2.82	3.85	-1.00
4	1.97	0.73	0.43	-1.00	-1.00
5	1.72	1.35	0.56	-0.48	-1.00
6	2.21	1.46	0.73	0.56	-0.48
7	2.24	1.57	1.41	0.92	-1.00
8	1.60	1.34	1.24	1.26	-0.48
9	2.15	1.73	0.82	1.14	-1.00
10	2.26	1.55	0.52	0.97	-1.00
11	2.25	1.50	1.16	0.85	0.67
12	2.59	2.32	1.57	1.64	-1.00
13	2.29	1.63	1.21	0.80	-1.00
n	13	26		13	13
Mean	2.41	1.54		1.31	-0.69
Median	2.25	1.39		0.97	-1.00
Min	1.60	0.73		-1.00	-1.00
Max	3.74	2.92		3.85	0.67
90%	3.68	2.79		3.45	0.48

Faecal coliforms per 100 ml					
#	Log Raw intake	Log Sedimentation		Log Post Filtr	Log Post Chlor
		Log Prim Sed	Log Sec Sed		
1	0.52	0.00	0.22	-0.18	-1.00
2	-1.00	1.26	0.22	-0.18	-1.00
3	-1.00	-1.00	-1.00	-1.00	-1.00
4	-1.00	-1.00	-1.00	-1.00	-1.00
5	0.82	0.12	-0.48	-1.00	-1.00
6	0.88	0.43	0.70	0.37	-1.00
7	0.82	0.22	0.22	0.12	-1.00
8	1.22	0.73	0.00	-1.00	-1.00
9	1.48	0.00	-0.48	0.00	-1.00
10	0.82	0.43	0.00	0.00	-1.00
11	-1.00	0.43	-1.00	-0.48	-1.00
12	-1.00	0.90	0.70	0.67	-1.00
13	1.30	0.60	0.43	-1.00	-1.00
n	13	26		13	13
Mean	0.22	0.06		-0.36	-1.00
Median	0.82	0.21		-0.18	-1.00
Min	-1.00	0.73		-1.00	-1.00
Max	1.48	2.92		0.67	-1.00
90%	1.67	0.70		0.48	-1

Turbidity in NTU's					
#	Log Raw intake	Log Sedimentation		Log Post Filtr	Log Post Chlor
		Log Prim Sed	Log Sec Sed		
1	1.65	0.73	0.67	-0.52	-0.36
2	1.27	0.68	-0.18	-0.87	-0.91
3	1.86	1.44	0.53	-0.60	-0.13
4	1.76	1.55	0.23	-0.24	-0.48
5	1.82	1.61	0.75	-0.39	-0.26
6	1.77	1.47	0.41	-0.31	-0.21
7	1.67	1.62	0.52	-0.38	-0.34
8	1.64	1.51	1.15	-0.46	-0.21
9	1.67	1.50	0.20	-0.38	-0.44
10	1.65	1.37	0.41	-0.34	-0.44
n	10	20		10	10
Mean	1.67	0.91		-0.45	-0.38
Median	1.67	0.95		-0.24	-0.35
Min	1.27	-0.18		-0.87	-0.91
Max	1.86	1.62		-0.24	-0.13
90%	1.84	1.58		-0.28	-0.17

2 MAZELSPOORT TREATMENT FACILITY

Total coliforms per 100 ml					
#	Log Raw intake	Log Sedimentation		Log Post Filtr	Log Post Chlor
		Log Prim Sed	Log Sec Sed		
1	3.66	3.03	0.73	1.26	-0.18
2	3.61	2.33	1.84	1.75	-0.48
3	2.92	2.80	2.87	1.32	-1.00
4	3.10	1.47	1.03	1.18	-1.00
5	1.78	0.48	0.12	-0.18	-1.00
6	3.37	1.49	0.22	0.00	-1.00
7	3.77	0.95	1.98	0.78	-1.00
8	3.91	1.94	2.36	2.19	-0.18
9	2.59	1.53	0.52	1.03	-1.00
10	3.28	1.51	0.52	1.17	0.67
11	3.15	1.92	0.87	1.57	-1.00
12	3.64	2.02	-0.48	0.90	-1.00
13	3.21	2.00	0.56	-1.00	-1.00
14	3.62	1.54	-0.18	-0.18	-1.00
15	3.03	0.64	-1.00	1.80	1.82
16	3.83	1.94	1.62	1.61	-1.00
17	3.63	1.40	1.49	1.81	-1.00
n	17	34		17	17
Mean	3.30	1.30		1.00	-0.61
Median	3.37	1.13		1.18	-1.00
Min	1.78	-1.00		-1.00	-1.00
Max	3.91	3.03		2.19	1.82
90%	3.83	2.43		1.81	0.60

Faecal coliforms per 100 ml					
#	Log Raw intake	Log Sedimentation		Log Post Filtr	Log Post Chlor
		Log Prim Sed	Log Sec Sed		
1	1.75	-1.00	-1.00	-0.18	-1.00
2	1.56	-1.00	1.09	0.73	-1.00
3	0.52	0.22	-0.18	0.00	-1.00
4	-1.00	0.48	-0.48	-0.48	-1.00
5	0.82	-1.00	-1.00	-1.00	-1.00
6	1.00	-0.48	-1.00	-1.00	-1.00
7	3.15	-1.00	-1.00	-1.00	-1.00
8	0.82	1.73	-1.00	-1.00	-1.00
9	1.78	1.43	1.84	1.56	-1.00
10	1.94	0.97	-1.00	-1.00	-1.00
11	1.67	0.00	-1.00	-0.48	-1.00
12	1.22	0.56	-1.00	-1.00	-1.00
13	2.12	0.56	-1.00	-0.48	-1.00
14	2.22	0.60	-1.00	-1.00	-1.00
15	2.05	0.30	-1.00	-0.18	-1.00
16	1.48	-1.00	-1.00	-0.48	-1.00
17	1.92	0.94	-1.00	0.52	-1.00
18	1.52	-0.18	-0.48	0.80	-1.00
n	18	54		18	18
Mean	1.48	-0.25		-0.31	-1.00
Median	1.62	-0.45		0.10	-1.00
Min	-1.00	-1.00		-1.00	-1.00
Max	3.15	1.84		1.56	-1.00
90%	2.20	1.00		0.78	-1.00

Turbidity in NTU's					
#	Log Raw intake	Log Sedimentation		Log Post Filtr	Log Post Chlor
		Log Prim Sed	Log Sec Sed		
1	1.14	0.34	0.40	-1.07	-0.72
2	0.94	1.03	0.90	0.84	0.94
3	1.37	0.05	0.08	-0.01	0.06
4	1.27	0.80	0.60	0.38	0.41
5	1.29	0.70	0.58	0.24	0.50
6	1.77	0.24	0.15	0.12	0.17
7	2.21	1.50	0.94	1.01	0.94
8	2.20	1.01	0.17	-0.02	-0.09
9	2.05	0.97	1.31	1.36	0.77
10	1.98	0.49	0.48	0.63	0.48
11	1.98	0.39	0.58	0.42	0.81
12	1.95	0.51	0.12	0.48	1.06
13	1.85	1.19	0.60	0.51	0.50
14	1.84	0.82	0.32	0.56	0.44
15	1.83	0.16	0.11	0.09	0.26
16	1.82	0.49	0.45	0.45	0.45
17	1.66	0.39	0.10	0.09	0.11
n	17	34		17	17
Mean	1.72	0.56		0.36	0.42
Median	1.83	0.48		0.42	0.45
Min	0.94	0.08		-1.07	-0.72
Max	2.21	1.50		1.36	1.06
90%	2.17	1.05		0.98	0.94

APPLICATION OF HACCP PRINCIPLES AS A MANAGEMENT TOOL FOR MONITORING AND CONTROLLING MICROBIOLOGICAL HAZARDS IN WATER TREATMENT FACILITIES

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ABSTRACT

HACCP (hazard analysis and critical control points) principles were applied to evaluate the effectiveness of two water treatment facilities to continually produce potable water free of microbiological health hazards. This paper reports a hazard analyses protocol (microbiological hazards based on faecal coliforms (FC) and turbidity (TBY) as indicators) for critical control points (CCP's) within each facility. The CCP's were raw resource water, sedimentation, filtration, and chlorine-disinfection. The aim was to determine the effectiveness of each CCP to remove the indicators from the water under treatment. Arbitrary critical performance limit targets (CPLT's) were set up for each CCP to determine to what extent each CCP contributed to effective removal and to predict what the effect would be if any of the CCP's should fail. Health-related water quality guideline limits for expected health effects were applied and compliance measured at the 90th percentile. The raw resource river water used at both treatment facilities complied with raw resource water extraction CPLT's. The treated potable water complied with health-related drinking water guidelines. Sedimentation removed the largest proportion of the indicators from the raw water, but showed failure potential that could overload the consequent system. Filtration effectiveness at both treatment facilities showed potential to breakdown the overall effectiveness of the entire treatment facility since the filter systems failed to meet their respective CPLT's. This left the disinfection phase to remove the remaining portion of indicators. Faecal coliforms appeared completely removed from post-chlorination samples, indicating that both chlorine disinfection phases were 100% effective in meeting their disinfection CPLT's despite having to "clean up" the indicator organisms that spilt over from the upstream CCP's. This nevertheless implied a risk of unsafe water release into distribution. CCP's at these treatment facilities have some difficulties in reducing the health-related risks to meet their respective CPLT. Applying a HACCP programme would minimise the risk of contaminated water distribution in cases of system component failure.

INTRODUCTION

Despite advances in water treatment-technology development, water-related disease outbreaks still occur even in areas where treated water is supplied. In the United Kingdom for instance, 25 known outbreaks of cryptosporidiosis were associated with consumption of drinking water from public supplies in the UK since 1988 (Bouchier, 1998). In developing countries such as South Africa, communicable water-related diseases, especially diarrhoea, are of the most widespread health problems related to consumption of contaminated water at the point of use. The transmission and prevention of such infections largely depend on the microbiological water quality (Genthe and Seager, 1996). Recent outbreaks of Salmonella infections in South Africa were associated with contaminated drinking water supplies (Potgieter, 2002).

Water treatment facilities in general, and end-of-process chlorination in particular, are heavily relied on to remove health-related microorganisms from water during treatment (World Health Organisation (WHO), 1996). Much of water treatment management rely on operational experience of people, and on the inherent design effectiveness of the treatment process to produce safe water without knowing what would happen if any of the processes within a particular system failed. It is quite customary at water-treatment facilities to, for instance, monitor only the intake water and endproduct (treated tap water) – practices that could lead to improperly treated or contaminated water being distributed through the piped supply. Even if monitoring of the microbiological quality of the treated water is done regularly, and it provides evidence of contamination, the information is often received too late for corrective action prior to significant volumes being consumed. This indicates a need for preventive measures and corrective actions early in the drinking water treatment process.

From a health-related microbiological perspective, HACCP can provide a quality control mechanism for the water treatment industry to produce continual safe product to consumers and can therefore add real value to management during of drinking water treatment. A study from which this paper reports certain elements, investigated the feasibility to apply a HACCP programme at water treatment facilities to monitor whether safe water was continually being produced.

The concept of HACCP (Hazard Analysis and Critical Control Points) is relatively new in water quality management (Hellier, 2002) but has long been the primary risk management system for the food industry. The HACCP Guidelines "Codex Alimentarius" (WHO, 1996; Mortimore and Wallace, 2001) means food code, which details seven principles for implementing HACCP. The intention of using a HACCP system in water treatment (rather than on the whole system of supply and distribution) would be to focus on managing hazards early in the process rather than relying mainly on end-point treatment such as chlorination for health-related water quality control. By applying HACCP, managers at potable water treatment facilities manage treatment processes based on Hazard Analyses data measured at points in the treatment system, referred to as Critical Control Points (Dewettinck et al., 2001). The HACCP process can however, be quite elaborate or out of context for application in water treatment management because of the diverse range of water-borne hazards, (particularly from multi-use catchments), the continuous nature of supply between raw water sources and consumption of treated tap water and the large, complex distribution networks that receive the treated product (Hellier, 2002).

In this context, the aim of this paper is to present, from the study, a simplified HACCP programme that was applied at two potable water treatment facilities in the Modder River catchment (Free State Province, South Africa) to evaluate the system effectiveness to continually produce microbiologically-safe drinking water. Four of the seven HACCP principles were applied namely to identify microbiological hazards (hazard analyses); parameterise critical control points (CCP's); establish critical performance criteria for each CCP and to monitor the selected CCP's systematically with the most effective assessment method available.

CCP's are points, processes, or procedures (Mortimore and Wallace, 2001) in a water treatment facility at which control can be applied and as a result, waterborne pathogens can be eliminated or their numbers reduced to acceptable levels. The primary study objective was to select CCP's at the two facilities and then to investigate whether these CCP's were sufficient as barriers to remove reduce the numbers of health-related microorganisms that entered the system in the raw resource water, to acceptable levels in the final product (safe potable water delivered to the distribution networks). This paper reports on the effectiveness.

Hazard analyses for this study were based on health-related microbiological water quality using faecal coliforms and turbidity as indicators. To measure whether a CCP was effective in removing hazards, benchmarks were needed (WHO, 1997). The second objective for this study was to compile a set of critical performance level targets (CPLT's) for each CCP to remove a target percentage of faecal coliforms (FC). These are reported on in this paper.

While microbiological assessment might play a critical hazard analyses role in applying HACCP, microbiological testing (such as with FC) in the application of HACCP is generally not considered an effective means of monitoring CCP's because of the lengthy time required to obtain results (United Stated Department of Agriculture (USDA), 1997). This implies that more rapid testing that would enable water quality managers to react quicker. Rapid measurement at CCP's can at best be accomplished by using more a rapid physical water quality tests such as turbidity (Mortimore and Wallace, 2001; Water Research Commission (WRC), 2001). Relationships between the occurrence of microorganisms and other quality criteria such as turbidity in water are acknowledged but not yet clearly understood (Chapra, 1997; Tchobanoglous and Schroeder, 1987). This study provided the opportunity (the third objective) to investigate "quick testing" for the potential occurrence of faecal coliforms by using turbidity as a gross parameter indicator in a CCP monitoring system. This paper discusses the outcome.

METHODOLOGY

Study sites: The two potable water treatment facilities (TFA and TFB) selected for this study are both in the Middle Modder River catchment area, Free State Province, South Africa. Resource water treated at TFB is withdrawn from an impoundment which health-related water quality was described as unpolluted river water (Jagals, 2000). The resource water extracted for treatment at TBA was described by Jagals (2000) as polluted river water because of discharges from upstream urban areas and poorly managed wastewater treatment facilities from surrounding cities and townships (Jagals et al., 1995; Jagals, 1997).

HACCP principles applied

Hazard analyses assessed the reduction of faecal coliform numbers (organisms per 100 mℓ) and turbidity levels (expressed in nephelometric turbidity units - NTU's) as measures of treatment effectiveness. The guideline values applied for drinking water quality were those in the South African Water Quality Guidelines (Department of Water Affairs and Forestry (DWAF), 1996), which meant that the collective effectiveness of the processes within each treatment facility had to remove whatever indicator levels the raw intake water might have contained, to less than 1 FC / 100 mℓ and 1 NTU. Compliance was measured at the 90th percentile. Faecal coliforms were cultured on MFc Agar (Biolab®) using membrane filtration (Standard Methods, 1998). Blue colonies were counted as faecal coliforms and expressed as organisms per 100 mℓ. A HACH 2100 turbidity meter was used to measure turbidity levels in the same water samples used for microbiological analyses and the measurements recorded as NTU's.

Critical Control Points (CCP's) were raw river water, sedimentation, filtration, and chlorination. While each treatment component selected as a CCP performs critical functions within the system configuration, the raw river water CCP was not essentially a CCP in the context of treatment system control. While the raw product is not often included as a CCP in the food industry, including raw river water as a CCP for this study was done for a specific purpose. While treatment facility managers often have very little control over the quality of raw water they have to treat, they can play an important role in management of the upstream catchment. It is a generally accepted principle that the less contaminants the raw water have, the better the treatment system will cope with the contaminant load and less the risk of

contaminant release into the distribution network in the case of accidental or other types of system failure (DWAF, 2002; Chapra, 1997). Since it is at the treatment facility where the quality of the surface water in the resource is most often measured, including the raw water as a CCP not only provided a redflag to prepare the receiving system, it also provided information on the efficiency of the management system operating in the catchment.

Critical performance limit targets (CPLT's) for hazard removal (FC and Turbidity) were not readily obtainable in a single comprehensive guideline. Table 1 shows arbitrary CPLT's collated from national and international guidelines. While national health-related water quality guidelines were used for raw water extraction for drinking water treatment as well as treated water, literature does not provide clear turbidity removal guidelines for an acceptable raw water quality. Percentage removal criteria were compiled for sedimentation, filtration and chlorination. Results were compared to these criteria to measure the performance of each CCP.

Table 1: Arbitrary critical performance limit targets for treatment processes applied in this study

Indicator	Raw water extraction	Sedimentation	Filtration	Chlorination / Treated water	
Faecal coliforms	2,000 / 100 mℓ (DWAF, 2002)	90% (WHO, 2000)	98 – 99 % (WHO, 1996)	99.99 % (WHO, 2000)	0 / 100 mℓ (DWAF, 1996)
Turbidity	None	85% (USEPA, 1999)	< 1 NTU (WHO, 2000)	< 1 NTU (WHO, 2000)	1 NTU (DWAF, 1996)

Monitoring the CCP's meant measuring or observing whether each CCP operated within its CPLT's and what cumulative effect is would have should any one or more CCP fail to meet its CPLT. Compliance was measured at the 90th percentile (upper whiskers of the boxes in the figures to follow). Associations between the occurrence of FC's and turbidity were also measured to see whether the latter could be used in lieu of the more cumbersome FC testing methodology.

RESULTS AND DISCUSSION

Faecal coliform removal measured at CCP's

Figure 1 shows that the health-related microbiological water quality (HRMWQ) of the raw water extracted from the Modder River by both facilities was well within the guideline values of 2,000 FC per 100 mℓ (from Table 1). This implied that although the raw water showed signs of faecal pollution, conventional treatment should effectively remove the microbiological contaminants if the system was properly designed, maintained, and operated.

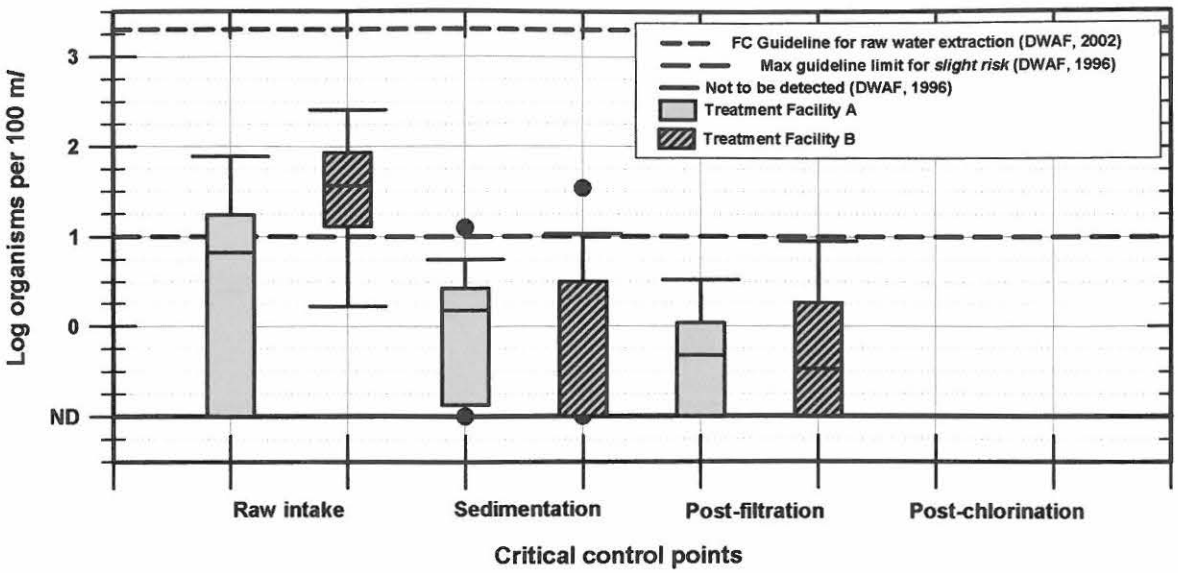
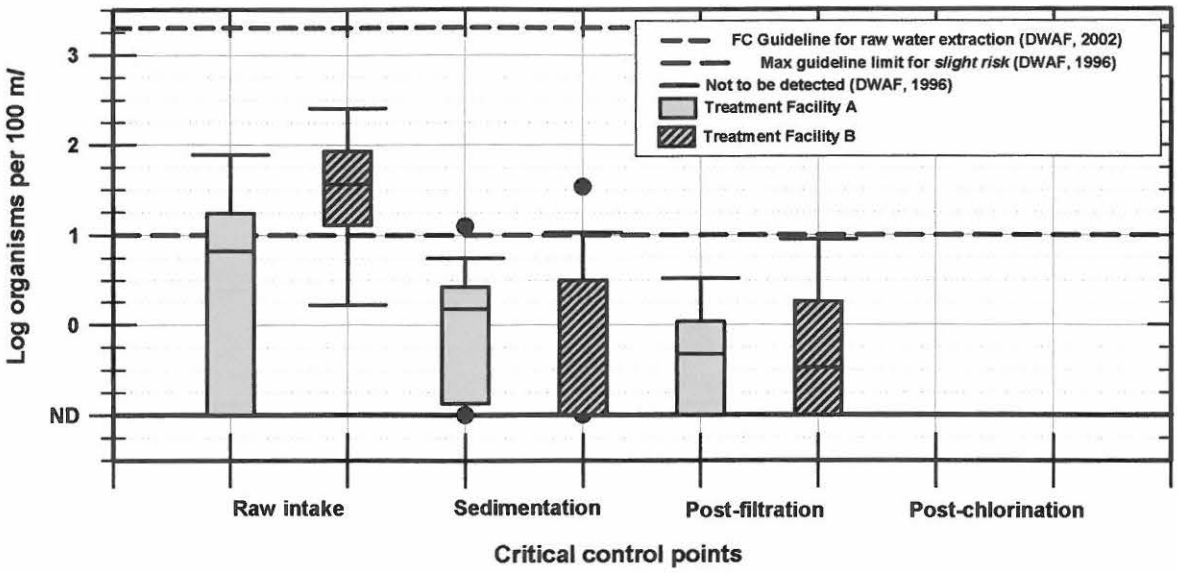


Figure 1: Faecal coliforms measured at critical control points in two water treatment facilities

The FC numbers detected after sedimentation at both treatment facilities were above the maximum water quality guideline level for slight risk of microbial infection with continuous exposure (DWAF, 1996), whilst the FC numbers after filtration were below this guideline limit. No faecal coliforms were detected in the samples collected at the post-chlorination point. This indicated that the chlorination processes played a major role in effectively rendering these indicator organisms inculturable, that is not active or assumed killed off.

Turbidity removal at the CCP's

Figure 2 illustrates the turbidity levels measured at each CCP at the water treatment facilities. Turbidity levels of 69 and 149.4 NTU were measured at the two raw water extraction points. The levels of turbidity in the raw water as well as water overflowing from the sedimentation processes at both treatment facilities were above the visible turbidity and health risk guideline of 5 NTU of the South African Water Quality Guidelines (DWAF, 1996). The turbidity levels of the post-filtration water and the post chlorination water at TFA were below the maximum water quality guideline limit of slight health risk (DWAF, 1996), but the turbidity levels measured in the water from post-filtration and post chlorination from TFB were above the visible turbidity and health risk guideline (DWAF, 1996).



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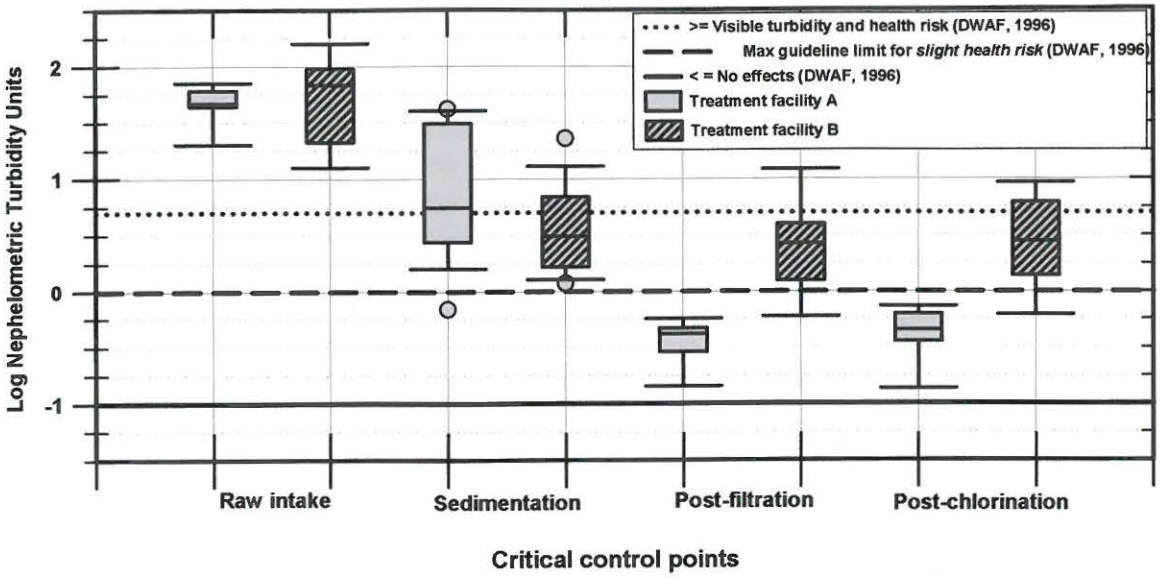

Figure 2: Turbidity levels measured at critical control points in two water treatment facilities

Turbidity levels in the treated water from TFB were significantly higher ($P \leq 0.001$) than those in TFA treated water with the turbidity in approximately 23% of the treated water samples from TFB exceeding the maximum water quality guideline limit of 5 NTU (DWAF, 1996). This implies that the final waters may often have visible turbidity that will be objectionable to users, while some chance existed of disease transmission by micro-organisms associated with particulate matter, particularly for agents with a low infective dose such as viruses and protozoan parasites. None of the waters collected from the various components in the treatment facilities complied to the no effects guidelines of <1 NTU (DWAF, 1996).

Percentage removal of the health-related microbiological indicators and turbidity at TFA

For this study, the performance measurement approach was designed on the work of Poda et al. (1994) and comprised two stages i.e. 1) the overall target removal CPLT's and 2) CPLT's for cumulative removal per stage. Table 2 shows the targets as well as the performance of each CCP. Negative values indicate that the CCP underachieved thereby assumed not functioning effectively.

Table 2: Critical control point removal rates for faecal coliforms at two water treatment facilities

Guideline value: No organisms detectable per 100 mℓ	**Organisms per 100 mℓ**		**% Removal per stage**		**% Cumulative removal**		**% CPLT**		**Compliance % of target**	
Facility	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Raw intake water	47	157								
Sedimentation	5	10	89.36	93.63	89.36	93.63	90.00	90.00	-0.64	3.63
Post filtration	3	6	40.00	40.00	93.62	96.18	99.00	99.00	-5.38	-2.82
Post chlorination	None detected	None detected	100	100	100	100	100*	100*	100	100

**Overall removal targets per facility are based on reduction from raw intake levels to guideline level (0 FC/100 mℓ)

Of the sedimentation processes Facility A was not as effective as B but not significantly so. Both facilities the filtration processes underachieved, causing a larger FC load on the chlorine disinfection processes. The disinfection processes nevertheless effectively achieved 100% reduction the FC numbers despite the under-achievements of the prior system components. However, was chlorination to fail with the underachievement of sedimentation and filtration, TFA would, based on the results of this study, release an estimated approximately 6% of the FC measured in the raw water (3 FC / 100-mℓ) into the distribution system. For TFB, this would amount to 1 FC/100 mℓ. These numbers were within the 0 – 10 FC 100-mℓ category of the South African Water Quality Guidelines (DWAF, 1996) which indicated a slight risk of microbial infection with continuous exposure.

Table 3 shows that the effectiveness of the two facilities to reduce the level of turbidity. The sedimentation process at A was not effective to reduce turbidity to the required CPTL, leaving the filtration process to handle a much larger percentage removal than required by its CPLT. The sedimentation process for B overachieved.

Table 3: Critical control point removal rates for turbidity at two water treatment facilities

Guideline value 0.1 NTU	Turbidity levels		% Removal per stage		% Cumulative removal		% CPLT		Compliance % of target	
Facility	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Raw intake water	69	149								
Sedimentation	38	11	44.93	92.57	44.93	92.57	85.00	85.00	-40.07	7.57
Post filtration	0.53	9.64	98.61	13.19	99.23	93.55	99.86*	99.93*	-0.62	-6.38
Post chlorination	0.68	8.73	-28.30	9.38	99.01	94.16	100% CPTL	100% CPTL	-0.84	-5.78

*Overall removal targets per facility are based on reduction from raw intake levels to guideline level (0.1 NTU)

The situation was reversed at the filtration processes of the two facilities, where the process for A largely corrected the underachievement of its sedimentation process, but the process for B completely nullified the achievement of its effective sedimentation process.

Chlorine-disinfection is not a process that should contribute to reducing turbidity. In fact, CPTL's for turbidity reduction should be achieved before the process water reaches the disinfection stage. This is to ensure minimum interference with the chlorination process (WHO, 1993). This means that the complete CPTL achievement for the removal of turbidity should be reached at filtration. In the case of facility A, if the filtration processes should fail (consider the 40 % underachievement of sedimentation) water would be released to the chlorination stage containing 19NTU, which implied suspended materials that was likely to interfere with disinfection. Ironically for B, if the filtration process should fail, the chlorination process would have less turbidity to contend with. From Table 2 it was evident that the chlorination processes could effectively disinfect the water, despite the turbidity carry over. From a risk point of view, the question is what could be expected should chlorination failed during such carry-overs. From the results it is reasonable to expect water with high turbidity levels exceeding the critical 10 NTU level (DWAF, 1996), indicating that the water may cause severe aesthetic effects and chances of disease transmission at epidemic levels.

Turbidity measurement in lieu of microbiological measurement

There were no significant relationships between FC numbers and turbidity ($P > 0.050$) in any of the water samples taken from the CCP's at both treatment facilities. FC numbers and turbidity levels were measured in the same water samples, but showed weak correlations, which indicated that these indicators do not always co-vary. This was peculiar, since strong relationships between the reduction of turbidity and bacteria are reported in other studies.

According to the USEPA (1999), low filtered water turbidity can be correlated with low bacterial counts and low incidences of viral disease. Positive correlations between removal of pathogens and turbidity have also been observed in several studies. In fact, in every study to date where pathogens and turbidity occur in the source water, pathogen removal coincides with turbidity/particle removal (Fox, 1995).

These weak associations found for this study could be due to insufficient sample sizes. A larger data base, with additional features such as seasonal variance, might strengthen the correlation figures. Nevertheless, the assumption for this study was that turbidity could not be used as a solitary indicator of process effectiveness in lieu of FC measurement.

CONCLUSION

The health-related water quality results obtained in this study indicated that both the treatment facilities were effective in treating the raw resource water to an acceptable quality potable water to be distributed to the potential consumers. Some CCP's at these treatment facilities showed inefficiency in reducing the hazards to meet their respective CPLT's. The study did show that the two facilities relied heavily on the chlorination-disinfection processes as a final barrier for faecal coliforms and turbidity release into their respective distribution systems. A certain risk of quality parameter non-compliance (faecal coliforms and turbidity) was demonstrated should the chlorination process fail. The results of this study imply that facility managers need to include faecal coliform assessment in combination with turbidity testing at the various CCP's in a daily monitoring programme. Whilst this implies short-term cost increases, removal correlation could be achieved if management could result in sustained achievement of CPLT's at CCP's. This could mean that management might eventually resort back to rely solely on regular turbidity monitoring at each CCP, which could be more effective as a quick-monitoring tool to detect problems before the water reached the disinfection stage.

Monitoring for health-related hazards at only two points (raw water and treated water) at the two study facilities may not be sufficient to maintain effective barriers against system supply contamination since the risk of system failure is masked by the good results obtained of the final water. It is suggested that water supply managers and facility operators resort to the elaboration towards, and application of a comprehensive HACCP plan with the inclusion of various assessments and also their critical performance limits in monitoring programmes.

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