Investigation into the Influence of Hydraulic Contacting on Disinfection Efficiency in Small Waterworks

Report to the
Water Research Commission

by

P Maduray
Umgeni Water

WRC Report No. 2809/1/20
ISBN 978-0-6392-0186-3

September 2020

Obtainable from
Water Research Commission
Private Bag X03
Gezina
PRETORIA 0031

orders@ www.wrc.org.za or download from www.wrc.org.za

EXECUTIVE SUMMARY

This research project focuses on the influence of hydraulic contacting on disinfection efficiency in small waterworks (<2 Ml/d). Small water works in the rural areas of South Africa have difficulties in achieving adequate disinfection to meet final water quality standards (Momba et al., 2008). The final tank in a small water system is typically used for storage or as a buffer tank prior to distribution pumps. Correct disinfectant dosing could still result in microbial failures due to inefficiencies in the contact tank, such as short-circuiting. The CT value is generally utilised as a design basis for contact tanks. It is therefore important to investigate the impact of hydraulic disinfection efficiency in contact tanks.

A review of small water works and various contact tank designs will be conducted. The focus of the study is on the geometry and design of contact tanks and their impact on the contact time through tracer tests. The theoretical residence time will be compared to the actual residence time, and the baffling factor will be determined. Possible interventions to increase disinfection efficiency are recommended.

A desktop survey of various municipalities and water-boards was conducted to determine the number of applicable sites that could be investigated for this research project. The criteria for selection of sites were to be less than 2 Ml/d in capacity, have distinct contact tanks, access for input of tracer, sampling points, flowmeters, continuous flowrates and constant electricity supply. Various contact tank shapes and designs were shortlisted to determine their impact on the contact time.

Four sites in KwaZulu-Natal and North West province were available as testing sites. These sites had a circular tank with no baffle, rectangular tank with no baffle, rectangular tank with a single baffle and two circular tanks in series with no baffles. The results indicate that both circular and rectangular contact tanks with no baffles or mixers results in poor, ineffective contact time. The rectangular contact tank with a single baffle was also insufficient to achieve the required contact time. It is recommended that the water treatment system must be assessed holistically when troubleshooting the disinfection process. Plant designers must consider the importance of residence time for disinfection and allow for variable flow considerations. When applying the Ct concept, efforts should be to increase the contact time, rather than disinfectant concentration to prevent any harmful by-products, or added costs.

ACKNOWLEDGEMENTS

The authors would like to thank the Reference Group of the WRC Project K5/2809/3 for the assistance and the constructive discussions during the duration of the project as well as the contributors:

Reference group member	**Institution**
Dr N Kalebaila	Water Research Commission (Research Manager)
Mr C Swartz	Chris Swartz Water Utilisation Engineers
Ms L Moodley	eThekwini Municipality
Dr L Maharaj	Umgeni Water
Mrs M Schalkwyk	Umgeni Water
Mr P Thompson	Umgeni Water
Mr M Ncube	Development Bank of SA
Prof. VL Pillay	Stellenbosch University
Dr E Ncube	Rand Water

Contributor	**Institution**
Mr R Rajagopaul	Umgeni Water
Prof. SK Venayagamoorthy	Colorado State University
Ms J Baker	Colorado State University
Ms N Dlamini	Umgeni Water
Mr S Dube	Umgeni Water
Mr S Sithole	Umgeni Water
Ms B Mthiyane	Umgeni Water
Ms P Gopi	eThekwini Municipality
Mr L Khathi	eThekwini Municipality
Mr B Mthetwa	Illembe Municipality
Mr W Hlela	Illembe Municipality
Mr S Ngcobo	Magalies Water

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

BF	Baffling Factor
CCT	Chlorine Contact tank
CFU	Colony Forming Units
CT	Product of the concentration (C) of a disinfectant and the contac time (T)
Ml/d	Mega / million litres per day
MPN	Most probable number
mS/m	Millisiemen per metre
OSEC	Onsite Electrolytic Chlorination
SANS	South African National Standards
TDT	Theoretical detention time
μS/m	Microsiemen per metre
WW	Water works

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Access to water is a basic human right in South Africa as stated in the Constitution (1996). According to the 2018 Statistics South Africa's General Household Survey, only 46.3% of households in South Africa have access to piped water (South African Government, 2020). Further, 2,7% of households still have to fetch water from rivers, streams, stagnant water pools, dams, wells and springs. Research done by the South African Human Rights Commission (2014) states that residents in rural and peri-urban communities still face unacceptable challenges to accessing water and sanitation services.

Small water treatment works (less than 2 Ml/d) in the rural/peri-urban areas of South Africa, struggle to achieve adequate disinfection to meet the SANS 241:2015 final water quality standards (Momba, et al., 2008). Inadequate disinfection could result in the regrowth of pathogens, and negatively affects the health of the consumer. It is an important stage of the treatment process, and prevents the outbreak of waterborne diseases such as cholera or dysentery. Small waterworks face a number of challenges, such as poor operation and maintenance, inappropriate process design, deteriorating infrastructure and limited budgets.

The final tank in a small water system is typically used for storage or as a buffer tank prior to distribution pumps. In small water treatment systems, contacting is typically achieved through un-baffled rectangular or circular storage tanks. Correct disinfectant dosing could still result in microbial failures due to inefficiencies in the contact tank, such as short-circuiting. The CT value is generally utilised as a design basis for contact tanks. It is therefore important to investigate the impact of hydraulic disinfection efficiency in contact tanks. A number of studies have focused on the type of chemical used for disinfection, comparing chlorine, chlorine dioxide, sodium hydroxide, etc. but the impact of contact time has not been researched in South Africa in detail.

Colorado State University (CSU) in the United States have done extensive research on baffling factors and hydraulic disinfection efficiency using lab-scale models and computational fluid dynamic modelling (Carlston, 2015; Taylor, 2015; Wilson 2010). A collaboration was formed between CSU and Umgeni Water in order to conduct testing on a small water treatment works, which initiated this research project.

1.2 OBJECTIVES

This research project aims to investigate the influence of hydraulic contacting on the disinfection efficiency in small water treatment works in South Africa. A review of small water works and various contact tank designs will be conducted. The focus of the study is on the geometry and design of contact tanks and their impact on the contact time. The theoretical residence time will be compared to the actual residence time, and the baffling factor will be determined. Possible interventions to increase disinfection efficiency are recommended.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The importance of safe, potable water to public health cannot be overstated. Globally, 785 million people lack basic access to water. It is therefore one of the United Nation's Sustainable Development Goals to ensure availability and sustainable management of water and sanitation for all (United Nations, 2019)

Disinfection is a vital stage in the water purification process. The main purpose of this stage is to kill the growing form of pathogenic microorganisms. Chemical disinfection processes inactivate pathogenic microorganisms and the recommended free chlorine residual to ensure properly disinfected water should be 0.5 mg/l after a contact time of 30 minutes (Schutte, 2006). The primary methods for disinfection include free chlorine, chloramines, chlorine dioxide, ozone and ultraviolet irradiation. Drinking water utilities must balance the provision of good disinfection without forming excessive disinfection by-products (Jacangelo & Trussell, 2002).

Research conducted in South Africa considered drinking water microbial quality in rural areas. Mackintosh & Colvin (2002) researched groundwater schemes in the Eastern Cape Province. It was found that a high number of schemes had no disinfection capability. Heterotrophic plate counts, total coliform and faecal coliform counts were measured to determine the compliance of the final water. Their results indicated 50% failure of microbial limits in SANS 241:2015. The South African National Standard (SABS, 2015) sets the microbiological determinand limits as below:

Table 1: SANS 241:2015 Microbiological Standard limits

1 Determinand	2 Risk	3 Unit	4 Standard Limits
E. Coli or faecal coliforms	Acute health	Count per 100 mL	Not detected
Protozoan parasites			
Cryptosporidium species	Acute health	Count per 10 L	Not detected
Giardia species	Acute health	Count per 10 L	Not detected
Total coliforms	Operational	Count per 100 mL	≤ 10
Heterotrophic plate count	Operational	Count per mL	≤ 1 000
Somatic coliphages	Operational	Count per 10 mL	Not detected

Momba et al. (2008) conducted a survey of 181 water treatment works in South Africa, which varied in size between 0.3 Ml/d to 120 Ml/d. This survey was focused on the type of disinfectant utilised in South Africa. Their results indicated that 69% of the water treatment works utilised chlorine gas as a disinfectant, followed by sodium hypochlorite (15%) and calcium hypochlorite (HTH) at 14%. Their study compared safety concerns and costs of disinfectants, but did not consider the design of the contact tanks at the works. The free chlorine residuals at small waterworks were also tested, and ranged between ≤0.1 mg/l and ≤0.5 mg/l. This indicated inadequate disinfection, and a reduced contact time could have been a contributing factor to these low concentrations.

2.2 CONTACT TIME (CT)

Kawamura (2000) lists the major considerations of designing a disinfection process as:

- Presence of surrogate organisms
- Feasibility of alternative disinfectant
- Residual contact time relationship (C x t)
- Formation of disinfectant by-products
- Quality of the process water
- Safety problems
- Cost of each disinfectant

The hydraulic design of contact tanks has traditionally been based on the assumption that the contact time for all fluid elements corresponds to the theoretical hydraulic residence time (T) of a given tank which can be estimated as T =V/Q, where V is the tank volume and Q the mean flow rate. In an ideal plug flow tank, the residence time of all the elements of water would be equal to T if dispersion and diffusion were ignored. In practice however, hydraulic conditions are non-ideal, and would require an increase the chlorine dosage in order to maintain an appropriate disinfectant residual. This supports the need for the research into the effect of chlorine contact tank hydraulic impact on disinfection, as simple modifications could reduce unnecessary chemical usage.

When discussing contact time, the "Ct" value is a concept utilised. As described in Kawamura (2000),

$$C\ x\ \ t\ = constant \qquad ...(1)$$

Where C = disinfectant residual in mg/l
t = contact time in minutes

i.e. a low concentration of a disinfectant with a long contact time achieves the same as a short contact time with a high disinfectant concentration. Ct is influenced by pH, temperature, type of disinfectant and type of microorganism as shown in Tables 2 and 3 below. Table 2 below indicates guideline values for various disinfectants to achieve inactivation of *Giardia Lambia*.

Table 2 : C x t Values for Achieving 90% Inactivation of *Giardia Lambia* (Kawamura, 2000)

	pH	Temperature					
		0.5°C	**5°C**	**10°C**	**15°C**	**20°C**	**25°C**
Free Chlorine	6	49	35	26	18	13	9
	7	70	50	37	25	19	12
	8	101	72	54	36	27	18
	9	146	104	78	52	39	26
Ozone	6-9	0.97	0.63	0.48	0.32	0.24	0.16
Chlorine dioxide	6-9	20	13	10	5	5	3.3
Chloramines (Preformed)	6-9	1295	737	675	505	366	260

Table 3 below indicates the Ct (mg.min/l) values required to achieve 99% inactivation of different microorganisms, comparing the different disinfectants.

Table 3: Ct values to achieve 99% Inactivation of Microorganisms (Schutte, 2006)

Microorganism	Disinfectant			
	Free Available Chlorine pH 6-7	Chloramine pH 8-9	Chlorine dioxide pH 6-7	Ozone pH 6-7
	Ct Values			
E. coli	0.034-0.05	95-100	0.5-0.75	0.02
Polio 1 Virus	1.1-2.5	768-3740	0.2-6.7	0.1-0.2
Rota virus	0.01-0.05	3806-6476	0.2-2.1	0.006-0.06
Phage f2	0.08-0.18			
G lamblia cysts	47- >150			0.5-0.6
G muris cysts	60-630	1400	7.2-18.5	1.8-2.0

2.3 CONTACT TANK DESIGN

In real-world installations, non-ideal flow patterns exist; this results in ineffective contacting than in an ideal case (Fogler, 2006). The extent of deviation from the target flow pattern depends strongly on constructive features, such as: the geometry of the tank, the use of flow-modifier structures, such as baffles, and their orientation and inlet and outlet configurations (Rauen, et al., 2012). The experimentation work on contact tanks conducted to date has made use of scaled models, since experiments on site cannot always be cost-efficient and may disrupt water treatment processes. However, this method can be problematic as a physical hydraulic model is constructed by scaling either the Froude or Reynolds number, but not both. A major advantage to this research project is the real-time full-scale plant details relating to contact time.

Computational fluid dynamic (CFD) modelling is utilised in the design of contact tanks to some degree of success. The theoretical basis of CFD modelling are the Navier-Stokes fluid dynamics equations, and it can be compared to conducting a virtual tracer test (Templeton, et al., 2006). However CFD models can only be accurate if they are based on correct and detailed process information. Some recommendations by Momba et al. (2008) to improve contact tank design are:

- Circular or square tanks must have vertical walls to prevent direct flow from inlet to outlet.
- A fixed volume of water must be maintained in the tank by either a weir or high outlet.
- Flow in a long straight pipe or narrow channel is ideal.

2.4 THE BAFFLING FACTOR

There are different indicators of the effectiveness of hydraulic mixing, such as the baffling factor (BF), the Morrill Index (MI) and the dispersion index (σ^2) (Taylor, et al., 2015).

The baffling factor is defined as:

$$BF = \frac{T_{10}}{TDT} \quad \text{...(2}$$

where T_{10} is the time required for the first 10% of the fluid to travel through the tank to the residual sampling point and TDT is the theoretical detention (or residence) time. The baffling factor provides a measure of the short circuiting in the tank. Un-baffled tanks usually have a BF of the order of 0.1, while tanks with ideal plug flows have a BF of 1.0.

Table 4: Baffling Factors (USEPA, 2003)

Baffling Condition	Baffling Factor	Description
Un-baffled	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities.
Poor	0.3	Single or multiple un-baffled inlets and outlets, no intra-basin baffles.
Average	0.5	Baffled inlet or outlet with some intra-basin baffles.
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders.
Perfect (Plug Flow)	1	Very high length to width ratio (pipeline flow), perforated inlet and outlet, and intra-basin baffles.

CHAPTER 3: EXPERIMENTAL PROCEDURES

3.1 STUDY SITES

A desktop survey of various municipalities and water-boards was conducted to determine the number of applicable sites that could be investigated for this research project. Umgeni Water, Rand Water, Magalies Water, Midvaal Water, uMhlatuze Water as well as eThekwini, iLembe, uThukela, Moses Kotane and Ugu, Municipalities were surveyed. Although a large number of sites were below 2 Ml/d in size, sites that fit all criteria were few. This included distinct contact tanks, access for input of tracer, sampling points, flowmeters, continuous flowrates, constant electricity supply, etc. Various contact tank shapes and designs were shortlisted to determine their impact on the contact time.

3.2 DETERMINATION OF THE HYDRAULIC PERFROMANCE OF CONTACT TANKS

3.2.1 The tracer test analysis method

The tracer test analysis method was used to measure the hydraulic performance of the contact tanks. The chemicals used as tracers are compounds that flow in the fluid phase without altering the transport properties of the phase. As discussed in Teefy (1996), the results from a tracer test can be used in several ways:

- To characterize flow patterns and to evaluate mixing performance (residence time distribution is useful for diagnosing short-circuiting).
- To characterize the storage properties of the process system.
- As a diagnostic tool to test for any internal configuration defects.

3.2.2 Protocols for conducting the trace test

Protocols to follow before conducting a tracer test on a live plant recommended by Schott (1999) are detailed below:

3.2.2.1 Pre-test preparation

a. Before the tracer test begins, certain pre-checks must be done. This included ensuring the plant was online and that there was sufficient level in both the contact tanks and distribution reservoirs. The control philosophy was also verified to ensure pumps would not be switching off during the test period.
b. Before the tracer test was conducted, the initial turbidity and conductivity of the raw water was measured. The initial free chlorine concentration of the final water was also determined.
c. The measurements of the contact tank were confirmed on site to ensure the theoretical residence time calculation was accurate.
d. The plant flowmeter reading was noted for the TRT and actual residence time calculation.

e. These were done in conjunction with the plant Process Controller, who was kept informed of all actions throughout the test process.

3.2.2.2 Roles and responsibilities of participants

A team of ±3 people conducted the test, whereby responsibility was split as follows:

i. Adding the tracer to the inlet of contact tank.
ii. Confirmation of tank levels during testing.
iii. Sampling at outlet of contact tank and testing.
iv. Sampling at distribution reservoir and testing.

3.2.2.3 Selection of tracer

A tracer was selected which would alter some measurable characteristic of the fluid, such as its colour, fluorescence intensity or concentration of a given chemical, but otherwise behaves in a similar manner to the fluid (Rauen, et al., 2012). Fluorescein dye was selected which turns bright green in water and allows for easy visual confirmation of the residence time. Sodium chloride solution was also selected, which would increase the conductivity. In addition, the tracer should have physical properties similar to those of the medium and be completely soluble in the mixture. It also should not adsorb on the walls or other surfaces in the tank (Fogler, 2006).

3.2.2.4 Type of tracer test

The initial tracer test methodology utilised was the pulse input (slug dose) of fluorescein dye, allowing for a visual observation of the contact time through the contact tank. This is useful in preventing unnecessary sampling and also the possibility of missing the actual residence time sample, which may occur if only the theoretical time is used. This was followed by the usage of a sodium chloride (NaCl) solution, added as a pulse input into the inlet of the tank closest to the disinfectant dosage point. Conductivity was then measured at the outlet of the contact tank using the portable conductivity meter at frequent intervals. The solution was prepared to ensure that the final water conductivity did not exceed the SANS 241:2015 limit of 170 mS/m. The NaCl solution was also added with a step input into the system, i.e. dosed continuously and monitored.

3.2.2.5 Test duration and Sample frequency

Once the theoretical residence time (TRT) was calculated, the sampling frequency was selected based on practicality of sampling. The frequency utilised was every minute for shorter TRTs and every two minutes for the longer TRTs.

3.2.3 Method of sampling

Samples were taken at the outlet of the contact tank. The conductivity meter utilised has a probe which was submerged continuously in the final water where possible. At sites with sample taps, final water samples were taken and immediately tested on site.

3.2.4 Method of data analysis

Physical and chemical determinands turbidity, conductivity, pH and chlorine (free and total) were measured on site. The HACH 2100Q meter was used for turbidity measurement and the HACH H138 minilab for pH measurement. The Beckman Coulter LP92 was used for measurement of conductivity data. Free and total chlorine were analysed using the Lovibond MD100 meter. The data was recorded and used to plot the residence time distribution curve, to determine the Baffling Factor as per Section 2.4.

CHAPTER 4: RESULTS

4.1 DESIGN 1: CIRCULAR TANK – NO BAFFLES

4.1.1 Description of site

Site 1 is located in the Mooi River area of KZN and is operated by Umgeni Water. It has a design capacity of 0.25 Ml/d. Raw water is abstracted from the Mpofana River. Sodium hydroxide is utilised as a disinfectant and is dosed directly into a 10 m^3 polyethylene circular tank, with no mechanical mixing or baffles. The residual chlorine is monitored by an operator every 2 hours and dosage adjusted if required (Figure 1). The tank has a straight inlet at the top of the tank and outlet at the bottom of the tank, on the opposite side (Figure 2). A sampling point was available at the exit of the contact tanks.

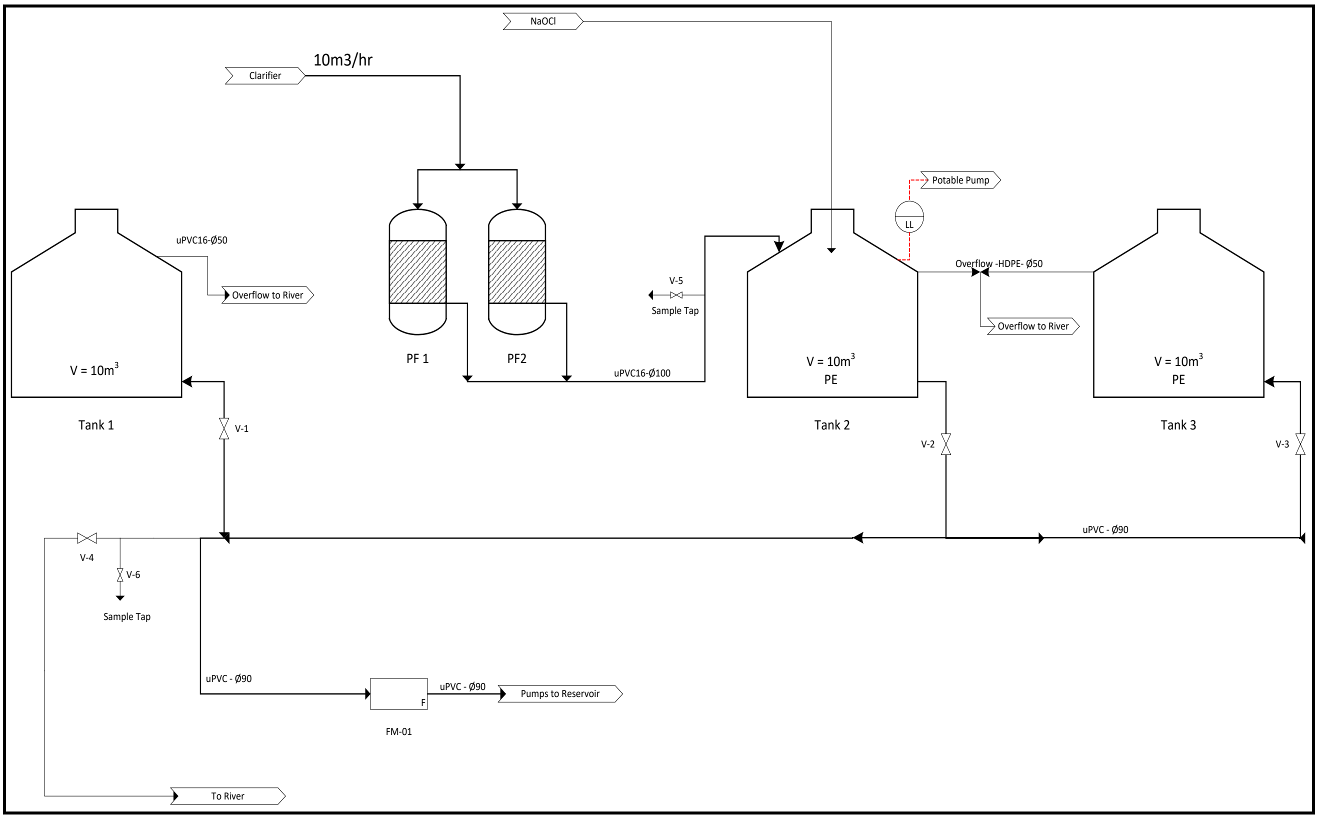

Figure 1: Schematic of Site 1 Contact Tank System

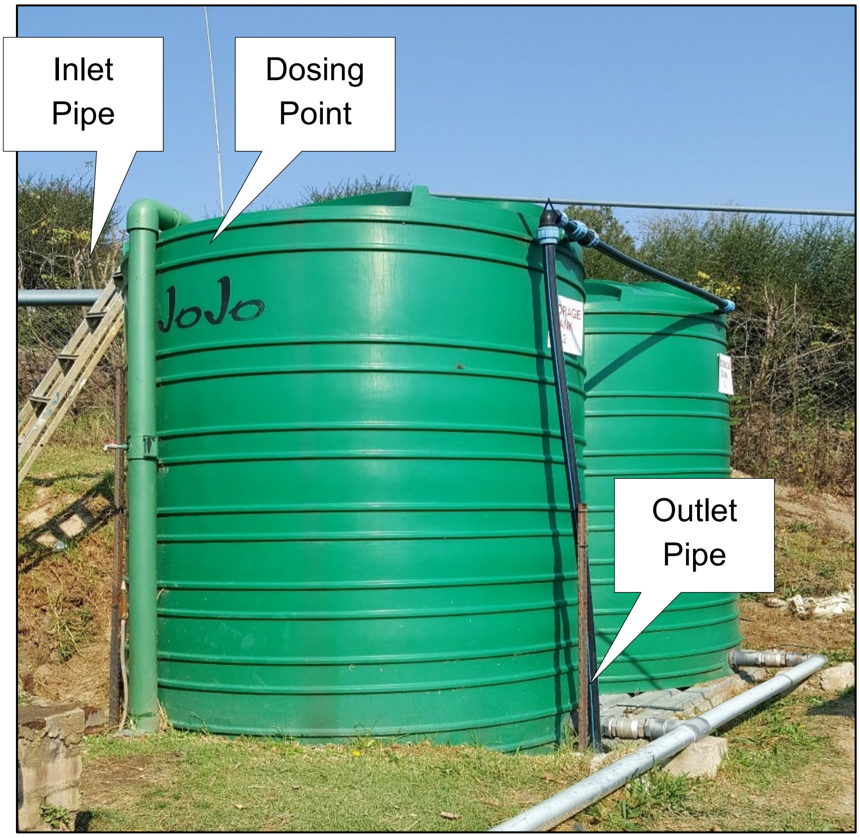

Figure 2: Site 1 Contact Tank

The historical quality data for the waterworks was available and is summarised in Tables 5 and 6 below. The final water data shows that the plant is capable of 100% *E. coli* removal, indicating an effective disinfection process.

Table 5: Site 1 Raw Water Quality Data

	2018		**2019**	
	Turbidity	***E. coli***	**Turbidity**	***E. coli***
	NTU	MPN/100 m	NTU	MPN/100 ml
Minimum	1.90	24.00	2.70	0.00
Maximum	21.10	2420.00	23.90	2420.00
Average	4.22	988.50	6.22	649.80

Table 6: Site 1 Final Water Quality Data

	2018			**2019**		
	Turbidity	**Chlorine**	***E. coli***	**Turbidity**	**Chlorine**	***E. coli***
	NTU	mg/l	MPN/100 ml	NTU	mg/l	MPN/100 ml
Minimum	0.10	1.00	0.00	0.20	1.00	0.00
Maximum	3.50	2.00	0.00	0.90	2.80	0.00
Average	0.39	1.43	0.00	0.34	1.69	0.00

4.1.2 Determination of residence time

The theoretical residence time was first calculated using equation (3) below:

$$T = \frac{V}{Q} \tag{3}$$

Where V = volume of tank (m^3)

Q = Flowrate (m^3/hr)

Test 1:

This was determined as follows at Site 1:

- Contact tank 2 empty volume = 10 m^3
- Storage tank 1 and 3 inlet valves closed.
- Water Volume at the time of test = 4.18 m^3
- Flowrate = 11.54 m^3/hr

$$T = \frac{V}{Q}$$
$$= \frac{4.18}{11.54}$$
$$= 0.36\ hours$$
$$= 21.7\ minutes$$

Fluorescein dye was added into the contact tank as a pulse input. Sample tap V-6 was opened to allow for visual observation of the dye reaching the outlet, and the time was measured. The dye was observed after 1.5 minutes, 20.2 minutes before the theoretical residence time was reached. This confirms the value in using a fluorescein dye test to plan the sampling frequency for the tests.

Test 2:

- Test 1 site conditions.
- Sodium chloride solution introduced at tank inlet (disinfection point).
- Samples taken from outlet sample tap (V-6).
- Outlet Conductivity [mS/m] measured.

Figure 3 indicates the results of the pulse tracer test using sodium chloride solution as a tracer. Conductivity of the outlet water was measured and confirmed the visual observation; the tracer spikes at 2 minutes after entering the contact tank. The tracer test results indicate that there is short-circuiting in the contact tank at Site 1, and that the disinfectant is not being effectively mixed into the filtrate water. There is a high possibility of dead zones in the contact tank, increasing the risk of microbiological quality failures. The projected flow pattern is shown in Figure 4.

Computational fluid dynamic (CFD) modelling is utilised to simulate the flow patterns within a tank. A laboratory study conducted by Colorado State University (Carlston & Venayagamoorthy, 2015) developed a CFD model based on a circular, un-baffled tank with a single inlet, single outlet configuration as shown in Figure 5 below. The model confirms that there are dead zones in the contact tank of this design, resulting in short-circuiting.

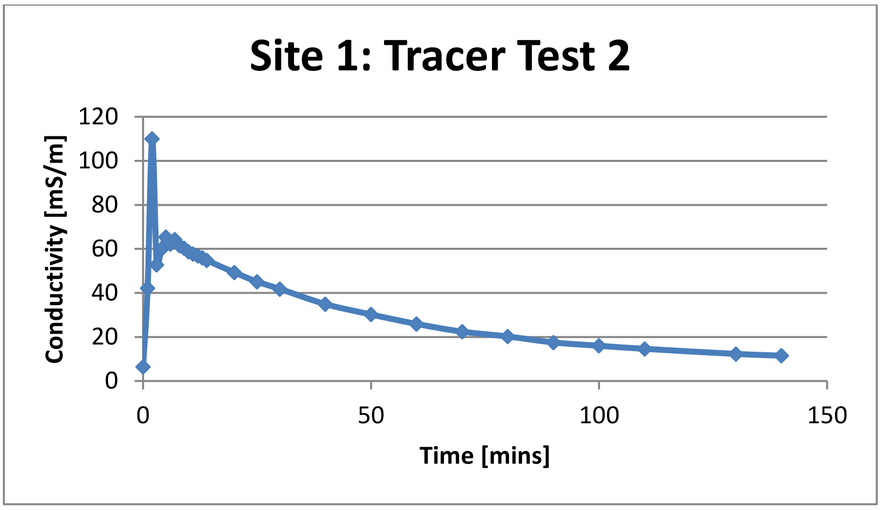

Figure 3: Site 1 Test 2 Results

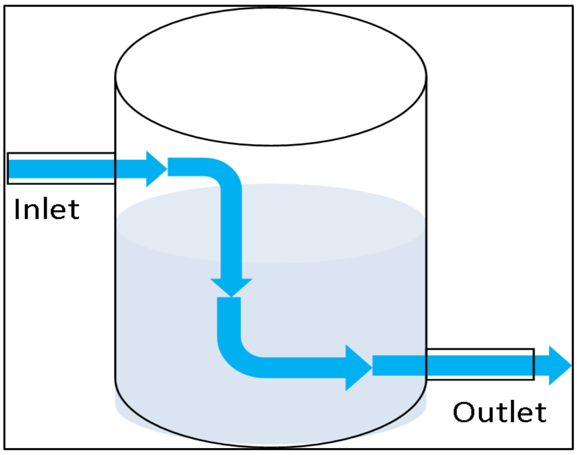

Figure 4: Schematic of Flow Pattern

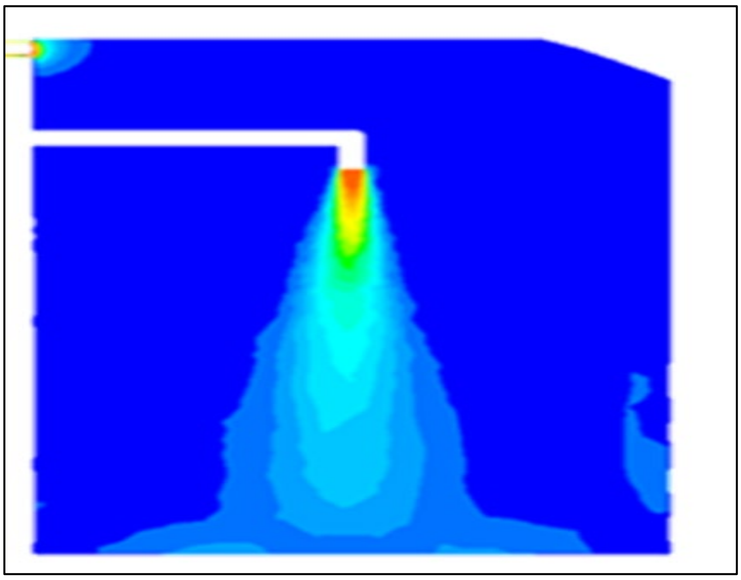

Figure 5 : CFD Model of Tank Flow Dispersion

Between 2018 and 2019, Site 1's raw water averaged an *E. coli* concentration of 650MPN/100ml-988 MPN/100 ml (Table 5). During the same time period, there were no MPN/100 ml *E. coli* detected in the final water (Table 6). This indicates effective disinfection, contradicting the tracer test results. The results prompted further investigation. The disinfected water is pumped from the contact tank through a 90 mm diameter pipe to a reservoir approximately 500 m away. The tracer test using the sodium chloride solution was repeated, with a sample taken at the contact tank outlet, and again at the reservoir inlet. The results of Tracer Test 3 indicate a further 14 minutes of contact time in the pipeline into the final water reservoir. The flow through a long pipeline before the reservoir increases the mixing and contact time of the disinfectant with the water. This may be assisting in effective hydraulic disinfection of the final water, and reducing the negative impact of short-circuiting in the contact tank.

Test 3:

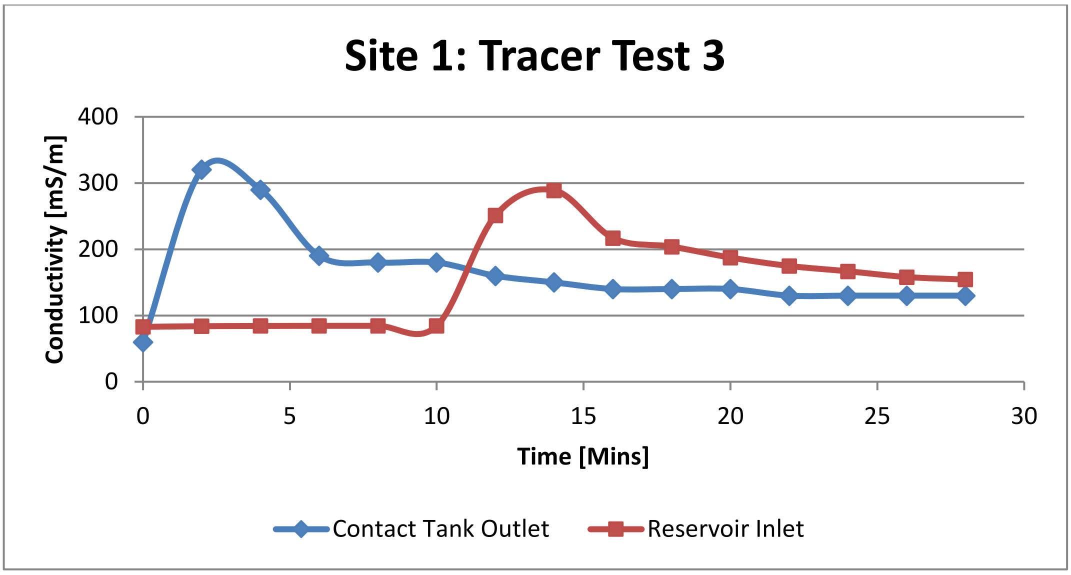

Figure 6 : Site 1 Test 3 Results

The tracer test was then carried out by pumping in the tracer solution at a constant dosing rate. The conductivity was measured at 1 minute intervals and the residence time curve was plotted as below.

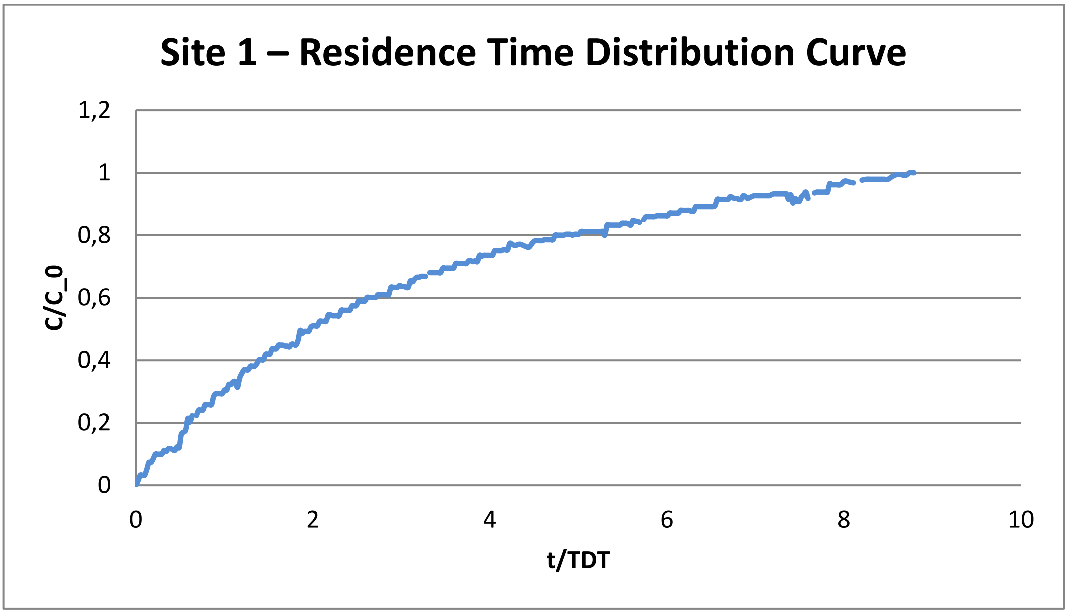

Figure 7: Site 1's RTD Curve

4.1.3 Determination of the baffling factor

Using equation (2) the baffling factor was determined:

$$BF = \frac{T_{10}}{TDT}$$
$$= \frac{4.5}{20}$$
$$= 0.23$$

Using Table 4 for analysis, this value falls between 0.1 un-baffled and 0.3 poor conditions.

4.2 DESIGN 2: RECTANGULAR TANK – BAFFLED

4.2.1 Description of site

Test site 2 is a water treatment works of capacity 2 Ml/d. The plant is located in the Mandeni area of KZN and is operated by Ilembe Municipality. Raw water is abstracted from the Tugela River. Chlorine gas is dosed at the inlet to the contact tank, and the final water is pumped to a reservoir off-site (Figure 8).

Figure 8: Site 2 Contact Tank

4.2.2 Determination of residence time

The contact tank is a concrete, rectangular tank and has two baffles as shown in Figure 9. The first baffle is at the inlet, forcing an underflow mixing of the disinfectant and filtrate. The tank volume is 26 m^3. At the design flow of 2 Ml/d, the contact tank has a design theoretical residence time of 18.72 minutes.

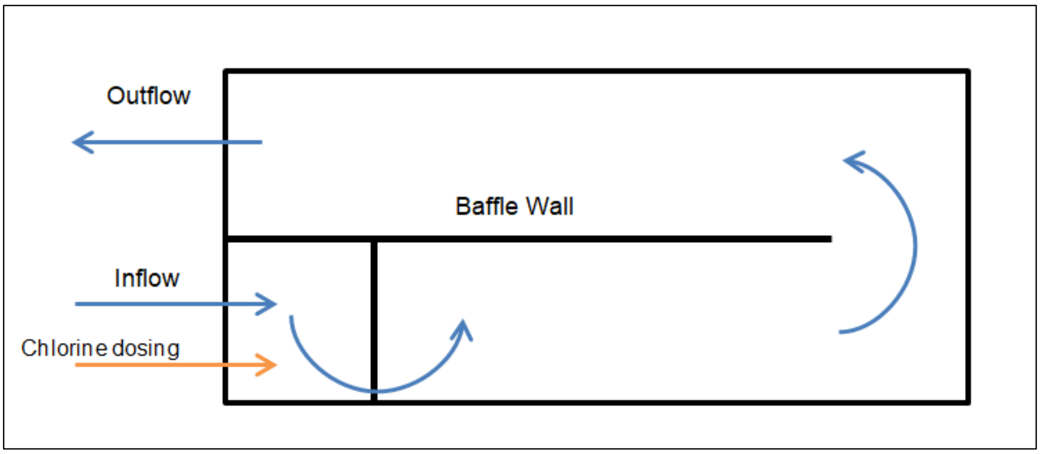

Figure 9: Site 2 Contact Tank Design

On the day of the testing, at a flowrate of 75 m^3/hr, the theoretical residence time was determined as:

$$\tau = \frac{V}{Q}$$
$$= \frac{26m^3}{75\frac{m^3}{hr}}$$
$$= 0.35\ hrs$$
$$= 20.8\ minutes$$

The tracer (sodium chloride solution) was added as a plug input at the inflow point, and conductivity measurements were taken at the outflow point at 1 minute intervals. The tracer spike was detected at 11 minutes (shown in Figure 10), 10 minutes earlier than the theoretical time. The test was repeated with a higher tracer concentration and the spike in conductivity was once again measured at 11 minutes.

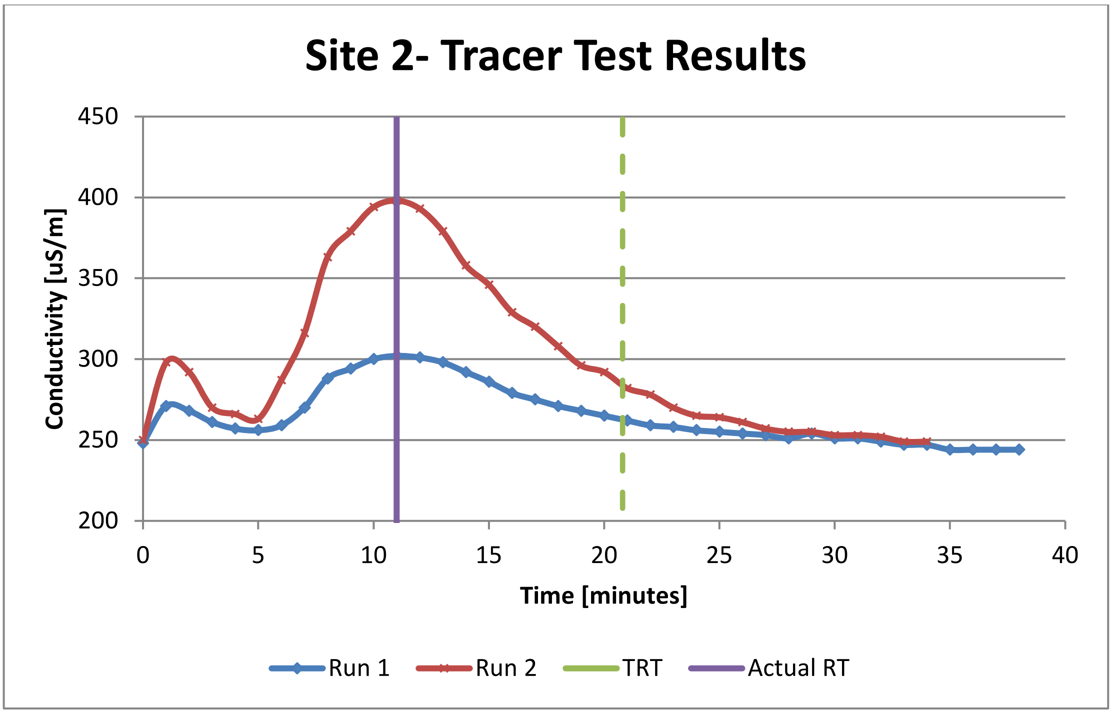

Figure 10 : Site 2 Tracer Test Results

4.2.3 of the baffling factor

Based on these results and using equation (2) the baffling factor was determined as:

$$BF = \frac{T_{10}}{TDT}$$
$$= \frac{4}{20}$$
$$= 0.2$$

Using Table 4 for analysis, this value falls between 0.1 un-baffled and 0.3 poor conditions. Despite having baffles in the tank, there is still a deviation from the theoretical contact time and results in poor mixing conditions. This indicates that the design of a single lengthwise baffle, with an initial overflow weir is insufficient to allow for the full residence time. The test was repeated to include the flow to the offsite reservoir in order to determine the extra contact time provided by a distribution system. Tracer was added to the contact tank at the site, and monitored at the off-site reservoir (Figure 11). One of the downfalls of small waterworks is the lack of sampling taps and access, therefore the off-site reservoir samples were taken at the inlet of the reservoir.

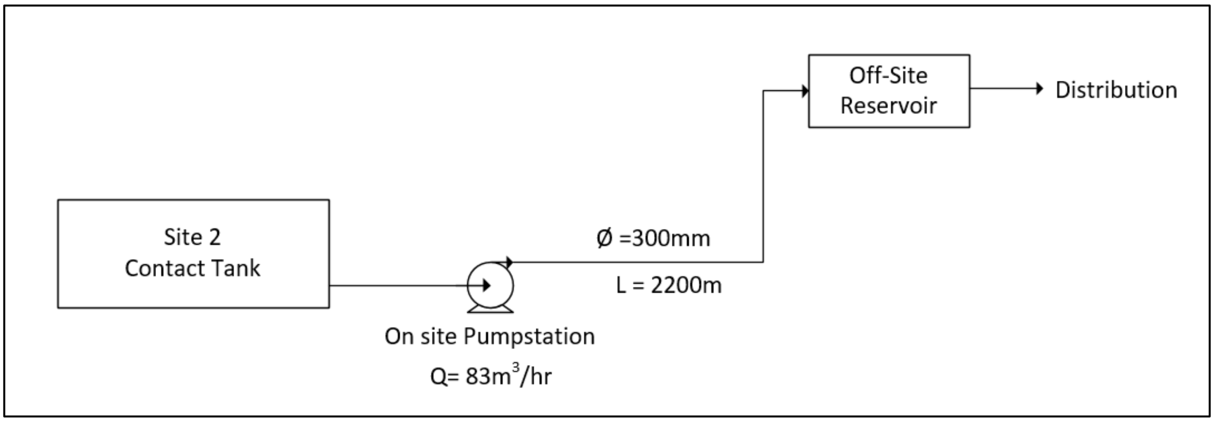

Figure 11: Site 2 Distribution Block Diagram

The expected contact time in the pipeline was determined as follows:

Table 7: Site 2 Distribution line Details

Variable	Value	Unit
Flow, Q	83	m^3/h
Diameter, d	0.3	m
Area, A	0.07	m^2
Length, L	2200	m
Volume, V	155.5	m^3
Contact Time, t	1.88	hours
	113	minutes

The results of the on-site tracer are comparable to previous test results, with a peak at 10 minutes, below the theoretical time of 20 minutes. The distribution line has a length of approximately 2.2km and a diameter of 300 mm. This allows for a contact time in the region of 113 minutes, far above the required contact time of 20-30 minutes. This is excluding the time in the storage reservoir before distribution to customers. Figure 12 shows that the contact time in the pipeline is >>140 minutes as no tracer was detected during this period.

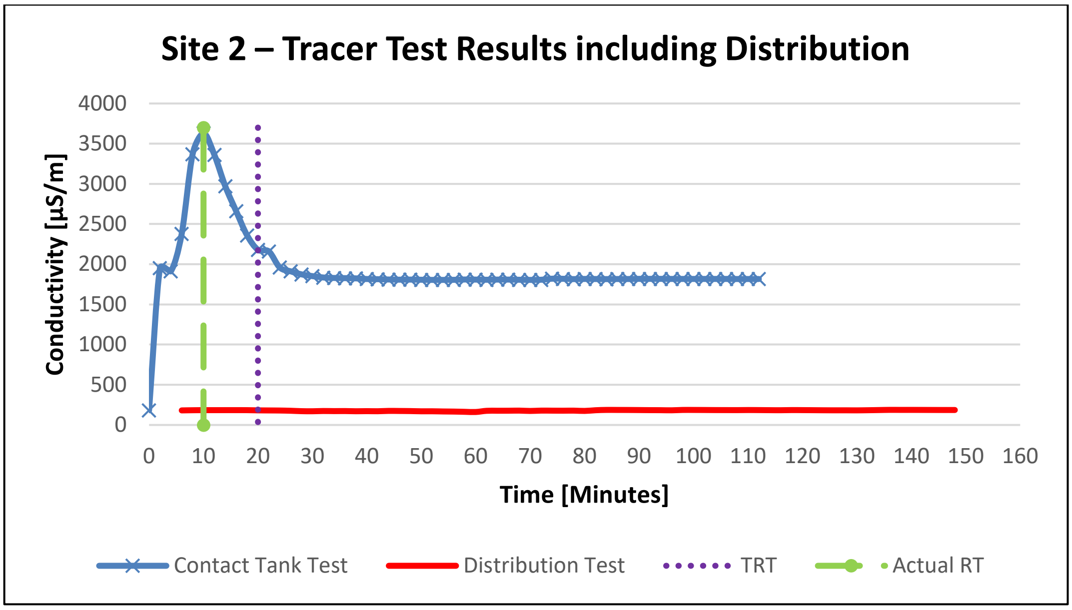

Figure 12: Site 2 Tracer Test including Distribution

4.3 DESIGN 3: RECTANGULAR TANK – NO BAFFLES

4.3.1 Description of site

The third test site has a design capacity of 1 Ml/d. The plant is operated by eThekwini Municipality in KZN and uses onsite electrolytic chlorination (OSEC) for disinfection. This system utilises salt, water and electricity to produce 0.8% sodium hypochlorite solution. The disinfectant is dosed at the inlet to the contact tank, and the final water is pumped to a reservoir off-site (Figure 13 and 14). The free chlorine residual is monitored every three hours. (Figure 15). Table 8 shows the historical water quality parameters.

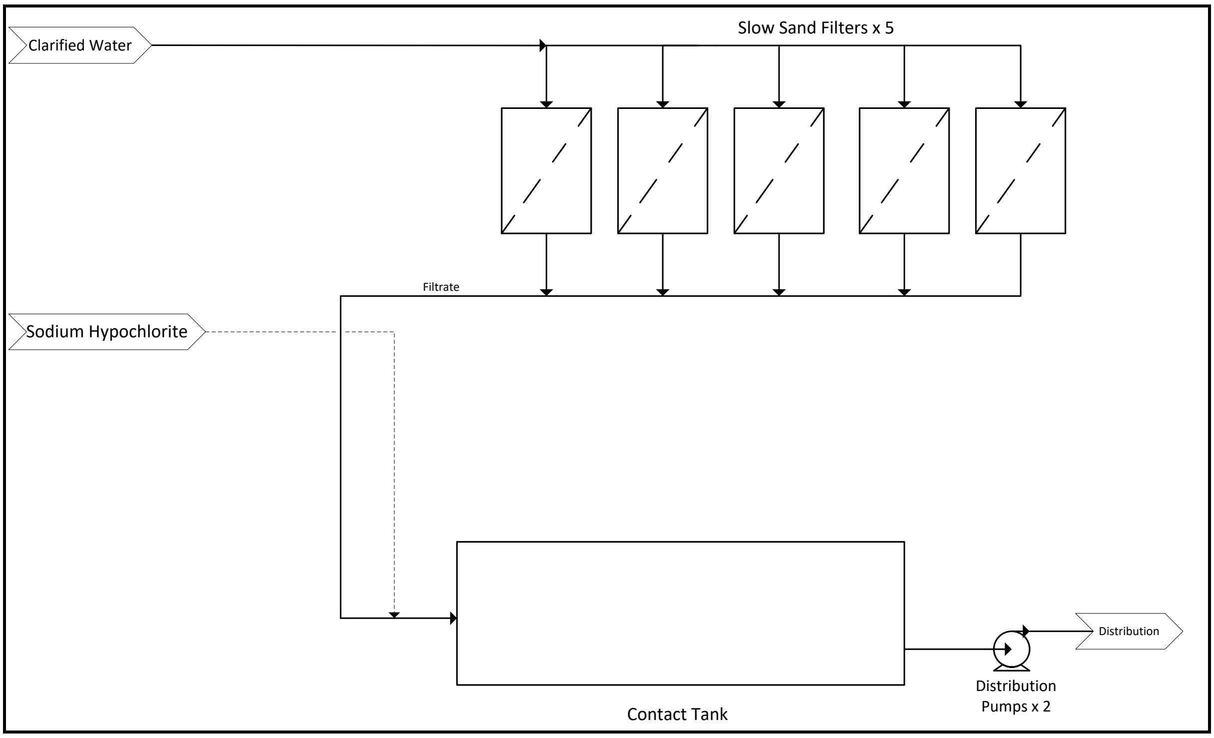

Figure 13: Schematic of Site 3 Contact Tank System

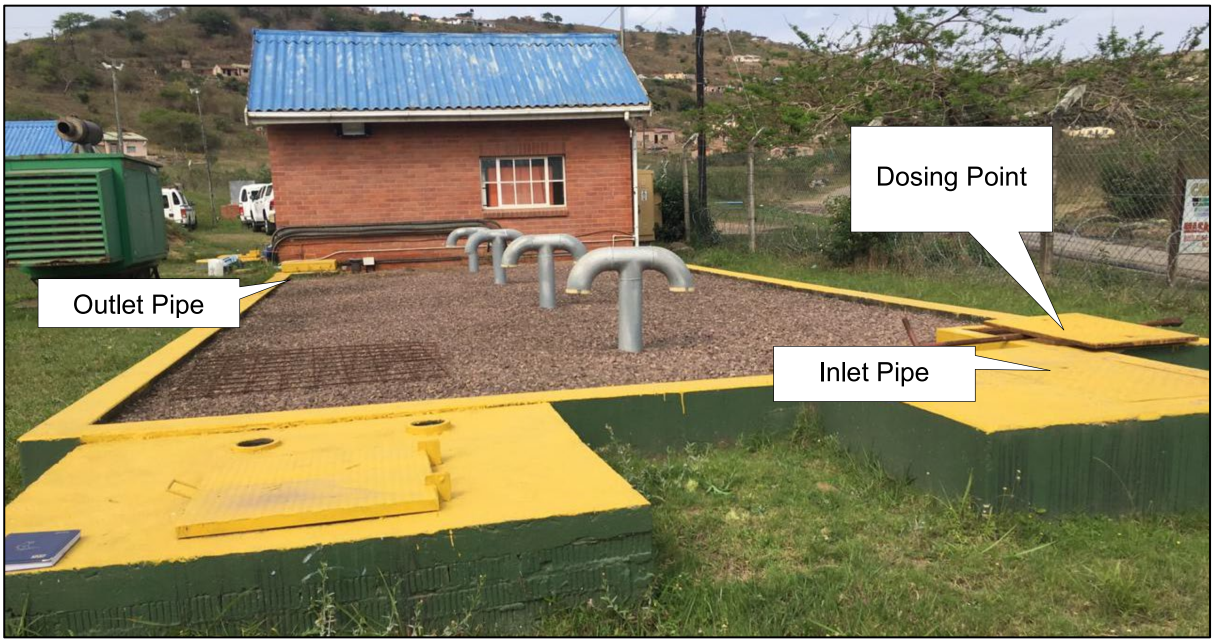

Figure 14: Site 3 Contact Tank

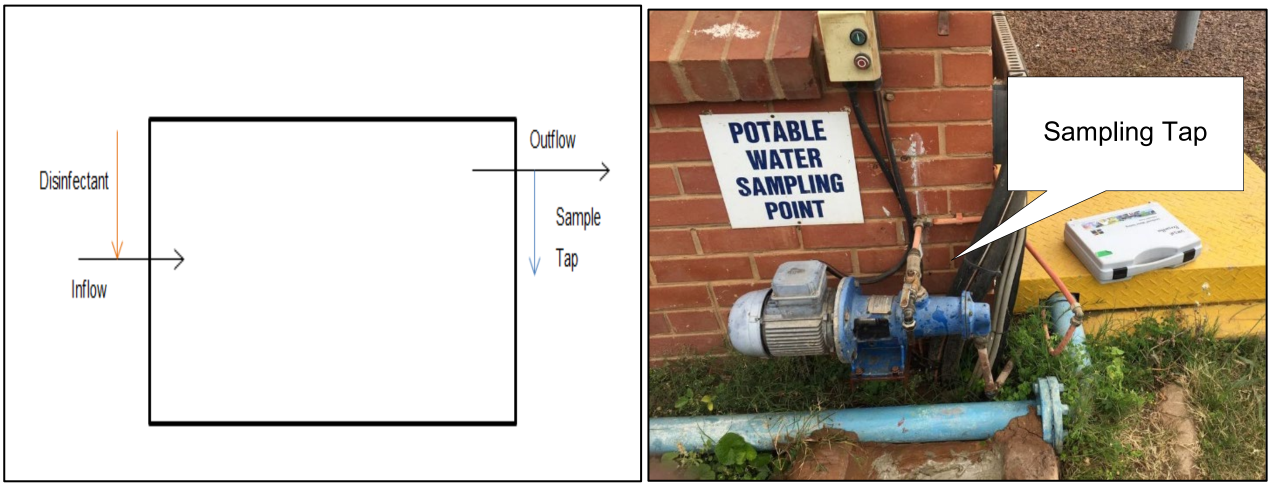

Figure 15: Site 3 Sampling Point

Table 8: Site 3 Final Water Quality Data

	2018			2019		
	Chlorine	**Turbidity**	***E. coli***	**Chlorine**	**Turbidity**	***E. coli***
	[mg/l]	NTU	CFU-100 ML	[mg/l]	NTU	CFU-100 ML
Minimum	0.65	0.07	0	0.58	0.08	0
Maximum	2.10	0.52	2	1.70	0.35	1
Average	1.29	0.17	1	1.15	0.15	0.25

4.3.2 Determination of residence time

At the design flow of 1 Ml/d, the contact tank (144 m^3) has a design theoretical residence time of 3.46 hours or 207 minutes. On the day of the testing, at a flowrate of 35.17 m^3/hr, the theoretical residence time was determined as:

$$\tau = \frac{V}{Q}$$
$$= \frac{144m^3}{35.17\frac{m^3}{hr}}$$
$$= 4.10\ hrs$$
$$= 246\ minutes$$

The tracer (sodium chloride solution) was added as a plug input at the inflow point, and conductivity measurements were taken at the outflow point at 2 minute intervals.

During the initial run a slight spike in the conductivity was detected at 14 minutes, however there was no definitive reading that confirmed the tracer at the outflow. This is much shorter than the expected residence time of 246 minutes. The test was repeated at a higher concentration of sodium chloride solution to confirm results. During run 2 an initial spike was detected at 14 minutes once again, with the peak detected at 20 minutes.

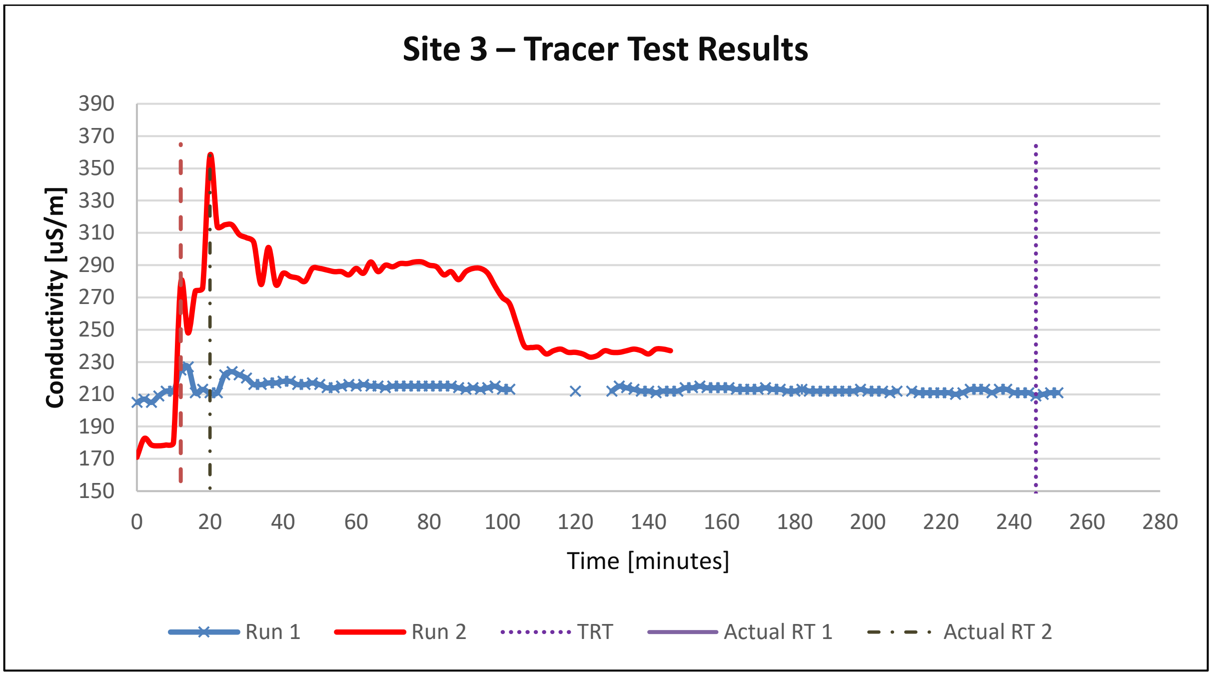

Figure 16: Site 3 Tracer Test Results

4.3.3 Determination of the baffling factor

Based on these results, the baffling factor for run 1 was determined as:

$$BF = \frac{T_{10}}{TDT}$$
$$= \frac{25}{246}$$
$$= 0.1$$

The baffling factor for run 2 was calculated to be 0.08, indicating very poor mixing. This matches the description in Table 4, where a baffling factor of 0.1 relates to un-baffled conditions.

The chlorinated water is pumped to an off-site reservoir. The pump control is based on the level of the reservoir. This prevented a tracer being carried out on the distribution as the flow rate was inconsistent and would result in incorrect data. The theoretical contact time for the pipeline to the reservoir in continuous flow using design flow rate was determined as:

Table 9: Site 3 Distribution Pipe Details

Variable	Value	Unit
Flow, Q	41.67	m^3/h
Diameter, d	0.16	m
Area, A	0.02	m^2
Length, L	1726	m
Volume, V	34.70	m^3
Contact Time, t	0.83	hours
	50	minutes

The final water quality results from the waterworks as indicated in Table 8, show that the plant has had no *E. coli* out of ranges, and has maintained their chlorine residual between 0.8 mg/l to 2.1 mg/l over the past two years. The extra 50 minutes contact time provided by the pipeline allows for this mixing of the final water with the disinfectant.

4.4 DESIGN 4: CIRCULAR TANKS IN SERIES

4.4.1 Description of site

Test site 4 is a water treatment plant of capacity 1.35 Ml/d in Moses Kotane Local Municipality in the North West Province. The site dosed sodium hypochlorite for disinfection, in-line before two circular contact tanks in series. The tanks are 10 m^3 each, with a top-entry bottom exit for the first tank, and bottom entry, bottom exit for the second tank (see Figures 18 and 19).

The plant does not have historical data record that were available. Whilst there was monitoring equipment available at the site, there were no quality records available. Sample results on the day of testing were as shown below:

Table 10: Test Site 4 Water Quality Data

		Raw Water	Final Water
Turbidity	NTU	227	36.1
Free chlorine	mg/l		0.85
Total chlorine	mg/l		0.86
pH		6.88	7.05
Conductivity	µS/m	150	155.8

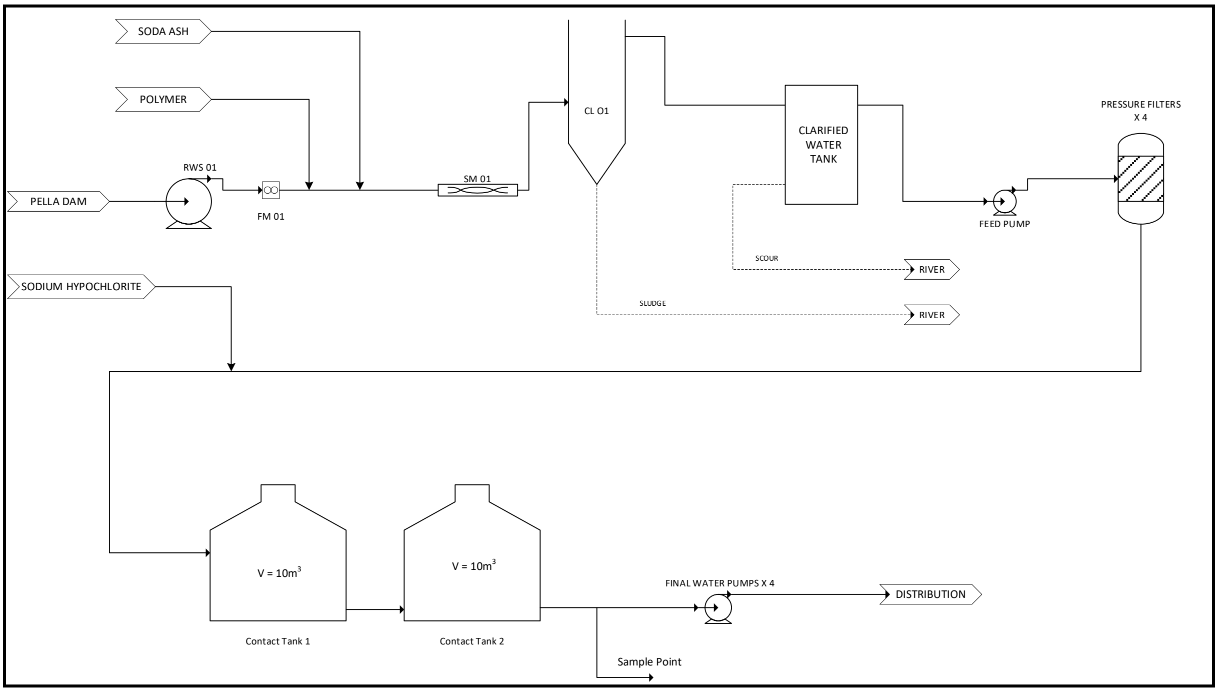

Figure 17: Schematic of Test Site 4

Figure 18: Site 4 Contact Tanks

4.4.2 Determination of residence time

At the design flow of 1.35 Ml/d, the contact tanks (2 x 10 m^3) have a design theoretical residence time of 21 minutes. On the day of the testing, at a flowrate of 32.90/hr, the theoretical residence time was determined as:

$$\tau = \frac{V}{Q}$$
$$= \frac{20m^3}{32.90\frac{m^3}{hr}}$$
$$= 0.6\, hrs$$
$$= 36.5\, minutes$$

The sodium chloride solution was added as a plug input at the top of contact tank 1, and conductivity measurements were taken at 2 minute intervals from the outflow (contact tank 2) sample point. The tracer spike was detected at 16 minutes (shown in Figure 19), 20 minutes earlier than the theoretical time. The test was repeated with a higher tracer concentration and the spike in conductivity was measured at 18 minutes. Comparing these results to Test site 1 shows the addition of a tank in series does not improve the contact time of the system.

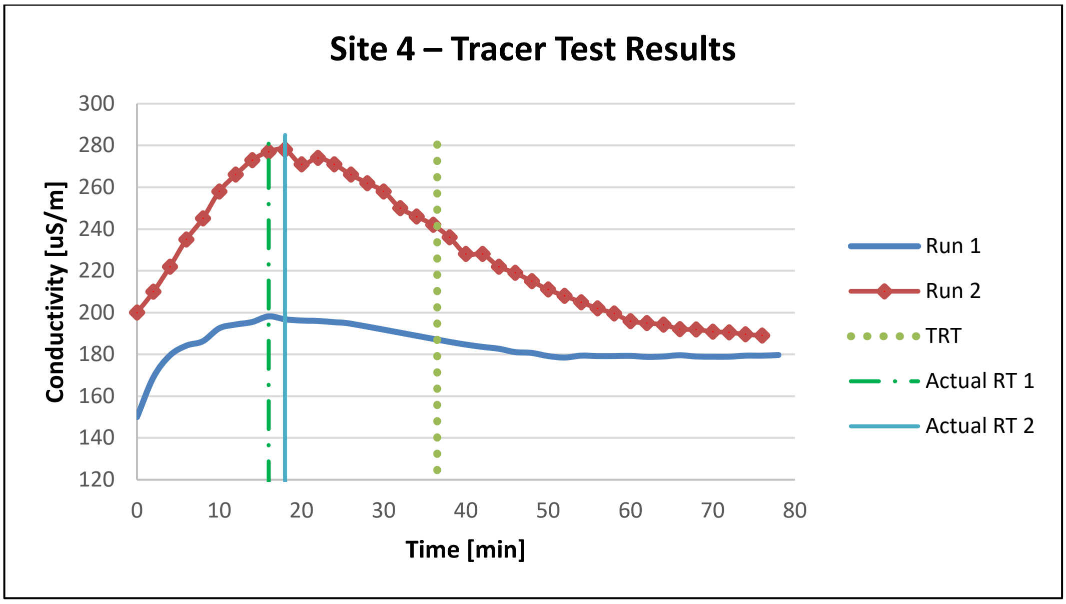

Figure 19: Site 4 Tracer Test Results

4.4.3 Determination of the baffling factor

The residence time distribution curve was plotted and the Baffling Factor was determined as:

$$BF = \frac{T_{10}}{TDT}$$
$$= \frac{7}{36.5}$$
$$= 0.19$$

The baffling factor result from Run 2 was determined as 0.16. These results indicate poor mixing, and are in line with no-baffle conditions.

The final water is pumped to a distribution reservoir approximately 4 kilometres away. Tracer tests could not be conducted due to access restrictions. Due to the distance from the site, it was recommended to the operator that the chlorine dosage be increased to reduce the risk of poor final water quality to the consumer.

4.5 DISCUSSION

4.5.1 Challenges

During the evaluation and testing process, a number of challenges were noted. Due to the tests being done on a live system, every precaution had to be taken not to impact the final water quality or supply to the consumer.

Fluorescein dye was used to allow for an easy visual detection of the residence time at the contact tank. During the first test, a small amount of fluorescein dye was added to the 10 m^3 tank. At the waterworks sample point, small amounts of the dye were observed. However, the dye spread across the surface volume of the off-site reservoir. This led to customer complaints over the next day of receiving “bright green” water out of their household taps. It was decided to stop the use of the dye in future tests to prevent re-occurrence of this problem. This affected the planning of the sampling frequency in future tests, as the actual residence time was not known before the sodium chloride solution tracer was added.

A number of sites have level control of their pumps based on the level in either the on-site or the off-site reservoirs. This often resulted in disruptions of the test process as the tracer test must be run with continuous flow. Pre-planning had to be done with site operations to maintain the reservoir levels such that the pumps are always on, without impacting on supply to the customer.

A number of sites which met the testing criteria, could not be utilised for the tracer tests as there were no suitable access points for adding the tracer. A number of sites do not have manholes or sample taps at the dosing points or outlets of the contact tanks. Pipeline dosing is often used at waterworks, but could not be assessed due to this reason. Some rural waterworks dosed the disinfectant at the clarified buffer tank (prior to the filtration process) either due to maintenance problems at the correct dosing point or no dosing point allocated in the plant design. These were not suitable for accurate representation of the contact tank hydraulic effectiveness.

Another issue faced at waterworks in rural areas was a lack of metering. Often there were no inflow or outflow meters installed. Some sites did have flowmeters, however these were not operational. This limited the ability to calculate the residence times through the contact tanks.

4.5.2 Contact Time and Baffling Factor

Four sites in KZN and North West province were available as testing sites. These sites had a circular tank with no baffle, rectangular tank with no baffle, rectangular tank with a single baffle and two circular tanks in series with no baffles. The results indicate that both circular and rectangular contact tanks with no baffles or mixers results in poor, ineffective contact time. Site 2‘s contact tank is designed with a single baffle; however, this proved insufficient to achieve the required time. The actual contact time in each tank was far less than the theoretical contact time. The Baffling factors were determined and were in line with the USEPA (2003) descriptions.

By ensuring effective disinfection at the contact tank, one can control the disinfectant dosage better and reduce unnecessary wastage of chemicals. As described by Equation (1), the C x t concept indicates that a shorter contact time requires a higher dosage. It allows for proactive, rather than reactive dosage control of the disinfectant.

4.6 SUMMARY

Table 11: Summary of Results

Waterworks	Geometry	Baffling Factor	Description
Site 1: 0.25 Ml/d	Circular No Baffles Top inlet, bottom outlet	0.23	Between 0.1 un-baffled and 0.3 poor conditions.
Site 2: 2 Ml/d	Rectangular Baffled Tank Single Longitudinal Baffle Underflow weir at inlet	0.20	Between 0.1 un-baffled and 0.3 poor conditions.
Site 3: 1 Ml/d	Rectangular No Baffles	0.10	Un-baffled conditions
Site 4: 1.35 Ml/d	Circular in Series No Baffles Top inlet, bottom outlet Bottom inlet, bottom outlet	0.19	Between 0.1 un-baffled and 0.3 poor conditions.

It was found that the negative impact to the consumers was reduced by the presence of storage reservoirs before distribution. These pipelines and reservoirs increased the contact time with the disinfectant, thus resulting in no *E. coli* in the final water and a sufficient chlorine residual. The water treatment system must be assessed holistically when troubleshooting the disinfection process.

It must be noted, that this does not negate the need for accurate design and construction of contact tanks in a water treatment works. The storage time in a reservoir often fluctuates with demand from the consumers. Whilst longer distribution lines and storage reservoirs provide extra contact time, the disinfectant dosage must be adjusted accordingly to prevent chlorine decay and pathogen regrowth. Chlorine demand tests should always be carried out. Certain distribution systems may require higher dosages of disinfectant at the contact tank, or “booster” doses in the reticulation.

In order to improve the efficiency of the disinfection process hydraulically at existing contact tanks at small water treatment works in South Africa, one must first assess the actual contact time using tracer tests. For Water Boards such as Umgeni Water, the main control point for chlorine residual measurement is often at the water treatment works boundary. It is therefore essential to have correctly designed contact tanks as part of the overall plant design.

CHAPTER 5: CONCLUSIONS AND RECOOMENDATIONS

5.1 CONCLUSIONS

Four water treatment works of capacity below 2 Ml/d were selected for the study. Each of these tanks had different contact tank designs as shown in Table 11. Tracer studies were utilised to determine the residence time in each tank and the Baffling Factor used to assess the hydraulic efficiency of the contact tank for disinfection.

The desktop study found that most small waterworks in South Africa do not have a distinct contact tank for disinfection. Final water is generally pumped or flows by gravity to a storage reservoir before distribution.

The theoretical residence time calculation does not reflect the actual residence time in a tank. For accurate determination of residence time, a tracer test should be conducted and baffle factor determined.

The waterworks with separate contact tanks as part of the process were either circular or rectangular with no baffles or mechanical mixing. Tanks with baffles did not have multiple baffles to ensure adequate mixing to prevent short circuiting within the tank. The results indicate that both circular and rectangular contact tanks with no baffles or mixers results in poor, ineffective contact time. All tracer tests indicated an actual residence time below the theoretical residence time. Site 2's contact tank is designed with a single baffle; however, this proved insufficient to achieve the required contact time.

Contact tanks without baffles or mixers will not be able to achieve the required contact time as per the theoretical calculation. Plant designers must consider the importance of residence time for disinfection and allow for variable flow considerations. When applying the Ct concept, efforts should be to increase the contact time, rather than disinfectant concentration to prevent any harmful byproducts, or added costs. The water treatment system must be assessed holistically when troubleshooting the disinfection process. Sampling points should also be included as part of plant designs at each unit process to allow for ease of optimisation.

5.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Modifications such as extra baffles, mechanical mixers and split inlets should be investigated further to determine their impact on improving the Baffling Factor. These modifications should be implemented on live sites to improve the contact time and reduce short circuiting. Tracer tests should be done to monitor and measure the degree of improvement to the Baffling factor. The number and orientation of baffles must maximise the contact time at design flow, such that during periods of low flow, effective contact time is achieved. Computational Fluid Dynamic (CFD) modelling may be considered as part of the plant designs as it a useful tool to validate the hydraulics and disinfection residence time for contact tanks.

REFERENCES

Anon., 1996. *Constitution of the Republic of South Africa.* s.l.:National Legislative Bodies.

Anon., 2015. *South African National Standard Drinking Water Part 1,* Pretoria: SABS.

Carlston, J. S. & Venayagamoorthy, S. K., 2015. Impact of Modified Inlets on Residence Times in Baffled Tanks. *Journal AWWA.*

Fogler, 2006. *Elements of Chemical Reaction Engineering.* 4 ed. s.l.:Prentice-Hall.

Jacangelo, J. G. & Trussell, R. R., 2002. Internation Report: Water and Wastewater disinfection: Trends, Issues and Practices.

Kawamura, S., 2000. *Integrated Design of Water Treatment Facilities.* s.l.:John Wiley and Sons.

Mackintosh, G. & Colvin, C., 2002. Failure of Rural Schemes in South Africa to provide potable water. *Environmental Geology,* Volume 44, pp. 101-105.

Momba, M. N., Thompson, P. & Obi, C. L., 2008. *Guidelines for the Improved Disinfection of Small Water Treatment Plants.* TT 355/08 ed. s.l.:WRC.

Rauen, W. B., Angeloudis, A. & Falconer , R. A., 2012. Appraisal of chlorine contact tank modelling practices. *Water Research,* Volume 46.

SABS, 2015. *South African National Standard Drinking Water Part 1,* Pretoria: SABS.

Schott, G. J., 1999. *Case Study: City of Napa – Tracer Analysis of Chlorine Contact Tank at Hennessey WTP.* [Online]
Available at: https://www.waterboards.ca.gov/.../napa_case_study_chlorinecontact_tanks_July1999
[Accessed 11 June 2018].

Schutte, F., 2006. *Handbook for the Operation of Water Treatment Works.* Pretoria: WRC.

South African Government, 2020. *Water and sanitation.* [Online]
Available at: https://www.gov.za/about-sa/water-affairs
[Accessed 05 03 2020].

South African Human Rights Commission, 2014. *Report on the Right to Access Sufficient Water and Decent Sanitation in South Africa:,* s.l.: s.n.

Taylor, Z. H., Carlston, J. S. & Venayagamoorthy, S. K., 2015. Hydraulic design of baffles in disinfection contact tanks. *Journal of Hydraulic Research.*

Teefy, S., 1996. Tracer Studies in Water Treatment Facilities: A Protocol and Case Studies. *AWWA.*

Templeton, M. R., Hofmann, R. & Andrews, R. C., 2006. Case study comparisons of computational fluid dynamics (CFD) modeling versus tracer testing for determining clearwell residence times in drinking water treatment. *Environmental Engineering Science,* Volume 5, pp. 529-536.

United Nations, 2019. *Sustainable Development Goal 6.* [Online]
Available at: https://sustainabledevelopment.un.org/sdg6
[Accessed 12 March 2020].

USEPA, 2003. *Disinfection Profiling and Benchmarking Technical Guidance Manual.* EPA 816-R-03-004 ed. Washington: Office of Water.

Wilson, J. M. & Venayagamoorthy, S. K., 2010. Evaluation of hydraulic efficiency of disinfection systems based on residence time distribution curves. *Environmental science and technology,* 44(24).