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Application of the HACCP Concept for the Microbiological Monitoring of Drinking Water Quality: A Case Study of Three Water Treatment Plants in the Gauteng Province, South Africa

A. Okeyo, M.N.B. Momba and M. Coetzee

Department of Environmental, Water and Earth Sciences, Tshwane University of Technology, P/Bag X680, Pretoria, 0001, South Africa

Corresponding Author: M.N.B. Momba, Department of Environmental, Water and Earth Sciences, Tshwane University of Technology, P/Bag X680, Pretoria, 0001, South Africa Tel: +27 (0) 12 382 6365 Fax: +27 (0) 12 382 6233

ABSTRACT

The Hazard Analysis and Critical Control Points (HACCP) concept was used in the present study to identify any potential process failures in the Temba, Klipdrift and Wallmansthal water treatment plants. Water samples were collected at various critical points: raw water, after sedimentation, after filtration, after chlorination and at the Point of Use (POU). Turbidity, pH, temperature, chlorine residual and indicator bacteria (total and faecal coliforms) were measured using standard methods. On average, results revealed that pH and temperature conformed to the limits allowed by the National Standards. The average percentage removal of turbidity was from 41.1 to 80.5% after sedimentation and from 75.1 to 97.8% after filtration. At the Point of Treatment (POT) and POU, the turbidity ranged from 0.3 to 1.1 NTU and from 0.4 to 1.4 NTU, respectively. The concentration of chlorine residual in these two critical points ranged from 1.9 to 2.3 mg L⁻¹ and from 0.3 to 0.6 mg L⁻¹, respectively. The average percentage removal for indicator bacteria ranged from 35.8 to 86.1% after sedimentation, from 74.2 to 97.3% after filtration and from 99.6 to 100% after chlorination. The failure of the pre-treatment stages and the chlorination process to remove potential pathogenic bacteria such as *Aeromonas* and *Pseudomonas* sp. resulted in the presence of these microorganisms at the POU. Efforts should be focused on the pre-disinfection stages to deliver a low microbial load that chlorine may be able to handle.

Key words: Water treatment, water quality, critical hazard analysis

INTRODUCTION

Improving access to safe drinking water has been the thrust of most governments, United Nations agencies and other organizations dating back to the 1980s (Makoni *et al.*, 2004). In South Africa, the supply of quality water to consumers is presently the top priority of the government. This is mainly because of the role of water in the transmission of water related diseases, which are a major health burden (Momba *et al.*, 2008).

The task of any water treatment plant is to safeguard the quality of the drinking water it produces. It is mandatory that the water supplied to consumers should satisfy the national standards for potable water (Kasrils, 2004). In principle, drinking water treatment is related to the quality of the raw water to be treated and the desired product standards.

South African metropolitan areas are known for their well-developed water infrastructure. Water treatment plants in these areas are designed with the capacity and efficiency to carry out a comprehensive water quality control, involving periodic testing of samples in combination with various online measurements (Damikouka *et al.*, 2007). This is however not the norm in many small cities, towns and villages, better known as non-metropolitan areas; in most instances there are high incidences of poor drinking water quality provision (Momba *et al.*, 2003). Some Water Service Authorities in non-metropolitan areas fail to comply with the national standards, which are a regulatory governance methodology for ensuring water quality (Hodgson and Manus, 2006).

Challenges faced by water treatment plants in non-metropolitan areas are a result of the lack of knowledge of basic treatment principles by the plant operators, inadequate maintenance of equipment used in the plants, financial constraints and lack of community awareness or involvement (Swartz, 2000; Momba and Brouckaert, 2005). Thus, in these water treatment plants, monitoring is inadequate; i.e., basic physicochemical parameters such as turbidity and chlorine residual are monitored with occasional end product bacterial analysis facilitated by the local municipalities of these areas (Zamxaka *et al.*, 2004; Momba and Brouckaert, 2005; Momba *et al.*, 2006). In instances where there is deterioration in water quality, it is often hard to identify which process in the water treatment system is not working up to standard.

The drinking water sector worldwide is increasingly becoming aware of the limitations of end product testing. The World Health Organization (WHO) Guidelines for drinking water quality (World Health Organization, 2004) has so far provided a developmental Water Safety Plan (WSP). The plan is developed using a water safety framework that combines the Hazard Analysis and Critical Control Points (HACCP) principles with water quality management. This common framework deals with identifying the critical points throughout the entire water treatment system and then focusing resources on these critical locations and processes, minimising the occurrence and effects of incidents that degrade water quality and cause a public health threat (USEPA, 2006). Conventionally, water treatment consists of the following processes (barriers): screening, coagulation, flocculation, sedimentation, clarification and disinfection. Each treatment process or barrier system in a water treatment plant is referred to as a critical point. This is a point where potential process failures can cause microbiological hazard overloads and overall underperformance (Jagals and Jagals, 2004).

It is well known that no single treatment barrier can be expected to remove all the different types of pathogens that can be found in water under all conditions. It is also not always certain to what extent the break down of one barrier could influence the microbial quality of the final drinking water product (World Health Organization, 2004; De Traversay *et al.*, 2006). In cases where, the pre-disinfection stages in a plant deliver high microbial loads than what a particular chlorine delivery process is set to handle, there would be a definite under performance of the process of chlorination; thus, it is evident that optimization of each barrier is of essence (Jagals and Jagals, 2004).

The present study focused on the application of the HACCP concept in treating and monitoring drinking water supplied by the Temba, Klipdrift and Wallmansthal water treatment plants, located in the Gauteng Province, South Africa. Our intention was to identify any potential process failures that might result in the decline of the performance of these plants in the removal of coliform groups. Also considered were physical and chemical parameters such as pH, temperature, turbidity and chlorine residual. These plants were chosen because they supply drinking water to surrounding semi-urban areas, which according to the literature often face water related problems.

MATERIALS AND METHODS

Description of study area: The Gauteng province, also referred to as the place of gold, is the smallest (17000 km²), wealthiest and most densely populated (approximately 9.8 million people) province in South Africa. It is situated in the North-Eastern part of the country and is landlocked. The province is bordered by Limpopo in the North, Mpumalanga in the East, the Free State in the South and the North West in the West.

It mainly comprises of three urban areas, which are Pretoria, Johannesburg and the Southern Vereeniging-Vanderbijlpark industrial complex. The Gauteng Province consists of three Metropolitan Municipalities (Johannesburg, Tshwane and Ekurhuleni) and 3 District Municipalities which are further divided into eight Local Municipalities (Nokeng, Kungwini, Lesidi, Midvaal, Emfuleni, Westonarea, Randfontein and Mogale local Municipalities) (Municipal Demarcation Board, Gauteng Province, 2004/2005).

Plants managers were interviewed on the first day of the visit to each Water Treatment plant. This procedure was followed to obtain general information about the operation of the plants, indicating the source of raw water and various processes utilized during the treatment of water.

Description of the water treatment plants

Temba water treatment plant (WTP): The Temba water treatment plant is situated in the Temba Township near Hammanskraal, currently being managed Magalies water. The plant conventionally treats water that is supplied for residential, industrial and commercial purposes within the Temba, Hammanskraal and Moretele areas. The initial operating capacity of the plant was 30 mL day⁻¹, which has been increased as a result of growing demand to 60 ML day⁻¹ with 5 distinctive divisions. The expansion has alleviated the water shortage problem that used to occur within the Moretele 1 Water Supply scheme (Magalies Water, 2007).

Water treated by the Temba waterworks is obtained from the Leeukraal Dam situated on the Apies River. Raw water from the dam undergoes coagulation/flocculation (lime, Powdered Activated Carbon (PAC), ferric chloride and polyamide) before passing through one of five phase (phases 1 to 5) divisions in the plant. Briefly: Phase 1 and 2 (old section) pre-treated water undergoes sedimentation, rapid sand filtration (sand particle size ranging from 0.7 to 1 mm) and then the water is stored in a storage tank. Phase 3 and 4 pre-treated water undergoes sedimentation, passes through a direct flotation filtration unit (sand and gravel particle size ranging from 0.7 to 12 mm) and then the water is stored in a storage tank. Phase 5 (newest section) pre-treated water undergoes sedimentation, rapid sand filtration (sand particle size ranging from 0.6 to 1 mm) and then the water is stored in a storage tank. The pressure and the backwash systems for filtration are automated. All water that goes through the 5 phases are combined before disinfection, which is constituted of ultraviolet irradiation and gas chlorination.

Klipdrift water treatment plant (WTP): The Klipdrift water treatment plant is situated on Klipdrift farm, managed by Magalies Water. The plant was extended and upgraded by the Department of Water Affairs and Forestry in 2004. It has an operational capacity of 18 ML day⁻¹ (Magalies Water, 2007).

The plant obtains its raw water supply from the Roodeplaat canal and Pienaars River. Raw water obtained from the canal goes through mesh screens for the removal of algae. The water is then subjected to pre-chlorination, coagulation/flocculation (lime, polyelectrolite); counter current dissolved air flotation filtration (cocoDAFF) (sand particle size ranging from 0.6 to 7mm) and

disinfection (gas chlorination). The plant's pressure and backwash systems are manually operated. Treated water from the Temba and Klipdrift water treatment plants combines in a reservoir, from where it is distributed. The plant supplies water to the Ramotse and Marokolong communities as well as to the industrial area of Babelegi in Tshwane and the Carousel Hotel in the Moretele Local Municipality. It also supplies bulk water to the Local Municipalities of Bela-Bela and Modimolle in the Limpopo Province.

Wallmansthal water treatment plant (WTP): Wallmansthal water treatment plant is situated on the Buffelsdrift farm, managed also by Magalies Water. The plant has an operational capacity of 12 ML day⁻¹. It supplies water to the South African National Defence Force, Tshwane, the Department of Public Works, the Agricultural Research Council, Roodeplaat Laboratories, the Hydrological Research Institute and several other small consumers (Magalies Water, 2007).

The plant obtains its raw water from the Roodeplaat Dam and Pienaars River. These water sources go through drum screens for the removal of algae, pre-chlorination, coagulation/flocculation (lime, Powdered Activated Carbon (PAC), ferric chloride and polyamide), dissolved air flotation unit (DAF), tube settlers, rapid sand filtration (sand particle size ranging from 0.7-1.1 mm) and disinfection (gas chlorination). The pressure and the backwash systems for filtration are automated.

Application of the HACCP concept for water quality monitoring: The study was conducted over a period of 8 months from May 2007 to April 2008 (except for the months of July 2007 and November to January 2008). For each water treatment plant, water samples were collected from the critical points on a weekly basis. For the first two months, the critical points were as follows:

- **At the Point of Treatment (POT):** Raw water sources before coagulation/flocculation, after filtration and after chlorination
- **At the Point of Use (POU):** In the distribution system at a tap situated approximately 5 km away from the point of treatment

For the rest of the study period the critical points were: raw water sources before coagulation/flocculation, sedimentation and after filtration. The main goal of this sampling procedure was to establish whether any potential process failure could result in contaminant overloads during drinking water treatment. It was important to evaluate the effectiveness of the filtration system in each water treatment plant. Samples were collected and preserved according to standard procedure (APHA, 2001) and analysed within 4 h of collection.

Physicochemical analysis of water samples: Turbidity (EUTECH instruments-TN 100), pH, temperature (EUTECH instruments- cyberscan PC 300) and residual chlorine (LOVIBOND-photometer kit PC01) meters were used for on-site physicochemical analysis of the water samples.

Microbiological analysis of water samples: Water samples were analysed for total and faecal coliform bacteria, using the membrane filtration technique and chromocult coliform agar (Merk, South Africa). Internationally accepted techniques and principles were applied for the detection of these organisms (APHA, 2001). Water quality variables that were used to measure the environmental and human health impact of these water supply systems were the Standards for potable water (SANS, 2005) and the South African water quality guidelines (DWAF, 1996a).

Identification of coliform isolates: The identification of coliform isolates was done for the water samples collected during the first two months of the study. Bacterial colonies were selected randomly, differed in size, shape and colour. The colonies were purified 3 times on nutrient agar (Merk, South Africa) plates by streak plate technique and the plates were incubated at 37°C for 24 h. Oxidase test was then done on those isolates that were identified as Gram negative. API 20E kits were used for oxidase negative colonies; the strips were incubated at 37°C for 24 h. The strips were then read and final identification was done using API LAB PLUS computer software (BioMérieux).

RESULTS

Characteristics of water at various critical points between May and June 2007

Raw water source: The average physicochemical values for Temba, Klipdrift and Wallmansthal raw water were 22.4 NTU, 11.9 NTU and 18.3 NTU for turbidity; 15.4, 14 and 17.8°C for temperature and 8.6, 8.4 and 8.5 for pH, respectively (Table 1). The microbiological values were 4.39×10^5 cfu/100 mL, 4.21×10^5 cfu/100 mL and 5.62×10^5 cfu/100 mL for Total Coliform (TC) and 1.18×10^5 cfu/100 mL, 2.68×10^2 cfu/100 mL and 1.22×10^2 cfu/100 mL for Faecal Coliform (FC), respectively (Table 2).

Filtration: After filtration, the average turbidity values were 0.4 NTU, 1.1 NTU and 0.7 NTU (Table 1); this gave a percentage turbidity reduction of 97.8, 86.9 and 95.8%, respectively (Table 3). The average temperature values were 14.6, 13.2 and 16.1°C while pH values were 8.6, 8.5 and 8.2, respectively (Table 1). The average microbiological values were 1.11×10^5 cfu/100 mL, 8.02×10^2 cfu/100 mL and 1.15×10^5 cfu/100 mL for TC (Table 2) indicating percentage removals of

Table 1: General physicochemical quality from Water Treatment Plants (WTP) at various critical points between May and June 2007 (N = 8)

WTP Plant	Critical points	Parameters measured							
		Turbidity (NTU)		Temperature (°C)		pH		Chlorine residual (L ⁻¹)	
		Average	Max-Min	Average	Max-Min	Average	Max-Min	Average	Max-Min
Temba	Raw water source	22.4 (±7.2)	15.7 - 34.1	15.4 (±2.2)	13.2-18.5	8.6 (±0.4)	8.21-9.05	N/A	N/A
	Filtration	0.4 (±0.2)	0.1-0.73	14.6 (±1.1)	13.5-16.5	8.6 (±0.3)	8.2-9.09	N/A	N/A
	Chlorination	0.3 (±0.3)	0.12-0.41	14.7 (±0.8)	13.8-16.2	8.5 (±0.3)	8.15-8.94	2.1 (1.1)	0.8-4.1
	Distribution system								
	*(Combined treated water)								
Klipdrift	Raw water source	11.9 (±7.5)	9.3-21.5	14 (±1.6)	12.2-16.4	8.4 (±0.2)	8.17-8.97	N/A	N/A
	Filtration	1.1 (±0.5)	0.29-1.29	13.2 (±1.6)	11.2-15.1	8.5 (±0.1)	8.37-8.58	N/A	N/A
	Chlorination	1.1 (±0.2)	0.64-1.38	14 (±1.1)	12.4-14.9	8.3 (±0.1)	8.09-8.49	2.3 (±0.2)	2.15-2.56
	Distribution system	1.4 (±0.5)	0.75-2.06	19.6 (±1.4)	17.7 - 22	8.4 (±0.3)	8.14-8.86	0.3 (±0.2)	0.2-0.82
	*(Combined treated water)								
Wallmansthal	Raw water source	18.3 (±4.2)	13.4-26.2	17.8 (±1.1)	17-19.5	8.5 (±0.3)	8.13-9.05	N/A	N/A
	Filtration	0.7 (0.7)	0.2-1.69	16.1 (±1.7)	14.5-18.4	8.2 (±0.4)	7.89-8.88	N/A	N/A
	Chlorination	0.2 (±0.2)	0.03-0.45	16.6 (±2.0)	13.5-18.5	7.9 (±0.3)	7.7-8.63	1.9 (±1.9)	0.89-6
	Distribution system	0.4 (±0.2)	0.1-0.79	19.1 (±2.3)	14 - 20	8.1 (±0.4)	7.76-8.86	0.6 (±0.2)	0.29-0.76

Target limits at the point of distribution: Turbidity ≤ 1 NTU, pH-6-9, Temperature = 25°C, chlorine residual 0.5 mg L⁻¹ (DWAf, 1996a, b; SANS, 2005). N/A = Not applicable. No. in brackets are Standard deviation. *(Combined treated water): Treated water from Temba and Klipdrift combined; values are the same

Table 2: General microbial quality from Water Treatment Plants (WTP) at various critical points between May and June 2007 (N = 8)

WTP plant	Critical points	Parameters measured			
		Total Coliform (cfu/100 mL)		Faecal Coliform (cfu/100 mL)	
		Average	Min - Max	Average	Min - Max
Temba	Raw water source	$4.39 \times 10^3 (\pm 9.65 \times 10_2)$	3×10^3 - 5.5×10^3	$1.18 \times 10^3 (\pm 1.26 \times 10^3)$	1×10^2 - 4.05×10^3
	Filtration	$1.11 \times 10^3 (\pm 2.86 \times 10_2)$	8.40×10^2 - 1.69×10^3	36 (± 43)	0 - 1.1×10^2
	Chlorination	1 (± 3)	0 -10	0 (± 1)	0-3
	Distribution system *(Combined treated water)				
Klipdrift	Raw water source	$4.21 \times 10_3 (\pm 1.48 \times 10_3)$	1.39×10^3 - 6.4×10^3	$2.68 \times 10^2 (\pm 2.1 \times 10^2)$	26 to 5.23×10^2
	Filtration	$8.02 \times 10^2 (\pm 3.42 \times 10^2)$	4.1×10^2 - 1.3×10^3	11 (± 9)	0-22
	Chlorination	0 (± 0)	-	0 (± 0)	-
	Distribution system *(Combined treated water)	8 (± 4)	16-Jan	2 (± 3)	0-10
Wallmansthal	Raw water source	$5.62 \times 10^3 (\pm 3.74 \times 10^2)$	5×10^3 - 6.15×10^3	$1.22 \times 10^2 (\pm 79)$	22 - 2.75×10^2
	Filtration	$1.15 \times 10^3 (\pm 2.96 \times 10^2)$	6.55×10^2 - 1.15×10^3	4 (± 12)	0-31
	Chlorination	1 (± 2)	0-4	0 (± 0)	-
	Distribution system	1 (± 4)	0-10	0 (± 0)	0-1

Target limits at the point of distribution: TC 5 cfu/100 mL, FC 0 cfu/100 mL (DWAF, 1996a, b; SANS, 2005). No. in brackets are Standard deviation. *(Combined treated water): Treated water from Temba and Klipdrift combined; values are the same

74.2, 78.4 and 79.3% (Table 3) and 36 cfu/100 mL, 11 cfu/100 mL and 4 cfu/100 mL for FC (Table 2), with percentage removals of 93.4, 96 and 96%, respectively.

Chlorination: The average physicochemical values after chlorination (treatment) were 0.3 NTU, 1.1 NTU and 0.2 NTU for turbidity; 14.7, 14 and 16.6°C for temperature; 8.5, 8.3 and 7.9 for pH and 2.1, 2.3 and 1.9 mg L⁻¹, respectively from the Temba, Klipdrift and Wallmansthal WTP. The average TC values were 1 cfu/100 mL for Temba, 0 cfu/100 mL for Klipdrift and 1 cfu/100 mL for Wallmansthal (Table 2). The percentage removal of TC was 99.9, 100 and 99.9%, respectively (Table 3). On average, there was no FC in the treated water samples (Table 2) indicating 100% removal for each WTP after chlorination (Table 3).

Distribution: Average turbidity values recorded for the distribution system were 1.4 NTU and 0.4 NTU; temperature were 19.6 and 19.1°C; pH were 8.4 and 8.1 and chlorine residual were 0.3 and 0.6 mg L⁻¹ for the Temba/Klipdrift and Wallmansthal taps, respectively (Table 1). The TC values recorded for water samples from the Temba/Klipdrift and Wallmansthal tap were 8 cfu/100 mL and 1 cfu/100 mL. On average, 2 cfu/100 mL was recorded for FC from the Temba/Klipdrift tap (Table 2).

Characteristics of water at various critical points between September 2007 and April 2008

Raw water sources: The average turbidity, pH and temperature values for raw water were 39.8 NTU, 8 and 22.8°C for Temba WTP; 18.5 NTU, 9 and 23.6°C for Klipdrift WTP and 11.9 NTU, 8.4 and 22.5°C for Wallmansthal WTP (Table 4). Total Coliform values were 4.091×10^3 cfu/100 mL,

Table 3: Efficiency of plants for the removal of turbidity and coliform bacteria at various critical points between May and June 2007 (N = 8)

	Critical points									
	Raw water NTU						% Removal after filtration			
Plant name	Ave.		Ave.		Min-Max					
Turbidity										
Temba	22.4		97.8		95.8-99.4					
Klipdrift	11.9		86.9		60.3-96.7					
Wallmansthal	18.3		95.8		87.4-99					
Coliforms										
	Critical points									
	Raw water (cfu/100 mL)		Filtration average % removal				Chlorination average % removal			
	TC	FC	TC	FC	TC	FC	TC	FC	TC	FC
Plant name	Ave.	Ave.	Ave.	Min-Max	Ave.	Min-Max	Ave.	Min-Max	Ave.	Min-Max
Coliform										
Temba	4.39×10 ³	1.18×10 ³	74.2	65.8-82.9	93.4	75.3-100	99.9	98.9-100	99.6	97.5-100
Klipdrift	4.21×10 ³	2.68×10 ²	78.4	61.9-90.4	96.0	90-100	100	-	100	-
Wallmansthal	5.62×10 ³	1.22×10 ²	79.3	70.2-88.9	96.0	71.8-100	99.9	97.7-100	100	-

Ave. : Average

Table 4: Physiochemical characteristics of water at critical points of the water treatment plants between September 2007 and April 2008 (N = 32)

	Turbidity (NTU)		pH		Temperature (°C)	
	Average	Min-Max	Average	Min-Max	Average	Min-Max
Temba						
Raw water source	39.8 (±16.8)	4.85-66.9	8 (±0.3)	7.6-8.69	22.8 (±2.5)	18-26.7
Sedimentation	6.8 (±6.5)	1.54-10.45	8.9 (±0.5)	7.83-9.47	23.3 (±2.8)	18.5-27.8
Filtration	0.4 (±0.3)	0.08-1.64	8.8 (±0.5)	7.8-9.37	23.9 (±2.5)	19.7-26.4
Klipdrift						
Raw water source	18.5 (±15)	4.66-76.7	9 (±0.4)	8-9.81	23.6 (±2.1)	20-28.6
Sedimentation	16.8 (±13.3)	5-60.6	8.8 (±0.5)	8.2-9.78	23.3 (±2.2)	19.1-26.1
Filtration	1.1 (±0.4)	0.34-1.88	8.8 (±0.6)	8-9.62	23.1 (±2.2)	18.6-25.8
Wallmansthal						
Raw water source	11.9 (±7.3)	3.51-25.4	8.4 (±0.5)	7.95-9.54	22.5 (±1.7)	19.2-24.9
Sedimentation	1.4 (±2.8)	0.69-5.05	8.3 (±0.3)	7.71-8.96	23.4 (±2.8)	18.2-26.6
Filtration	0.5 (±0.2)	0.05-0.94	8.3 (±0.3)	7.86-8.91	22.2 (±1.7)	18.3-25.2

Targeted limits at point of treatment: Turbidity after sedimentation ≤ 5 NTU, Turbidity after filtration = 1 NTU, pH 6-9, Temperature = 25°C, TC 5 cfu/100 mL, FC 0 cfu/100 mL after chlorination. No. in brackets are Standard deviation

3.306×10³ cfu/100 mL and 5.109×10³ cfu/100 mL; while FC values were 4.82×10³ cfu/100 mL, 1.23×10² cfu/100 mL and 43 cfu/100 mL, respectively for the 3 WTP (Table 5).

Sedimentation: After sedimentation, the Temba, Klipdrift and Wallmansthal average physicochemical values were 6.8 NTU, 16.8 NTU and 1.4 NTU for turbidity; 8.9, 8.8 and 8.3 for pH

Table 5: Efficiency of plants for the removal of turbidity and coliform bacteria at various critical points between September 2007 and April 2008 (N = 32)

	Raw water turbidity (NTU)				Sedimentation average % removal				Filtration average % removal			
Plant name	Ave.		Ave.		Min-Max		Ave.		Min-Max			
Turbidity												
Temba	39.8		80.5		34.6-96.8		90.8		72.7-98.2			
Klipdrift	18.5		41.1		2.2-75		89		71.6-98			
Wallmansthal	11.9		69.8		22.3-90.4		75.1		20.7-98.2			
	Raw water cfu/100 mL				Sedimentation average % removal				Filtration average % removal			
	TC		FC		TC		FC		TC		FC	
Plant name	Ave.	Min-Max	Ave.	Min-Max	Ave.	Min-Max	Ave.	Min-Max	Ave.	Min-Max	Ave.	Min-Max
Coliform bacteria												
Temba	4091	1250-7750	482	0-2375	44.2	1.3-79.4	86.1	30.8-100	84.7	71-97.4	90.7	40-100
Klipdrift	3306	1610-4600	123	0-2300	35.8	11.6-73.5	79.1	42.1-100	87.9	77.3-96.1	96.9	65.9-100
Wallmansthal	5109	3020-7820	43	0- 760	51.6	2.6-91	83.7	21.4-100	82.9	61.9-92.6	97.3	86.7-100

Ave. : Average

and 23.3°C, 23.3 and 23.4°C for temperature, respectively (Table 4). The average percentage removals of turbidity after sedimentation for the 3 WTP were 80.5, 41.1 and 69.8%, respectively. The percentage microbial removals were 44.2, 35.8 and 51.6% for TC and 86.1, 79.1 and 83.7% for FC, respectively for the 3 WTP (Table 5).

Filtration: The average turbidity values after filtration were 0.4 NTU, 1.1 NTU and 0.5 NTU, respectively (Table 4). There were percentage turbidity removals of 90.8, 89 and 75.1% for the 3 WTP, respectively (Table 5). The average pH values were 8.8, 8.8 and 8.3 and the temperature values were 23.9, 23.1 and 22.2°C, respectively (Table 4). The percentage microbial removals after filtration were 84.7, 87.9 and 82.9% for TC and 90.7, 96.9 and 97.3% for FC, respectively for the 3 WTP (Table 5).

Bacterial species identified

Temba water treatment plant: Seven bacterial species were identified from the Temba raw water. These bacteria included *Serratia*, *Vibrio*, *Aeromonas*, *Pseudomonas*, *Photobacterium* and *Erwina*. After filtration, only *Photobacterium* and *Erwina* species were removed. Moreover, there was the presence of *Enterobacter* that was not initially detected in raw water. The Chlorination process resulted in the removal of most bacterial species except *Aeromonas* and *Pseudomonas* species. In the distribution system, there was re-appearance of *Vibrio*, *Aeromonas*, *Serratia* and *Pseudomonas* species (Table 6).

Klipdrift water treatment plant: *Vibrio*, *Aeromonas*, *Enterobacter*, *Raoultella* and *Ornithinolytica* species were identified in Klipdrift raw water. After filtration, the presence of *Serratia*, *Aeromonas*, *Vibrio* and *Enterobacter* species still persisted. No bacterial isolates were identified in chlorinated water. Organisms identified from the Klipdrift distribution system were the same as those found in Temba tap water; this is because Temba and Klipdrift combine their treated water during distribution (Table 6).

Table 6: Profile of bacterial isolates identified from critical points through out the study, May 2007 to April 2008

Critical point	Plants name		
	Temba	Klipdrift	Wallmansthal
Raw water	<i>Serratia odorifera</i>	<i>Serratia odorifera</i>	<i>Aeromonashydrophila/caviae/sobria</i>
	<i>Vibrio fluvialis</i>	<i>Vibrio fluvialis</i>	<i>Vibrio fluvialis</i>
	<i>Aeromonas hydrophila/caviae/sobria</i>	<i>Aeromonas hydrophila/caviae/sobria</i>	<i>Enterobacter cloacae</i>
	<i>Pseudomonas fluorescens/putida</i>	<i>Enterobacter cloacae</i>	<i>Enterobacter aerogenes</i>
	<i>Photobacterium damsela</i>	<i>Serratia liquefaciens</i>	
	<i>Serratia plymuthica/ficaria</i>	<i>Raoultella ornithinolytica</i>	
	<i>Erwinia</i> sp.	<i>Enterobacter sakazakii</i>	
Filtration	<i>Serratia odorifera</i>	<i>Serratia odorifera</i>	<i>Aeromonashydrophila/caviae/sobria</i>
	<i>Vibrio fluvialis</i>	<i>Aeromonas hydrophila/caviae/sobria</i>	<i>Vibrio fluvialis</i>
	<i>Aeromonas hydrophila/caviae/sobria</i>	<i>Vibrio fluvialis</i>	<i>Enterobacter cloacae</i>
	<i>Pseudomonas fluorescens/putida</i>	<i>Enterobacter cloacae</i>	<i>Enterobacter aerogenes</i>
	<i>Pseudomonas luteola</i>		
	<i>Enterobacter sakazakii</i>		
Chlorination	<i>Aeromonas hydrophila/caviae/sobria</i> <i>Pseudomonas fluorescens/putida</i>	No Organisms identified	<i>Aeromonashydrophila/caviae/sobria</i>
Distribution	<i>Vibrio fluvialis/cholera</i>	Organisms identified similar to Temba	<i>Aeromonashydrophila/caviae/sobria</i>
	<i>Aeromonas hydrophila/caviae/sobria</i>		<i>Chromobacterium violaceum</i>
	<i>Pseudomonas fluorescens/putida</i>		
	<i>Serratia odorifera</i>		

Wallmansthal water treatment plant: Among the four organisms identified from the raw water of the Wallmansthal water treatment plant, *Aeromonas*, *Vibrio* and *Enterobacter* species were also identified after filtration. Only *Aeromonas* species resisted the chlorination process. In the distribution system *Aeromonas* and *Chromobacterium* species were detected (Table 6).

DISCUSSION

Three water treatment plants were selected in non-metropolitan areas of the Gauteng Province, South Africa. The choice of these plants was deliberate, since some investigators have reported non-compliance with water quality standards in non-metropolitan plants, as compared to metropolitan ones (Swartz, 2000; Momba *et al.*, 2003; Momba and Brouckaert, 2005). Each barrier point selected during the study (raw water, sedimentation, filtration, chlorination and the point of distribution) has been referred to in the literature as a critical point. Potential process failures in any of these barriers can cause both physicochemical and microbiological hazard overloads and overall underperformance of the plant (Jagals and Jagals, 2004).

It was our intention to analyse the general integrity of the water produced and distributed by the treatment plants and assess the efficiency of all the treatment barriers. The study was drawn on the basis of the worldwide awareness of the limitations of end product testing and the importance of the Hazard Analysis and Critical Control Points (HACCP) principles for water quality management (USEPA, 2006). Effective treatment barriers are essential in all treatment plants for the effective regulation of both physico-chemical and microbial integrity of water distributed to consumers (Momba *et al.*, 2008).

The evaluation of raw water quality, of which turbidity is an important parameter, is paramount in the selection of appropriate treatment processes (Page *et al.*, 2006). It was apparent that this parameter played an important role in influencing the choice of barrier systems in each water treatment plant in this study. Despite having the highest raw water turbidity on average

(up to 39.8 NTU), the Temba water treatment plant's detailed barrier system was able to remove turbidity of up to 90.8%. Under optimal conditions, coagulation, flocculation and sedimentation processes efficiently reduce raw water turbidity to values of (≤ 5 NTU) suited for filtration processes such as Dissolved Air Flotation Filtration (DAFF) and rapid sand filtration (World Health Organization, 2004). Screening and pre-chlorination are essential for treating water with lower turbidities but with suspected high levels of bacteria (Page *et al.*, 2006), as was recorded for both the Klipdrift and Wallmansthal water treatment plants (Table 4). These two barriers are also often used to minimize operational problems associated with algae, coagulation, biological growth and re-growth on filters, pipes, tanks and through out the treatment barrier system (USEPA, 1999). Thus these two barriers seemed suited for both the Klipdrift and Wallmansthal water treatment plant, as they are smaller plants.

It is obvious that the general barrier systems that are currently applied in the treatment of drinking water in each plant influenced the quality of the treated water. Physicochemical parameters analysed during the study are commonly used during general water quality assessment (DWAf, 1996a; SANS, 2005). On the average, there was a reduction in turbidity during the pre-treatment stages of the raw water sources. During the preliminary study conducted in May and June 2007 (Table 2), 86.9 to 97.8% of turbidity was removed in all water samples by filtration systems. Similar trends were also observed during the September 2007 to April 2008 study period (Table 4). In all the plants, turbidity decreases of 41.1 to 80.5 and 75.1 to 90.8% were observed after sedimentation and after filtration, respectively. The Temba and Klipdrift water samples had turbidity values above the recommended limits after sedimentation and filtration (Table 3). There was evidence of a turbidity increase at the point of distribution in all water samples (Table 1). The Temba and Klipdrift tap water samples fell slightly above the recommended limits (SANS, 2005).

Evidently it is important to obtain a reduction in turbidity through out the process of treatment, which will eventually coincide with the recommended limits during and at the end of treatment and ultimately maintain it through out the distribution system. Each treatment barrier should reduce turbidity to a level at which the next barrier will function to its maximum capacity. For instance, for filtration, which is one of the major critical points, to be effective, it is recommended that the turbidity value after sedimentation be below 5 NTU (Momba and Brouckaert, 2005). As observed, there were instances where the turbidity values after sedimentation from the Temba and Klipdrift water samples consequently had a negative effect on the turbidity values obtained after filtration. An increase in turbidity during distribution is motivated by factor such as, having turbidity values above the recommended limit from the point of treatment, the type of distribution pipes (problems), bacterial re-growth and a reduction in the chlorine residual (Momba *et al.*, 2006; Hallam *et al.*, 2001). Invariably, it is important to check these factors in order to maintain ideal turbidity levels at the point of use.

Although, on the average, temperature and pH values were within the recommended limits during the treatment processes (SANS, 2005), values exceeding the recommended limits were recorded during the study, values above 9 for pH and 25°C for temperature (Table 4). Temperature and pH are essentially important for some of the reactions that take place in water. An ideal temperature ($\leq 25^\circ\text{C}$) is essential to maintain the rate of disinfection during water treatment and also to prevent the toxicity of probable metals that may be found in the water (USEPA, 1999; Momba *et al.*, 2006). On the other hand, an ideal basic pH of 6-9 in the water is essential for chemical reactions e.g., coagulation (recommended pH 6-8.5). The residual chlorine concentrations

ranged between 1.9 and 2.3 mg L⁻¹ at the point of treatment. Thereafter a decrease occurred and resulted in chlorine residual concentrations ranging between 0.3 and 0.6 mg L⁻¹ in the distributed water (Table 1). The average residual chlorine values from the Temba and Klipdrift tap water were below the recommended limits during the study period. This could clearly explain the presence of at least 4 bacterial species in the final water. It is essential that a residual chlorine value of 0.5 mg L⁻¹ be kept at all times in drinking water distributed for consumption. This is ideal to prevent the re-growth phenomenon (USEPA, 1999). Controlling adversity towards human health is paramount also when maintaining an ideal chlorine residual limit in water during distribution (Chlorine Chemistry Council, 2003). There were instances where the recorded chlorine residual concentrations in the treated water were above the limits (Table 1); this could be detrimental to human health with continued exposure (Chlorine Chemistry Council, 2003).

Microbial indicators investigated in this study were Total Coliforms (TC) and Faecal Coliforms *E. coli* (FC). This group of organisms was selected because coliforms are widely used as indicators of the general sanitary quality of water, especially in treated water. Primarily, this group includes bacteria of faecal origin, although, many of the bacteria in this group may originate from growth in the aquatic environment. On the other hand, *E. coli* is used to evaluate the possible faecal origin of total and faecal coliforms, usually when isolated from drinking water (DWAF, 1996a; Sundram *et al.*, 2006).

Despite a drastic decrease in TC and FC counts from raw water to chlorinated water, potential pathogenic bacteria such as *Aeromonas hydrophila* persisted in chlorinated water collected from the Temba and Wallmansthal WTP (Table 6). This bacterial species was also predominant at the point of use of each plant. Although it was not observed in the Klipdrift chlorinated water, combining the Temba treated water with the Klipdrift treated water affected the overall quality of the treated water in the distribution system. Generally, *Aeromonas* sp., are said to be ubiquitous bacteria found in a variety of aquatic environments (DWAF, 1996b; Seshadri *et al.*, 2006). These species have been isolated in drinking water even after chlorination (Burke *et al.*, 1984). Although, *Aeromonas* sp. is known widely as an opportunistic pathogen in immuno-compromised humans, an increasing number of cases of intestinal and extra-intestinal disease documented worldwide suggest that it is an emerging human pathogen irrespective of the host's immune status (Figueras, 2005). There is much need to address the microbial quality of these water supplies, as safe drinking water is critical to good health and economic development.

In conclusion, this study, which was based on assessing the importance of implementing the HACCP concept for water treatment and management, revealed the following:

CONCLUSION

- In order to ensure optimum operation of a water treatment plant, the following critical points must be monitored regularly: raw, sedimentation, filtration, treatment and tap points.
- Both physicochemical and microbial parameters should always be kept within the recommended limits from one barrier to the next.
- The quality of the raw water influenced the application of barrier systems for water treatment. It is recommended that raw water be monitored at all times for proper pre-barrier applications.
- Combining final water from the Temba and the Klipdrift water treatment plants resulted in the deterioration of the drinking water distributed to consumers. One major recommendation for this study would be to make sure that the water from each plant complies with the standards before combining them for distribution.

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