THESIS

ASSESSMENT AND IMPROVEMENT OF HYDRAULIC DISINFECTION EFFICIENCY OF A LIVE SMALL DRINKING WATER SYSTEM IN SOUTH AFRICA

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ABSTRACT

ASSESSMENT AND IMPROVEMENT OF HYDRAULIC DISINFECTION EFFICIENCY OF A LIVE SMALL DRINKING WATER SYSTEM IN SOUTH AFRICA

Since the implementation of chlorination, the most common method of water disinfection, diseases such as Cholera, Typhoid Fever, and Dysentery have been essentially eliminated in the U.S. and other industrialized countries (WHO 2017). However, these nations still experience challenges in meeting drinking water standards. In 2009, the Colorado Department of Public Health and Environment contracted Colorado State University (CSU)'s Department of Civil and Environmental Engineering to address the poor hydraulic disinfection efficiency of contact tanks of small-scale drinking water systems. From this research, the *Baffling Factor Guidance Manual* (2014) was published, which presents innovative modifications proven to increase the hydraulic disinfection efficiency of small-scale contact tanks. The proposed innovative technology has the potential to have a significant positive impact in developing nations since at least 2 billion people worldwide use a drinking water source that is contaminated with feces (WHO 2017). Historical experience suggests that simply transporting a technology does not necessarily equate to long-lasting impact, but how that technology is transferred is critical to its sustainability. A successful solution to the need for disinfected water must be holistic, taking into consideration culture, law, politics, economics, environment, etc.

The focus of this thesis is to investigate further the application of the innovative contact tank modifications of an inlet manifold and random packing material (RPM) on live systems. A case study was conducted on a small waterworks in the rural town of Rosetta, KwaZulu-Natal, South Africa, in collaboration with Umgeni Water. Physical tracer tests were conducted on a 10,000L cylindrical tank acting as the contact chamber to assess the hydraulic disinfection efficiency in terms of baffling factor (*BF*), before and after the installation of a 4-way inlet manifold modification. This modification resulted in a 37% improvement in the *BF*, increasing the contact time (*CT*), an important aspect of disinfection, in the cylindrical contact tank from 8.4 min-mg/L to 11.0 min-mg/L.

In addition to the international case study, a pilot study was conducted at CSU to address the biofilm formation concerns of the innovative use of random packing material (RPM) in contact tanks. Preliminary results support the hypothesis that the presence of a disinfectant in the contact tank, though in the process of disinfecting the water, would mitigate the growth of a biofilm on the RPM.

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LIST OF ACRONYMS

BF	Baffling Factor
CDPHE	Colorado Department of Public Health and Environment
CFD	Computational Fluid Dynamics
CSU	Colorado State University
CT	Contact Time
DBP	Disinfection By-Products
DoH	Department of Health
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
DWQ	Drinking Water Quality
EFML	Environmental Fluid Mechanics Laboratory
EPS	Exopolysaccharides
FBW	Free Basic Water
FTC	Flow Through Curve
gpm	gallons per minute
HDI	Human Development Index
IHDI	In-equality adjusted HDI
KZN	KwaZulu-Natal
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
ML/d	Mega liters per day
RPM	Random Packing Material
RTD	Residence Time Distribution
SANS 241	South African National Standards for Drinking Water
SDWA	Safe Drinking Water Act
SWTS	Small Water Treatment Systems
TDT	Theoretical Detention Time
UN	United Nations
U.S.	United States of America
USEPA	United States Environmental Protection Agency
WISA	Water Institute of Southern Africa
WHO	World Health Organization

WRC	Water Research Commission
WSA	Water Services Authority
WSP	Water Services Provider
WW	Waterworks

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Access to clean water remains a serious problem in many developing countries worldwide. The World Health Organization (WHO) estimates that, globally, 844 million people lack basic drinking-water services and at least 2 billion people use a drinking water source contaminated with feces (WHO 2017). Water that is contaminated can transmit diseases such Cholera, Dysentery, Typhoid, and Polio (WHO 2017). Also, it is estimated that diarrhea, from drinking contaminated water, causes 502,000 deaths each year (WHO 2017). Chronic poor health has other implications such as reduced productivity, lack of school attendance, and costly treatments, all of which steal from the quality of life and the ability to improve one's situation (WHO 2017). The strong link between access to safe and reliable water and poor health, with all its consequences, implies that safe water ultimately impacts multiple aspects of society. While this may not be as evident in the context of an industrialized country such as the United States (U.S.), issues concerning drinking water treatment are still prevalent. For example, small drinking water systems (less than 5,000 gallons operating up to 50 GPM, typical of rural water treatment plants), account for 93% of the United States Environmental Protection Agency (USEPA) Drinking Water Quality violations even though they serve only 18% of the U.S. population (USEPA 2011).

Chlorination is the most widely used method of disinfection in drinking water treatment systems in the United States and worldwide. The United States Environmental Protection Agency's (USEPA) Long Term 1 Enhanced Surface Water Treatment Rule *Disinfection Profiling and Benchmarking Manual* (LT1ESWTR) (USEPA 2003) provides guidelines for the physical removal or inactivation of waterborne pathogens during disinfection in terms of contact time (*CT*).

CT is the product of the outlet disinfectant residual concentration (*C*) and a characteristic contact time, *T*. Baffling is used in many contact tanks (disinfection chambers) to increase the contact time of the disinfectant with the water by elongating the path the water must flow. USEPA provides guidelines developed from tracer studies for determining baffling factors based on baffling description (USEPA 2003). However, due to the over generalized descriptions, the contact tank baffling factor as specified in LT1ESWRT is a potentially imprecise factor in the log inactivation calculation. Furthermore, the baffling conditions described in the LT1ESWRT document have limited applicability for the contact tank configurations utilized by many small public water systems in the U.S. and worldwide due to a number of reasons such as impact of inlet/outlet piping configurations and transitions to laminar flow conditions under low flow rates, etc. Hence, it is a critical need to increase the knowledge base on the hydraulic disinfection efficiency of small contact tanks and develop innovative techniques to enhance the hydraulic disinfection efficiency of such systems in order to ensure compliance with disinfection rules.

To this end, the Colorado Department of Public Health and Environment (CDPHE) collaborated with Colorado State University (CSU) to conduct extensive research examining several different types of disinfection contact systems. The hydraulics and mixing characteristics of a number of pre-engineered tanks were determined through a multi-pronged approach that involved analysis through a combination of computational modeling and experimental studies. Specifically, these studies utilized computational fluid dynamic (CFD) models and physical tracer experiments. Valuable insight and design guidance has been gathered through this extensive study and a guidance document, the *Baffling Factor Guidance Manual* (2014), culminating from this study is now used by the CDPHE to provide technical guidance for small systems in the State of Colorado. This work has direct impact on the well-being of the citizens of Colorado and can be applied throughout the U.S. and overseas, particularly in developing communities as they typically lack extensive infrastructure, finances, and technical support. It is to this aim that this master's thesis finds its relevance.

1.2 OBJECTIVES

In a world where systems (i.e. water systems) function within larger societal systems that influence one another, the technical and social aspects are discussed. This is in line with the idea of sustainable international development. The first objective is to build a foundational understanding of water treatment in South Africa from law and policy, politics, management, and technology, as well as the theory of contact time (*CT*) and baffling factor (*BF*).

The main objective of this thesis is to apply the research put forth in the *Baffling Factor Guidance Manual* to improve the hydraulic disinfection efficiency of a live small water system, specifically in an international context. A collaboration was forged with a local water provider, Umgeni Water, in Durban, South Africa as the preferred avenue to work within the nation. Umgeni Water selected the small water system in Rosetta, KwaZulu-Natal for a case study. The modification chosen to apply to the live system in Rosetta was an inlet manifold, which reduces the inflow velocity into the contact tank and better distributes the inflow across the cross-sectional area on the contact tank to promote greater plug flow like conditions. The hydraulic disinfection efficiency of the live system was assessed before and after the inlet manifold was installed by method of a physical tracer study.

Another objective is to further investigate the long-term use of random packing material (RPM) in contact tanks, also presented in the *Baffling Factor Guidance Manual* (2014). A pilot study was conducted to investigate the potential formation of a biofilm, which would oppose the action of disinfection, on the surfaces of the RPM from any microbiological contaminants present in the water entering a contact tank.

1.3 NEW CONTRIBUTIONS

The significant new research contributions presented in this thesis include:

- The application of suggested contact tank modifications found in the *Baffling Factor Guidance Manual* on a live plant and the importance of a holistic hydraulic disinfection efficiency assessment.
- Preliminary support that the presence of a disinfectant will mitigate the formation of a biofilm on RPM used in a contact tank.

1.4 RESEARCH PUBLICATIONS

The case study research presented in Chapter 3 is being prepared for submission to the *Journal of American Water Works Association.*

1.5 ORGANIZATION OF WORK

Chapter 2 contains a literature review covering water policy and regulations in South Africa, current status and issues concerning South African small water treatment systems (also called waterworks), and water treatment processes including disinfection and *CT* method. The literature review also covers *BF* and relevant contact tank modifications as presented in the *Baffling Factor Guidance Manual* and previous MS students' thesis projects at CSU.

Chapter 3 presents the case study conducted at Rosetta Waterworks in KwaZulu-Natal, South Africa. Chapter 4 discusses the pilot study conducted in the Environmental Fluid Mechanics Laboratory (EFML) at CSU to evaluate the long-term use of random packing material (RPM) in contact tanks. Chapter 5 provides conclusions of the work presented as well as a brief scope of the proposed research to be conducted through a PhD dissertation.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

The *Baffling Factor Guidance Manual* was created for the CDPHE relevant to small water treatment plants in the state of Colorado. The technologies presented in this document are relatively simple and inexpensive in order to be practical for small, rural water systems that typically lack financial, technical, and managerial support. Similar situations are common in developing communities. Therefore the transfer of these technologies has the potential to have a significant positive impact in nations that struggle with providing access to safe water.

The nation of South Africa was chosen as the location for a case study. South Africa was selected based on several factors: 1. South Africa has a medium developed society (UN 2016) such that water infrastructure exists, 2. South Africa has many small water systems, similar to those in the U.S., for which these technologies could be more easily transferred to, and 3. Useful connections already existed within the nation. This literature review focuses on small water treatment systems in South Africa to build a better understanding of the current operations in order to discern a reasonable direction to transfer the technology from the *Baffling Factor Guidance Manual* to a South African context. The literature review not only covers the technical aspects of drinking water treatment but also non-technical aspects that influence the drinking water treatment operations.

2.2 SOUTH AFRICA

South Africa is located at the southern tip of the continent of Africa as seen in **Figure 1** and shares borders with Namibia, Botswana, and Zimbabwe to the north, Swaziland and Mozambique to the east, and surrounds Lesotho. According to the United Nations (UN), South

Africa is considered to have 'medium' development based upon the Human Development Index (HDI) score of 0.666 as compared to the U.S.'s HDI of 0.920 (where an HDI of 1 is considered to be 'fully' developed) (UN 2016).

South Africa is a very diverse nation with many different cultures and 11 official languages. There is a multi-racial population of 54.5 million people that is 80.2% black, 8.8% coloured, 8.4% white, and 2.5% Asian, warranting the name "rainbow nation". Race in South Africa has historically been a major subject since apartheid legally segregated all racial groups for nearly 50 years. Though apartheid ended in the mid-1990's, its effects are still felt. This is reflected in the in-equality adjusted HDI (IHDI) score of 0.435.

Currently, South Africa is suffering from high unemployment, upwards of 50% for citizens aged 15-24 (UN 2016). The UN estimates that 64.8% of the population resides in urban areas which implies that 35.2%, or 19.2 million people, live in rural areas. The focus of this thesis is concerned with small water treat systems that are found in the rural areas of South Africa.

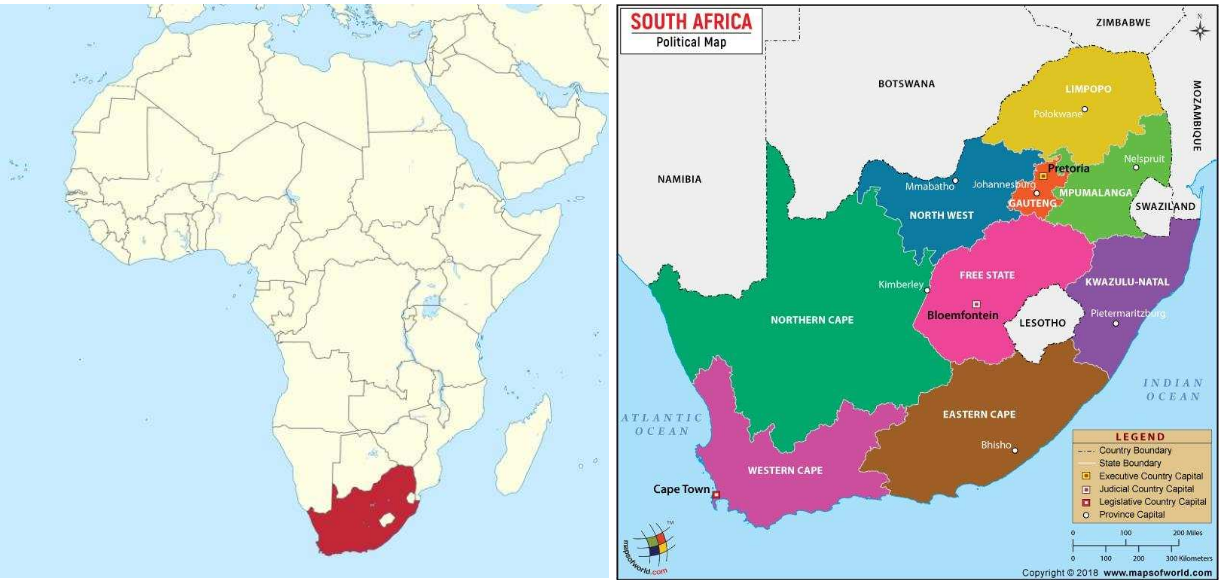


Figure 2.1: Map of the continent of Africa (the country of South Africa indicated in red) (left, TUBS 2011), and the nation of South Africa by provinces (right, www.mapsofworld.com 2018)

2.2.1 WATER LAW

There are a number of legislative documents regarding water and its governance in the nation of South Africa. The Constitution of South Africa of 1996, states in Sec 27.1.b "Everyone has the right to have access to sufficient food and water." The constitution also delegates the responsibilities of water services to the local governments while the national and provincial governments are to simply support, monitor, and regulate the local government's provision of water services. At the national level, the Department of Water and Sanitation (DWS) is the entity that formulates and implements water management principles. There are three key principles by which South Africa manages its water as found in the National Water Act, Act 36, 1998; "*Sustainability* in social, economic, and environmental aspects, *Equity* such that every citizen must have access and benefit by the use of water, and *Efficiency* since South Africa is not a water rich country therefore water must not be wasted" (Mackintosh and Unathi 2008).

Subsequent acts detail the specifics of water service organization in order to ensure the provision of water services (Mackintosh and Unathi 2008).

- The Water Services Act, 1997, outlines the municipal functions.
- The National Water Act, 1998, "rationalizes that water is an indivisible national resource for which the national government is the overseer."
- The Local Government: Municipal Demarcation, 1998, provides a legal framework for defining and implementing the transition to the local government system.
- The Local Government: Municipal Structures, 1998, defines the types and structures of municipalities (i.e. Metropolitan, District, or Local).
- The Local Government: Municipal Systems Acts, 2000, clarifies how the local governments should operate as well as allowable partnerships a municipality may enter.

Durban was the first South African city to implement a policy of Free Basic Water (FBW) in 1998 that included 6 cubic meters of free water per month per household (Galvin 2012). In 2001 the policy of FBW became a national policy, to be implemented gradually according to a municipality's capability to do so (Galvin 2012).

2.2.2 WATER STAKEHOLDERS

There are multiple stakeholders involved in water management in South Africa including regulators, water service authorities, water service providers, facilitators, users, and conflict resolvers (Mackintosh and Unathi 2008). Each stakeholder has a different role therefore all must work together. The regulating organizations are the Department of Water and Sanitation (DWS) as well as the Department of Health (DoH).

Water Boards and/or municipalities are considered water service authorities (WSA). The WSAs are responsible for the provision of safe drinking water. Specifically, WSAs have a legal responsibility of the realization of rights to basic water services, planning, regulation, and communication. Legally, the rights to basic water services are subject to available resources. This also includes the provision of effective and efficient ongoing services, i.e. performance management and by-laws, as well as sustainability with regard to financial planning, tariffs, service level choices, and environmental monitoring (Mackintosh and Unathi 2008). WSA planning incorporates preparing water services development plans involving integrated financial, institutional, social, technical, and environmental planning in order to progressively ensure efficient, affordable, economical, and sustainable access to water. In addition to planning, WSAs are responsible for the selection, procurement, and contracting of water services providers (WSP) (Mackintosh and Unathi 2008). Beyond selection there is also regulation of water service provision and WSP through by-laws, contract regulation, monitoring, and performance management. A large component of monitoring is concentrated on the quality of drinking water provided to consumers as compared to the South African National Standards on Drinking Water (SANS 241) (Mackintosh and Unathi 2008). Finally, the WSAs are responsible for consumer education and communication. This includes health and hygiene promotion, water conservation and demand management, information sharing, and communicating any health risks to consumers and the appropriate authorities as described in the regulations of the Water Services Act (No. 108 of 1997) (Mackintosh and Unathi 2008).

Referring back to a WSA's responsibility to select a WSP, the WSA may either provide water services itself or contract another organization to act as the WSP. A WSP is responsible to provide water services in accordance with the South African water laws previously discussed and in terms of any specific conditions set by the WSA in a contract (Mackintosh and Unathi 2008). In addition to the provision of water services, a WSP must publish a consumer charter that is consistent with by-laws and other regulations and approved by the WSA. This charter includes the duties and responsibilities of both the WSP and the consumer together with conditions of supply of water services and payment (Mackintosh and Unathi 2008). Municipalities are most commonly the WSP. There are three levels of municipalities: local, district, and metropolitan. A local municipality typically includes two to three towns amid surrounding rural areas. A district municipality typically encompasses three to six local municipalities. A metropolitan municipality comprises a large city and the surrounding metropolitan area (Mackintosh and Unathi 2008). In South Africa there are 6 metropolitan municipalities, 47 district municipalities, and 231 local municipalities located within the areas of the district municipalities.

2.2.3 DRINKING WATER QUALITY STANDARD

In the USEPA sets the standards for drinking water quality in accordance with the Safe Drinking Water Act (SDWA) that all public water treatment systems must meet. Similarly in South Africa, there is the SANS 241 that categorizes two classes of drinking water based upon three basic parameters: physical, microbiological, and chemical quality. Water that is Class I is considered acceptable for consumption over a lifetime whereas Class II water is considered acceptable for only short-term consumption, i.e. not exceeding a certain number of years. If water fails to meet Class II standards it is classified as unfit for human consumption. The microbiological safety requirements set by SANS 241, which are most relevant to this thesis, are given in **Table 2.1** below. These requirements are less stringent than WHO's Guideline that states E. coli and Thermotolerant coliform bacteria "must not be detectable in any 100-ml sample" (WHO 2017).

Table 2.1. Microbiological Safety Requirements (WRC Report No TT 265, 32)

Determinant	Unit	Allowable Compliance Contribution		
		95% of samples (min)	4% of samples (max)	1% of samples (max)
		Upper Limits		
E. Coli	Count/100mL	Not Detected	Not Detected	1
Thermotolerant (fecal) coliform bacteria	Count/100mL	Not Detected	1	10

All WSAs in South Africa are legally required to monitor drinking water quality on a monthly basis depending on the size of the population that it services (see **Table 2.2**). The Water Services Act does not criminalize non-compliance with the national standards nonetheless there are penalties. However, as long as a WSA informs the necessary parties of its failure to meet this obligation then the WSA significantly reduces the risk of suffering these penalties (Mackintosh and Unathi 2008).

Table 2.2. Minimum Frequency of Sampling (Schutte 2006)

Population Served	Frequency* (minimum)
More than 100,000	10 every month per 100,000
25,001 – 100,000	10 every month
10,001 – 25,000	3 every month
2,500 – 10,000	2 every month
Less than 2,500	1 every month
* During the rainy season, sampling should be carried out more frequently	

2.2.4 BLUE DROP CERTIFICATION PROGRAMME

In an attempt to ensure a sustainable supply of safe drinking water at a national level South Africa has instituted the Blue Drop Certification Programme. The Blue Drop Certification goes beyond merely drinking water quality (DWQ) but takes into consideration the whole water treatment plant operation including five key performance areas: water safety planning (weighted 35%), treatment process management and control (weighted 10%), drinking water quality (DWQ) compliance (weighted 30%), management, accountability, and local regulation (weighted 10%), and asset management (weighted 15%) (Blue Drop Report 2012). Blue Drop scores are given in the form of a percentage (see **Table 2.3**) and current scores are made publicly available and can be found on The Local Government Handbook website for each municipality (see **Table 2.4**).

Table 2.3. Blue Drop Score Clarification (Blue Drop Report 2012)

The 5 Key Performance Areas assessed for Blue Drop Certification 2011		
Color Codes		Appropriate action by municipality
Blue	90 – 100%	Excellent situation, need to maintain via improvement
Green	75 – 90%	Good status, improve on gaps identified to shift to ‘excellent’
Black	50 – 75%	Average performance, ample room for improvement
Yellow	33 – 50%	Very poor performance, needs attention
Red	0 – 33%	Critical state, need urgent attention

2.2.5 SMALL WATER TREATMNET SYSTEMS (SWTS)

Almost 20% of the South African population is dependent on small water treatment systems (Makungo et al. 2001). Taking into consideration that 35.2% of South Africans live in rural areas, then upwards of 15% of the population is still lacking improved water treatment services. Small water treatment systems (SWTS), or waterworks, in South Africa are defined differently than in the U.S. In South Africa SWTS are those located in areas that are not well serviced and do not normally fall within urban areas. These include water supplies from treatment plants of small municipalities as well as establishments such as rural hospitals, schools, clinics, and forestry stations (Momba et al. 2008).

2.2.6 CURRENT OPERATIONAL STATUS OF SWTS

Operations of SWTS face multiple challenges in pursuit of providing the required quantity and quality of drinking water to its consumers. For the purposes of this thesis, the technical and non-technical issues of small water treatment systems in South Africa will be discussed to gain a better understanding of the current situation. However, water treatment plants are not isolated from larger systems at work. An example of this is also given as it relates to the operation of small water treatment systems.

2.2.6.1 TECHNICAL

Surveys of SWTS have discovered that 50% are not producing the desired water quantity or quality (Makungo et al. 2001). In terms of microbiological compliance, only 67% of the plants complied with the SANS 241 recommended limits for total coliforms and only 72% for fecal coliforms at the point of treatment (Momba et al. 2008). Distribution systems of the pipe network often do not show acceptable levels of residual chlorine even when the plant chlorination systems gave adequate dosage at the dosing points. Specifically, 40% of plants did not comply with the ideal free chlorine residual range of 0.3-0.6 mg/L in their consumer’s tap water (Momba et al. 2008). Moreover, only 43% of municipalities across all provinces had acceptable water quality monitoring. In most cases, the flow rate of the water and the initial chlorine dose were not known, which regularly resulted in under chlorinated drinking water. On a broader spectrum, there is the issue of aging infrastructure as well as inappropriate technology or poor design of the water treatment plants (Mackintosh and Unathi 2008).

2.2.6.2 NON-TECHNICAL

There have been multiple studies done to determine the causes of these technical failings at SWTS in South Africa. As a result, a number of guidance manuals have been created to try and correct the underlying causes. The most prominent issues found were non-technical. There are a number of managerial struggles for SWTS in South Africa. Most local municipalities do not understand requirements for effective drinking water service delivery due to the poor definition of the roles and responsibilities of key players in the municipality (Mackintosh and Unathi 2008). Likewise, there is a lack of understanding of process selection, design, techniques of chlorination, process quality monitoring and evaluation, and a lack of appreciation by operators and management of the importance of disinfection (Momba et al. 2008). These misunderstandings ultimately lead to inadequate management (Makungo et al. 2001).

A study conducted by Momba et al. in 2008 revealed that SWTS experienced frequent depletions of chemical stock, poor recording documentation and communication of data and information, a lack of maintenance of infrastructures from the lack of a maintenance culture, poor working conditions, and inadequate community involvement. Another study by Grant Mackintosh and Jack Unathi in 2008 indicated issues such as a lack of communication between technical officials and political decision makers, a lack of motivation of staff, inadequate monitoring, as well as the reality that there is often one process controller that controls all the machinery, performs tests, keeps records, handles complaints, and performs repairs and maintenance. Beyond regular operations and maintenance, the September/October 2016 issue of The Water Wheel published by

The Water Research Commission (WRC) discussed the lack of risk management and governance in managing water in South Africa.

Ultimately, one of the greatest issues is having inadequate staff. This is realized through the incapability of retaining skilled staff to run small water treatment plants but also from the lack of proper training, or any training at all. Studies have indicated that, often, plant operators are unable to calculate chlorine dosages, determine flow rate, estimate free chlorine residual concentrations, undertake readings of turbidity and pH values, repair basic equipment (Momba et al. 2008), nor deal with water quality control issues. In some cases process controllers are illiterate (Mackintosh and Unathi 2008).

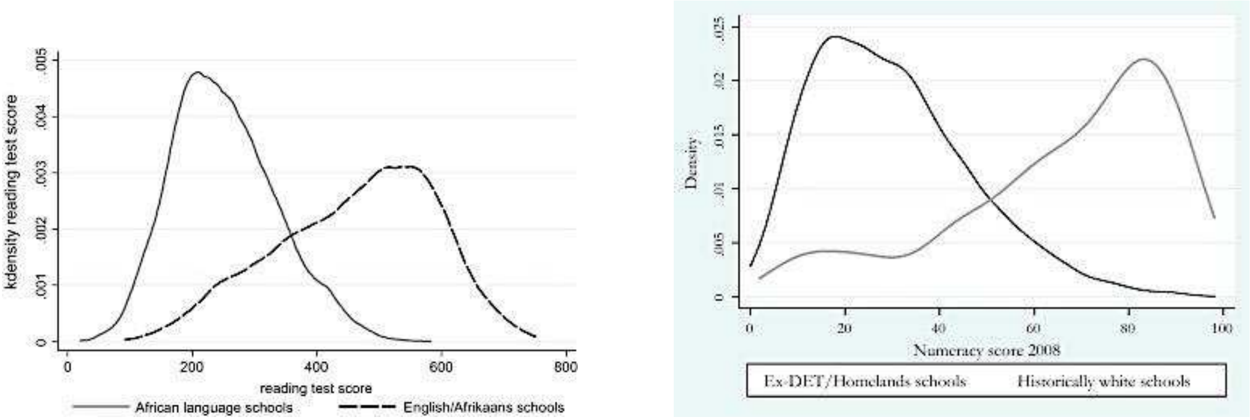
2.2.6.3 UNDERLYING SYSTEMATIC COMPLICATIONS

When working on international development projects, various societal spheres must be taken into account. Therefore, to gain a better understanding of where the managerial issues of SWTS stem from, the relatively recent political shift in South Africa should be considered. Apartheid was the systematic segregation and legislated racial exclusivity that ruled South Africa for decades, which came to an end in the early 1990's. As a means to promote expanding service delivery (including water services), reduce widespread unemployment, and facilitate economic growth, education was a large focus of the new democratic government constituting 20% of the national budget (Spaull 2013). Despite the significant emphasis on education, Nicholas Spaull states in *Poverty & privilege: Primary school inequality in South Africa* that,

> "The main explanation behind the bimodality of the schooling system in South Africa is twofold: (1) For whatever reason, historically disadvantaged schools remain dysfunctional and unable to produce student learning, while historically advantaged schools remain functional and able to impart cognitive skills; (2) The constituencies of these two school systems are vastly different with the historically Black schools still being racially homogenous (i.e. Black, despite the abolition of racial segregation) and largely poor; while the historically White and Indian schools serve a more racially diverse

> constituency, although almost all of these students are from middle and upper class backgrounds, irrespective of race."

It is clear when comparing test scores in both reading and mathematics that there is a significant disparity in the educational status between different racial communities even more than a decade since apartheid ended despite the substantial effort that has been made to equalize education. The majority of grade 6 students in African language (black) schools scored around 200 in reading compared to the majority of grade 6 students in English/Afrikaans (white) schools scoring around 550 (see **Figure 2.2 (a)**). There is a similar distribution of numeracy scores for grade 4 students seen in **Figure 2.2 (b)**.



(a) (b)

Figure 2.2: Primary education distributions in South Africa (a) grade 6 reading performance by school wealth quartile (Data: SACMEQ III 2007) and (b) grade 4 numeracy achievement by historical education department (Data: NSES 2007/8/9). (Spaull 2013)

This trend extends to higher education in South Africa as well. The main South African universities including the University of KwaZulu-Natal, Pretoria, Stellenbosch, etc. were historically white universities. In February of 1995 the Committee for Higher Education was appointed and proposed the Transformation Policies, which aimed to "provide part of a remedy to the crisis of apartheid's segregated admissions policies" (Moguerane 2007). In order to de-segregate at the university level, these universities needed to admit black African students.

However, as discussed previously, black students still regularly experience poor primary education and therefore are often not at the same educational level as white students.

According to the World Economic Forum's *Global Competitiveness Report 2013-2014*, under the 5th Pillar of Higher Education and Training, when compared with 147 other nations, the quality of South Africa's educational system is ranked nearly last (146/148) and the quality of math and science education ranked last (148/148). Moreover, the most problematic factor for doing business in South Africa was an inadequately educated workforce. This is consistent with the managerial issues of small water treatment systems as previously discussed.

2.2.7 KWAZULU-NATAL PROVINCE

The SWTS, or waterworks (WW) selected for the case study is located in Rosetta, South Africa, which is in the KwaZulu-Natal (KZN) province. KZN is a coastal province on the southeast corner of South Africa bounded by the Drakensberg Mountain Range as well as bordering the nations of Mozambique, Swaziland, and Lesotho. KZN has an area of 94,361km² making it the third smallest in the country but has a population of 11,074,800 making it the second most populous province in South Africa (Mid-year population estimates 2017). The capital of KZN is Pietermaritzburg while its largest city is Durban. KZN is divided into eleven municipalities, one metropolitan (eThekwini, comprising Durban and the surrounding area) and ten districts that are separated into local municipalities (see **Figure 2.3**).

Figure 2.3. A map of KwaZulu-Natal province divided by district (Htonl 2011)

The district municipalities of KZN are the designated responsible party of water services (a.k.a. WSAs) with the exception of three local municipalities, which include Newcastle Local of Amajuba District, City of uMhlathuze Local of uThungulu (King Cetshwayo) District, and Msunduzi Local of uMgungundlovu District. The AbaQulusi Local municipality of the Zululand district, while not the designated WSA, has the infrastructure and is its own WSP (The Local Government Handbook). Blue Drop scores vary across the KZN province. The most recently published Blue Drop scores for the WSAs in KZN are found in **Table 2.4**. Rosetta, the rural town where the case study was conducted, is located in the uMgungundlovu District.

Table 2.4. Blue Drop Scores 2013/14 in the province of KwaZulu-Natal (The Local Government Handbook)

Municipality	**Blue Drop Score**
eThekwini Metropolitan	95.90
Amajuba District	58.18
Newcastle Local	89.06
Harry Gwala (Sisonke) District	63.41
iLembe District	86.72
King Cetshwayo (uThungulu) District	74.08
City of uMhlathuze Local	89.60
Ugu District	66.29
uMgungundlovu District	89.94
Msunduzi Local	97.97
uMkhanyakude District	57.87
uMzinyathi District	78.02
uThukela District	34.50
Zululand District	51.18

2.2.8 UMGENI WATER

Umgeni Water is the local partner through which this case study was performed. Under South African water law, as described above, the WSA has the responsibility to either provide water service itself or must select, procure, and contract a WSP. In KZN, Umgeni Water is a major contracted WSP that is a public, or state-owned, entity that was established in 1974. The organization operates in accordance with the Water Services Act (Act 108 of 1997) and the Public Finance Management Act (Act 1 of 1999), reporting directly to the Department of Water Affairs (DWA) through the Chairman of the Board and the Chief Executive (Umgeni Water-Amanzi 2016). Umgeni Water is currently contracted by the eThekwini Metropolitan Municipality, the ILembe, Harry Gwala (Sisonke), uMgungundlovu and Ugu District Municipalities and the Msunduzi Local Municipality, as well as other customers.

Over all, Umgeni Water sells a total bulk water volume of 440 million kiloliters per year, serving 6.1 million people. Umgeni Water's infrastructure is comprised of (Umgeni Water-Amanzi 2016):

- ~ 746 km of pipelines and 66 km of tunnels
- 13 dams; 5 of which are managed on behalf of the DWA and on behalf of the Ugu District Municipality
- 11 water treatment works; 2 of which are managed on behalf of the Ugu District Municipality
- 18 small water treatment works and 19 borehole schemes managed on behalf of the iLembe District Municipality

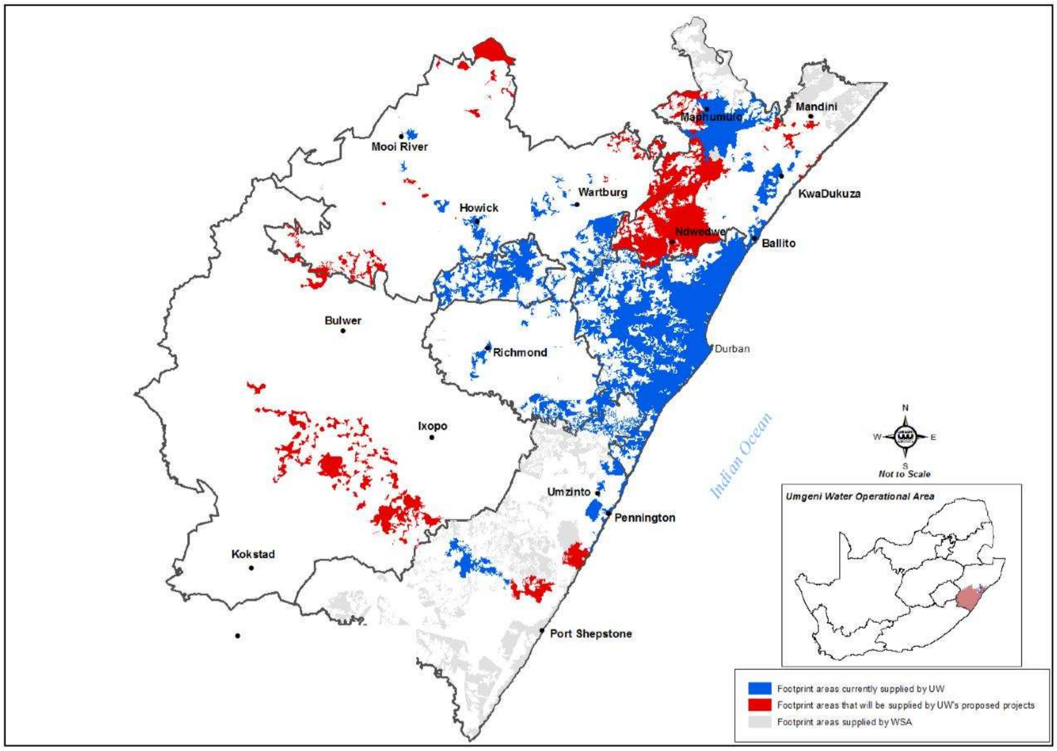


Figure 2.4. Umgeni Water Service Area Map; blue indicating areas currently served by Umgeni, red indicating areas Umgeni is planning expansion projects, and grey indicating areas where the WSA is the WSP (Umgeni 2016)

Umgeni Water's water strategy has four features including vision, mission, strategic intent, and benevolent intent. Umgeni Water's *vision* is to be the leading water utility that enhances value in the provision of bulk water and sanitation services with a *benevolent intent* to do so in order to improve quality of life and enhance sustainable economic development. Umgeni Water's *mission* is to provide innovative, sustainable, effective, and affordable bulk water and sanitation services in accordance with its *strategic intent* to enable the government to deliver these services effectively and efficiently. While Umgeni Water mainly serves the urban area in and around Durban, they are planning to expand their operations (see **Figure 2.4**) including working on rural development projects in communities that have failing or no water services at all (Umgeni Water-Amanzi 2016).

2.3 WATER TREATMENT

Raw water sources vary in South Africa with 86% of small water treatment systems using surface water, 10% groundwater, and 4% a combination of both sources. Boreholes or springs, which are ground water sources, typically only use disinfection to make the water potable (Momba et al. 2008). Treatment plants whose raw water source is typically surface water involve a multi-step process. The first step in treating surface waters is coagulation and flocculation. The coagulation, or rapid mixing, step involves the addition of chemicals, such as Aluminum or ferric sulfate, to the raw water to destabilize any colloidal matter (i.e. microscopic suspended insoluble particles) allowing them to form a loosely clumped mass of fine particles or 'floc'. The water is stirred slowly allowing the floc to grow, which is called flocculation. The water then flows into a clarifier where the floc aggregates formed in the previous step are removed by sedimentation and floatation. At this stage, the majority of particles in the water have been removed, however, smaller particles remain that require filtration. Sand filters are commonly used as well as pressure filters. The filtration step is an important precursor to the final step of disinfection, which requires a low turbidity level (<1 [preferably <0.5] NTU) to be effective. Once the filtered water is disinfected it is either stored in a reservoir (or tank) or directly distributed to consumers (Schutte 2006).

This treatment process is similar to water treatment in the U.S. (**Figure 2.5**). Most of these small water treatment plants have a capacity between 0.3ML/d (55gpm) and 120 ML/d

(22,000gpm) but are typically operating below their design capacity (Momba et al. 2008). This is a large range compared to small water treatment plants in the U.S. that only operate up to 50gpm.

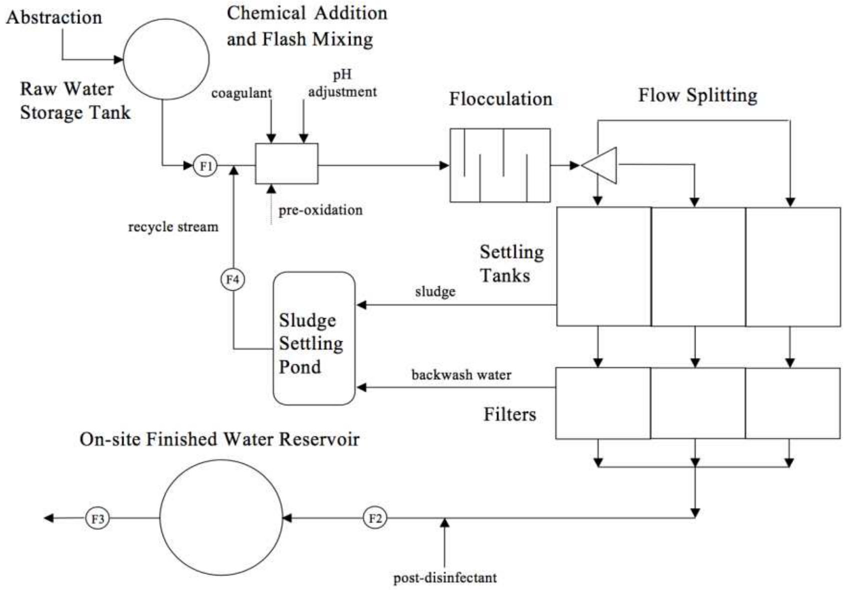


Figure 2.5. Schematic of a conventional water treatment plant (Momba and Brouckaert 2005)

2.3.1 DISINFECTION

While there has been a notion of 'clean' water for the last few millennia, the concept of disinfection as a necessary aspect of treatment was first adopted in the U.S. in 1908. The main goal of disinfection is to kill any pathogenic organisms present in the water supply that were not removed by the filtration step (Schutte 2006). There are different methods of disinfection used that involve physical and/or chemical processes. Physical processes include UV radiation and membrane filtration, such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Chemicals used for drinking water disinfection include chlorine (Cl_2), chloramines (NH_2Cl), ozone (O_3), chlorine dioxide (ClO_2), and potassium permanganate ($KMnO_4$) (USEPA 2003).

The most common disinfection method worldwide is chlorination. Chlorine is an ideal disinfectant as it is a strong oxidizing agent and therefore readily reacts with the cellular membranes and vital cellular systems. It is these reactions that 'de-activate' or destroy any microorganisms remaining in the treated water, rendering them harmless to human health. Chlorine gas is most often used due to its cost-effectiveness but can be difficult to store and is moderately hazardous to handle. For these reasons, Sodium Hypochlorite (NaOCl, i.e. bleach) and Calcium Hypochlorite ($Ca(OCl)_2$, i.e. HTH) are often used. The actual disinfecting agent is hypochlorous acid (HOCl) combined with the hypochlorous ion ($^-$OCl), which HOCl dissociates into, constitutes the free chlorine residual. The chemical reaction that takes place is given below (Schutte 2006).

$$OCl\ \ + H_2O \Leftrightarrow HOCl + OH \qquad (1)$$

It must be noted that this chemical reaction is dependent on the pH of the water that can range from 6 to 9. **Figure 2.6** illustrates this dependence. At a pH of 6, the reaction moves forward so that the chlorine is in the form hypochlorous acid (HOCl). As the pH rises, the reverse reaction becomes favored therefore chlorine is increasingly in the form of the hypochlorous ion (-OCl). Both hypochlorous acid and ion are active disinfectants, however the hypochlorous acid is more effective (Schutte 2006).

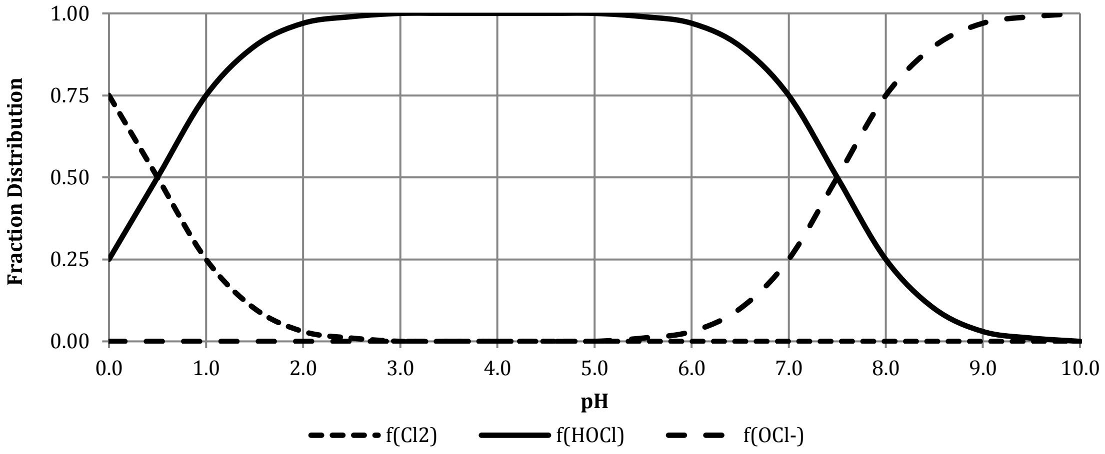


Figure 2.6: "The effect of pH on the dissociation of hypochlorous acid" (Schutte 2006)

A disadvantage associated with chemical disinfection is the potential formation of disinfection by-products (DBPs). DBPs are the result of excess disinfectant (i.e. chlorine), not consumed in the process of de-activating microbes, which react with any organic materials present in the filtered water (USEPA 2003). DBPs from chlorination include, but not limited to, trihalomethanes (THMs), haloacetic acids (HAAs) and haloacetonitriles. The maximum allowable concentration of THMs in drinking water in South Africa is 100 μg/L, which is equivalent to the USEPA's standards in the U.S. and WHO's guideline (WHO 2017) but is much higher than the standards set by the European Union (1 μg/L) (Schutte 2006). Exposure to high levels of DBPs is of concern as they could lead to liver damage and decreased nervous system activity (CDC 2009).

2.3.2 LOG REDUCTION

Log reduction is a relevant concept when considering microbiological compliance of drinking water. Log reduction relates to the percentage of microorganisms removed and/or inactivated. The 'log number' corresponds with the number of nines in the percentage reduction; therefore log-1 reduction equates 90% removal/inactivation of microorganisms, log-2 corresponds to 99%, log-3 to 99.9%, and log-4 to 99.99% (USEPA 2003).

2.3.3 *CT* METHOD

The method of contact time (*CT*) is used in the U.S. and South Africa (Mackintosh and Unathi 2008) to ensure that drinking water is fully disinfected before it reaches any consumer's tap. *CT* is a product of the disinfectant residual concentration at the outlet of the contact system (*C*, typically measured in mg/L) multiplied by the characteristic time (*T* (min)) in which the disinfectant is in contact with the water. The required *CT* ($CT_{\%required}$) to ensure full disinfection of drinking water varies based on the disinfectant used, the type of microorganism, temperature, and pH. An example table of *CT* values is shown in **Table 2.5**.

Table 2.5: "*CT* values to achieve 99.9% (log-3) inactivation of *Giardia lamblia* with free residual chlorine at different temperatures and pH values." (Schutte 2006)

		Temperature °C			
Free available chlorine 2mg/*l*	**pH**	0.5	5	10	15
		***CT* values** (min.mg/*l*)			
	6	170	120	90	60
	7	260	190	130	100
	8	380	270	190	140
	9	520	370	260	190

The required *CT* value, which is dictated by the microbiological requirements, is used to determine the actual log inactivation (USEPA 2003):

$$\text{The Actual Log Removal} = (\log\#)\, x \left({}^{CT_{calc}}\!/\!{}_{CT_{\%required}} \right) \tag{2}$$

Likewise, the calculated *CT* (CT_{calc}) is dependent upon the system. In the U.S., the characteristic time used in *CT* calculations is 't_{10}', which is the time at which 10% of a given disinfectant concentration is observed at the outlet of the system:

$$CT = C * t_{10} \tag{3}$$

This t_{10} is used due to the nature of short-circuiting and dead zones in contact tanks. The t_{10} of a particular system is determined from a Residence Time Distribution (RTD) Curve (see **Figure 2.7**) that is typically found by method of a physical tracer test.

In South Africa, it is conventional (Schutte 2006) to calculate *CT* using the theoretical detention time (*TDT*):

$$CT = C * TDT \tag{4}$$

The *TDT* is calculated from the system volume during operation (*V*) divided by the maximum flow-rate of the system, *Q*:

$$TDT = \tfrac{V}{Q} \tag{5}$$

While SANS 241 sets microbiological compliance limits (see **Table 2.1**), it does not set standards for *CT*. The closest standard used is the WHO Guideline, which states that treated water should have a free available chlorine concentration of at least 0.5 mg/L (*C*) after a contact time of 30 minutes (*T*). In order to be comparable, this guideline is converted to *CT* as defined in Eq 3, providing a *CT* requirement of 15 min-mg/L. **Table 2.6** sets forth the typical *CT* values considered sufficient to achieve the microbiological quality requirements set by SANS 241 (Schutte 2006).

Table 2.6: "Typical *CT* values at water treatment plant and at point 5km from the plant" (Schutte 2006)

	Contact time (min)	Minimum free available chlorine conc. (mg/L)	Maximum free available chlorine conc. (mg/L)	Minimum *CT* value (min-mg/L)	Maximum *CT* value (min-mg/L)
Point on treatment plant	3.3	0.8	2.5	2.6	8.25
Points 5 km away from plant	67	0.8	1.2	54	80

2.3.4 BAFFLING FACTOR

The USEPA has designated a parameter to measure hydraulic disinfection efficiency, e.g. displaying the effects of short-circuiting, called the baffling factor (*BF*). The *BF* is the ratio of t_{10} over the *TDT*:

$$BF = \frac{t_{10}}{TDT} \tag{6}$$

Combining equations Eq 3 and Eq 6 yields the following equation for *CT* (USEPA 2003):

$$CT = C * TDT * BF \tag{7}$$

As a normalized parameter, a *BF* of 1 is indicative of ideal 'plug flow' conditions, which implies that the fluid moves with a uniform velocity, or no shear between adjacent layers, over the cross-sectional area of the tank. Of course, in practical application some level of short-circuiting occurs. The differing extent of short-circuiting that occurs is influenced by the geometry of the tank as well as the incoming flow velocity, inlet location, and inlet orientation.

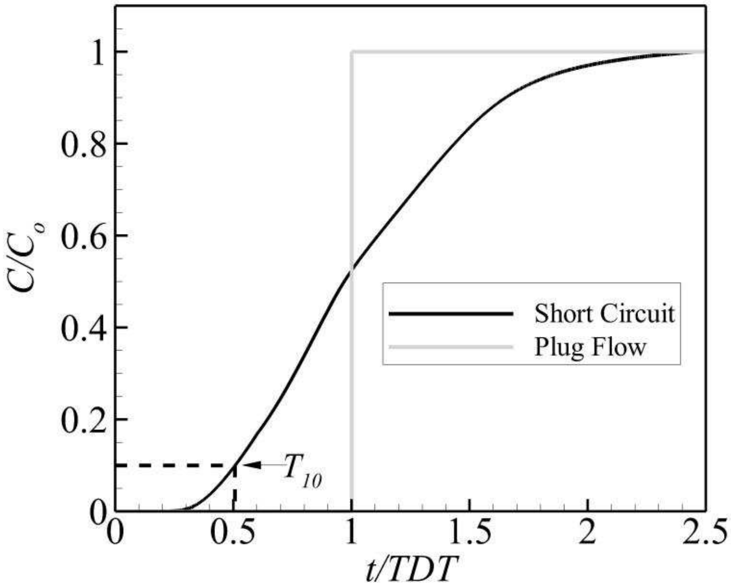


Figure 2.7: A general RTD Curve from a step-tracer test; Note: time t has been normalized by *TDT*.

The inclusion of the *BF* of a contact tank adjusts the *TDT* to a more realistic value of the characteristic contact time. A reliable and accurate method to determine the *BF* of a disinfection system is through a tracer study from which a RTD curve is found. **Figure 2.7** shows an example of a RTD curve of a step dose tracer input for a hypothetical contact system. This RTD curve would be associated with a moderately efficient disinfection chamber, having a *BF* ($=T_{10}/TDT$) of 0.5, indicating that the flow short circuits through the disinfection chamber (i.e. contact tank). In contrast, the plug flow line shown in **Figure 2.7** depicts the idealized case when all of the tracer material sent through the contact tank reaches the outlet at the theoretical detention time (*TDT*) of the contact tank.

As an alternative to performing a physical tracer test on every contact system, the USEPA suggests that the *BF* of a system can be estimated using **Table 2.7** (USEPA 2003). However, preliminary tracer studies and computational flow modeling studies performed by researchers in the EFML at CSU on full-scale small systems ranging in volume from 25 gallons to 1500 gallons indicate that the baffling factors listed in **Table 2.7** are not necessarily applicable to small systems, and often over predict the baffling factors for both small and large systems (*Baffling Factor Guidance Manual* 2014). Hence, it appears that **Table 2.7** should not be blindly used as a justification for claiming credit of a *BF* unless more detailed descriptions of small system are given, which would, however, be difficult due to the wide variety of small system design.

Table 2.7: Baffling Factors by Qualitative Description of Contact Tank (USEPA 2003)

Baffling Condition	Baffling Factor	Baffling Description
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities
Poor	0.3	Single or multiple unbaffled 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)	1.0	Very high length to width ratio (pipeline flow), perforated inlet and outlet, and intra-basin baffles

In South Africa, the design of a chlorine contact tank, specifically the geometry of the tank, is acknowledged to influence the residence time and consequently *CT* (Mackintosh and Unathi 2008). The use of baffles (i.e. internal walls) to increase the residence time is also discussed (Momba et al. 2008). However, there are no specifications of the tank geometry, inlet location or orientation, or *BF*. Without the inclusion of a *BF* in Eq 4, as compared to Eq 7 used in the U.S., South African design parameters do not take the short-circuiting that occurs in the contact tanks into consideration when calculating *CT* of a system. Without any correction for short-circuiting through a *BF*, the actual *CT* is significantly less than the *CT* for which a system was designed.

An insufficient *CT* is problematic for drinking water due to the potential of consumers ingesting water that is not fully disinfected, which could lead to the transmission of diseases such as cholera, hepatitis A, typhoid, and polio (WHO 2017). Also, the presence of short-circuiting is coupled with the existence of dead zones, areas where water is re-circulating, within a tank, which is problematic when considering the formation of DBPs.

2.4 PHYSICAL TRACER TESTS

There are two types of physical tracer tests: pulse or step-dose. A pulse tracer test is conducted by instantaneously injecting a determined amount of tracer into a system and measuring the tracer concentration at the outlet of the system until the known quantity of inputted tracer has left the system. Alternatively, a step-does tracer is performed by continuously injecting a stable concentration of a tracer into a system while measuring the tracer concentration at the outlet until the tracer concentration stabilizes. The injection point should be as close as possible to the disinfectant injection port. For either option, an appropriate tracer must be detectable, measurable, and in this case, safe for use in drinking water.

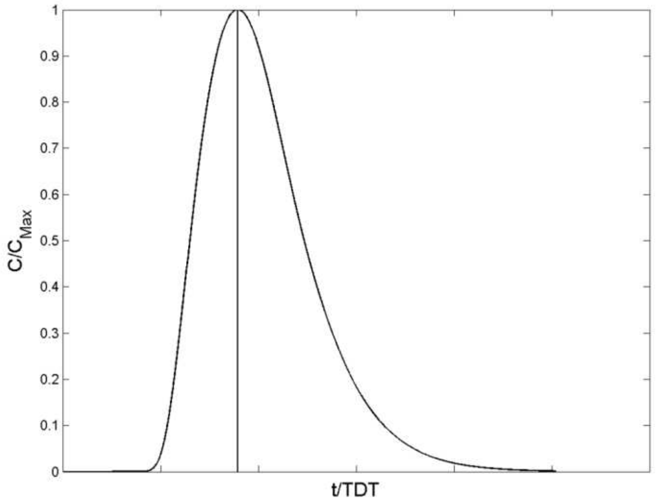


Figure 2.8: A general Flow Through Curve (FTC) from a pulse tracer test; when integrated a FTC becomes a RTD curve (Carlston 2015)

A RTD curve (**Figure 2.7**) can be generated by plotting the normalized concentration of tracer (C/C_0) from a step-dose tracer test at the outlet as a function of the normalized time (t/TDT). For a pulse tracer test, the normalized concentration of tracer (C/C_{max}) at the outlet is plotted as a function of the normalized time, which gives a flow through curve (FTC) seen in **Figure 2.8**. The FTC can then be integrated to ascertain the corresponding RTD curve needed to determine the *BF*. Both tracer methods theoretically will give the same results, however each has its own pros and cons. For example, a step-dose tracer requires a dosing pump, which can be costly and requires electricity, to continuously inject a tracer into a system whereas a pulse tracer does not. However, realistically to inject a tracer instantaneously can be difficult.

2.5 CONTACT TANK MODIFICATION

When considering *CT*, the disinfectant concentration (*C*) and the characteristic contact time (*T*) must be considered. Since *CT* is a product, an increase in disinfectant concentration or contact time would have the same effect. An increase in contact time (*T*) is preferable because an increase in disinfectant concentration would require the use of more chemicals, which would have environmental, health, and financial consequences that an increase in time would not. There are two different modifications that have been shown to increase the *BF*, which is the non-dimensional time t_{10}/TDT, presented in the *Baffling Factor Guidance Manual* that are applicable to cylindrical tanks. These are inlet manifolds and random packing material (RPM). Both modifications are considered in this thesis. Research findings on inlet manifolds in cylindrical tanks will be discussed in this section while the use of RPM will be discussed in Chapter 4.

The previous research on inlet manifolds was two-fold, which included computational fluid dynamics (CFD) modeling and validation by physical experiments. The idea of an inlet manifold stems from the continuity equation, a foundational concept in fluid mechanics. The continuity equation is fundamentally a statement of conservation of mass. That is that the mass of a constant density fluid entering a control volume, under steady-state conditions, must exit the volume:

$$Q_{in} = Q_{out} \tag{6}$$

The flow rate, Q, is the product of the velocity of the fluid, V, and the cross-sectional area through which the fluid is flowing, A:

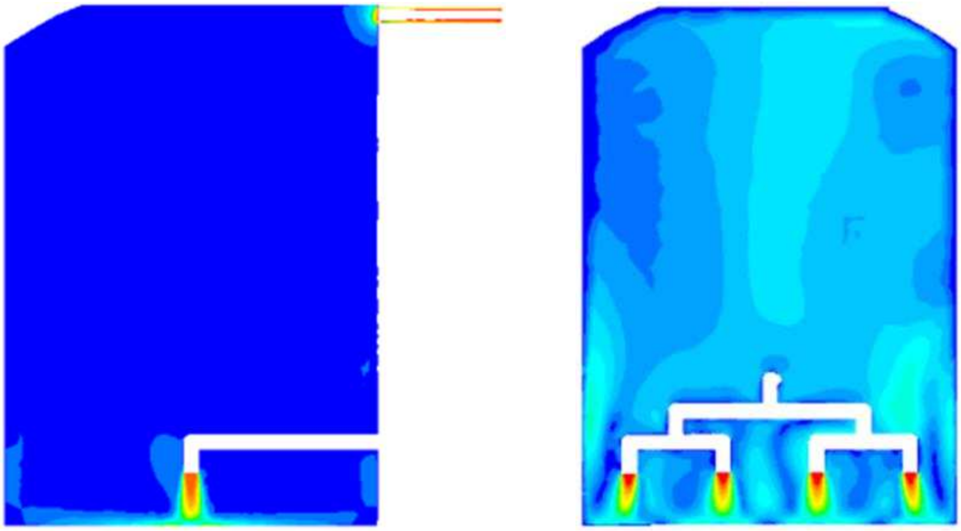
$$Q = VA \tag{7}$$

Therefore, according to the continuity equation, if A is increased then V is decreased.

$$V_{in} A_{in} = V_{out} A_{out} \tag{8}$$

By splitting Q_{in} through an inlet manifold, the area through which the flow enters the tank, A_{in}, is increased thus decreasing the inlet jet velocity, V_{in}. A slower velocity of the incoming jet is preferable as it reduces the extent of short-circuiting.

Aside from the beneficial reduction in V_{in}, multiple inlets also allows for greater distribution of inflow across the cross-sectional area of the tank itself. This is visible from the CFD velocity plots using FLUENT in **Figure 2.9**. Both simulations were run for the same tank geometry, height of the inlet (e.g. H_I/H_T=10%), Q, and identical turbulence parameters (for more information see Taylor 2012). In the tank with a single inlet, **Figure 2.9 (a)**, the majority of the volumetric flow has a very low velocity (darker blue) compared to the high velocity (red) flow coming in through the inlet and exiting through the outlet. This large difference in velocities is indicative of the presence of a large dead zone in the center of the tank and short-circuiting along the tank walls. Conversely, the tank with a 16-manifold inlet, **Figure 2.9 (b)**, has more movement throughout the entire tank, which is closer to plug flow conditions.



(a) (b)

Figure 2.9: Center plane velocity plots of a 550gal cylindrical contact tank; (a) with one inlet and (b) with 16 inlet manifold at H_I/H_T=10% from the bottom of the tank and single outlet at the top. (scale is blue to red indicating low to high velocities) (Taylor 2012).

Altogether, there were 3 different inlet manifolds considered, 4, 8, and 16, in addition to a single inlet. A CFD simulation was run for each inlet manifold at varying heights (H_I/H_T) for a bottom inlet, top outlet configuration of a 550-gallon cylindrical tank. The resulting *BF*s can be found in **Table 2.8**.

Table 2.8: '*BF*s for $Q_{total} = Q$' (Taylor 2012)

BF (Q = 15gpm)				
$H_I/H_T(\%)$	1 Inlet	4 Inlets	8 Inlets	16 Inlets
5	0.21	0.18	0.19	0.37
10	0.18	0.26	0.17	0.51
20	0.23	0.17	0.34	0.37
40	0.10	0.12	0.27	0.29
75	0.15	0.22	0.15	0.11

The *BF* for the same tank ranged from 0.10 to 0.51 depending on the number of inlets and the H_I/H_T, yielding up to a 400% increase in hydraulic disinfection efficiency. The CFD simulation of the 16 inlet manifold at H_I/H_T=10% was validated with a physical experiment (Taylor 2012).

CHAPTER 3. ROSETTA WATERWORKS CASE STUDY

3.1 INTRODUCTION

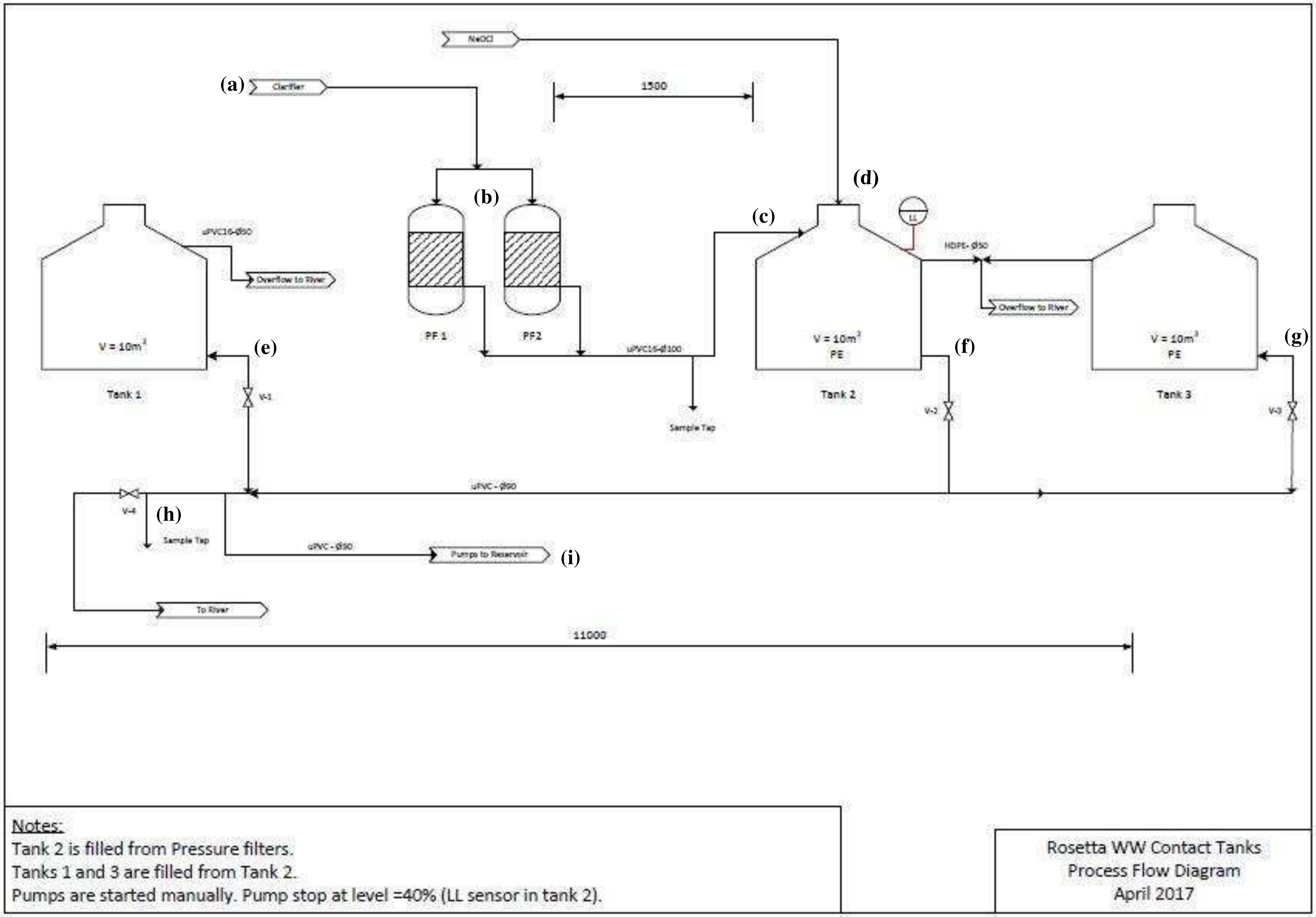
The principal concentration of this thesis is to apply the proposed cost-effective modifications for contact tanks found in the *Baffling Factor Guidance Manual* (2014) on a live system. Having a focus on water and international development, different nations were considered when choosing a location for a case study. After reviewing the statistics of SWTS in South Africa, specifically those concerning disinfection, it was considered worthwhile to investigate the hydraulic disinfection efficiency of a small WW and implement a modification based upon the aforementioned research conducted at CSU. After investigating who are the prominent stakeholders in South Africa, the Water Research Commission (WRC) and Umgeni Water were contacted. Both the WRC and Umgeni Water were interested and welcomed a presentation on the research findings in the *Baffling Factor Guidance Manual* along with the idea for a live system case study. Umgeni Water agreed to collaborate on such a study.

3.2 BACKGROUND

Umgeni Water, a state owned entity and the largest water provider in the province of KZN, South Africa, has recently been taking over operations of small waterworks. Faced with challenges typical of small waterworks, Umgeni Water collaborated with the EFML at CSU to conduct a case study. The case study involved assessing the hydraulic disinfection efficiency and applying the research presented in the *Baffling Factor Guidance Manual* (2014) to modify a live system in the rural town of Rosetta. Umgeni Water selected the Rosetta Waterworks (WW) for this case study as it is similar to other small waterworks in KZN and was meeting standards, therefore had no other outstanding issues. This made Rosetta WW an attractive site for experimentation. **Figure 3.1** depicts the layout of the contact system of the small waterworks in Rosetta.

At Rosetta WW, raw water is pumped at an average inflow rate of 3 L/s (47.6 gpm) from an intake on the Mooi River downstream of the Spring Grove Dam. At the pump house a coagulant is injected into the raw water pipe before moving to the clarifier. The clarified water (**Figure 3.1** (**a**)) then flows by gravity to the pressure filters, (**b**). The filtered or 'finished' water flows into the top of Tank 2, (**c**), where a chlorine drip is situated at the access point of Tank 2, (**d**). From Tank 2, (**e**), the chlorinated ('final') water flows to Tanks 1, (**f**), and Tank 3, (**g**). Separate pumps draw the final water from Tanks 1, 2, and 3 (**i**) to an offsite reservoir about 0.5 km away at an average outflow rate of 3.9 L/s (61.8 gpm). The outflow rate is greater than the inflow rate because the outflow pumps run periodically (unsteady system). The reservoir is connected to the distribution network that serves the community.

An initial assessment of Rosetta WW considered the three cylindrical 10,000 L tanks (Tanks 1, 2, and 3) as contact tanks, providing a total volume of 30,000 L with an inflow rate of 11.54 m^3/hr (50.8 gpm). These values yielded a *TDT* of 156 min (Maduray 2017). However, the hydraulics of this system are considerably more complex as the three 'contact' tanks are neither in parallel nor series configuration. The filtered water enters the three-tank system at the top of Tank 2, where it is also dosed with chlorine, then from the bottom of Tank 2 can flow to Tanks 1 and 3 or directly to the offsite reservoir. Tanks 1 and 3 each have one connection at the bottom that acts as the inlet and outlet, therefore the direction of flow is dependent on whether or not the outflow pumps are on or off.



Notes:

Tank 2 is filled from Pressure filters.

Tanks 1 and 3 are filled from Tank 2.

Pumps are started manually. Pump stop at level =40% (LL sensor in tank 2).

Rosetta WW Contact Tanks
Process Flow Diagram
April 2017

Figure 3.1: Rosetta Waterworks Contact Tanks Process Flow Diagram (Maduray 2017); (a) water flowing by gravity from clarifier, (b) pressure filters, (c) filtered water flowing from pressure filters to inlet of Tank 2, (d) chlorine dosage point, (e) inlet/outlet to Tank 1, (f) outlet of Tank 2 (g) inlet/outlet to Tank 3, (h) sampling tap, (i) final water pumped to reservoir.

Based on the hydraulic system analysis, it was determined that only Tank 2 (see **Figure 3.2**) should be considered a contact tank since the shortest flow path the final water can take is from Tank 2 directly to the reservoir. Tanks 1 and 3, therefore, should be considered as additional storage tanks acting as buffers for the unsteady operations of the system. This distinction reduces the *TDT* to 52 min. With an average free chlorine residual measured at the sampling tap (see **Figure 3.1 (h)**) being 1.4 mg/L, the calculated *CT* is 72.8 min-mg/L, which is well above the required 15 min-mg/L.

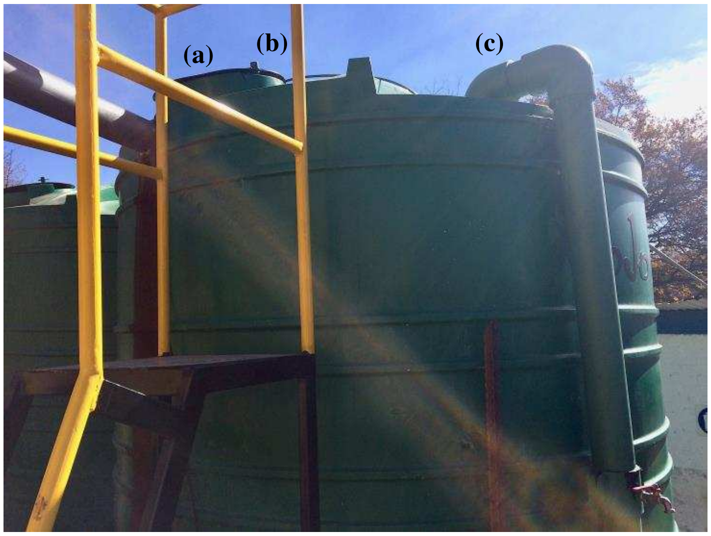


Figure 3.2: Photograph of the top of Tank 2; (a) access point, (b) chlorine drip dosage point, (c) vertical inlet

3.3 MODIFICATION

The *Baffling Factor Guidance Manual* describes how inlet manifolds reduce the incoming velocity by splitting the flow and better distributing the flow across the surface area of a contact tank (2014). In order to modify the inlet to Tank 2 internally, the location where the inflow entered the tank needed to be moved to the access point where a manifold could be attached. This required an external modification (see **Figure 3.3 (d)**) to divert the inflow from the original vertical inlet **(b)** to a horizontal inlet **(c)** at the access point **(a)**.

Figure 3.3: Photograph of Tank 2 with external modification; (a) access point, (b) original vertical inlet, (c) new horizontal inlet, (d) external modification

A 4-way manifold inlet was designed and installed in Tank 2 (**Figure 3.4**). This particular design was chosen due to time and physical constraints. Time was restricted in two ways. The CSU collaborators were in South Africa for six weeks, which is limited when considering the time required to observe, analyze, modify, and test the contact system. The other time restraint was the reality of working on a live system that could only be offline for a few hours at a time before needing to go back online to meet service demands. A significant physical restraint of the tank was that it had only one access point 0.4 m in diameter. This limited the size of the modification, consequently limiting the number of manifolds, so that it could fit through the access point. Structural support for the manifold was also necessary since the inlet was at the top of the tank. The railing of the ladder near the access point was used as a support anchor for the manifold.

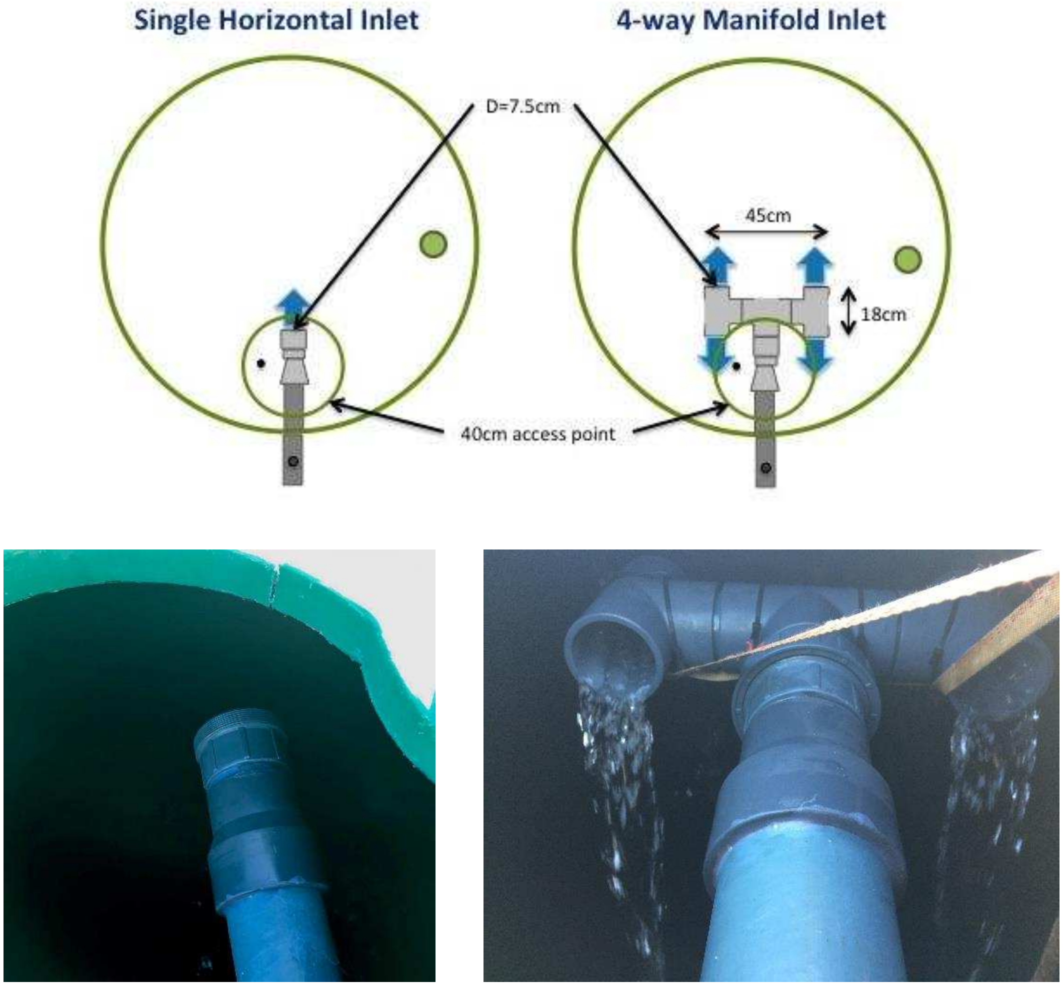


Figure 3.4: Planar schematic and picture of single inlet (left) & 4-way manifold inlet (right)

3.4 METHODOLOGY

A total of seven tracer tests were conducted for this case study: three pulse tracer tests and four step tracer tests. The 'tracer' used for the Rosetta WW system was a concentrated sodium chloride (NaCl) solution, which would notably raise the conductivity of the final water to be detectable by a conductivity meter. A Beckman Coulter portable conductivity meter (**Figure 3.5 (b)**) was used to measure the conductivity of the final water at the sampling tap (see **Figure 3.1 (h)**). The conductivity probe was submerged in a continuous flow of the final water, as to not allow the exiting waters to collect, in order to provide instantaneous readings (**Figure 3.5 (a)**). Due to the complex hydraulics between Tanks 1, 2, and 3, as discussed previously, the valves to Tanks 1

(V-1) and 3 (V-3) seen in **Figure 3.1** were closed. This simplification of the system was reasonable since the shortest flow path the ‘disinfected’ finished water could take was from Tank 2 directly to the reservoir.

(a) **(b)**

Figure 3.5: Photographs of (a) sampling setup at tap (allowed conductivity probe to be submerged in outflow to get continuous readings) and (b) portable conductivity meter (Beckman Coulter Model Number PHI 460)

The first scenario of the original vertical inlet was assessed by a pulse tracer test. A pulse tracer was chosen since this was the initial test to assess the contact system and there was no point to inject the NaCl solution continuously into the inflow (i.e. before external modifications). The highly concentrated NaCl solution was added at the access point, where the chlorine drip was located (see **Figure 3.2 (b)**). The resulting FTC of the initial pulse tracer test was integrated to obtain a RTD curve. The second scenario was after the external modification was installed, which created a horizontal inlet at the access point. This scenario was assessed by duplicated step tracer tests with the NaCl solution injected inline by a Grundfos Alldos Digital Dosing, DDI pump at point **(a)** in **Figure 3.6**. The final scenario included the 4-way manifold inlet attached to the horizontal inlet at the access point that was also assessed by duplicated step tracer tests. The conductivity readings were normalized to create RTD curves for last two scenarios.

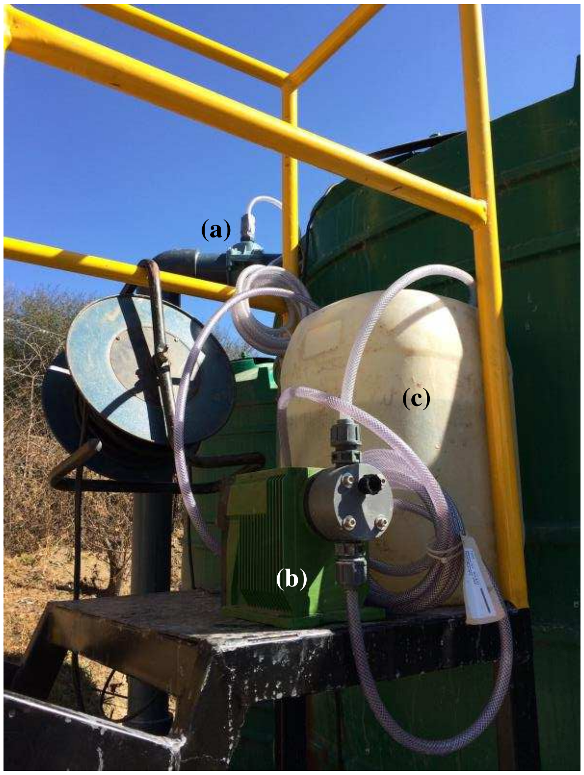


Figure 3.6: Photograph of the inline dosage set-up for step tracer tests; (a) dosage point, (b) Grundfos Alldos Digital Dosing, DDI pump, (c) highly concentrated NaCl tracer solution

In order to provide a better understanding of the total *CT* of the WW system as a whole, since the contact tank is not the only place in the system where contacting may be occurring, fluorescent dye (pulse tracer) tests were performed. A fluorescent dye tracer test visually indicated the time it took for the final water to travel from Tank 2 and reach the reservoir, from which the water enters the distribution system. A fluorescent dye was added at the access point where the chlorine dose is injected (refer to **Figure 3.2 (b)**). The time was recorded when the presence of dye was visible at the sampling tap and then again at the inlet to the reservoir.

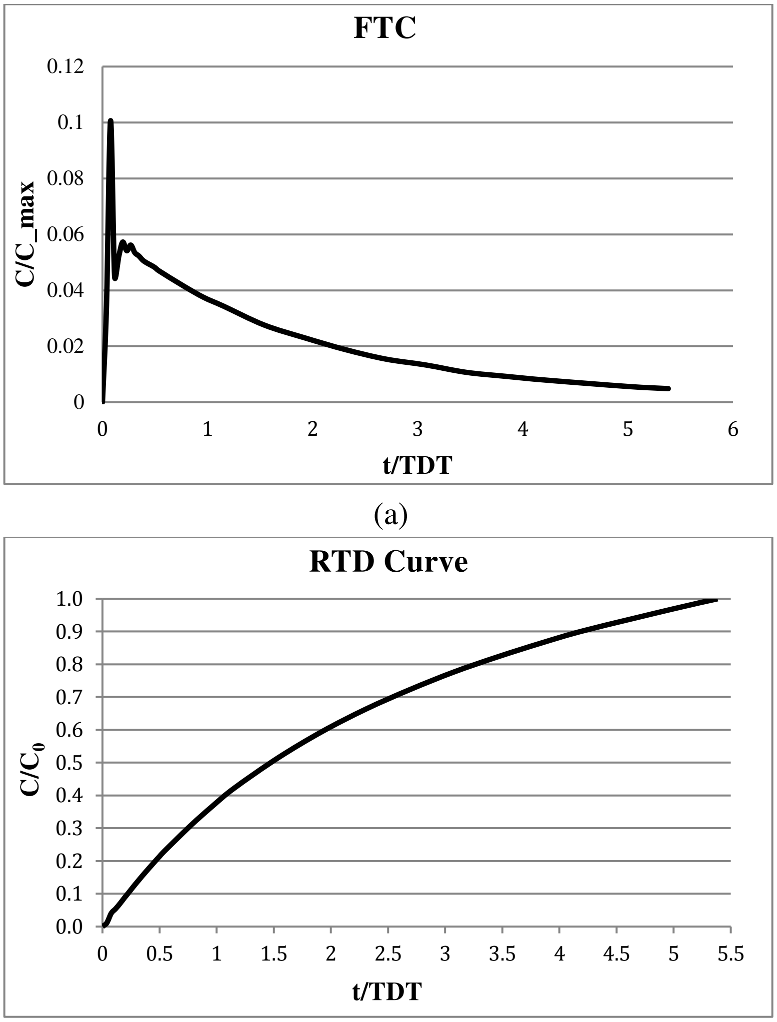
The portable conductivity meter that was used during the tracer tests was calibrated in the lab at Umgeni Water Darvill Plant in Pietermaritzburg before any tracer tests were conducted.

Each tracer test took about 3 hours to complete. During testing, the portable conductivity meter would automatically power down as a battery power conservation feature after about 20 minutes and would need to be turned on again. Early on during three of the four step tracer tests conducted, when the conductivity meter shut off and was subsequently turned back on the conductivity reading was significantly higher than the previous reading. The subsequent readings continued at elevated values for the remainder of the test in a pattern that was consistent with what was expected (e.g. increasing at a slower rate). Throughout the remainder of the test, the conductivity meter would continue to shut off periodically and be turned on again but without any erratic behavior in the conductivity readings. The daily records from the previous month were referenced and it was found that the conductivity of the raw water was typically about 10 mS/m below the conductivity of the final (chlorinated) water. By cross-referencing these records, and comparing readings with a second conductivity meter, it was determined that the initial lower readings were unreasonable and the elevated readings after the conductivity meter was turned back on were accurate. Therefore, the raw data before the jump was shifted by the amount of the jump. This can be seen in **Figure 3.9** in the Results section below.

3.5 RESULTS

The tracer studies conducted on the small waterworks in Rosetta, South Africa revealed the extent to which the original *CT* calculation (dismissing the *BF*) was clearly over estimated. Tank 2, the cylindrical contact tank, was typically around 45-50% full during the tracer test, automatically reducing the *TDT* to 26 minutes. The results of the pulse tracer of the original inlet are presented in a FTC in **Figure 3.7 (a)**. The FTC was integrated to give the RTD curve seen in **Figure 3.7 (b)**. From the RTD curve a *BF* of 0.23 was determined (refer to Chapter 2 Section

2.3.4) for Tank 2 with the original vertical inlet. The *BF* revealed that the originally calculated *T* (*TDT*) of 52 minutes is more accurately only 6 minutes (t_{10}), yielding a *CT* of 8.4 min-mg/L.

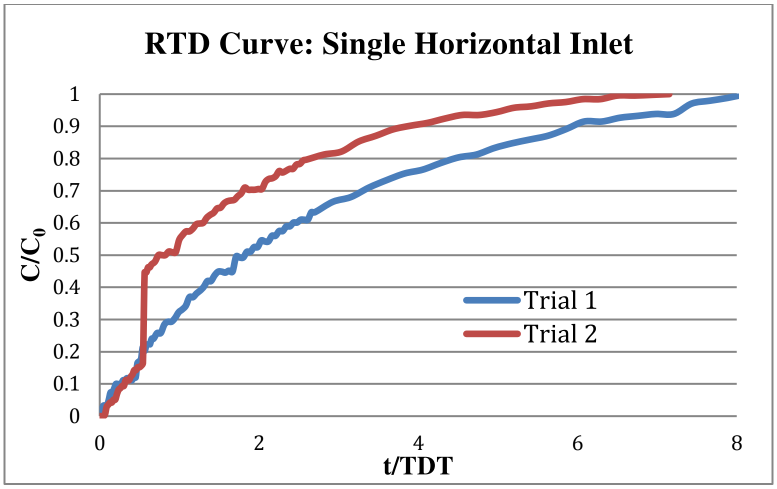


(a)

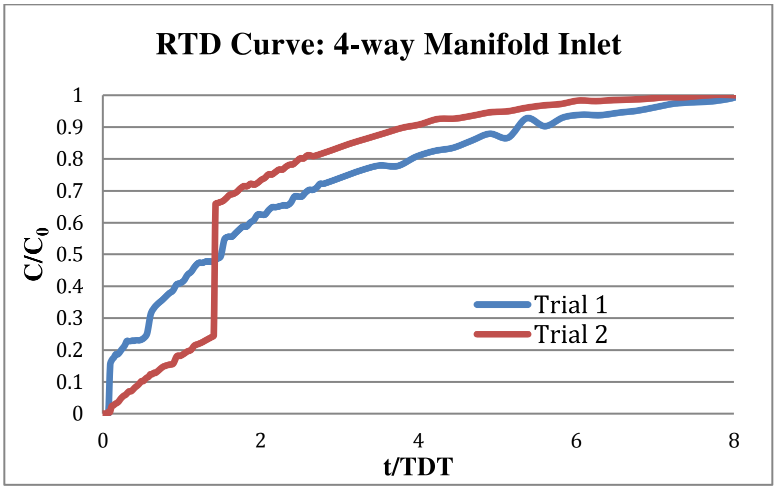
(b)

Figure 3.7: (a) FTC from pulse tracer test of Tank 2 & (b) Integrated FTC=RTD Curve; *BF* = 0.23 (Maduray 2017)

The RTD curves constructed from the raw data of the step tracer tests for the single horizontal inlet and the 4-way manifold inlet can be seen in **Figure 3.8**. The significant jumps in conductivity readings are evident in the RTD curves for Trial 2 for the single horizontal inlet and for both trials for the 4-way manifold inlet.



(a)



(b)

Figure 3.8: Original RTD curves of Tank 2; (a) with a single horizontal inlet and (b) with the 4-way manifold

As discussed in the methodology section above, the data before the jump was shifted up by the amount that the conductivity readings jumped resulting in smooth RTD curves for these step tracer tests. **Figure 3.9** shows an example of the data shift for Trial 2 of the 4-way manifold, from which it is clear that the shift maintains the same trend and is therefore reasonable. The adjusted RTD curves for the single horizontal inlet and the 4-way manifold inlet can be seen in **Figure 3.10**.

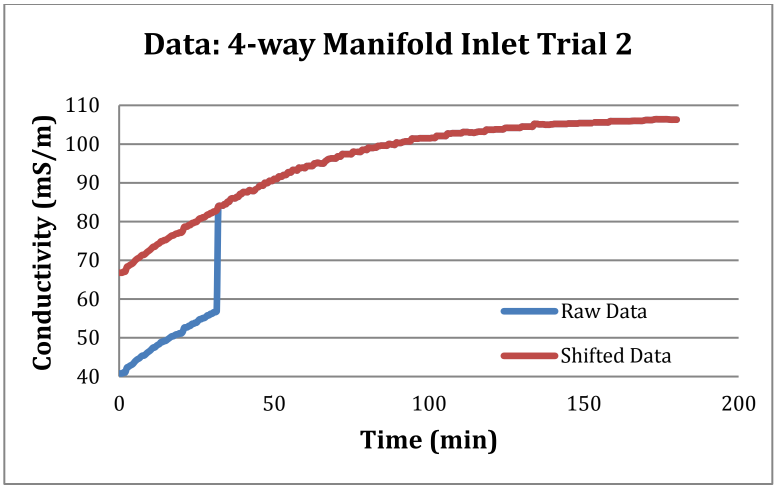
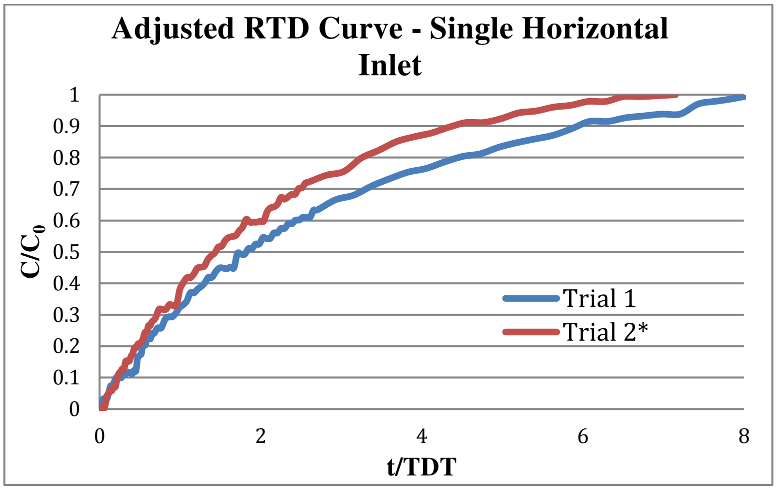
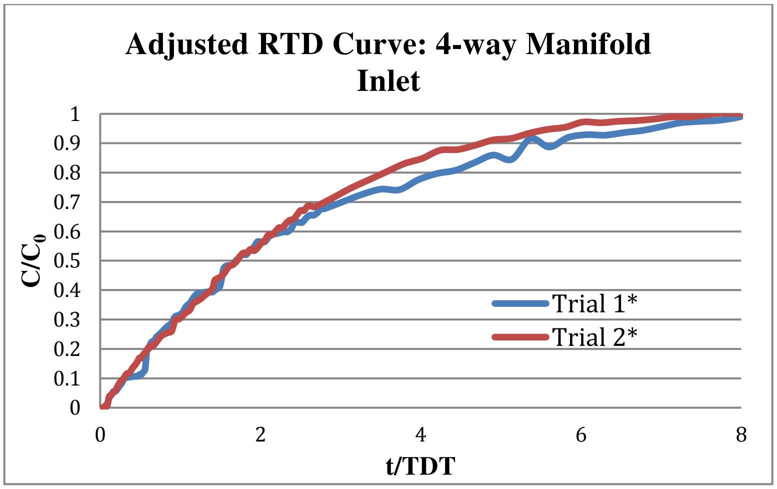


Figure 3.9: Raw and shifted data for Trial 2 with the 4-way manifold inlet



(a)



(b)

Figure 3.10: Adjusted RTD Curves of Tank 2; (a) with a single horizontal inlet and (b) with the 4-way manifold

The resultant RTD curves of the horizontal inlet at the access point indicated a *BF* of 0.22, which is similar to the original vertical inlet. This is reasonable since both scenarios have a single inlet. The 4-way manifold was then installed and another step tracer test conducted that resulted in a *BF* of 0.30 (see **Table 3.1**). These tracer tests indicated a 37% improvement of the hydraulic disinfection efficiency by splitting the inflow by four. The new *T* after modifying the inlet is now about 8 minutes therefore providing a *CT* of 11 min-mg/L.

Table 3.1: Baffling Factors determined from RTD curves by trial (*Patched)

BF	Trial 1	Trial 2	Average *BF*
Horizontal Inlet	0.214	0.228*	0.22
4-way Manifold Inlet	0.304*	0.301*	0.30

This result is consistent with the CFD simulations of a 550-gallon cylindrical tank with a single and 4-way manifold inlet at the bottom of the tank with an outlet at the top that were conducted as part of the research done at CSU for CDPHE. The single inlet at the optimal height from the bottom of the tank (10%) had a *BF* of 0.18 while the 4-way manifold inlet at the same height had a *BF* of 0.26 (see **Table 2.8**). The CFD simulations showed a 44% improvement.

The results of the fluorescent dye tests (see **Table 3.2**) show the variable residence time of the contact tank as the water level changes. Test 1 indicated that it took 2 minutes and 40 seconds for the water to flow from the point of disinfection to the sampling point when Tank 2 was 55% full. When Tank 2 was 90% full, it took 6 minutes and 11 seconds (Test 2) to reach the same sampling point, more than double the time as Test 1. Since the goal of this test was to look at the system as a whole, the valves to all three tanks were open for this test. From both tests, the time from the sampling point to the reservoir is about 2 minutes. This is reasonable since the pumps draw the final water from the Tanks 1, 2, and 3 at a relatively constant flow rate of 3.9 L/s (62 gpm) through a 90mm (3½ in) pipe. A *BF* correction is unnecessary since flow through a pipe is considered plug flow (*BF* = 1).

Table 3.2: Fluorescent Dye Test

	(Units)	Test 1	Test 2
Water level of Tank 2	%	55	90
Time to sampling point	min:sec	2:40	6:11
Time to reservoir	min:sec	2:05	2:00
Total	min:sec	4:45	8:11

3.6 DISCUSSION

Through discussion with engineers at Umgeni Water, it was found that the general design parameter for a contact chamber is that it provides 20 minutes of contact time (*T*). Since South Africa's guideline uses the *TDT* as *T*, Tank 2 was considered sufficient even when it is only half full (*TDT* = 26 min). However, the purpose of the *BF* parameter is to account for short-circuiting in a tank to provide a more accurate characteristic time (*T*). The pulse tracer of the original set up of Tank 2 indicated a *BF* of 0.23. When this *BF* was applied, the characteristic contact time (*T*) was reduced to about 6 minutes, which is well below the 20-minute design parameter and revealed the hydraulic inefficiency of the 10,000 L cylindrical tank. It is noted that there is a discrepancy between the contact chamber design parameter of 20 minutes (*T*) used in practice, the WHO Guideline of a chlorine residual of 0.5 mg/L (*C*) after 30 minutes of contacting (*T*) that South Africa uses as its standard, and the U.S. definition of $CT=C*t_{10}$. This inconsistency needs further attention.

Another point to discuss is that the 10,000 L cylindrical tank used as the contactor at Rosetta WW has the inlet at the top and the outlet at the bottom. This was an intentional part of the original design of the plant as contact tanks are commonly used as supply water during peak water usage hours. Through observation of Rosetta WW operations, it was discovered that the outlet pump that draws from Tanks 1, 2, and 3 to an off-site reservoir, shuts off every 20 minutes for a duration of 6 minutes. Also, the inlet pump, which draws water from the river to the clarifier, is shut off manually while the pressure filters are being backwashed (daily). The consequence of the discontinuous pumping in combination with the inlet-outlet configuration causes the water level to vary greatly throughout the day. This variability in volume affects the *TDT* and consequently the *BF* of the contact system. Thus, an evaluation of system operations is necessary to determine a reasonable *CT* value. The unsteady operations also had implications when performing tracer tests. When the outflow pumps shut off the conductivity readings did not change much until the pumps turned back on. This can be seen in the RTD curves in **Figure 3.10**.

Since Tank 2 was determined to be an inefficient contactor, the question of why the Rosetta WW was not receiving any complaints of consumers getting sick came about. A holistic assessment of the waterworks system from the river source to the point of distribution, determined that the reservoir was compensating for the insufficient contact time in the designated contact tank. An estimated residence time of the reservoir, based on its dimensions and an assumed *BF* of 0.3 based on the existence of internal walls acting as baffles (USEPA 2003), was determined to be about 300 minutes. This added residence time provides the remaining contact time before the final water enters the distribution line. Therefore, by the time the final water reaches the first consumers, it is fully contacted. However, for small WW that do not have a reservoir, the inefficient contacting is a serious concern.

This case study illustrates that assuming a water system is functioning properly based on basic standards being met can be dangerous. Despite the regular chlorine residual tests at the sampling point of Rosetta WW being within an acceptable range, the final water leaving the contact tank is not fully contacted as it was assumed. Regular chemical and microbiological water quality tests may not be enough to recognize system failure, as they do not monitor the hydraulic aspects. A holistic assessment of a water treatment plant with a focus on a specific function of the system (i.e. contact time), typically meant to be accomplished within a certain part of the system (i.e.

contact tank), may reveal that standards are not being met at the appropriate stage. To conclude that a 10,000 L cylindrical tank acting as the contactor is sufficient based upon Rosetta WW meeting SANS 241 standards would be problematic when assessing or designing future small waterworks.

During the case study, two seminars were held, one in Durban and another in Pietermaritzburg, where the innovative modifications presented in the *Baffling Factor Guidance Manual* and the importance of a *BF* were discussed in the context of the case study at Rosetta WW. Since the conclusion of the Rosetta WW case study, Umgeni Water has been accepted to present these results at the Water Institute of Southern Africa (WISA) Conference in June 2018. Furthermore, the WRC has awarded Umgeni Water with a grant to continue this case study by assessing the hydraulic disinfection efficiency of multiple different contact systems that are used nationally throughout South Africa.

3.7 CONCLUSION

The main objective of this case study was assessing and improving the hydraulic disinfection efficiency of a live small drinking water system in South Africa using the innovative and cost-effective modifications presented in the *Baffling Factor Guidance Manual* (2014). The assessment of the hydraulic disinfection efficiency of the contact system at Rosetta WW in KZN, showed that the contact system was significantly inefficient (*BF*=0.23). The main concern is that the *BF* is not included in the *CT* calculations seen in the grossly over estimated *CT* of 72.8 min-mg/L from Eq 4 as compared to the *CT* of 8.4 min-mg/L when including the *BF* (Eq 7). By installing a 4-way inlet manifold to the 10,000 L cylindrical contact tank, a 37% improvement in the hydraulic disinfection efficiency was achieved. This case study has added to the understanding of how to assess for hydraulic disinfection efficiency and modify disinfection contact tanks of live water systems that often operate under unsteady circumstances unlike the controlled laboratory studies presented in the *Baffling Factor Guidance Manual*. The effort of sharing this study at the WISA Conference, as well as the extension of this case study to assess and potentially modify systems across the nation of South Africa by Umgeni Water and WRC is an indication that this 'technology transfer' is on the route to becoming successful.

CHAPTER 4. LONGTERM USE OF RANDOM PACKING MATERIAL PILOT STUDY

4.1 INTRODUCTION

Random packing material (RPM) is commonly used in phase reaction devices or columns for purposes of distillation, extraction, or absorption (Cannon 1952). RPM is also used for water treatment purposes in trickling filters for wastewater treatment (Richards and Reinhart 1986) and aeration columns for treatment of volatile organic compounds (VOCs) in drinking water (Kavanaugh and Trussell 1980). However, RPM has not been used for disinfection purposes in drinking water systems.

RPM can be made from different types of material including polypropylene, carbon or stainless steel, ceramic, PVC/C-PVC, or PVDF/PFA. There are many different manufacturers, both in the U.S. and internationally, of RPM, for which some RPM meet the National Sanitation Foundation/ American National Standard (NSF/ANSI) 61 criteria. The NSF/ANSI 61 certification ensures that a product (i.e. any water system component) meets the regulatory requirements of the U.S. and Canada such that it is fit for use in drinking water applications. Specifically, this certification "*establishes minimum health effects requirements for the chemical contaminants and impurities that are indirectly imparted to drinking water from products, components, and materials used in drinking water systems*" (NSF/ANSI 2016).

The general design concept for RPM is to have high surface area and void fraction that allows fluid to flow through its 'pores'. There are multiple different geometries available including raschig, pall, cascade, beta, or helix rings, saddle, snowflake/star, tellerette, polyhedral hollow, and spherical. RPM vary in size, typically ranging from 1-3 inches, with a void fraction usually between 60 to 98% (various RPM manufacture manuals). **Figure 4.1** shows an example of spherical RPM of different sizes. The reason they are called 'random' is that each unit does not lie within the same plane as the others (Cannon 1952) thus creating a 'random' flow pattern by forcing the fluid to flow through the void spaces arbitrarily. This random flow cuts down on short-circuiting in a tank and promotes plug flow conditions. The forcing of the flow around and through RPM in combination with added shear stress that results from the high surface area of the RPM promotes turbulence. An important characteristic of turbulence is mixing, which is key for disinfecting water through the use of chemicals such as chlorine.

Figure 4.1: A photo of Jaeger Tri-Pack random packing material; 1" (Left), 2" (middle), and 3.5" (Right)

An initial study of the use of RPM in a cylindrical 'contact' tank was conducted for the Water Quality Control Division of the CDPHE. In these laboratory-scale studies, an empty 50-gallon cylindrical tank had a *BF* of 0.33, however, when the same tank was 100% filled with 1" spherical RPM (90% void fraction), a *BF* of 0.95 was obtained (Barnett 2014). The addition of RPM to the cylindrical tank, despite the 10% reduction on fluid volume of the tank, created near plug flow conditions is seen in **Figure 4.2**.

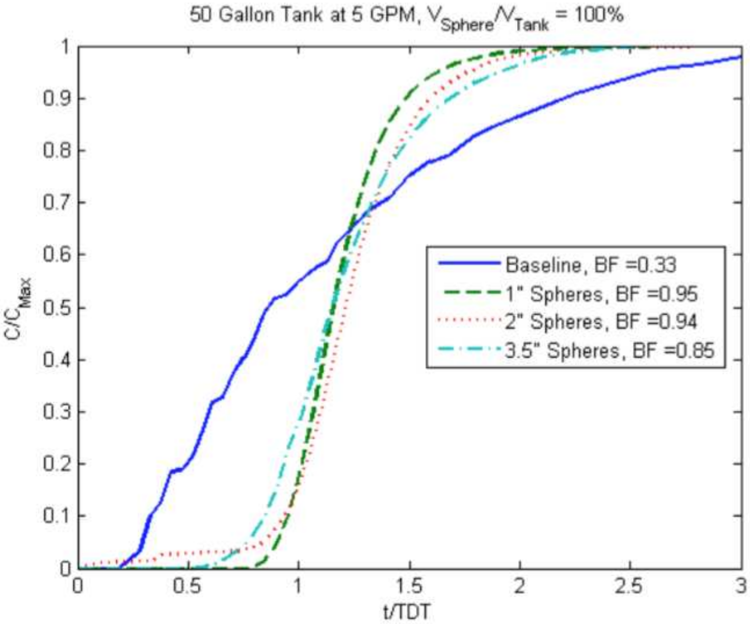


Figure 4.2: RTD curve of 50-gallon cylindrical tank completely filled with RPM (Barnett 2013).

Despite the promising benefit in terms of decreased short-circuiting and increased residence time, which results in improved contacting, there are practical concerns surrounding the use of RPM in this context. While the NSF/ANSI 61 certification ensures the chemical safety for use in drinking water, it "*does not establish performance, taste and odor, or microbial growth support requirements for drinking water system products, components, or materials*" (NSF/ANSI 2016). The relevant concern of using RPM in contact tanks, even if NSF/ANSI 61 certified, is the 'microbial growth support' aspect. Due to the quality of water entering a contact tank combined with the high surface area of RPM, there is a potential for a biofilm to form. This characteristic is exploited in trickling filters but would be counteractive when disinfecting drinking water. Therefore, a fundamental study focused on the microbiological component is required in order to provide a scientific basis to underpin the potential use of RPM in drinking water disinfection.

4.2 BIOFILM GROWTH

A biofilm is a natural phenomenon where individual bacteria interact together to form 'highly structured matrix-enclosed communities' that protect the individual bacteria that compose it (Stoodley et al. 2002). There are multiple mechanisms by which a biofilm can form including redistribution of attached cells, binary division of attached cells, and/or aggregation of cells from the bulk fluid to the developing biofilm (Stoodley et al. 2002). There are five stages in the formation of a biofilm beginning with individual bacteria attaching a surface that start to form microcolonies. As these microcolonies grow, exopolysaccharides (EPS) are produced which create a structure or 'film' that results in a firmer attachment. Once a biofilm is mature, sections will start to dissociate from the surface that it is growing on. At this stage, any bacteria from a biofilm will be detectable in a water sample. This process is depicted in **Figure 4.3** below. From a hydraulics perspective, intuition suggests that a turbulent flow may prevent the formation of a biofilm, however, studies have shown that biofilm structures become elongated and form 'mats' as well as become denser and stronger in turbulent flows (Stoodley et al. 2002). Therefore the formation of a biofilm on RPM in a contact tank is a legitimate concern that needs to be addressed.

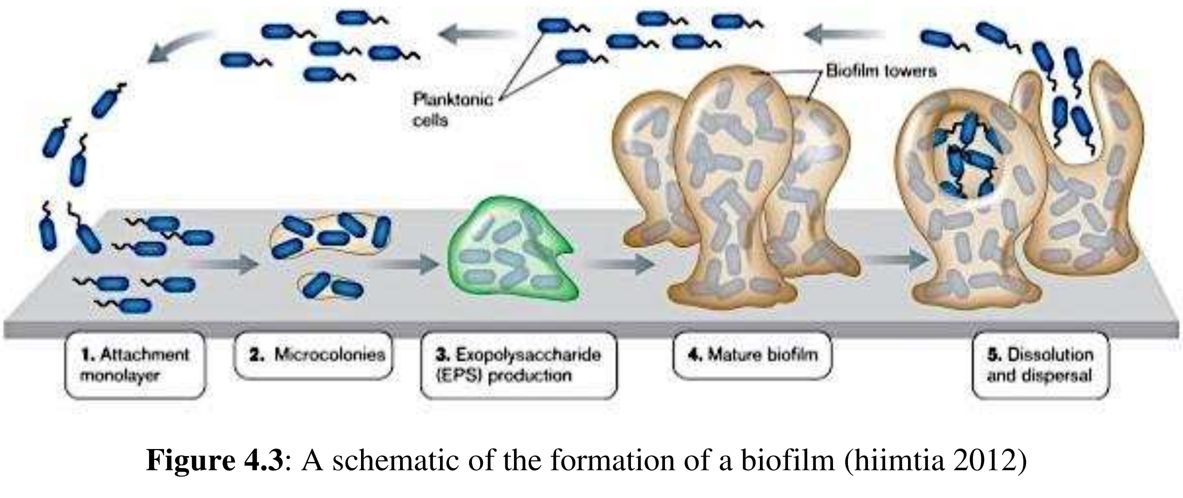


Figure 4.3: A schematic of the formation of a biofilm (hiimtia 2012)

4.3 PILOT STUDY

The pilot study conducted at CSU to investigate whether a biofilm will form on the RPM in a contact tank consisted of two tasks. The first task is the worst-case scenario, that is no injection of a disinfectant, which is a common occurrence in SWTS in developing communities. The second task is to inject a disinfectant along with the inflow to simulate the quality of water entering a contact tank.

4.3.1 METHOD OF EVALUATION

When considering the potential biofilm growth in a contact tank filled with RPM, the quality of the water entering the tank is vital. As discussed in Chapter 2, surface water sources must be clarified and filtered as a necessary precursor before disinfection. Consequently, the water entering a contact tank has already been treated to a certain level. Essentially any sediment from the water source has been removed. Therefore raw water from Horsetooth Reservoir, which was used in the initial research studies at CSU, was not a sensible source for this study due to the high sediment load. Nonetheless, despite the previous filtration, water entering a contact tank could still contain bacteria, viruses, protozoa, etc., making disinfection necessary. For this reason tap water would not be useful for this study, as it has already been disinfected. In an effort to simulate the appropriate water quality, the best option available was to use the irrigation water at CSU. The irrigation water is raw water (i.e. not disinfected) that has been drawn from College Lake at CSU and has been filtered to 250μm, removing a large amount of sediment that could damage the irrigation pumps and sprinklers. For a disinfectant, a diluted bleach (NaOHCl) solution was used as a source of chlorine.

The inflow and outflow were sampled on a weekly basis and were analyzed for Pseudomonas count at the Environmental Health Services Water Quality Lab at CSU. The presence of Pseudomonas is a reasonable indication of a biofilm as they are gram-negative bacteria that can produce exopolysaccharides (EPS) that are associated with the formation of biofilm (Mena & Gerba 2009).

In the interest of reuse to minimize costs, the 1” and 2” spherical RPM that was used in CDPHE study were used. The challenge with biofilms is the ‘film’ that is responsible for the strong attachment to surfaces. In an effort to clean the RPM for reuse, three actions were taken. First, high-pressured water by a power washer was used to physically remove any sediment and/or biofilm. Second, since the film protects the bacteria from the effects of chlorine, the RPM, in the tanks used for the experiments, were soaked in a low concentration of hydrogen peroxide. Studies have shown that the depolymerizing properties of hydrogen peroxide, even at non-toxic levels, are effective in degrading the extra-cellular (EPS) network of biofilms (Christensen, et al. 1990). Finally, under the assumption that the high-pressure water and hydrogen peroxide were able to break up any possible biofilms, the RPM was soaked in a highly concentrated chlorine solution to deactivate any remaining bacteria.

4.3.2 TASK 1

The first task was to determine if a biofilm would grow on RPM when water is not yet disinfected. **Figure 4.4** shows the setup of the first task of the pilot study that was conducted in the EFML at CSU. A 50-gallon tank was filled with 1” diameter spherical RPM that has a porosity of 90%. The irrigation water entered the tank at the bottom and exited at the top. The flow rate was about 5 gpm, providing a retention time of about 9 minutes.

(a) Front (b) Back

Figure 4.4: Photograph of the set-up used for Task 1; (1) incoming raw irrigation water, (2) Inlet, and (3) Outlet.

4.3.2.1 RESULTS

The incoming irrigation water had a lower pseudomonas count than at the outlet during the first week depicted by **Figure 4.5**. There was also a 300% greater difference between the Pseudomonas count of the incoming irrigation water and the water from the outlet from the beginning of the experiment, T_0, to after one week, T_1. This could indicate the growth of a biofilm. A visual inspection near the outlet revealed some sediment or biological growth on the RPM (**Figure 4.6**). After two weeks of continuously running irrigation water through the tank, there was a decrease in pseudomonas count (see **Figure 4.5**), which was unexpected. This may be due to the cyclical nature of biofilm maturation entraining bacteria from the flow.

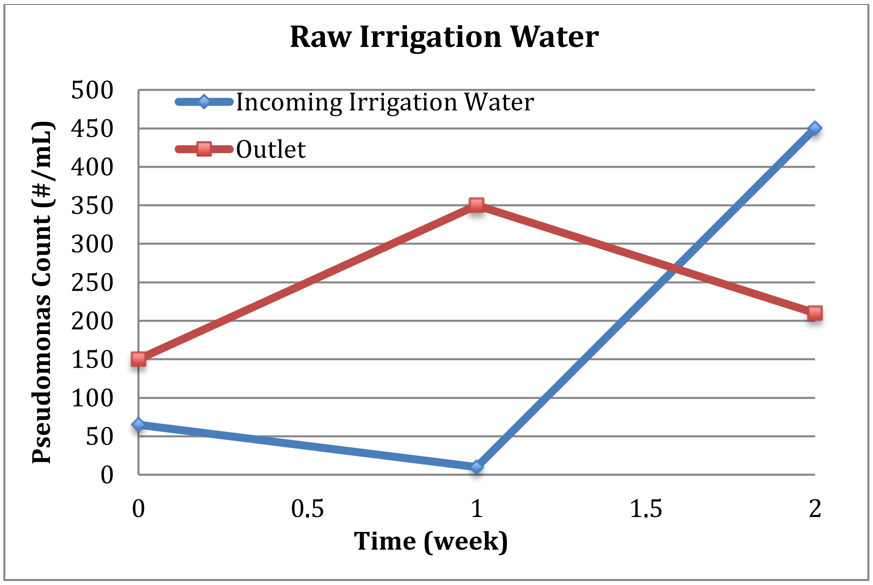


Figure 4.5: Pseudomonas counts for irrigation water

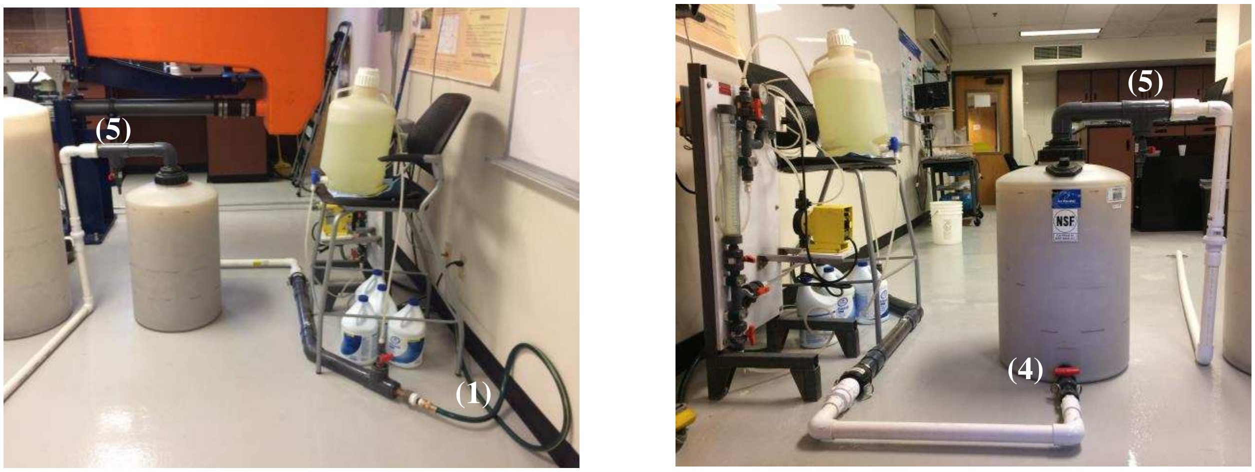

(a) (b)

Figure 4.6: Photographs of RPM near the outlet; (a) before the study began and (b) at the end of the 2-week study.

4.3.3 TASK 2

The second task was to inject a disinfectant into the inflowing filtered water to simulate the water quality circumstances characteristic of contact tanks. **Figure 4.7** shows the setup of the second experiment of the pilot study that was also undertaken at the EFML at CSU. A 25-gallon tank is filled with 2” diameter spherical packing material that also has a porosity of 90%. While the volume of the tank and the size of the RPM were different than those used in the first experiment, the difference was not considered to be relevant since the focus of these experiments was to evaluate the biological aspect, not the hydraulics. Similar to the first experiment, the irrigation water entered the tank at the bottom and exited at the top. The flow rate was about 5 gpm, this time providing a retention time of about 4.5 minutes.

(a) Chorine dosing system



(b) Front (c) Back

Figure 4.7: Photograph of the set-up for Task 2; (1) incoming raw irrigation water, (2) dosing pump, (3) dosing point, (4) Inlet, and (5) Outlet.

The key difference between this experiment and the first is that the incoming irrigation water was continually dosed with chlorine (disinfectant) using a dosing pump characteristic of contact tanks in practice. To ensure consistency with practice, chlorine residuals were monitored using pool test strips. The chlorine dosage was on the order of 3-5 mg/L (**Figure 4.8**).

Figure 4.8: Pool test strip of chlorine residual at the outlet

4.3.3.1 RESULTS

Figure 4.9 shows that the pseudomonas count was less at the outlet than that of the incoming irrigation water. This lower count is consistent with the hypothesis of the disinfectant mitigating any growth of a biofilm. The results shown are only after one week because three days after the 1-week sample was taken, it was noticed that the level of chlorine solution had not changed in the supply container. The chlorine residual at the outlet indicated that there was no presence of chlorine. After an investigation, it was concluded that the dosing pump was no longer primed and, though the pump was audibly running, it had stopped dosing chlorine. At this point the experiment was terminated since the exact time that the pump failed was not known. Any results would not have been representative of a continuous disinfection.

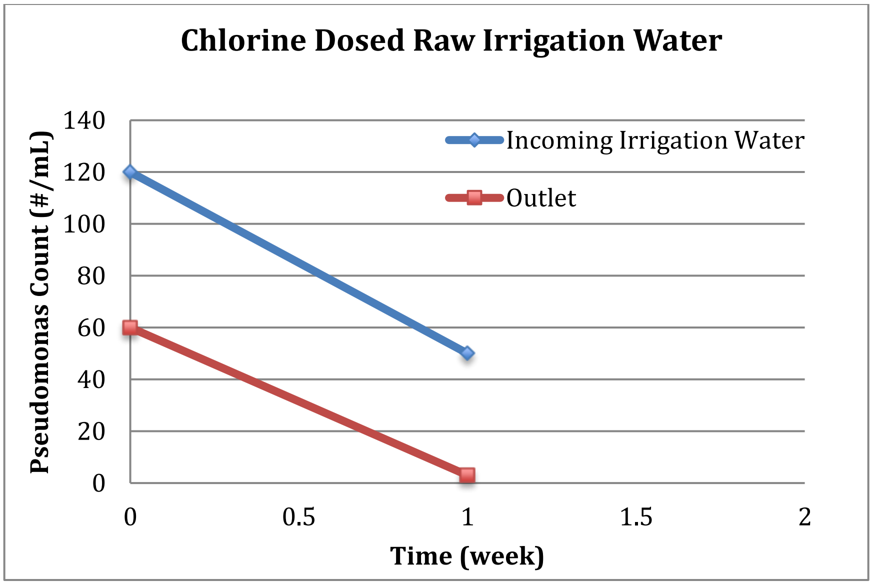


Figure 4.9: Pseudomonas counts for irrigation water dosed with chlorine.

4.4 DISCUSSION

While these two experiments were rudimentary, it can be seen that the presence of chlorine, a disinfectant, reduced the amount of pseudomonas in the raw irrigation water by about 50% (see **Figure 4.9**). However, the drop in pseudomonas at the outlet of the first experiment, which used irrigation water without any injection of a disinfectant, after two weeks was unexpected. This result will need further investigation in order to determine the cause of the drop and any ramifications. A potential concern with these results is that the quality of the irrigation water was highly variable. This variability is due to the irrigation water only being filtered to 250µm. This of course is not the case for water entering a contact tank and therefore is not fully representative. Another aspect that needs to be considered is that the RPM used in these experiments were from previous studies. Though the RPM were cleaned using hydrogen peroxide and then a concentrated chlorine solution it was still possible that a biofilm was already present. This is a likely scenario when looking at **Figure 4.5** where the incoming raw irrigation water has a lower pseudomonas count than the outflow at the initial time, t_0.

4.5 CONCLUSION

While the results of this pilot study suggest the hypothesis that the presence of a disinfectant will mitigate the formation of a biofilm, it does not prove this. In order to confidently ascertain the potential for biofilm growth these experiments would need to be repeated in a more controlled setting and for a longer period of time.

CHAPTER 5. CONCLUSION

5.1 SUMMARY OF RESEARCH

The literature review in Chapter 2 focused on the relevant aspects of water law, policy, treatment, and the operational status of small water treatment systems in South Africa. This information is important in order to have a better understanding of an international context and foundation as to why this research is relevant and beneficial. The theory of *CT* and *BF* was also explained along with research presented in the *Baffling Factor Guidance Manual* concerning inlet manifolds.

Chapter 3 focused on the application of the suggested modifications on a live system with a motivation to share this knowledge in an international context. A collaboration was built with a large water service provider in South Africa called Umgeni Water. Umgeni Water selected a rural waterworks in Rosetta, KZN, which they recently had taken over operations, for a case study. The system was holistically assessed and the *BF* was determined by physical tracer tests to be 0.22. A 4-way manifold inlet was installed in order to reduce the inflowing velocity and better distribute the flow across the cross-sectional area of the tank. The *BF* was reassessed and was determined to be 0.30, a 37% improvement resulting in an increase in characteristic contact time (*T*) from 6 minutes to about 8 minutes thereby improving the *CT*. Moreover, the process of assessing and modifying the contact tank at Rosetta Waterworks brought to light the restrictions of working on a live system in terms of time and physical restrictions as well as the necessity of a system level analysis.

Chapter 4 discussed the long-term use of RPM in contact tanks. A pilot study was conducted in the EMFL at CSU using filtered irrigation water to determine if a biofilm would grow on the RPM in a contact tank due to the quality of the water (i.e. not yet disinfected) entering the tank in combination with the high surface area of the RPM. Preliminary results suggest that without a disinfectant, a biofilm would grow but that if a disinfectant were injected, the formation of a biofilm would be mitigated.

5.2 MAJOR CONCLUSIONS

While the laboratory studies found in the *Baffling Factor Guidance Manual* demonstrated the benefit of modifying contact tanks to improve their hydraulic disinfection efficiency, they were not all encompassing in terms of applicability. This case study revealed the importance of a holistic approach when assessing and modifying a live system with unsteady operations. There are many variables that influence the hydraulic disinfection efficiency of a contact tank. To make over-arching conclusions about a particular tank, such as a 10,000 L cylindrical tank, or modification can be misleading if taken out of the context of the entire water treatment system.

The pilot study concerning the potential formation of a biofilm due to the presence of RPM in a contact tank, though not definitive, gave promising results that the use of RPM is a potential option to improve the hydraulic disinfection efficiency of contact tanks. Due to their tremendous ability to promote near plug flow conditions, the continued research of the use of RPM in contact tanks is worthwhile.

In regard to the international development aspect of this thesis, a general question that arises from this project is: Was it successful? The definition of a successful international development project is debated. However, some key elements that are associated with a ‘successful’ international development project include involvement of stakeholders throughout the entire process, achieving results, impact, skills of the project team, method of implementation, and management of project by the community (Brière and Proulx 2013). The method of implementation, or transfer in this case, was by collaboration with Umgeni Water, a significant stakeholder in the water arena of South Africa. Since Umgeni Water is the acting WSP for Rosetta WW, their involvement was high as they were the ones to grant access to the plant plus provided equipment and supplies. In terms of 'achieving results', the modification of the contact tank showed an improvement in the hydraulic disinfection efficiency, which was the purpose of the modification. The reality of larger systems at play, such as political change and education as discussed in Chapter 2, were taken into consideration with the understanding that a case study such as at Rosetta WW would not impact these societal systems. However, with education being a significant avenue to influence change, two seminars were held for engineers working with Umgeni Water in Durban and Pietermaritzburg. The focus of the seminars was to discuss the importance of including a *BF* in calculating *CT* of a particular system as well as introduce the innovative technologies in order to modify contact systems as presented in the *Baffling Factor Guidance Manual*. Ultimately, these seminars were seen as opportunities for further education for those who are monitoring and designing small water systems in KZN, South Africa. The impact of this transfer is more difficult measure. Nonetheless, after the case study at Rosetta WW was completed, Umgeni Water pursued expanding this study. They were awarded a small grant through the WRC to assess the hydraulic disinfection efficiency of other contact systems used nationally in South Africa. Also Umgeni Water will be presenting the results of this case study at the WISA Conference where other important stakeholders in the water arena in South Africa, as well as other Sub-Saharan African nations, will be present. This effort shows the motivation of Umgeni Water to adopt and apply this research to their context. Thus it is reasonable to consider this transfer of technology, i.e. contact tank modifications, a success.

5.3 PROPSED RESEARCH FOR FURTHER WORK AS A PHD DISSERTATION

Further work is necessary to demonstrate the beneficial use of RPM in contact tanks for live systems. In addition to a more extensive and controlled biofilm study, the areas of focus involve the quantification of drag that is relevant when considering energy requirements, the feasibility and scalability for different size and geometry of tanks, and finally creating a CFD model to simulate flow through RPM in a contact tank.

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