WATER QUALITY INDICES FOR WATER DISTRIBUTION NETWORK OPTIMISATION

Mercy Sibongile Nyirenda

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Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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(Signature of candidate)

16th day of July 2025 at Johannesburg

In memory of my father

Ken Edwin Nyirenda

1963 - 2022

List of Publications

Nyirenda, M. S. & Tanyimboh, T. T., 2018. Service Reservoir Design in Water Distribution Network Optimisation Models: Water Quality Concerns [Presentation], 2018 Sustainable Sanitation, Waste and Water Management Conference held in Cape Town, South Africa. 20 November

Nyirenda, M. S. & Tanyimboh, T. T., 2019. Appraisal of water quality indices for service reservoirs. Proceedings of Watermatex 2019 International Water Association (IWA) Symposium on Modelling and Integrated Assessment. Denmark Copenhagen.

Nyirenda, M. S. & Tanyimboh, T. T., 2020. Appraisal of water quality indices for service reservoirs. Journal of Water Science and Technology, 81(8), pp. 1606-1614.

Abstract

Safe drinking water is the basis for human health, survival, growth and development. The provision of safe drinking water is additionally recognised as a basic human right and even though numerous global initiatives exist to this end; it is reported that at least 1.9 billion people rely on an unimproved source or an improved source that is faecal contaminated for drinking water. The provision of safe drinking water is protected by standards for drinking water quality where water supply agencies must ensure when planning, designing and running water treatment and supply infrastructure. These standards are not always upheld as reports of higher levels of salinity, microbial contamination, eutrophication and endocrine disrupting compounds are being reported at treatment plants in South Africa and worldwide.

The design and optimisation of water distribution/reticulation networks using computational methods is a widely researched area in water design and management and is gaining more popularity as technological advances increase. Water distribution network design and optimisation typically includes selecting pipe elements, determining nodes, selecting tank locations and sizes, selecting pumps and pumping schedules while considering cost efficiency; however, inclusion of water quality has generally been excluded due to the increase in complexity resulting in increased computational time and space. However, to ensure efficient and safe provision of clean water; water quality has to be included in the design of water distribution networks to minimise potentially harmful effects.

This research dissertation developed and tested the use of water quality indices that were historically used for studies on surface water bodies. The water quality indices are capable of transforming and combining multiple water quality constituents into a single aggregated value that can be incorporated into optimisation algorithms.

Five water quality indices were developed and used here to assess the incorporation of water quality into the optimization of service reservoir designs. A set of sub-indices were developed for the four chosen water quality constituents: water age, chlorine, tri-halomethanes and halo-acetic acids and were then aggregated into indices that quantified the water quality for each reservoir. This formulation provided an estimate of the overall water quality in a reservoir where multiple water quality constituents with various units of measurement are involved. The formulation was intended to reduce computational effort for the optimisation of water distribution systems which include water quality as an objective.

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1 CHAPTER 1: INTRODUCTION

1.1 Background

Water distribution or reticulation networks are some of the largest infrastructure assets of modern society providing clean potable water to domestic, industrial and commercial users. In order to provide clean and safe water to its required users; simulation, design or optimisation of water distribution networks need to be completed; however, these systems are complex in nature. Water distribution network design and optimisation includes selecting pipe elements, determining nodes and assigning demands to these nodes, selecting tank locations and sizes, selecting pumps and pumping schedules while incorporating cost efficiency. Because of the multiple number of elements to be considered during design, water distribution networks have been a good candidate for computational methods.

The design and optimisation of water distribution networks through the use of computational methods has been a widely researched area in water design and management since the early 1950s (Barricelli, 1962) when the introduction of automated problem solving began. Since then, optimisation procedures for water distribution networks have been researched and enhanced. These enhancements follow a traditional approach where hydraulic efficiency is optimised against cost efficiency; however, this approach rarely includes other objectives that a designer may want to optimise. As computational power and technological advances increase exponentially, more research is going into expanding the capabilities of water distribution modelling software. For water distribution this includes being able to conduct reliability assessments, predicting failure, upgrading aging infrastructure, long-term water supply and a key element of distributing drinking water: water quality.

1.2 Purpose

Provision of 'clean' or 'safe' drinking water is fundamentally a constitutional right and is regulated through legislative acts such as the South African Water Services Act 108 of 1997, United States Safe Drinking Water Act (SDWA) and the Water Act 1989 of the Parliament of the United Kingdom. The right to water is also recognised internationally as part of "the right of everyone to an adequate standard of living for himself and his family" as defined by Article 11 of the International Covenant on Economic, Social and Cultural Rights (ICESCR). This right is additionally highlighted by the United Nations (UN) Sustainable Development Goals (SDGs) which defines Goal No. 6 as Clean Water and Sanitation for all. The seventeen UN SDGs are essentially a "to-do list for people and planet, and a blueprint for success," which aim to wipe out poverty, fight inequality and tackle climate change over the next 15 years (United Nations, 2023).

Water quality is part and parcel of providing clean water to all. By not including water quality in design or optimisation poor water quality is a potential downstream effect on its consumers. Poor water quality, which is at times associated with long-water ages, results in bacterial growth, disinfection by products which have been linked to disease and illness (Seyoum et al., 2014). These problems can be compounded by pressure deficient conditions in a water distribution network where low velocities exacerbate bacterial growth, increase water age and deplete chlorine residual (Seyoum et al., 2014).

Additionally, the importance of safe water and water infrastructure for human health and to the smooth functioning of a commercial and industrial economy makes water and water systems targets for terrorism (Gleick, 2006). 162 attacks on water infrastructure were recorded between 1980 and 2012 with a sharp increase between 1980 to 2000 while 30 attacks were recorded in 2012 only (Birkett, 2017). These reported attacks varied from retaliation by army groups by poisoning water sources with typhoid, to bombing water infrastructure, to intrusion of water distribution control systems. The attacks highlight the importance of resource protection and safe water provision for consumption and economic activity as water distribution and safety can easily be considered a soft target (Birkett, 2017). By poisoning clean water sources or disrupting water infrastructure supply, multiple population groups can be affected; allowing weakened immune systems, loss of jobs or economic activities to take over which makes these systems an easy or soft target for potential terrorists. An efficient management or analysis procedure to counter these attacks will rely on the ability of water supply agencies to quickly predict the movement of pollutants based on various modes of attack.

To ensure efficient and safe provision of clean water; water quality must be included in the design of water distribution networks. In this way, poor water quality can be eliminated or minimised by the time water meets its demand downstream of a source. To quantitatively assess the impacts of water quality at the point of distribution; robust methods are required that can assess or optimise various water quality constituents in a relatively short period of time. Water quality in distribution network is a complex concept to assess and optimise as it consists of multiple constituents (chemical, physical and biological) with varying units of measurement that can change based on temporal and spatial conditions influenced by the unique arrangement of each network. The water supply source itself is subject to varying constituents which then enter the treatment train and influence the water quality within the network. Water supply agencies have traditionally designed treatment plants to achieve a certain water quality at the point that water leaves the treatment train without assessing the potential effects of likely constituents at the point of use as water testing usually occurs in laboratories under strictly controlled conditions (UNICEF , 2018). This is also likely due to the unlikelihood of assessing multiple constituents at the point of use which would take extensive time and financial resources which are usually limited for water supply agencies.

Through computer modelling, a model water distribution network can mimic real life conditions enabling a water supply agency to optimise water quality throughout the network. Water quality can be assessed during the design or planned upgrades for a water distribution network through optimisation procedures and algorithms which have the ability to optimise hydraulic and cost efficiency. As these algorithms are limited by computational capacity, water quality indices for aggregating multiple water constituents can aid in including water quality as a design objective. The indices method involved using a water quality index to aggregate multiple water quality results for any node in a water distribution network into a singular value for analyses.

1.3 Objectives

This research dissertation developed and tested water quality indices for water distribution network design and optimisation. This was achieved through:

1. Reviewing applicable local and international legislation; guidelines and standards surrounding drinking water quality to determine a set of water quality constituents and targets that are suitable for water distribution systems design and optimisation. The review also included investigating design and optimisation of water distribution networks and water quality indices.
2. Determining an appropriate benchmark water distribution network for the study.
3. Modelling the benchmark water distribution network for the chosen water quality constituents and obtaining a set of water quality results for these constituents.
4. Formulating a set of water quality indices which may be suitable for water distribution systems.
5. Aggregating the water quality indices and compare them with the produced water quality results to assess their fitness for use.

Application of the water quality indices ideally allow optimisation procedures to include water quality as an objective and provide a framework that can be utilised in the design of optimal water distribution networks.

1.4 Research Outline

In Chapter 1; the problems intersecting water quality and design optimisation and an overview of the importance of water quality when looking at design objectives was introduced. The purpose and objectives for the dissertation were also presented in this chapter.

In Chapter 2; the literature surrounding water quality was explored. This includes a discussion on the prevailing legislation, optimisation of water distribution networks, a review on how water quality was included as an objective in past literature and current uses of water quality indices.

In Chapter 3; the research methodology is explained, outlying the methods that were used in assessing the research objectives.

Chapter 4 is a presentation of the research findings, results and discussion.

In Chapter 5; conclusions based on the research findings were made and recommendations for further work were outlined.

2 CHAPTER 2: LITERATURE REVIEW

This section summarises the findings of the literature review. The literature review aims to gain an understanding of the following topics in an attempt to achieve the study objectives:

- To what extent water quality issues are prevalent in potable water;
- How water quality is defined and measured;
- Local and international guidelines and standards used for water quality constituents;
- What are optimisation algorithms and how these are applied to water distribution networks;
- How optimisation algorithms have attempted to include water quality as an objective;
- Understand benchmark network problems and how these can be beneficial for the study ; and
- What are water quality indices and how have these been used previously.

2.1 Water Quality Issues in Potable Water

Safe drinking water is essential to sustain life. It is the basis for human health, survival, growth and development. Therefore, access to clean drinking-water is a basic human right. Article 11 of the International Covenant on Economic, Social and Cultural Rights (ICESCR) (United Nations, 1966) touts safe drinking water as part of their definition of 'the right of everyone to an adequate standard of living for himself and his family'. The United Nations also prioritises clean and safe drinking water for all as part of their worldwide initiative for providing a successful way of living for people and planet (United Nations, 2023). These global initiatives aim to ensure that the right to clean water for all is upheld. However, the responsibility of providing this right is typically seen as the duty of the entity responsible for drinking water supply. This responsibility usually lies with government agencies responsible for public health and environmental issues (World Health Organization, 2016) as they can initiate and uphold the rights of the people that they serve.

Despite global initiatives, treaties and recognition of the basic human right; it is reported by the United Nations that at least 1.9 billion people rely on an unimproved source or an improved source that is faecal contaminated for drinking water. It is safe to say that the provision of safe and clean drinking water is of utmost importance globally. To this end, advanced countries/states have established standards for drinking water quality where water supply agencies have to ensure when planning, designing and running water treatment and supply infrastructure.

These standards are not always upheld as can be seen with the current status of water quality in South Africa which can be used as a case study of other water quality issues present in most parts of the world. Van der Merwe (2009) reported higher levels of salinity, microbial contamination, eutrophication and endocrine disrupting compounds at water treatment plants in South Africa. This is a reflection of non-compliance and inadequate disinfection and it is not expected that the status of water quality at treatment plants has improved. The same report highlights how South Africa is not an isolated incident; however, is a snapshot of global water quality issues faced around the world. To understand water quality, the associated issues and the severity of non-compliance, an understanding of the acceptable guides and standards were be assessed.

2.2 Local Water Quality Guidelines and Standards

South Africa relies on the South African Water Quality Guidelines published by the Department of Water Affairs and Forestry in 1996. The series contains eight volumes which specify water quality limits for all uses ranging from domestic water use to livestock watering. Volume 1 which is specifically aimed at domestic water use is the focus for this study.

The guideline is essentially a user needs specification of the quality of water required for different domestic uses. The document is intended to provide information required to make judgements as to the fitness of water to be used for domestic purposes, primarily for human consumption but also other household uses such as bathing.

The guidelines describe the following which are important in determining the fitness of water for domestic use:

Table 2-1: Important descriptions of water quality definitions

Term	Definition
Water quality	Physical, chemical, biological and aesthetic property of water which determines its fitness for a specific use
Constituent	Properties or substances suspended or dissolved in water
Water quality criteria	Numerical data or narrative descriptions of its effects on the fitness of water for a particular use

The terms described in Table 2-1 are useful for the remainder of this study and the definitions described here will be used in subsequent chapters. The guide is a first step in gaining an understanding on how water quality can be understood, quantified and categorised.

Of importance to this study is:

- Which water quality constituents are most important or highly regulated;
- How are these measured or enforced; and
- What are the limits (minimum, maximum etc.) for these constituents.

The understanding and quantification of these constituents enables methods or formulae to be created and integrated into design optimisation programs.

2.2.1 Water Quality Constituents

The South African Water Quality Guideline (Department of Water Affairs and Forestry, 1996) details thirty-eight water quality constituents that have been highlighted. It is noted by the guideline that it is not possible to include all constituents that may affect the fitness of water or water quality; however, the thirty-eight discussed in the guideline are a good starting point on determining which constituents are relevant to this study. Table 2-2 below summarises these constituents and their potential effects. Certain constituents were lumped under one category such as *Indicator Organisms* which group similar constituents which behave in the same manner.

Table 2-2: Water quality constituents discussed in the South African Water Quality Guideline

Constituent	Description	Effects	Type	Origin
Algae	Oxygen producing photosynthetic organisms	• Produce toxins which can lead to death • Precursor for trihalomethanes	Biological	Surface water exposed to sun
Aluminium	Metal	• Non-toxic at near neutral pH • Prolonged exposure linked to chronic neurological disorders	Chemical - inorganic	Common elemental metal found in nature
Ammonia	Salts or gas	• Taste and odour complaints • Linked to fish death	Chemical - inorganic	Pollution from raw untreated sewage
Arsenic	Metal	• Chronic effects include death, cancer and skin-lesions	Chemical - inorganic	Pollution from industrial sources
Asbestos	Mineral	• Risk of cancer	Chemical - inorganic	Weathering, mining and industrial uses
Cadmium	Metal	• Toxic chemical leading to kidney failure and death	Chemical - inorganic	Pollution from industrial sources
Calcium	Mineral	• Aesthetic effects including scaling of domestic appliances	Chemical - inorganic	Common elemental metal found in nature
Chloride	Mineral (anion of chlorine)	• Aesthetic effects including salty taste • Corrosion of domestic appliances • Nausea and dehydration at high concentrations	Chemical	Common element found in nature
Chromium (VI)	Salt	• Toxic effects including nausea, risk of cancer	Chemical - inorganic	Pollution from industrial sources
Colour	Appearance	• Aesthetic effects (turbidity)	Property	Pollution from industrial sources
Copper	Metal	• Aesthetic effects	Chemical - inorganic	Common elemental

Constituent	Description	Effects	Type	Origin
		• Gastrointestinal irritation which can lead to fatalities		metal found in nature
Corrosion	Interaction of corrosive chemicals	• Economic, aesthetics and health risks (bacterial growth)	Property	Water with metallic structures in contact with water
Dissolved Organic Carbon	Mineral	• Indication of organic matter • Precursor for trihalomethanes	Chemical - inorganic	Industrial, agricultural and domestic effluents
Fluoride	Mineral	• Severe tooth damage leading to skeletal fluorosis • Poisoning may lead to death	Chemical - inorganic	Common element found in nature
Indicator organisms	Variety of pathogenic viruses, protozoa and bacteria	• Cause diseases such as gastroenteritis, hepatitis, cholera etc. • Precursors to death	Microbiological	Faecal contamination
Iron	Metal	• Aesthetic and taste effects • Tissue damage as a result of iron accumulation	Chemical - inorganic	Common element found in nature
Lead	Metal	• Adverse effects of lead poisoning include neurological damage	Chemical - inorganic	Pollution from industrial sources
Magnesium	Mineral	• Aesthetic and taste effects • Possible diarrhoea	Chemical - inorganic	Common element found in nature
Manganese	Metal	• Aesthetic and taste effects	Chemical-inorganic	Common element found in nature / Pollution from industrial sources
Mercury	Metal	• Produce toxins which can lead to death or brain damage	Chemical-inorganic	Pollution from industrial sources or through food
Nitrate	Mineral	• Adverse health effects in infants and adults in high concentrations	Chemical-inorganic	Pollution through treated or raw sewage
Odour	Aesthetic	• Can indicate potential health effects if toxic	Property	Indicates presence of

Constituent	Description	Effects	Type	Origin
		organic substances are present		organic substances
pH	Indicates hydrogen ion concentration (acidic vs alkaline)	• Low pH – adverse health effects from dissolved toxic metal ions • High pH – adverse health effects from deprotonation of ions	Property	Can indicate raw water or presence of substances
Phenols	Chemical	• Aesthetic and toxic effects	Chemical-inorganic	Pollution from industrial sources
Potassium	Metal	• Aesthetic effects leading to nausea, vomiting and irritation of mucous membrane	Chemical-inorganic	Pollution from agricultural and domestic sources
Radioactivity	Radioactive nuclides	• Significant cancer risk dependent on nuclide	Chemical-inorganic	Naturally occurring and pollution from industrial sources
Selenium	Semi-metallic element	• Toxicity with long term use	Chemical-inorganic	Pollution from industrial sources
Settleable matter	Sediment, solids and floating material	• Aesthetic effects – affects turbidity and colour	Property	Inadequate treatment processes
Sodium	Alkali-metal	• Aesthetic effects • Nausea and vomiting • Not desirable for persons on a sodium restricted diet	Chemical - inorganic	Naturally occurring and pollution from industrial sources
Sulphate	Salts	• Aesthetic effects • Nausea, vomiting and diarrhoea	Chemical - inorganic	Naturally occurring and pollution from industrial sources
Trihalomethanes	Group of single carbon compounds	• Excessive levels associated with developing cancer	Organic	Water containing significant organic material
Total dissolved solids	Inorganic salts	• Aesthetic effects including scaling and corrosion in appliances • Disturbance of salt balance	Chemical - inorganic	Naturally occurring

Constituent	Description	Effects	Type	Origin
Total hardness	Sum of calcium and magnesium concentrations	• Scaling in appliances and plumbing • Decrease in soap effectiveness	Chemical - inorganic	Naturally occurring
Turbidity	Measure of light scattering ability	• Aesthetics effects • Possible indication of microbial contamination	Property	Presence of suspended matter – inorganic matter, clay, soil and organic matter
Vanadium	Metal	• Toxicity including growth suppression and respiratory symptoms	Chemical - inorganic	Naturally occurring and pollution from industrial sources
Zinc	Metal	• Aesthetic effects – bitter taste • Acute toxicity with renal damage	Chemical - inorganic	Naturally occurring and pollution from industrial sources

The effects described above are focussed on negative human effects mainly; however, environmental effects, animal and aquatic life and even positive effects can also be considered for other studies. The origin of the constituents can be determined from various sources and not only those listed in the table; however, the table lists origin sources that are most likely to cause the negative effects that are reported. Table 2-2 also highlights just how many constituents can affect water quality and it is unlikely that water regulators are able to test and treat all the water quality constituents that are present in the water source.

All the constituents in Table 2-2 can be lumped into three distinct groups. Table 2-3 below summaries the constituent types and the effects related to the group.

Table 2-3: Summary of constituent types and effects

Type	Major effects	Thresholds
Chemical -inorganic	• Toxicity effects at high thresholds • Aesthetic and taste effects • Renal damage • Diarrhoea, nausea and vomiting	• High thresholds not usually found in nature • Usually require long term exposure for critical effects
Biological/organic	• Cause diseases such as gastroenteritis, hepatitis, cholera etc. • Precursors to death	• Low thresholds re quired to cause disease • Dependent on immune system function

Aesthetic	• Bitter taste • Turbidity and colour problems • Scaling and corrosion problems	• Dependent on number and quantity of constituents' present

Although the extensive list considered in the South African Water Quality Guidelines indicates that there are a variety of constituents which can result in extreme adverse health effects; it also highlights that very few will enter and remain after the treatment train. Even fewer constituents are likely actively measured and used as a baseline. This is because as many of the constituents recorded are unlikely to enter domestic water sources or pose no to minor adverse effects unless these are at high concentrations which are unlikely to form (Department of Water Affairs and Forestry, 1996). It can be assumed that the constituents that are likely to be found in domestic water through pollution; such as ammonia, dissolved organic carbon, indicator organisms and certain metals are those which must be tracked; measured and limited to concentrations which pose little to no adverse effects. These constituents are further described in the water quality standards.

2.2.2 Water Quality Standards Defined by The South African National Bureau of Standards

Enforcement of the national water quality standards for South Africa are administered by the South African National Standard (SANS) 241 Part 1 of 2015 which is upheld by the South African Bureau of Standards. The SANS 241 document specifies the quality of drinking water and enforces water service institutions and intermediaries to comply with the numerical limits set within the Standard. The Standard also makes provision for water service authorities to monitor; maintain monitoring plans and risk assessments as set out in Part 2 of the Standard.

The Standard sets out physical, aesthetic and chemical numerical limits for human consumption in the document. These include a variety of microbiological; metals; chemical substances and physical constituents such as colour, turbidity and pH. The Standard aligns with the constituents recorded in Table 2-2. The Standard also clarifies that the taste, appearance and odour of drinking water should be acceptable to most consumers and hence aesthetic constituents can be easily monitored while provision of wholesome water should be maintained as a priority.

The Standard also makes a notable separation between chemical constituents which are organic and inorganic. Organic constituents like trihalomethanes can naturally grow or decay ; while inorganic constituents are the likes of chemicals and metals which are typically produced by source pollution. The document further reinforces that only a few chemicals have been proven to show widespread adverse effects when present in excessive concentrations over long periods of time while microbial contamination can pose real health effects from a single exposure.

The constituents discussed so far are those which may be present in drinking water and are limited to the specific economic climate; operations and environment that are present in South Africa. The Standard makes provision for constituents not listed in this document by referring the reader to the World Health Organization (WHO) Guidelines for drinking water quality.

2.3 International Water Quality Standards

International drinking water quality standards have been set out by the World Health Organization in the Guidelines for drinking water quality with the latest edition published in 2017. The guide provides over 50 years of knowledge, standards and guidelines to safeguard water safety for public health.

The guideline is the preface of many international water quality standards including American, British, Australian and South African water legislation and acts. The document is additionally recognised by the United Nations as the embodiment of their position on drinking water quality issues (World Health Organization, 2017).

The guideline describes four distinct types of health targets for consideration:

1. Health outcome targets (e.g. tolerable burdens of disease) – upper limits set at the national level to determine the level of incidence per period.
2. Water quality targets (e.g. guideline values for chemical hazards) – guideline values for individual chemicals based on local conditions and risk assessments.
3. Performance targets (e.g. log reductions of specific pathogens) – reduction of pathogens based on specific targets determined by the water supplier.
4. Specified technology targets (e.g. application of defined treatment processes) – treatment requirements set at the national level.

The targets provide benchmarks for water suppliers and regulators to confirm adequacy of existing systems and provisions for improvement. Water suppliers are required to set and adhere to these targets according to the standards and guidelines similar to those discussed here. Of particular interest to this study is the water quality target which provides guidance on which constituent and how much of the constituent should be included as an objective. For designers, researchers and planners; the water quality standards are the first point for considering which constituents need to be considered in design and optimisation.

2.4 Multi-objective Design Algorithms

Optimisation often plays a large role in decision making for complex problems with large data sets. A good optimisation algorithm can find optimal or near optimal values of a decision function (Das & Das, 2020). Due to their large range of applicability, there are various categories of optimisation algorithms that have been developed. These can be categorised as seen in Figure 2-1. Of particular interest to this study are meta-heuristic evolutionary or genetic algorithms. Meta-heuristic approaches can be applied to various problems by altering some of its parameters and evolutionary algorithms are based on a set of individual solutions known as the 'population' which re-generate, based on a set of criteria. The regeneration produces a superior set of population which continue to evolve (mutation) until convergence is achieved based on the set criteria. The updated population can also be tested to select better performing candidates (elitism) which are carried over into the next generation.

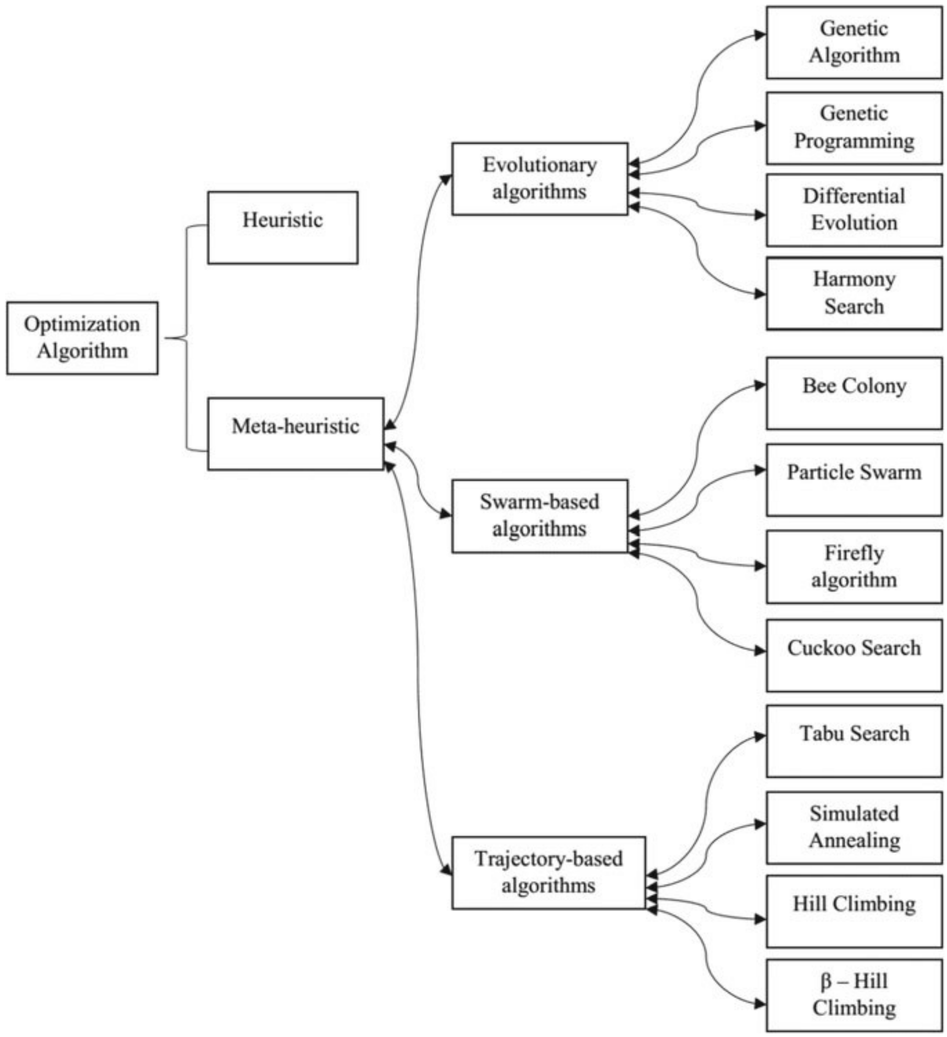


Figure 2-1: Defined categories of optimisation algorithms (from Das & Das, 2020)

Classical optimisations techniques have preceded the methods defined in Figure 2-1. These methods such as linear, dynamic programming and its hybrids would be a good candidate for inclusion in this study. However, classical methods are limited in size and may require excessive computation time and space for large networks, while limited by the number of variables which can be computed (Schaake & Lai, 1969). An example is the Two-Looped network (Alperovits & Shamir, 1977) which can be classified as a small network; has seven nodes and eight pipes arranged in two loops. For this problem, 14 commercial diameters can be selected and so the solution space is defined by 14^8 which equals 1.4758 x 10^9 possible configurations (Avila-Melgar et al., 2023). For real life networks, there are numerous variables with a number of solutions making the use of classical methods difficult.

Evolutionary algorithms are thus used for various engineering problems. Figure 2-2 is a simple illustration of an evolutionary algorithm. This procedure is easily applied to water distribution network optimisation where a population of probable solutions has evolved based on a set of constraints or equations (for a hydraulic model of a network in this case) until convergence is achieved.

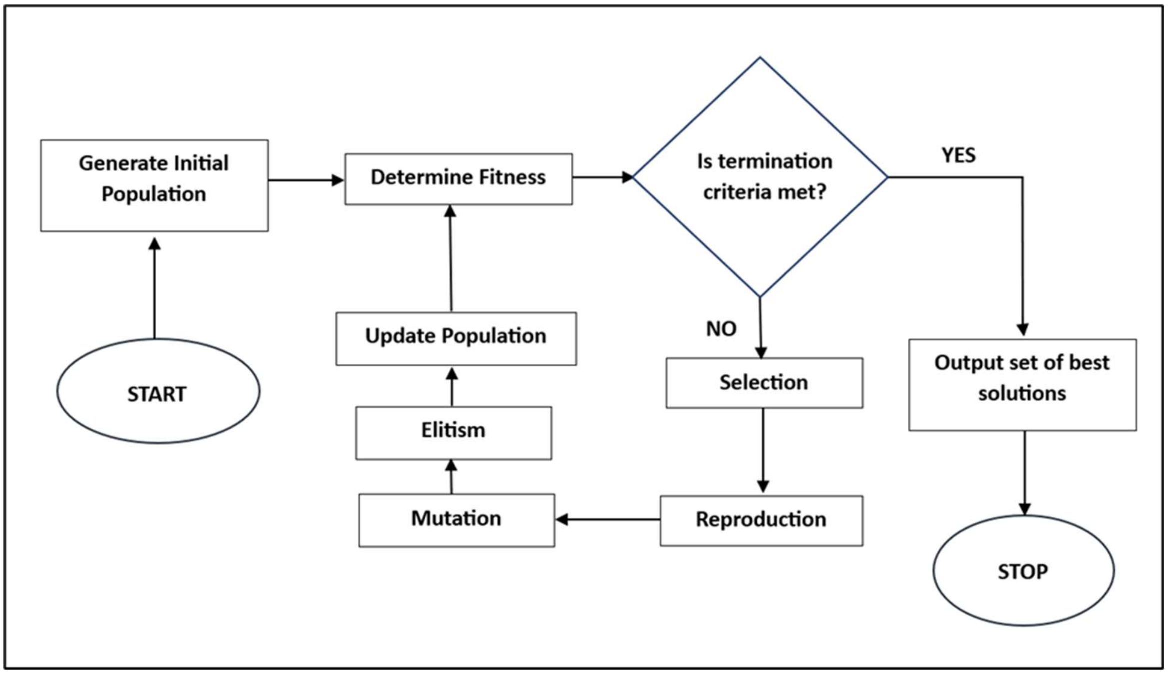


Figure 2-2: General evolutionary algorithm framework

Multi-objective evolutionary algorithms in particular use the evolutionary framework to find solutions for multiple criteria. To achieve this, the algorithms make use of the Pareto-optimal front curve or surface. The Pareto-optimal front is a widely used tool in engineering which allows a user to assess a set of solutions and make trade-offs based on the user's criteria to select the most efficient solutions. Instead of a single optimum, there is a set of trade-off solutions in the design space that are better than them or can dominate them when all the objectives are considered. In other words, all other solutions are dominated solutions that are worse than the Pareto-optimal solutions. The Pareto-optimal front is useful for multi-objective optimisation as a single solution is unlikely the best for all the objectives that need to be satisfied simultaneously.

A variety of multi-objective algorithms which were applied to design and optimise water distribution networks are discussed here. The discussion is based around how water quality can be included into the optimisation algorithms and how the proposed method could be included in the optimisation procedure. The algorithms discussed here are not an exhaustive list but a summary of what was applicable to the study objectives at the time the literature review was completed.

2.5 Optimisation Algorithms including Water Quality

The following evolutionary algorithms were identified as a case study during the literature review. The algorithms have both advantages and disadvantages based on the methods employed but are discussed here to investigate how they have attempted to include water quality as an objective.

2.5.1 Strength Pareto Evolutionary Algorithm (SPEA2) algorithm

Kurek and Ostfeld (2013) described and investigated a multi-objective model to optimise pumping cost and water quality for complex water distribution systems. The approach utilised by this method is by minimising the cost of energy consumed by pumps operating in the system and utilising a penalty function to control chlorine disinfectant concentration while ensuring network constraints for variables such as flows; pressures and velocities are met. Pumps in the system were evaluated for energy consumption and disinfectant concentration for all nodes was limited to between 0.1 and 0.5 mg/L.

The study was conducted through EPANET linked to a Strength Pareto Evolutionary Algorithm (SPEA2) algorithm. SPEA2 is an improved version of the SPEA algorithm (Zitzler et al., 2001) which aims to find or approximate the Pareto optimal front with faster convergence, improved fitness analysis and an improved guidance of the search process as compared to SPEA.

The algorithm was tested with the Anytown and EPANET NET 3 water distribution network problems. The study was successful, although it had major limitations. The algorithm did not include tank sizing but depended on prior selection of a suitable tank size based on reasonable knowledge, which could have major effects on the system and water quality. Another limitation was only one water quality constituent could be controlled or monitored by the algorithm. This is idealistic as multiple water quality constituents need to be considered in real-life water distribution network.

2.5.2 Multi-objective evolutionary algorithm

Farmani et al (2006) attempted to utilise a multi-objective evolutionary algorithm (MOEA) to simultaneously optimise and include as many widely known objectives usually considered for water distribution networks. The study included three objectives:

- Reliability – described as the networks' ability to provide consumers with water at an adequate pressure during normal and abnormal conditions. This was achieved by introducing a resilience index which accounts for surplus at nodes which can provide for consumers in the case of failures.
- Total cost – which included capital costs for pumps and tanks as required by the analysed network. Additionally costs for cleaning, laying and lining pipes were

included as well as operational costs incurred by energy requirements for the chosen pumps.

- Water quality – was addressed by considering minimisation of detention time or water age. Water age is the time it takes for a parcel of water to travel from treatment to the location of interest. It is linked to the deterioration of water quality as longer detention times are thought to decrease disinfection residual while increasing the formation of disinfection of by-products and bacterial growth and regrowth.

The optimisation procedure is described in Figure 2-3.

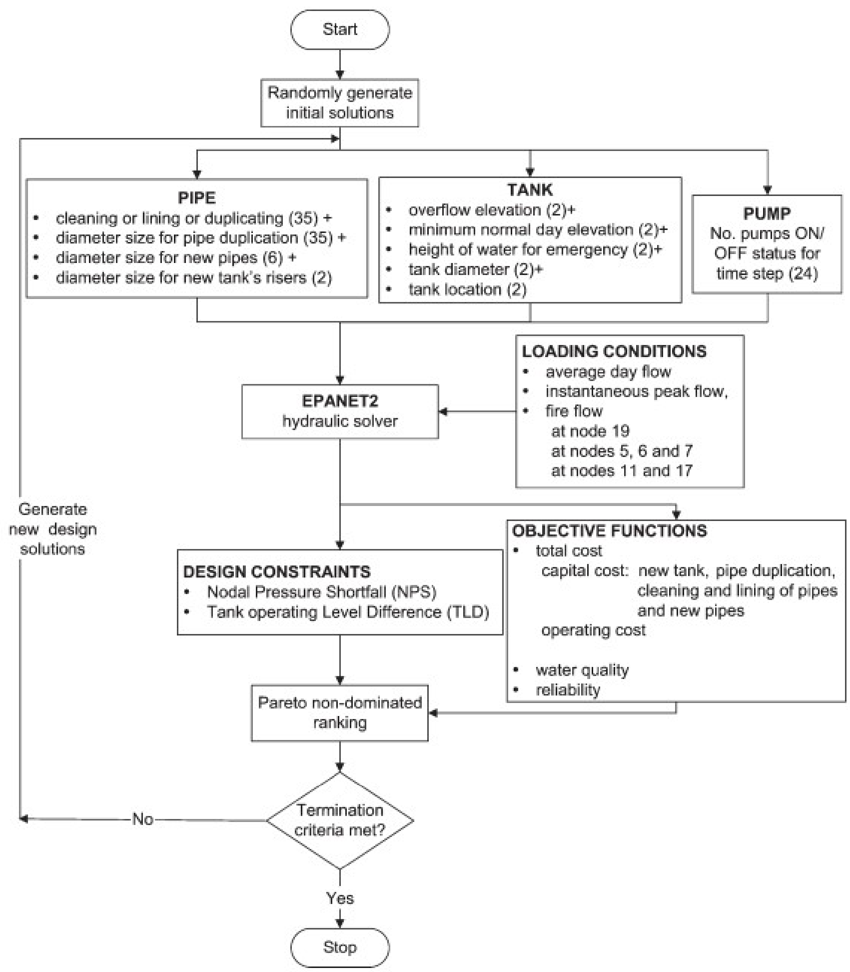


Figure 2-3: Optimisation procedure as described by Farmani et al., 2006

The optimisation method was capable of converging and water ages older than 80 hours in the analysis were reported. The required reliability was achieved for all feasible solutions and a total cost similar to that achieved in other published results was obtained. The algorithm is however restricted to only water age which is again inadequate for real life water quality consideration in water distribution networks.

2.5.3 Multi-criteria decision-making tool

Basile et al. (2009) presented a multi-criteria decision-making tool to optimise tank location, volume and water age by linking the model with the hydraulic solver EPANET. The decision tool was a two-stage algorithm which largely focused on water storage and location in an attempt to minimize residence time and hence water age.

The decision tool was able to achieve acceptable results but was however limited by providing enhanced designs which aid only one water quality constituent.

2.5.4 Penalty-Free Multi-Objective Evolutionary Algorithm

Penalty-Free Multi-Objective Evolutionary Algorithm (PF-MOEA) was developed by Siew et al. (2016) for the design and optimisation of water distribution networks. PF-MOEA can optimise pipe sizing, tank siting, pump scheduling and promotes tank depletion which is intended to implicitly encourage better water quality.PF-MOEA has been found to be robust, efficient and capable of producing more cost-effective solutions for benchmark water distribution networks than those presented in earlier studies. However, PF-MOEA does not feature water quality as a constraint in its determination of a suitable solution.

In general, the optimisation algorithms discussed above focus on a traditional approach which prioritises cost efficiency and hydraulic performance. This assumes that the treatment plant releases water that meets the potable water quality standards and that this reaches all points of the distribution system in the same state.. However, water quality changes during distribution and some optimization algorithms above have included water quality in their formulations.

The attempts to include water quality; however, have been made for only one constituent or a hydraulic variable with the aim to implicitly encourage water quality. This is likely due to the complexity introduced into the problem if several water quality constituents need to be monitored and controlled. The study also highlights that any of the above methods discussed above have the potential to robustly assess water quality if multiple water quality constituents can be combined into one to reduce complexity as the studies were able to produce feasible solutions by considering a singular water quality objective.

2.6 Benchmark Water Distribution Networks

Many water distribution networks have been presented as case studies for analyses of optimisation procedures. Several researchers have cited the same networks to compare the results to those obtained in other studies. These networks are aptly named benchmark water distribution networks as they allow several methods to be compared with the same optimisation problem.

A few notable networks are the Two Loop Network (Alperovits & Shamir, 1977); the New York Tunnel system (Schaake & Lai, 1969); the Hanoi network (Fujiwara et al., 1987) and the Anytown network (Walski et al., 1987). These networks are shown in Figure 2-4 to Figure 2-7.

Details of the problem statement including pipe lengths, nodes and hydraulic variables (roughness, friction factors etc) can be found in the referenced text.

The networks and associated problems vary in complexity and are utilised by researchers based on computational capacity and complexity as required by the methodologies applied. A summary of the benchmark water distribution problems discussed above is shown in Table 2-4.

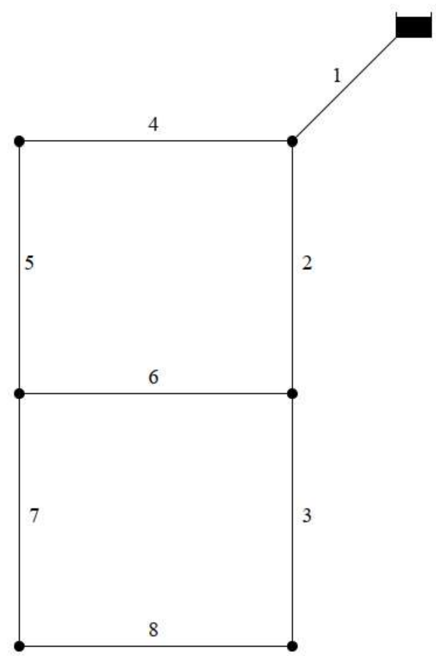


Figure 2-4: The Two Loop Network from Alperovits & Shamir, 1977

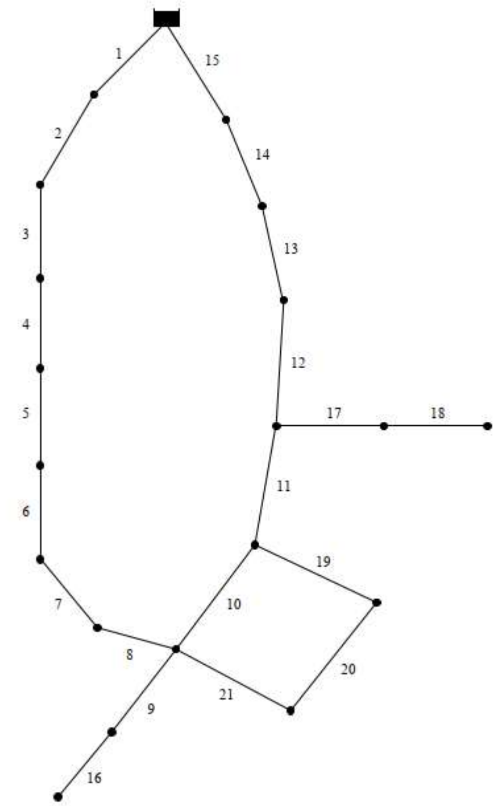


Figure 2-5:The New York Tunnel System from Schaake & Lai, 1969

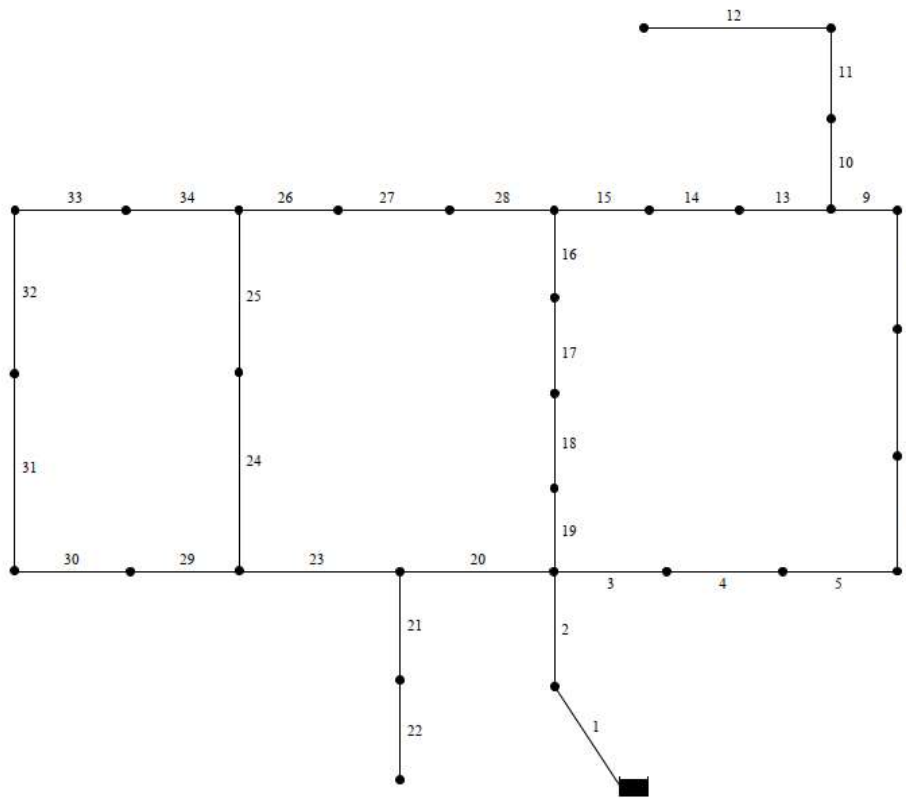


Figure 2-6: The Hanoi Network from Fujiwara et al., 1987

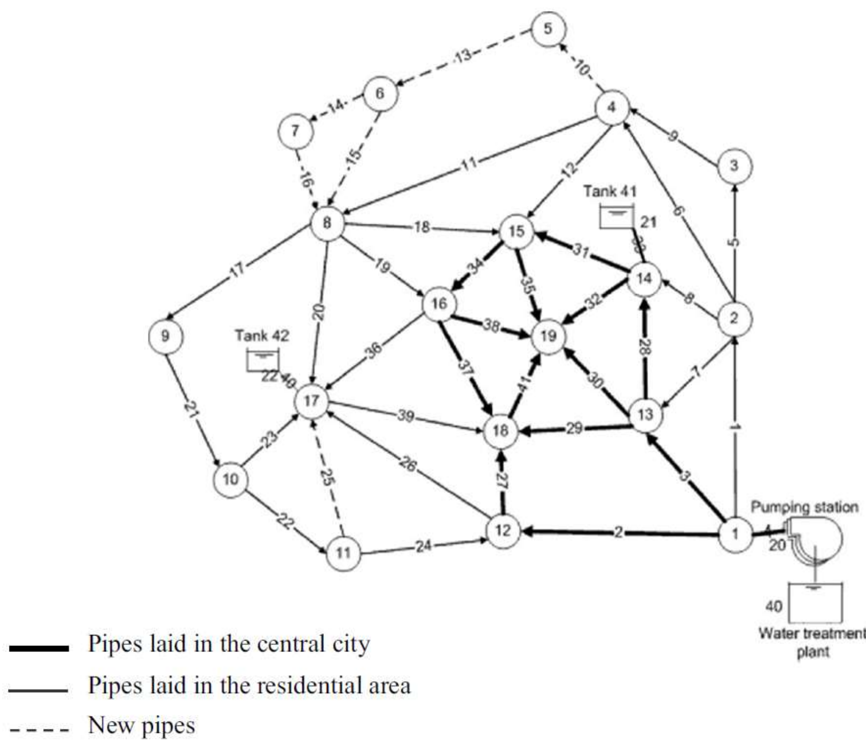


Figure 2-7: The Anytown Network from Walski et al., 1987

Table 2-4: Comparison of benchmark water distribution problems

Network	Variables	Conditions
Two Loop Network	• 8 links • 6 nodes	• Optimise pipe size • Minimise cost • Single demand loading = 30 m minimum pressure head • Head loss gradient between 0.0005 and 0.5
New York Tunnel System	• 21 links • 19 nodes	• Optimise total system including paralleling of pipes • Minimise cost • Demand loading = 225 ft minimum pressure head (except for specified nodes)
Hanoi Network	• 34 links • 31 nodes	• Optimise pipe size • Minimise cost • Demand loading = 30 m minimum pressure head (except for specified nodes)
Anytown Network	• 34 links • 19 nodes	• Optimise total system including paralleling of pipes, pumping and tank locations and sizing • Minimise cost • Demand loading = 40 psi minimum pressure head while meeting peak flows required at nodes • Demand loading = 20 psi minimum pressure head while meeting fire flows required at nodes

The Anytown network is a good candidate for this study as it aims to reproduce realistic water distribution networks. Additionally, the wide use of the network makes it easier to benchmark against the results for many optimisation techniques. It should be noted that a great number of distribution networks have been studied in past literature, some more complex or even mimicking real life networks; however, the Anytown network has been repeatedly used as a case study for optimisation algorithms as was initially intended in the original text. The network provides a variety of variables, realistic scenarios and several proposed solutions by several authors which are well suited for comparisons as is required by this study.

The original Anytown network has the following problems which need to be satisfied:

- Three demand scenarios:
    - An average-day flow scenario where the average nodal demands are applied to the nodes;
    - An instantaneous peak flow scenario where the optimised solutions are analysed using a single time step with a global peak factor of 1.8 applied to the nodal demands; and
    - Three fire flow scenarios based on 2-hour extended period simulations run with three critical fire-fighting demands applied along with a daily peak flow of 1.3 times average demand.

- The optimised solutions are required to provide a minimum residual pressure of 40 psi (28.12 m) throughout the network during the average-day and peak-flow scenarios;
- The fire flows require a minimum residual pressure of 20 psi (14.06 m) throughout the network;
- Optimisation of the existing pumping schedules and addition of new pumps if required. Pump operating costs are based on a unit cost for energy, constant throughout the 24-hours, equal to $0.12/kWh. New pumps can be added or upgraded at cost functions cited in the text;
- Operation of the existing tanks or addition of new tanks;
- 35 existing pipes can be considered for duplication, cleaning or lining. Additionally, 6 new pipes have to be sized. Pipes which were cleaned and lined have a Hazen-Williams coefficient of C=125 and for new pipes C=130; and
- Optimise construction cost of new additions and energy costs.

Further details of the network are contained in Appendix A.

2.7 Algorithmic solutions of the Anytown Network

Several evolutionary algorithms were found in the literature to be the most cost effective for the Anytown network. These algorithms claim to be robust and allow optimisation of a water distribution network for multiple criteria such as overall hydraulic performance and cost which can include capital, operational, maintenance and, replacement costs. These methods are discussed here as candidates for investigation of the proposed method.

2.7.1 Penalty-Free Multi-Objective Evolutionary Algorithm

Penalty-Free Multi-Objective Evolutionary Algorithm (PF-MOEA) developed by Siew et al., 2016) can optimise pipe sizing, tank siting, pump scheduling and tank depletion. PF-MOEA discussed under Section 2.5.4 does not feature water quality in its determination of a suitable solution.

The algorithm presented many feasible solutions for the Anytown network with various combinations of new tanks, pipe replacement, paralleling and cleaning and an optimised pump schedule (Siew et al., 2016); however, two of the cheapest PF-MOEA solutions were discussed in detail. Solution 1 applies a pressure dependent model which utilises an elitist genetic algorithm. Solution 2 is similar to Solution 1 but includes an additional tank depletion criterion aimed at implicitly reducing water age to improve the water quality in service reservoirs. This is achieved by choosing the right tank location, size and shape while attempting to force the tank to empty and re-fill every 24-hours, potentially decreasing water age and promoting proper mixing. Solution 1 and 2 are shown in Figure 2-8 and Figure 2-9 respectively. Tanks shown in blue represent new tanks for the Anytown network. Details of the other proposed upgrades such as pipe paralleling are not shown and are detailed in the reference text. In figures 2-8 to 2-13 of the Anytown network; pipes shown in bold are located in the inner city and dashed lines are new pipes which require sizing.

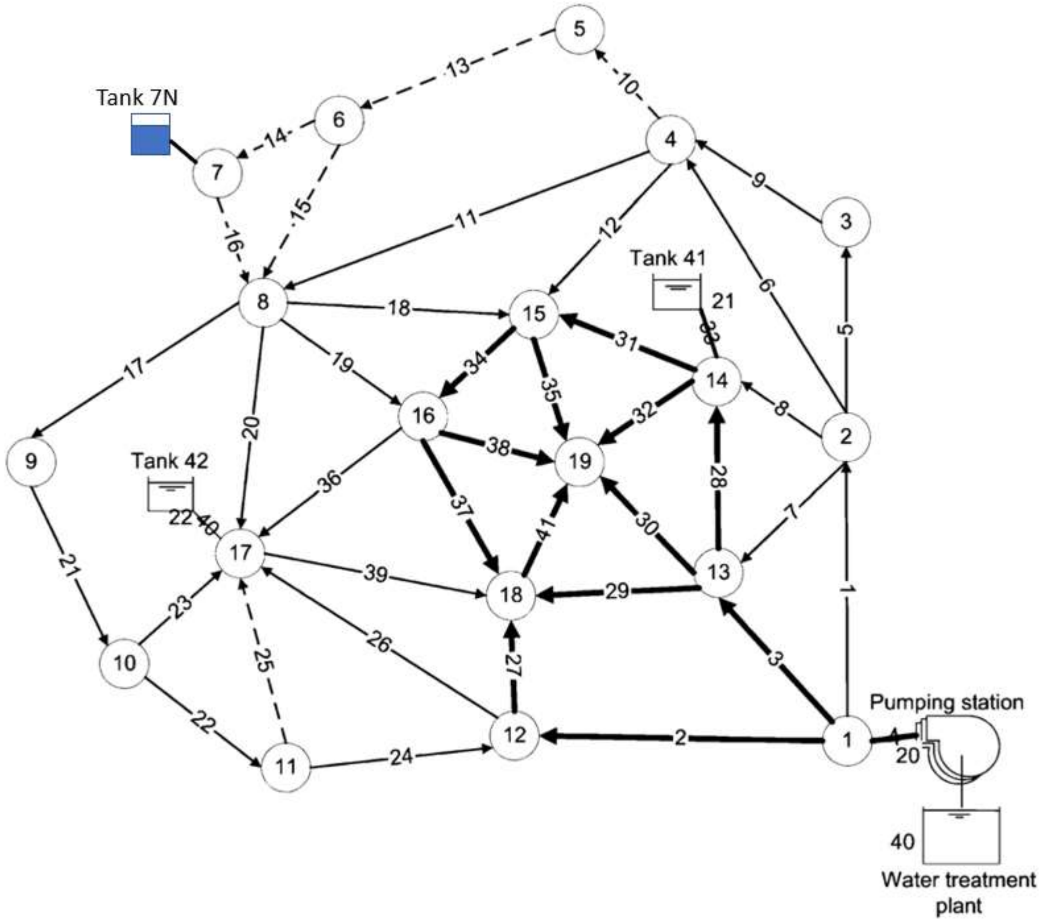


Figure 2-8: PF-MOEA Solution 1 shown with new tank 7N shown from Siew et al., 2016

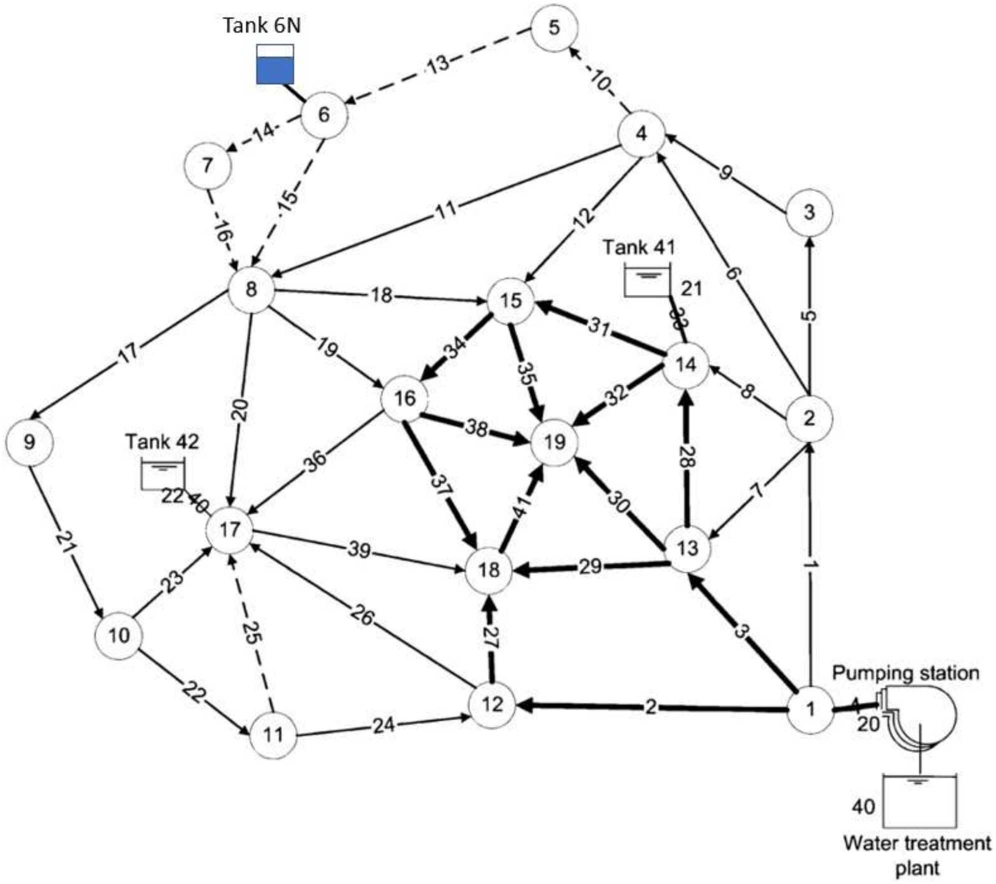


Figure 2-9: PF-MOEA Solution 2 shown with new tank 6N from Siew et al., 2016

Both solutions contain a new reservoir/tank located far north in the network. This is in collaboration with other improvements suggested by PF-MOEA; however, only the new service tanks are shown.

2.7.2 Fuzzy Multi-objective Optimisation (FMO)

The Fuzzy Multi-Objective Optimisation (FMO) developed by Vamvakeridou-Lyroudia et al, (2005) is a multi-objective optimisation which includes fuzzy set theory which models uncertainty in parameters such as nodal demands and roughness coefficients. FMO additionally takes into account tank shape with the use of a diameter to height ratio in order to avoid extremely wide, flat or high tanks. This can prove to be implicitly beneficial to the tank design as overly sized tanks are considered to negatively impact the water quality within the tank (Clark et al., 1996).

Two solutions were reported by the paper (Vamvakeridou-Lyroudia et al., 2005); however, the second solution only is analysed here due to small pressure deficiencies noted by the authors for the truly fuzzy solution. A ‘crisp’ solution was sought by amending pipe diameters to meet the pressure deficiencies and this solution is shown in Figure 2-10.

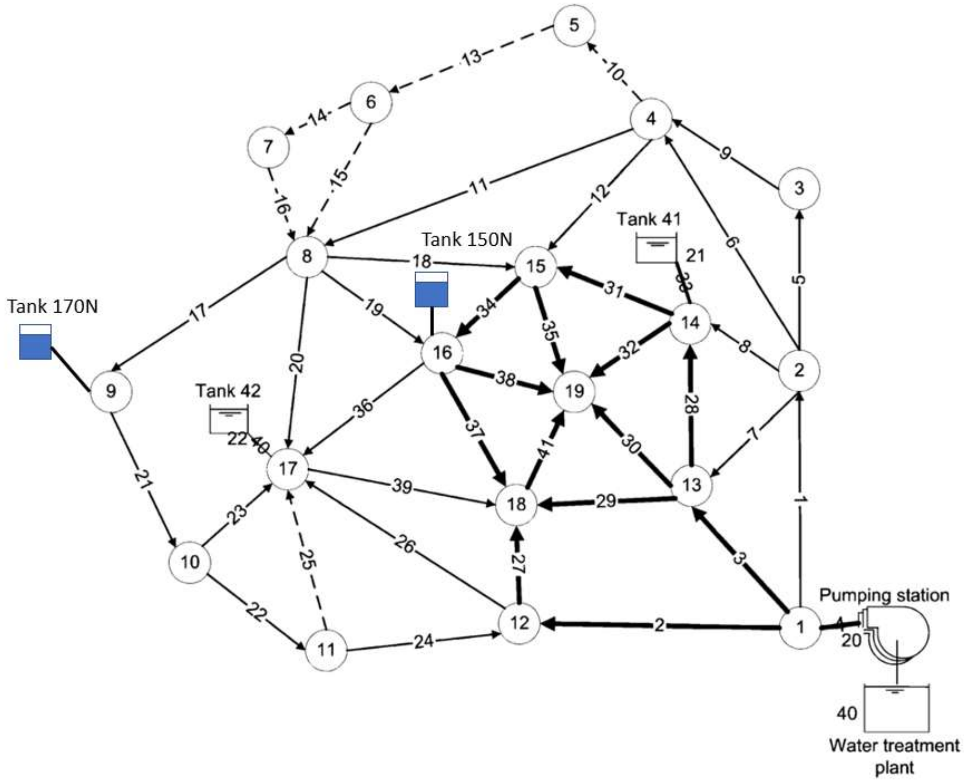


Figure 2-10: FMO Solution shown with new tanks 170N and 150N from Vamvakeridou-Lyroudia et al., 2005

2.7.3 Steady state genetic algorithm (SSGA)

Prasad (2010) utilised a steady state genetic algorithm to conduct an extended period simulation for every solution during the optimisation to select an appropriate tank size for the objectives described under Section 2.6. A steady state genetic algorithm is different to a simple genetic algorithm as there are no generations; instead, the two best solutions are chosen for mutation to keep the population constant (Agapie & Wright, 2014).

Two cases were analysed as part of this study; one excluding pressure constraints for the average day flows while one considered all pressure loadings (three demand scenarios described under Section 2.6). Case one indicated a considerable amount of pressure violations and hence is not feasible. It is assumed that the peak and fire flow scenarios did not cater for the average day scenario as the peak and fire flow scenarios occur over a shorter period (24-hours for the average flow scenario vs. a single snapshot or 3 hours for the peak and fire flow scenarios). This could possibly stress the system more by requiring more stringent constraints even though the average flows are smaller.

The feasible solution obtained under Case two is shown in Figure 2-11. The solution is similar in tank location as compared to the FMO optimisation. However, the tank sizes and corresponding pipe upgrades are different.

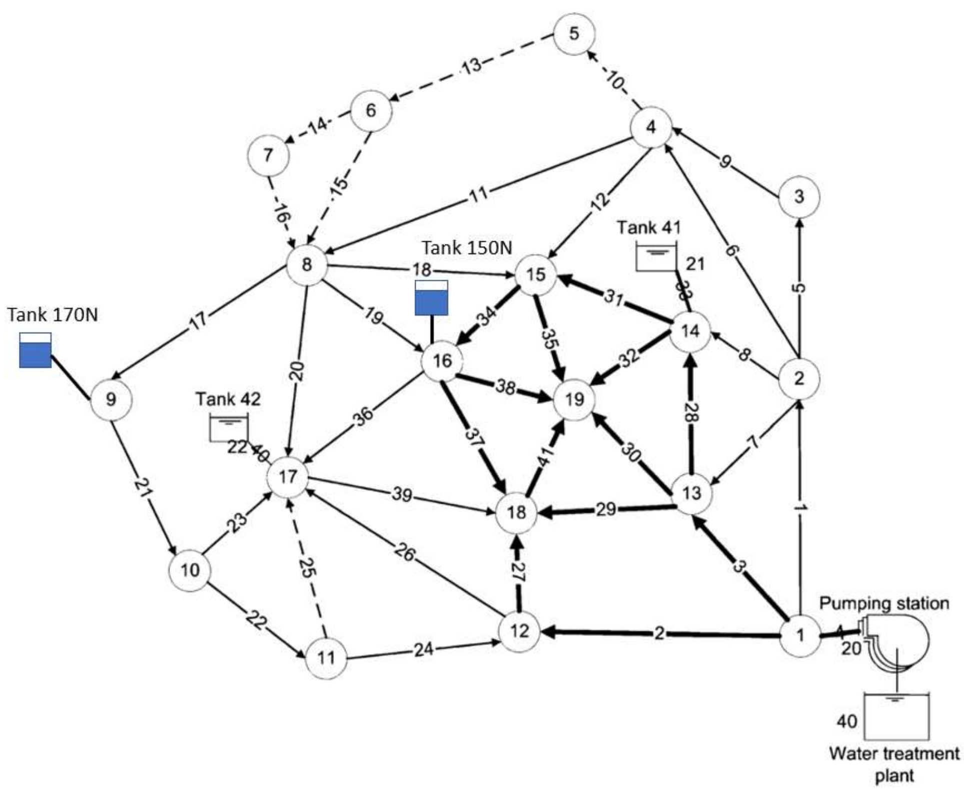


Figure 2-11: SSGA Solution shown with new tanks 170N and 150N from Prasad, 2010

2.7.4 Extended Structured Messy Genetic Algorithm (SMGA)

The extended Structured Messy Genetic Algorithm (SMGA) as presented by Walters et al. (1999) follows as an improved version of the earlier version which only focussed on gravity flow systems. SMGA was updated to include pumping and storage requirements as variables.

Walters et al. (1999) provided an extension to the SMGA optimisation method to include tank location and sizing as well as pumping regimes. Two methods were employed to incorporate tank sizing; one included analysing operating tank levels analytically at each step while the other defines tank levels as an independent decision variable. As both solutions are hydraulically feasible, they were both analysed as part of this study and are shown in Figure 2-12 and Figure 2-13 respectively.

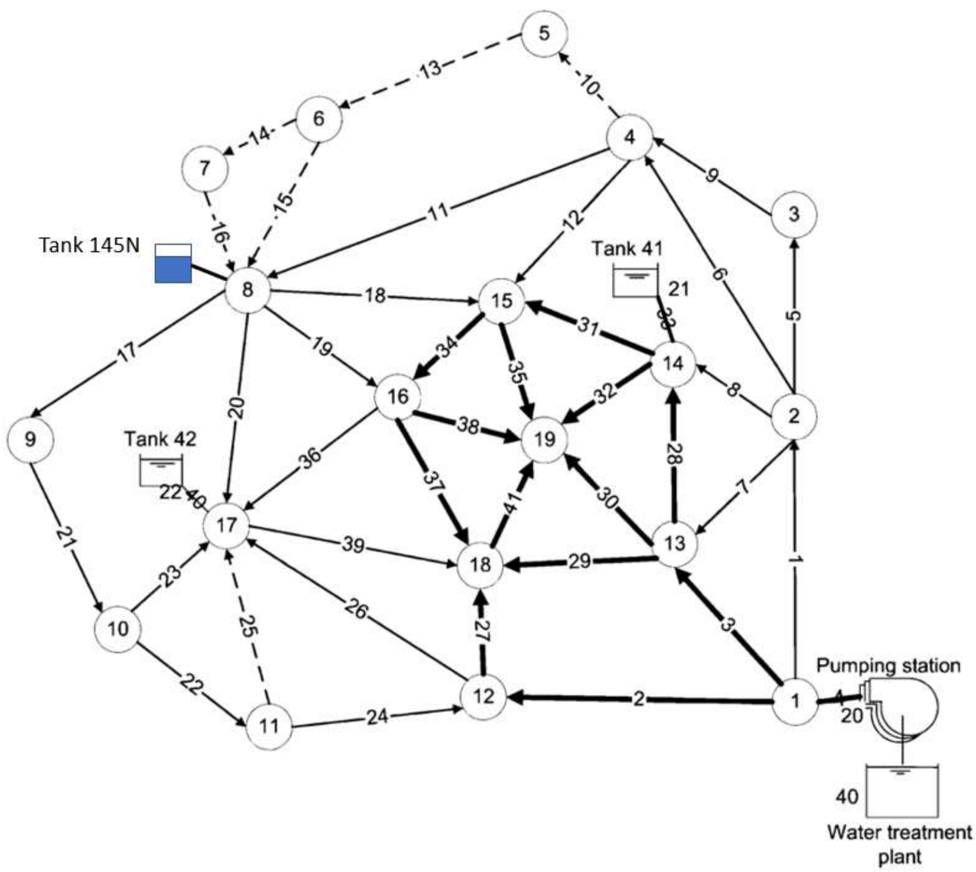


Figure 2-12: Extended SMGA Solution 1 shown with new tank 145N from Walters et al., 1999

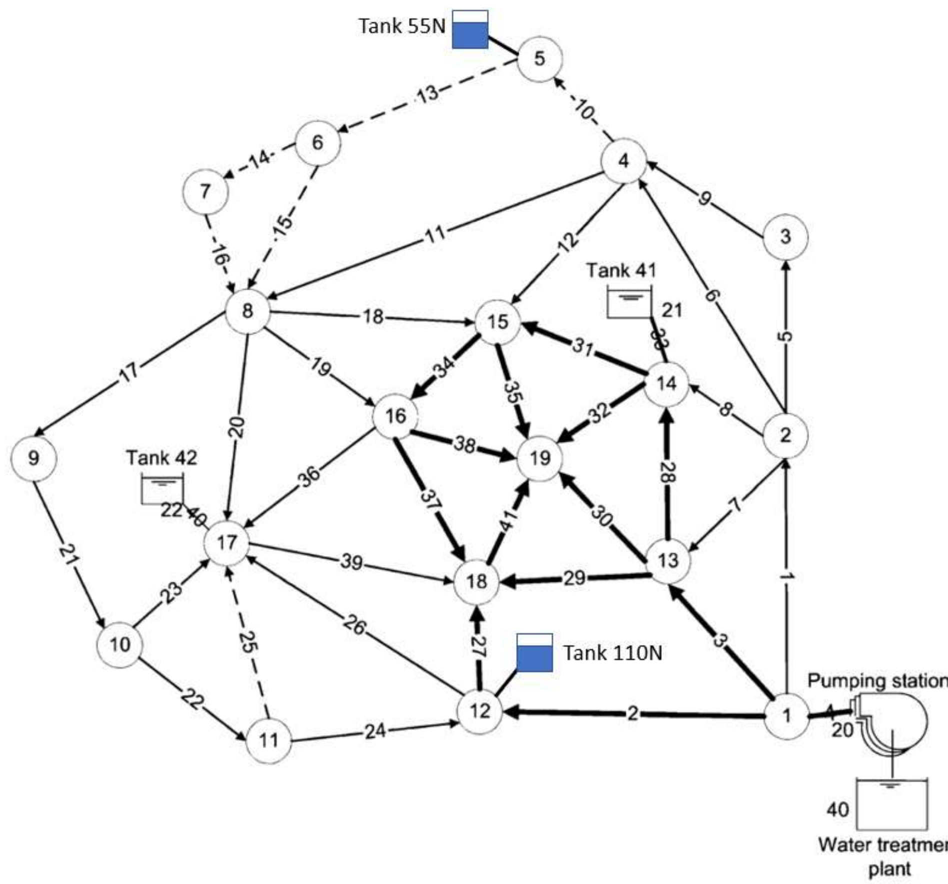


Figure 2-13: Extended SMGA Solution 2 shown with new tanks 55N and 110N from Walters et al., 1999

A comparison of the original and new tanks proposed by all four optimisation procedures is shown in Table 2-5.

Table 2-5 Cost comparisons of selected Anytown Network solutions

Optimisation method	Costs ($ Millions)			
	Pipes	Energy	Tanks	Total cost
PF-MOEA Solution 1	3.68	6.12	0.51	10.31
PF-MOEA Solution 2	3.68	6.22	0.51	10.41
FMO	3.78	6.15	0.61	10.54
SSGA	3.58	6.24	0.78	10.59
SMGA Solution 1	4.1	5.9	0.9	10.9
SMGA Solution 2	4.3	6.0	0.7	11.0

The PF-MOEA algorithm produced the cheapest solutions among the four algorithms reviewed here. Even though the solutions by Walter et al (1999) are the costliest among the solutions presented here; these solutions are still cheaper than other feasible solutions for the Anytown network as found in the literature. Farmani et al. (2006) and Prasad &

Tanyimboh (2008) are two examples of the Anytown solutions with estimated total costs of $11.65 million and more.

Table 2-6: Sizing comparison between original vs newly proposed Anytown tanks

Optimisation method	Tank	Effective volume (m^3)	Effective height (m)	Tank Elevation (m)	Diameter (m)
Original Anytown	41E*	596.9	7.6	65.5	10.0
	42E	596.9	7.6	65.5	10.0
PF-MOEA Solution 1	7N*	1587.8	5.8	61.0	18.7
PF-MOEA Solution 2	6N	1752.2	6.4	61.0	18.7
FMO	150N	814.1	4.1	65.5	15.9
	170N	308.0	4.1	62.1	9.8
SSGA	150N	729.2	4.4	63.4	14.5
	170N	535.7	4.7	63.7	12.1
SMGA Solution 1	55N	1135.6	4.6	51.5	17.7
	110N	946.4	3.0	72.2	20.0
SMGA Solution 1	145N	3596.1	6.1	64.0	27.5

*Tanks from the original problem are denoted with an E while newly proposed tanks are denoted with an N at the end.

2.8 Water Quality Indices

Water quality indices are currently widely used to quantify pollution loads in streams and rivers and have been used to describe the state of water quality at different points within rivers using a single aggregated value (Cude, 2001); (Madalina & Gabriela, 2014); (CCME, 2001) and (Rathnayake & Tanyimboh, 2015)). The indices have historically been applied to river reaches and were used to analyse several water quality constituents which are conventional for surface water bodies which are exposed to various environmental factors such as natural processes and anthropogenic influences (urban, industrial and agricultural activities) (Madalina & Gabriela, 2014). The oldest reference found in literature shows that the concept was introduced in the 1960’s when the water quality index was used as a tool to describe water quality in rivers (Horton, 1965) .

Service reservoirs or tanks in a water distribution network, similar to points in a river, are variably located and sized and are subjected to complex mixing mechanisms that impact various aspects of water quality in a complex manner. To describe the state of water quality in a service reservoir at a point in time, it is theorised to apply the same methods of the water quality index by aggregating the measured or calculated values of separate distinct water quality constituents. This could be useful when the performance of different water distribution network designs needs to be compared quantitatively. The water quality index can additionally be useful in optimisation algorithms to assess the suitability of the tanks at the selection step during an optimisation process in relation to water quality.

To formulate a water quality index, four common steps are reported in literature (Abbasi & Abbasi, 2012):

1. Selection of water quality constituents. Although many constituents may be available in a data set (refer to Section 2.2.2), those with a known considerable impact on water quality may be chosen to develop the water quality index (Tyagi et al., 2013);

2. Transformation of the data for the selected constituents into a common non-dimensionless scale. Different statistical approaches can be used to transform raw data that have different dimensions and units (µg/l, days, percentage etc.) into a common scale. A non-dimensional scale and sub-indices are generated;

3. Creation of sub-indices by assignment of a weighing factor to each transformed constituent. Weights are assigned according to their importance and their impact on water quality which is usually dependent on expert opinion; and

4. Computation of a final index score using the aggregation of sub-indices.

Although water quality indices have been traditionally used for natural river reaches, they were found to provide consistent results for water distribution network analysis (Nyirenda & Tanyimboh, 2020). A few common water quality indices encountered in the literature are described here.

2.8.1 Oregon Water Quality Index (OWQI)

One of the earliest formulations of water quality indices is the Oregon Water Quality Index (OWQI) originally presented by Dunnette (1979). The OWQI was one of the first widely investigated WQIs and is still widely cited in Northern America. It has recently been improved by Cude (2001); however, it was initially proposed by the Oregon Department of Environmental Quality as a means to compare temporal and spatial conditions of water quality between different reaches of the river system in Oregon, United States. The OWQI utilises an unweighted harmonic square mean to aggregate the developed sub-indices. The unweighted harmonic square mean was initially utilized in this manner by Horton (Horton, 1965). The OWQI originally made use of a basic arithmetic mean, however; Cude (2001) improved the formulation by making use of a geometric mean that is more sensitive to a constituent that exceeds the norm or acceptable values (Cude, 2001).

The OWQI includes aggregation of nine sub-index values informed by sub-index charts developed by the Department. Nine constituents were assessed: DO, coliforms, pH, temperature, biochemical oxygen demand (BOD), total phosphate, nitrate concentrations, turbidity and solid content. The aggregation allows a value between 10 and 100 to be calculated for each river reach depending on the actual measured water quality constituents. The unweighted harmonic square mean formula is given by the equation below.

$$WQI = \sqrt{\frac{n}{\sum_{i=1}^{n} s_i^{-2}}} \qquad (2.8.1)$$

WQI is the water quality index, n is the number of water quality constituents and s_i is the sub-index value which is a dimensionless number set to mimic their impact on water quality by assigning the measured value a rating between 10 and 100.

The classification proposed by Cude (2001) considers a water quality index of 10-59 to be very poor while 90-100 is considered to be excellent. This indicates a score of 10 to be the lowest possible rating while 100 is the highest possible rating.

2.8.2 Swamee and Tyagi (2000)

Swamee and Tyagi (2000) proposed an ambiguity and eclipsicity free aggregation method which, similar to the OWQI, makes use of sub-indices to describe a river reach according to nine measured water quality constituents. The authors of this aggregation method have described this method as one free from ambiguity and eclipsicity by removing the influence of an acceptable water quality variable while ensuring the bias of the aggregation toward a poor water quality variable (Swamee & Tyagi, 2000).

The sub-indices are aggregated as follows:

$$WQI = \left[1 - n + \sum_{i=1}^{n} s_i^{-1/k}\right]^{-k} \qquad (2.8.2)$$

where the variables are described as in Equation 2.8.1 with k being equal to 0.4.

This WQI is said to be less sensitive and applies more flexibility as compared to arithmetic and geometric products which were identified in other methods (Swamee & Tyagi, 2000).

2.8.3 Swamee and Tyagi (2007)

Swamee and Tyagi (2007) further proposed an improved water quality index similar to Equation 2.8.2. This index was claimed to be free from rigidity due to the replacement of the constant exponent parameter value k of 0.4 in Equation 2.8.2 by a function based on the number of water quality variables n. The improved index is as follows:

$$WQI = \left[1 - n + \sum_{i=1}^{n} s_i^{-\log_2(n-1)}\right]^{-1/\log_2(n-1)} \qquad (2.8.3)$$

where the variables are described the same as in Equation 2.8.2.

The interpretation of Equations 2.8.2 and 2.8.3 uses a scale of 0 to 100 with 100 being the highest and 0 being the lowest possible score.

2.8.4 Canadian Water Quality Index (CCME)

The Canadian Water Quality Index (CCME WQI) provides a straightforward mathematical method where there is no sub-index, establishing of weights, and conventional index aggregation involved. It measures the degree of violation of the regulation and is based on three significant factors: scope, frequency, and magnitude relative to a chosen benchmark (CCME, 2001). The index compares observations to a threshold value instead of normalising observed values to subjective rating or sub-index curves which traditionally need to be based on expert opinion. The WQI does not answer the question of whether water generally has good quality but more so it measures the degree of violation of the regulation in concern over a period, leaving the results to be analysed primarily by design of the regulation. The index quantifies scope, frequency, and amplitude using the following equation:

$$WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{\sqrt{3}} \tag{2.8.4}$$

Where:

F1 represents the number of variables whose objectives are not met expressed as a percentage and is defined by:

$$F_1 = \left(\frac{number\ of\ failed\ variable}{total\ number\ of\ variables}\right).100$$

F2 represents the frequency by which the objectives are not met expressed as a percentage and is defined by:

$$F_2 = \left(\frac{number\ of\ failed\ test}{total\ number\ of\ tests}\right).100$$

and F3 represents the amplitude of the objectives not met expressed as a percentage and is defined by:

$F_3 = \frac{nse}{nse+1}.100$ and $nse = \frac{\sum_{i=1}^{n} excursion_i}{number\ of\ tests}$ and

The excursion is defined as the below when the test value may not exceed the objective (or limit):

$$excursion = \left(\frac{failed\ test\ value_i}{objective_i}\right) - 1$$

or $excursion = \left(\frac{objective_i}{failed\ test\ value_i}\right) - 1$ when the test value may not fall below the objective.

The calculation of the CCME WQI does require at least four samples and leads to the impression that each variable is treated in the same way, ignoring interactive effects of different substances in the sample (Dao et al., 2020).

2.8.5 Modified Canadian Water Quality Index (MCWQI)

A modification of the CCME WQI was proposed by Dao et al. (2020) to improve on the sensitivities that the CCME is reported to have which include overestimation and ambiguity (Dao et al., 2020). The modified formulation includes the use of multiplication and the use of a geometric mean. The formulation follows the formula:

$$WQI = 100 - \sqrt[3]{F_1 \times F_2 \times F_3} \qquad (2.8.5)$$

Where F1, F2 and F3 have the same meaning as in equation 2.8.4.

The indices discussed above produce a value between 0 and 100 for a river reach depending on the measured water quality variables. For this study, the indices can be used for a produced set of water quality results that have been modelled or optimised in an appropriate modelling program. The rating allows a numerical value to be assigned to the calculated indices in order to classify the results. Lower ratings indicate poor or very poor water quality while higher ratings indicate excellent to good water quality. A summary of the indices and the applicable ratings are presented in Table 2-7. The table essentially summarises steps 2 and 4 as described at the beginning of Section 2.8 above leaving only the selection of variables creation of sub-indices which will be discussed later.

Table 2-7: Summary of water quality indices

Index	Formula	Quality rating	
		Ranges	**Classification**
Oregon Water Quality Index (OWQI)	$WQI = \sqrt{\frac{n}{\sum_{i=1}^{n} s_i^{-2}}}$	90-100	Excellent
		85-89	Good
		80-84	Fair
		60-79	Poor
		0-59	Very Poor
Swamee and Tyagi (2000)	$WQI = \left[1 - n + \sum_{i=1}^{n} s_i^{-1/k}\right]^{-k}$	91-100	Excellent
		71-90	Good
		51-70	Medium
		26-50	Fair
		0-25	Poor
Swamee and Tyagi (2007)	$WQI = \left[1 - n + \sum_{i=1}^{n} s_i^{-\log_2(n-1)}\right]^{-1/\log_2(n-1)}$	91-100	Excellent
		71-90	Good
		51-70	Medium
		26-50	Fair
		0-25	Poor
Canadian Water Quality Index (CCME WQI)	$WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{\sqrt{3}}$	95-100	Excellent
		80-94	Good
		65-79	Fair
		45-64	Marginal
		0-44	Poor
Modified Canadian Water Quality Index (MCWQI)	$WQI = 100 - \sqrt[3]{F_1 \times F_2 \times F_3}$	95-100	Excellent
		80-94	Good
		65-79	Fair
		45-64	Marginal
		0-44	Poor

2.9 Literature Review Summary

The literature has shown that significant gaps in water distribution modelling and water quality currently exist. Water distribution networks are rarely designed for water quality efficiency due to the complexity that comes with water quality. This is in addition to the number of variables that exist in a water distribution model problem.

Local and international standards and guides have shown that there are many water quality constituents that can make its way into a water distribution network; however, a limited number are measured and monitored. Despite this truncation, water quality is still limited in water distribution network design.

There are many bodies of research that have attempted to include aspects of water quality by including water quality as a constraint or objective into the design problem and subsequent algorithm; however, the algorithms are limited to a singular type of network elements or a limited number of water quality constituents. Genetic multi-objective algorithms are a good candidate for this method as it allows several objectives (which can be competing) to be included during the design and selection process. Of particular interest is the Anytown network problem which has been selected and solved by various researchers. The cheapest and feasible solutions were discussed here. These solutions provide a good range of network solutions/arrangements that can be used to test the fitness of water quality indices.

Water quality indices were introduced for use in surface water bodies. Several indices were developed since then and these were discussed in Section 2.8. The indices provide a method of aggregation for multiple water quality constituents which then provide a singular value which can be used for comparative purposes. The indices discussed here were tested for use in distribution networks. The generation of sub-indices and selection of water quality targets is discussed in later sections.

3 CHAPTER 3: METHODOLOGY

In order to meet the objectives of the study, the following methodology was applied:

1. A set of water quality constituents were chosen as the targets for this study. This is related to objective 1 from Section 1.3.
2. A dataset of water quality results was produced for a benchmark network to meet objectives 2 to 3. These were produced by:
   a. Modelling and analysing a representative set of water distribution networks for hydraulic efficiency in a suitable software program; and
   b. Analysing the water distribution networks for the chosen water quality constituents over a time period in a suitable software program.
3. Formulating suitable sub-indices for the set of chosen water quality constituents. This is related to objective 4.
4. Aggregating the obtained water quality results by applying the formulated sub-indices and water quality indices. This is related to Objective 5.
5. Evaluating the water quality indices to the produced water quality results for accuracy. This is related to Objective 5.

The methodology is further described in detail below. The results and evaluation are discussed in the next section.

3.1 Water Quality Targets

To work within the scope of the study, a select set of water quality constituents and targets were chosen for this study based on the standards and guidelines discussed under Section 2.2. A variety of substances and chemicals were considered. However, as it was not possible to analyse all of these, a representative set of constituents were chosen. The four chosen constituents are some of the most widely researched with governing models and equations developed to predict their growth or decay. The constituents are water age; residual chlorine; tri-halomethanes and halo-acetic acids (Table 3-1), and their targets relate to the limits or thresholds recommended at the furthest point of distribution (i.e. demand nodes).

Table 3-1: Selected water quality constituents

Constituent	Thresholds or limits	Notes
Water Age	< 72 hours	Water age is inherently a hydraulic variable that is analysed by EPANET 2.0. Water age can provide insights into how long a parcel of water travels a water distribution network. It additionally provides an indication of how well a reservoir/tank empties or fills. No standards are available on what water age is suitable as the unique spatial arrangement and properties of a specific network need to be understood. The Environmental Protection Agency of the United States provides guidance on this unique constituent by describing a water age of 72 hours as long enough to negatively impact water quality for a network (American Water Works Association, 2002).

Constituent	Thresholds or limits	Notes
Residual Chlorine	> 0.2 mg/l and < 0.5 mg/l	Chlorine in various forms is a widely used disinfectant for drinking water in the world. This is due to how convenient, relatively safe to handle, easy to dose and inexpensive as compared to other methods. It is used to effectively kill a wide assortment of microbial organisms and provides the benefit of maintaining a residual concentration after treatment that can provide continual treatment (World Health Organization, 2017). Many standards across the world were developed on what a safe chlorine residual should be after initial treatment but in most cases, a value of 0.2 to 0.5 mg/l is stated. High levels of chlorine can conversely cause negative health effects (World Health Organization, 2017). A maximum safe concentration for chlorine is rarely found in relevant water quality standards or guides; however, the World Health Organization loosely recommends a value of 0.5 mg/l at the end user.
Tri-halomethanes (THMs)	< 60 µg/l	Tri-halomethanes is one of the main by-products found in distribution networks that utilise chlorine as disinfection control. The various forms of tri-halomethanes commonly found in drinking water are chloroform, bromoform, dibromochloromethane and bromodichloromethane which all have different guideline amounts. Bromodichloromethane has the lowest limit (60 µg/l) while chloroform with a higher threshold limit should be limited to 300 µg/l. By maintaining levels of tri-halomethanes to below guideline levels provides adequate control over other chlorination by-products (World Health Organization, 2017). For the purpose of this study, tri-halomethanes will be treated as a single constituent that should be preferably kept to a maximum of 60 µg/l.
Halo-acetic acids (HAAs)	< 60 µg/l*	Halo-acetic acids like tri-halomethanes is one of the main by-products found in distribution networks that utilise chlorine as disinfection control; however, these were less studied over the years. Halo-acetic acids are usually considered as a group and are usually analysed as a sum of 3, 5 or 9 similar agents. A common grouping consists of monochloroacetic, dichloroacetic trichloroacetic monobromoacetic and dibromoacetic acids known as the HAA5. A guideline amount is to limit HAA5 to a value of 60 µg/l (United States Environmental Protection Agency, 2007).

*The South African water quality standards do not provide limiting values for halo-acetic acids or water age; however, the thresholds for tri-halomethanes and residual chlorine are provided in the standard and these follow the international guideline amounts chosen in the table above.

3.2 Modelling of Water Distribution Networks

Based on the literature review, it was decided to use a benchmark problem with comparative solutions. The Anytown network (Walski, 1987) was initially formulated to capture typical design problems encountered when designing real-world water distribution networks. The network design problem consists of sizing new pipes; scheduling of pumps; possible addition of new pumps; addition, sizing and siting of new service reservoirs; identifying pipes that need to be cleaned and re-lined; identifying pipes that may require pipes placed in parallel or replaced entirely while still meeting pressure requirements at minimum cost. There are two existing service reservoirs in the network, which are fed by a treatment plant and a pump house with three identical pumps. The Anytown network was therefore selected as the benchmark in this study. The six Anytown solutions (Refer to Table 2-5 and Section 2.7) described under the literature review section provided a basis for the hydraulic and water quality modelling.

3.2.1 Hydraulic modelling

An extended period simulation was conducted in EPANET 2.0 for each solution, in an attempt to fully understand how the solutions presented in Section 2.7 impact water quality and to conduct the water quality simulations. EPANET 2.0 is an updated version of the first open source EPANET software release in 1993 (Rossman, 2000). EPANET has been extensively used to analyse water distribution networks through extended-period simulations to model hydraulic and water quality behaviour within pressurized pipe networks, which consist of pipes, nodes, pumps, valves, storage tanks, and reservoirs. The unique algorithm allows the user to track pressures, flow, velocities, chemical concentrations and water age based on the user's inputs.

The Anytown network requires optimisation for five scenarios:

1. **Instantaneous peak flow**: A single time step simulation was conducted for all six Anytown solutions. The peak flows were based on the average daily demands factored by the peak flow factor (Refer to Appendix A). The network has to supply a minimum residual pressure of 40 psi (28.12 m) at all demand nodes for this scenario with the assumption that all tanks are full at the start of the simulation.
2. **Average day flow**: An extended period simulation (EPS) was conducted for the average-day flow scenario which required one hour time steps over a 24-hour period. The Anytown solutions were run using the average daily demands and pump schedule presented for each solution. The network has to supply a minimum residual pressure of 40 psi (28.12 m) at all demand nodes for this scenario with the assumption that all tanks are full at the start of the simulation.
3. **Three fire-fighting flows**: The fire flow simulations were run for a 3-hour period based on the assumption that only two pumps were operational with all tanks starting at the minimum operational levels using only the emergency storage volumes in the tanks for the entire duration of the simulation. A minimum residual pressure of 20 psi (14.06 m) is required at all demand nodes during fire flows.

The complete Anytown problem statement is provided in Appendix A.

The six chosen Anytown solutions (Refer to Table 2-5 and Section 2.7) are reported to be the most cost efficient and hydraulically feasible solutions based on the requirements of the problem. The hydraulic modelling results are thus expected to adhere to the minimum pressure requirements discussed above.

3.2.2 Water quality modelling

Following from the hydraulic modelling, all six solutions of the Anytown network were modelled for water quality. The governing equations and modelling theory utilised by EPANET are discussed below for the chosen constituents:

Water age is internally treated by EPANET as a reactive constituent which follows a zero-order kinetics model with a rate constant equal to 1 (Rossman, 2000).

- **Chlorine** concentration can be based on a first order kinetics model (Figueiredo, 2014). Bulk and wall reaction rate constants were assumed to be 0.5/day and 0.1 m/day, respectively (Seyoum and Tanyimboh, 2014). The model is run with the assumption that initial chlorine concentrations at the nodes, tanks and treatment plant were initially 0 mg/l while chlorine concentration at the treatment plant was assumed constant at 0.6 mg/L (Seyoum and Tanyimboh, 2014).
- **Tri-halomethanes and halo-acetic acids** were modelled using a first order kinetics model (Figueiredo, 2014) with bulk and wall reaction rate constants assumed to be negative at 0.5/day and 0.1 m/day, respectively (Seyoum and Tanyimboh, 2014). This is similar to the chlorine model but a limiting concentration is set to 80 µg/l at the treatment plant.

A complete mixing model was assumed for all tanks across all solutions which assumes that all water that enters a tank at a specific time step is instantaneously and completely mixed with the water already in the tank at the beginning of the time step. This is the simplest model of mixing in storage tanks (Rossman, 2000); however, is a fairly realistic estimation of the complex mixing mechanisms that can occur in a tank.

All six chosen Anytown solutions (Refer to Table 2-5 and Section 2.7) were analysed for the chosen water quality constituents over a 72-hour period allowing the water quality results to stabilise (Seyoum and Tanyimboh, 2014). The water quality results were then analysed using the formulated sub-indices and water quality indices described in the following section.

3.3 Formulation of sub-indices

Based on the traditional water quality index approach, four common steps were used to develop a suitable index. Section 2.8 discussed the four common steps for developing water indices. A crucial step in determining water quality indices is developing a suitable set of sub-indices. The sub-indices were developed by transforming the selected constituents into a common non-dimensionless scale based on expert opinion (Abbasi & Abbasi, 2012).

As no known sub-indices are currently available for use in this study (as the sub-indices currently available in literature were used for constituents usually found in surface water bodies); sub-indices charts were developed here for the first time based on the limits and thresholds for the chosen water quality constituents (water age, chlorine, tri-halomethanes and halo-acetic acids). The sub-indices charts are simplified linear piece wise graphs based on similar principles applied to obtain the sub-indices developed for the Oregon Water Quality

Index (Cude, 2001).The sub-indices were then assessed for the water quality analyses results completed in Section 3.2.2.

The application of the sub-indices (and hence water quality indices) is limited to the tanks/service reservoirs for this study as the tanks potentially have a significant impact on water quality throughout the system (Clark et al., 1996). The study can be expanded to the demand nodes in the future.

The water age sub-index is described as shown in Figure 3-1 below.The developed sub-index chart for water age attempts to describe calculated water ages of more than 72 hours to be long and is assigned the minimum value of 0.1. A water age of longer than three days (72 hours) is considered as long by the United States Environmental Protection Agency (American Water Works Association, 2002). To ensure that no division by zero occurs (particularly for the unweighted harmonic square mean formula) the minimum sub-index value is set to 0.1.

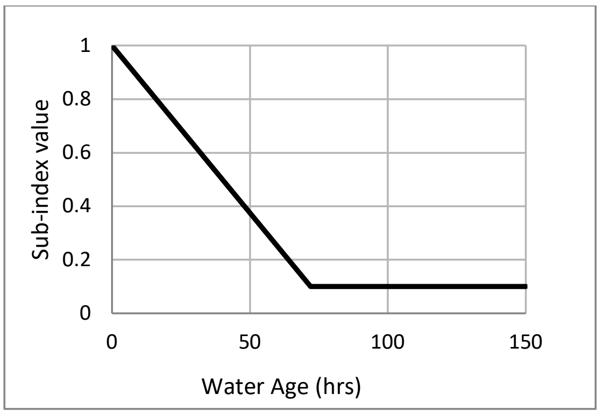


Figure 3-1: Water age sub-index

The developed chlorine sub-index (shown in Figure 3-2) describes a concentration of 0.2 mg/l (World Health Organization, 2017) as the minimum desired by setting a measured chlorine value greater than this value to between 0.1 and 1 increasing linearly. Higher values of chlorine concentration can potentially cause negative effects such as increasing the formation of disinfection by-products (Centers for Disease Control and Prevention, 2018) and thus measured values higher than the limit of 0.5 mg/L were assigned a decreasing sub-index value up to a value of 0.1. Values measured higher than 0.6 mg/L were given the value of 0.1.

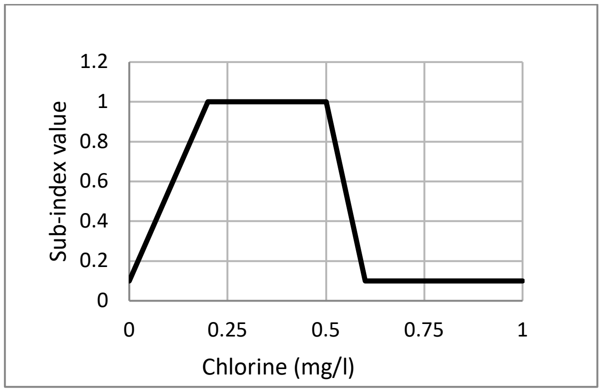


Figure 3-2: Chlorine sub-index

Tri-halomethanes and halo-acetic acids are both disinfection by-products that are similar in function (Refer to **Error! Reference source not found.**). In both cases, levels of both THM and halo-acetic acids were measured in the same units and were limited by similar thresholds. The developed sub-index sets a maximum acceptable value of 80 µg/l (World Health Organization, 2017) by assigning a calculated value over this threshold the minimum value of 0.1. A tri-halomethanes and halo-acetic acids concentration of zero would be ideal in a water distribution network. This is taken into account in the sub-index by assigning concentrations of 0 µg/l to 60 µg/l a value of 1. Concentrations between 60 and 80µg/l were assigned a decreasing value between 1 and 0.1. It may be worthwhile to test various sub-index charts for each variant of THM and halo-acetic acids that may be expected in a network. However, given the scope of this study, a single chart was used as shown in Figure 3-3.

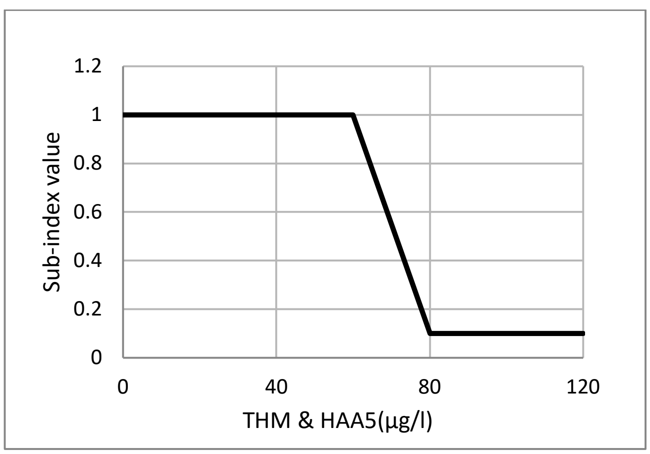


Figure 3-3: Tri-halomethanes and halo-acetic acids sub-index

The developed sub-indices in conjunction with the five water quality indices presented in Section 2.8 were evaluated here for the first time to assess whether the indices would be suitable for integration into optimisation methods. The estimated formulation of the sub-indices aims to provide a first estimate of the overall quality within a reservoir.

4 CHAPTER 4: ANALYSIS AND INTEPRETATION OF RESULTS

4.1 Hydraulic Modelling Results

The six Anytown solutions presented in Section 2.7 were analysed for hydraulic efficiency, to gain an understanding of the tank operations, and to determine the impacts of the optimisation/design on water quality. The six solutions were analysed in EPANET 2.0 to determine whether they satisfy the five flow requirements (Refer to Section 3.2.1) according to the original problem statement.

The results were condensed into Table 4-1 below which presents a summary of the hydraulic analyses results for each flow scenario per optimisation solution. The network solution has to supply a minimum residual pressure of 40 psi (28.12 m) at all demand nodes for the average and peak flows as well as minimum residual pressures of 20 psi (14.06 m) for all demand nodes during fire flows. The values in brackets present the nodes where the minimum pressure occurs and the time when the minimum pressure occurs is shown underneath each pressure value. Full results for the 24-hour EPS are presented in Appendix B.

Table 4-1: Minimum pressures at critical nodes

	Average day (24-hr EPS)	**Peak Flow [a]**	**Fire Flow 1 (2-hr EPS)**	**Fire Flow 2 (2-hr EPS)**	**Fire Flow 3 (2-hr EPS)**
PF-MOEA Solution 1	***27.48 (9) 11:00***	28.16 (9) N/A[b]	15.13 (16) 02:00	16.65 (16) 02:00	22.14 (16) 02:00
PF-MOEA Solution 2	28.88 (16) 11:00	29.86 (9) N/A[b]	16.90 (16) 02:00	16.23 (7) 02:00	20.39 (11) 02:00
FMO	29.49 (9) 13:00	33.03 (11) N/A[b]	26.26 (9) 02:00	***-8.80[c] (7) 02:00***	25.09 (11) 02:00
SSGA	29.18 (9) 09:00	34.17 (5) N/A[b]	27.75 (16) 02:00	15.85 (6) 02:00	28.27 (9) 02:00
SMGA Solution 1	28.73 (16) 08:00	40.01 (6) N/A[b]	43.83 (16) 02:00	16.98 (6) 02:00	38.98 (11) 02:00
SMGA Solution 2	***24.99 (16) 07:00***	52.79 (10) N/A[b]	22.84 (16) 02:00	22.69 (16) 02:00	22.31 (11) 02:00

[a]Single snapshot simulation; [b]Not applicable; [c]Infeasible solution
Values in brackets indicate nodes where minimum pressure occurs and the time when the minimum pressure occurs is shown below pressure values. Highlighted values indicate pressure violations.

Majority of the solutions provided pressures above the required minimum for the demand nodes except for PF-MOEA Solution 1, SMGA Solution 2 and the FMO Solution. The PF-MOEA Solution 1 and SMGA Solution 2 present pressures that are slightly below the required minimum; however, as these pressures are minimums and occur over one hour (according to simulation results) it can be deduced that the network will still provide the consumers with fairly adequate pressures at these nodes. According to the hydraulic analyses, PF-MOEA Solution 1 presents a pressure for the average day flow which is 0.64 m below the required minimum. This occurs during the period when the flows are highest (i.e. between 7-12 am).

SMGA Solution 2 resulted in a pressure 3.13 m below the required minimum for node 16, and this occurs at 7 am when the peak pressures begin. This coincides with peak demand when consumers are most likely to be using water early in the morning.

The FMO solution produces a negative pressure at node 7 for the second fire flow condition which indicates that the network cannot provide the required demand at that node. The FMO solution presents negative pressures within the last hour of the fire flow rendering the solution infeasible according to the requirements of the problem. The negative pressures are present as all of the tanks in the solution are empty by the end of the simulation. The short duration of the violation does indicate that a small increase in storage capacity could render this solution as feasible. This solution should be considered infeasible; however, the network was still analysed to investigate how a network with similar properties may impact water quality.

An interesting observation is which nodes experience the minimum pressures. These are nodes 5,6,7, 9, 10,11 and 16 across all of the solutions. Nodes 5,6,7,9, 10 and 11 are located at the periphery of the network (furthest from the treatment plant) while node 16 is located centrally to the network. This aligns with the thinking that water distribution networks tend to struggle to provide adequate pressures to nodes located furthest to the treatment source and node 16 is located centrally which indicates that the network characteristic may place preference to provide pressure to nodes surrounding the node before it reaches central nodes. It is also noted that most of the solutions except SMGA have suggested new tanks to be placed at these periphery nodes or at node 16 which can alleviate pressure deficiencies at these nodes.

It is also noted that minimum pressures tend to occur during the higher flows for the average day flows versus at the end of the simulation for fire flows. This coincides with high water use at the beginning of the day when most people would be getting ready for daily activities and during the end of a predicted fire flow when storage capacities reach zero capacity at the end of the simulation.

It can be deduced that water quality will be worse outside of the peak demand (7-12 am) due to extended periods of water age in the pipes and tanks due to inactivity. This inactivity allows chlorine residual to be diluted or diffused while by-products continue to increase.

A further investigation into the hydraulic performance of the networks included assessing the tank levels. Figure 4-1 to Figure 4-6 represent the water levels in each tank for each solution for a 24-hour period during the average flow scenario. The tanks were modelled as full at the start of the simulation. Full results for the 24-hour EPS are presented in Appendix B. In general, there is a trend for all of the tanks to empty and fill during the 24-hour simulation period which can point to lower water ages and hence better water quality.

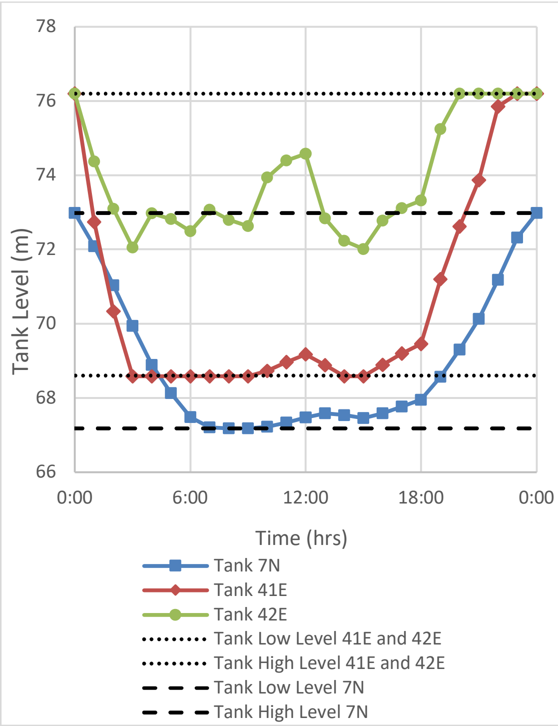


Figure 4-1: Tanks levels for PF-MOEA Solution 1 over the 24-hour simulation

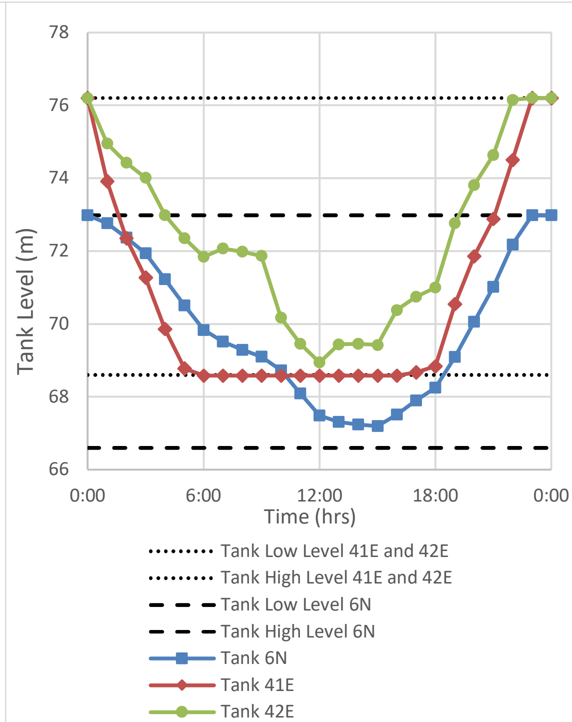


Figure 4-2: Tank levels for PF-MOEA Solution 2 over the 24-hour simulation

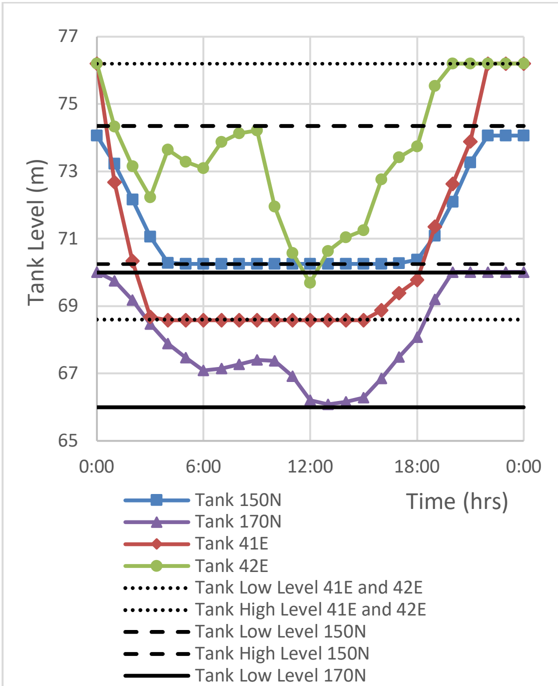


Figure 4-3: Tank levels for FMO Solution over the 24-hour simulation

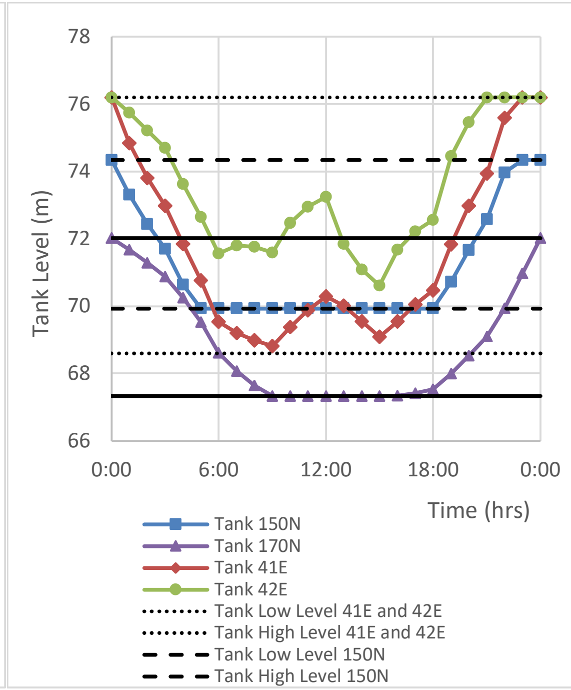


Figure 4-4: Tank levels for SSGA Solution over the 24-hour simulation

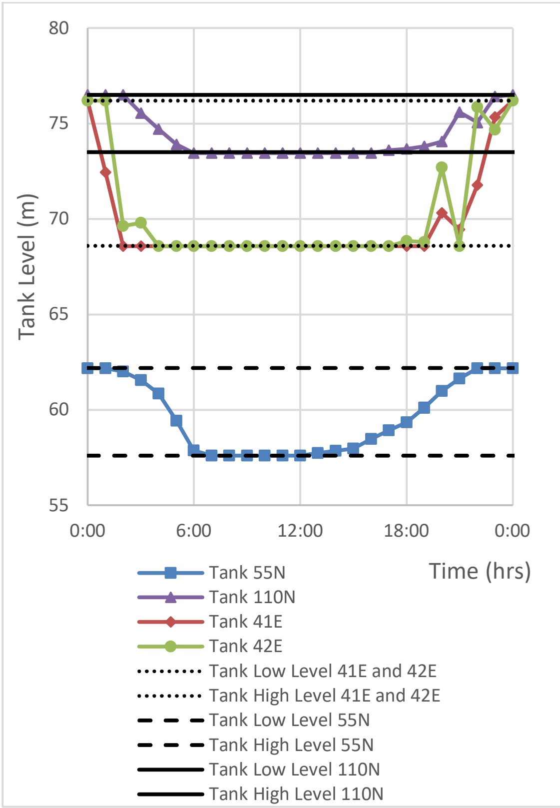


Figure 4-5: Tank levels for SMGA Solution 1 over the 24-hour simulation

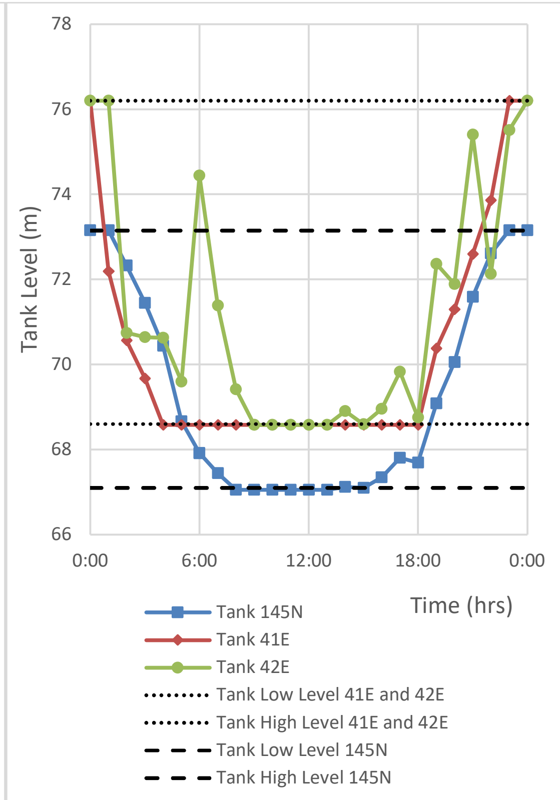


Figure 4-6: Tank levels for SMGA Solution 2 over the 24-hour simulation

However, all of the solutions (in particular PF-MOEA Solution 1) struggle to empty the existing tank located on node 42 except for SMGA Solution 1. This also includes the PF-MOEA Solution 2 which was programmed to include a tank depletion criterion (Refer to Section 2.7.1). Furthermore, the water level in Tank 42E in all of the solutions fluctuates erratically which agrees with the original literature of the Anytown network problem which was stated to have problems with emptying.

These results show that although the different solutions/designs to the Anytown network provide the required demand across a variety of demand scenarios and were found to be the most cost-effective; the response of the networks is vastly different. Particularly, the shape, size and location of the tanks have a vast impact on the hydraulics of the network as a whole. This lends to the idea that the water quality within the network can vary widely based on the hydraulic performance, network size and arrangement; however, if the tank designs can incorporate general design practices that will aid better water quality, then a more holistic design can be achieved.

4.2 Water Quality Results

The six Anytown solutions presented in Section 2.7 were analysed for four water quality constituents following the hydraulic analysis. The six solutions were analysed using EPANET's water quality module over a 72-hour period but only the last 24-hours were analysed to allow the water quality concentrations to stabilise. Full results for the 24-hour EPS are presented in Appendix B. The produced water quality results are discussed in the following sections.

Figure 4-7 to Figure 4-12 represent the water age results for each tank in each of the solutions. The general trend of water age results indicates an increase during the first 6 to 12 hours with a decline after 12pm. This would indicate an increase in water age as the tanks fill following from the previous day's use and decrease as the demands compound during the day. Generally, the recorded water age for most tanks is below the 72-hour limit over the entire analysis period except for the SMGA solutions which reach a 72-hour water age in Tank 42E which is known to have problems with filling and emptying. This draws a correlation between the hydraulic performance and water quality.

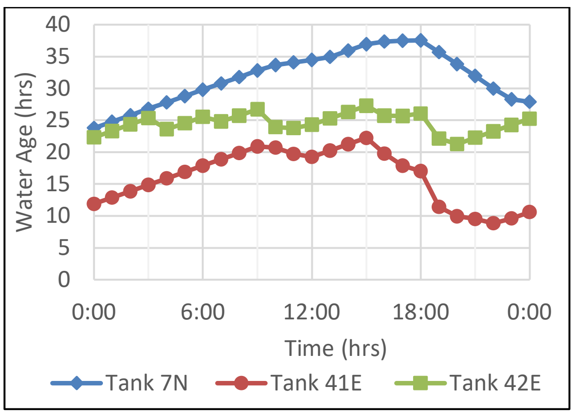


Figure 4-7:Water ages for PF-MOEA Solution 1 over the 24-hour period

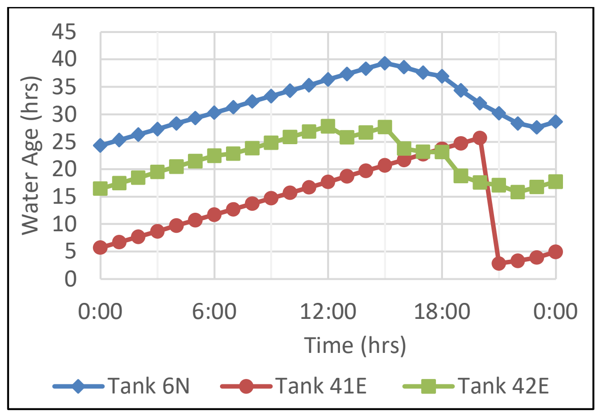


Figure 4-9: Water ages for PF-MOEA Solution 2 over the 24-hour period

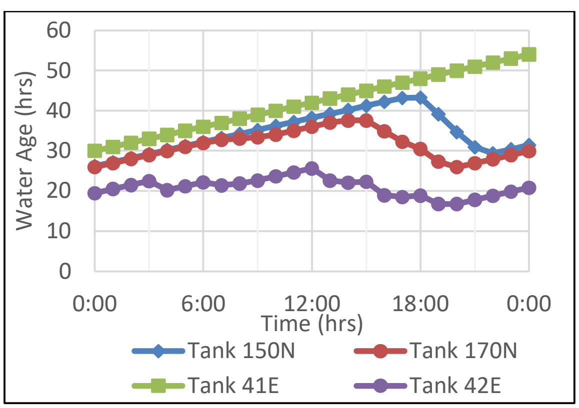


Figure 4-8: Water ages for FMO Solution over the 24-hour period

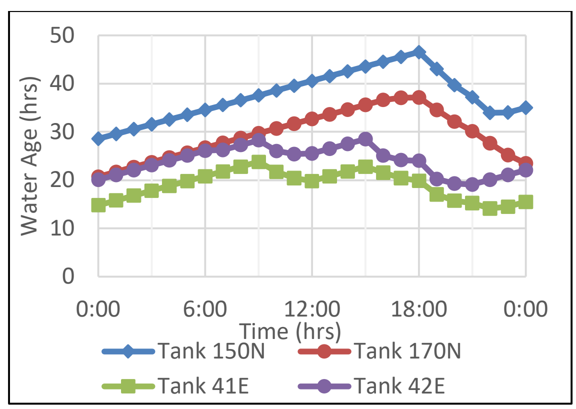


Figure 4-10: Water ages for SSGA Solution over the 24-hour period

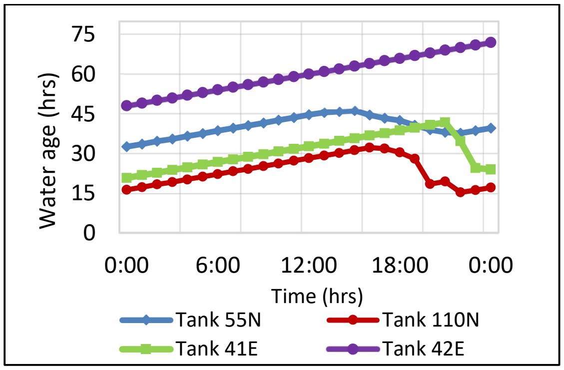


Figure 4-11: Water ages for SMGA Solution 1 over the 24-hour period

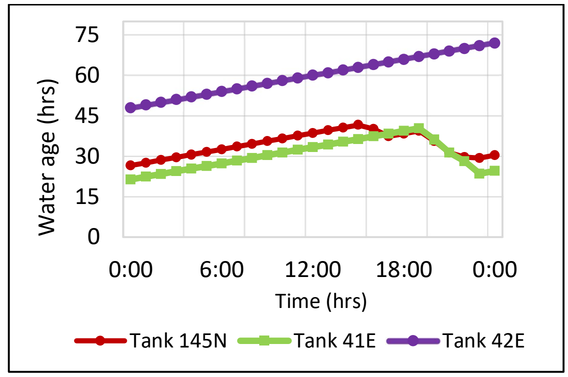


Figure 4-12: Water ages for SMGA Solution 2 over the 24-hour period

Figure 4-13 to Figure 4-18 represent the computed chlorine residual for each tank in each of the solutions. The chlorine concentrations, unlike water age, vary widely between 0 and 0.54 mg/l. Major violations of the minimum concentration for tank 41E and 42E in the FMO and SMGA solutions were recorded over the entire analysis period.

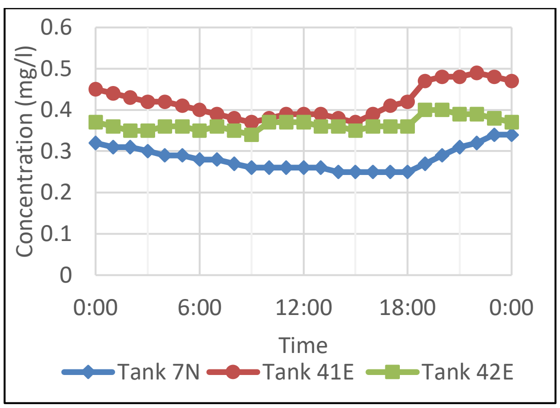


Figure 4-13:Chlorine concentration for PF-MOEA Solution 1 over the 24-hour period

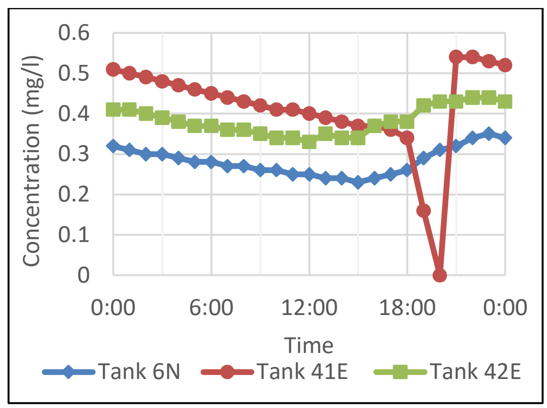


Figure 4-15:Chlorine concentration for PF-MOEA Solution 2 over the 24-hour period

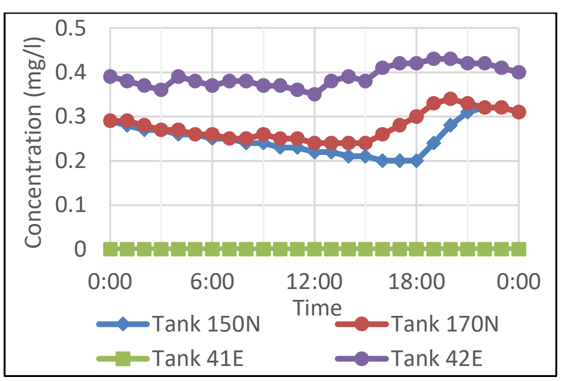


Figure 4-14: Chlorine concentration for FMO Solution over the 24-hour period

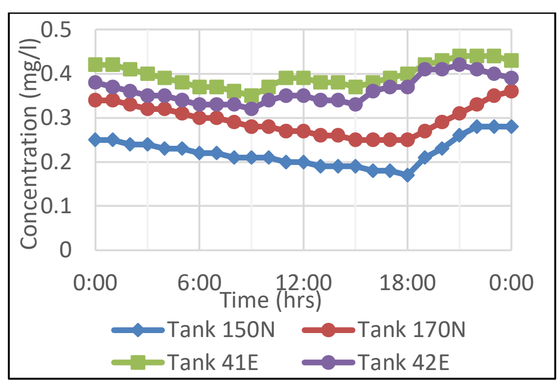


Figure 4-16: Chlorine concentration for Prasad Solution over the 24-hour period

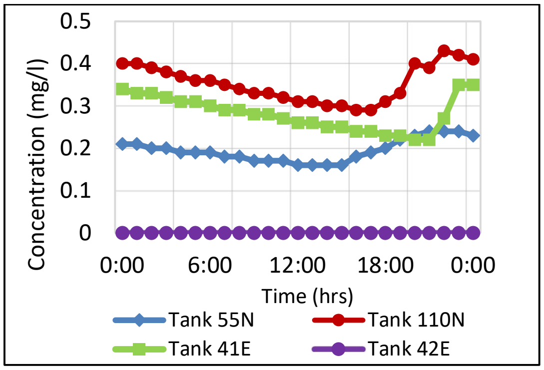


Figure 4-17: Chlorine concentration for SMGA Solution 1 over the 24-hour period

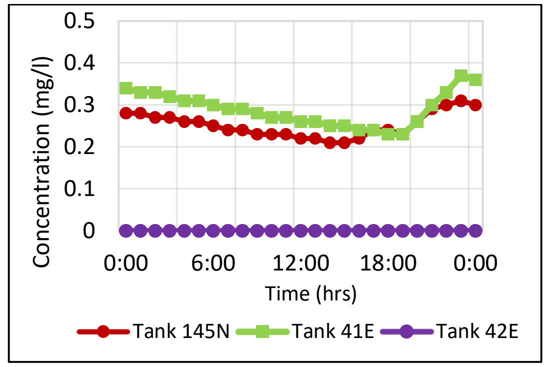


Figure 4-18: Chlorine concentration for SMGA Solution 2 over the 24-hour period

Figure 4-19 to Figure 4-24 represent the computed THM concentrations for each tank in each of the solutions. The general trend of the THM concentrations mimic the chlorine concentrations with increasing values at the beginning of the day and decreasing values towards the end of the day. The SMGA solutions are again the only solutions with violations of the 60 µg/l limit.

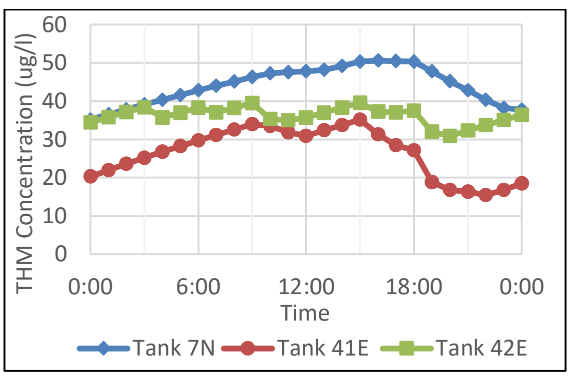


Figure 4-19: THM concentration for PF-MOEA Solution 1 over the 24-hour period

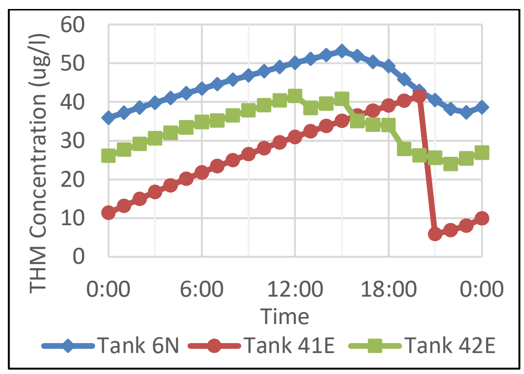


Figure 4-20: THM concentration for PF-MOEA Solution 2 over the 24-hour period

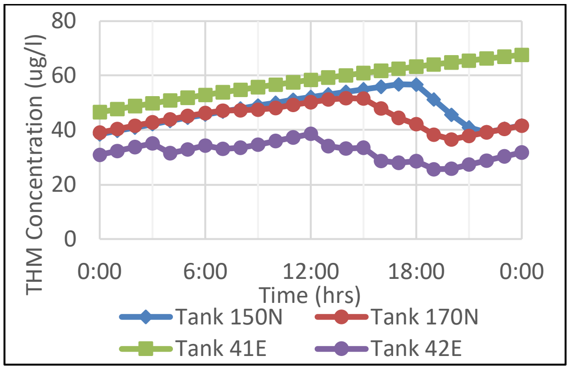


Figure 4-21:THM concentration for FMO Solution over the 24-hour period

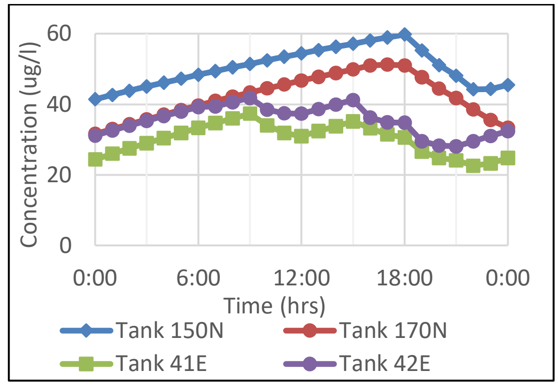


Figure 4-22: THM concentration for SSGA Solution over the 24-hour period

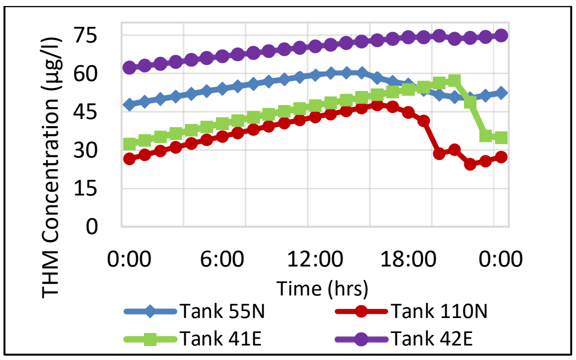


Figure 4-23: THM Concentration for SMGA Solution 1 over the 24-hour period

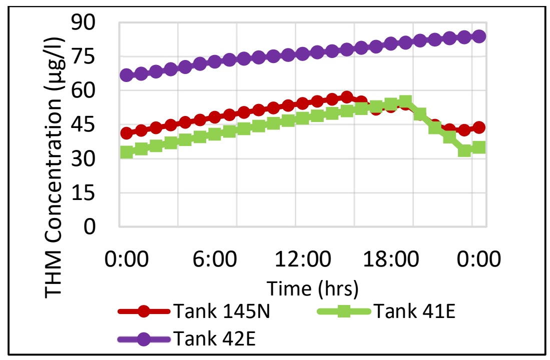


Figure 4-24: THM Concentration for SMGA Solution 2 over the 24-hour period

Figure 4-25 to Figure 4-30 represent the computed HAA5 concentrations for each tank in each of the solutions over the 24-hour analysis period. The trend varies here with HAA5 concentrations remaining steady around a constant value throughout the day for some of the solutions. There is a visible decrease in HAA5 concentrations at the end of the day as the fresh water is introduced into the tanks and the by-product is diluted.

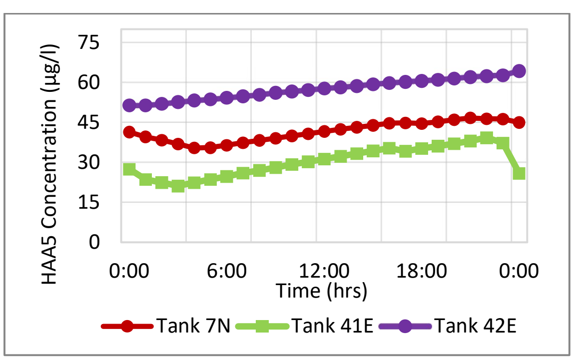


Figure 4-25: HAA5 Concentration for PF-MOEA Solution 1 over the 24-hour period

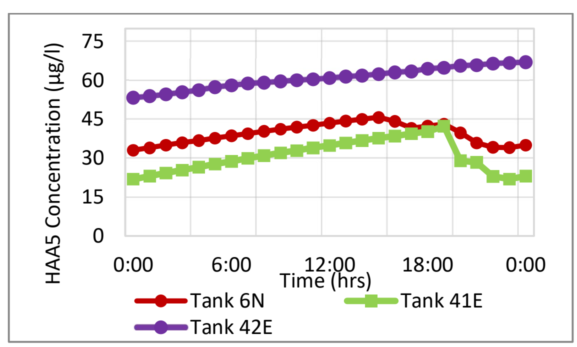


Figure 4-26: HAA5 Concentration for PF-MOEA Solution 2 over the 24-hour period

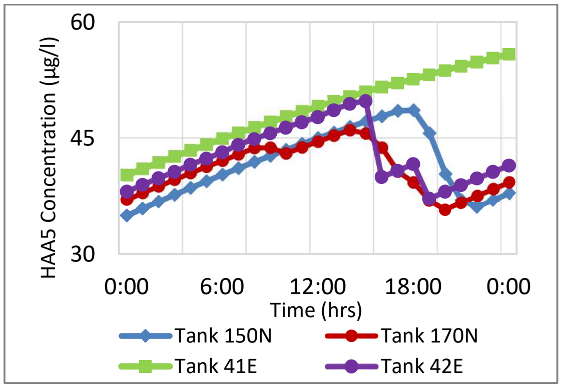


Figure 4-28: HAA5 Concentration for FMO Solution over the 24-hour period

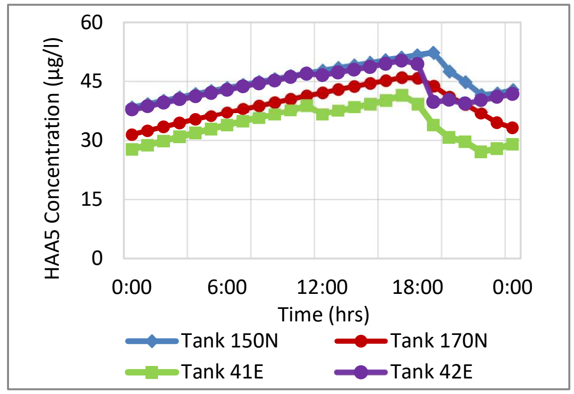


Figure 4-29: HAA5 Concentration for SSGA Solution over the 24-hour period

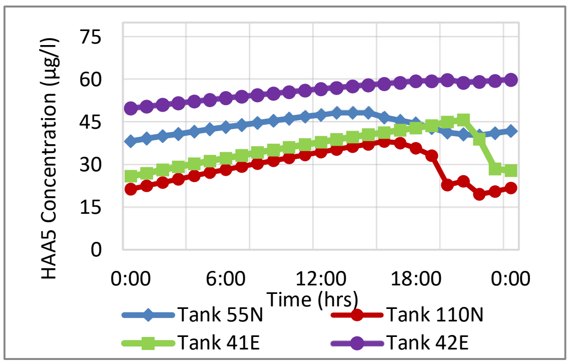


Figure 4-27: HAA5 Concentration for SMGA Solution 1 over the 24-hour period

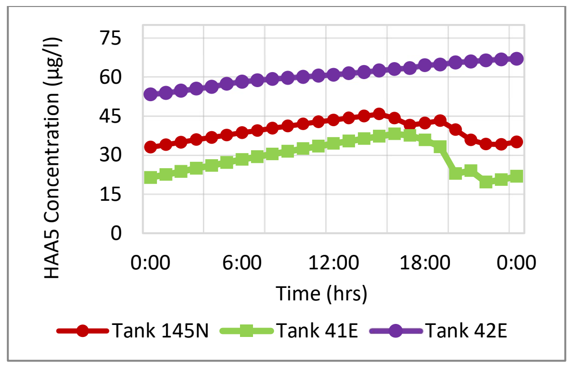


Figure 4-30:HAA5 Concentration for SMGA Solution 2 over the 24-hour period

4.2.1 Summary of results

Minimum and maximum values of the water quality results are shown in Table 4-2 for the tanks. The values in brackets present the nodes where the value occurs and the time when it occurs is shown underneath each pressure value. Bold and italic values indicate exceedance of the water quality constituent limits. Maximum chlorine residuals were not included in Table 4-2 as none of the tanks exceeded the limit of 0.5 mg/L except for tank 42E for the PF-MOEA Solution 2.

The tanks perform well except for tank 42E which aligns with the problems of filling and emptying of this tank as stated in the original problem and in the hydraulic results (Refer to Section 4.1). Long water ages, high concentrations of THM and HAA5 were recorded while chlorine concentrations reach 0 mg/l for tank 42E. A service reservoir with good water quality characteristics is described as having low water age and a chlorine concentration not lower than 0.2 mg/l (World Health Organization, 2017). All of the solutions except for PF-MOEA Solution 1 and the SMGA solutions recorded a chlorine concentration below 0.2 mg/l in at least one of the tanks. These results are comparable to those previously presented in the literature for the Anytown network (Seyoum et al., 2014).

Solutions with high THM and HAA5 concentrations align well with tanks that have low chlorine residual such as PF-MOEA Solution 2, SMGA Solution 1 and 2.

Table 4-2: Summary of water quality analyses results for tanks

	PF-MOEA Solution 1	PF-MOEA Solution 2	FMO	SSGA	SMGA Solution 1	SMGA Solution 2
Maximum water age (hrs)	37.53 (7N) 18:00	39.32 (6N) 15:00	54.02 (41E) 00:00	46.57 (150N) 18:00	***72.00 (42E) 00:00***	***72.00 (42E) 00:00***
Minimum chlorine concentration (mg/L)	0.25 (7N) 14:00	***0 (41E) 20:00***	***0 (41E) 00:00***	***0.17 (150N) 18:00***	***0 (42E) 00:00***	***0 (42E) 00:00***
Maximum THM concentration (µg/l)	50.59 (7N) 16:00	53.1 (6N) 15:00	***67.59 (41E) 00:00***	59.74 (150N) 18:00	***74.87 (42E) 00:00***	**83.8 *(42E)* *00:00***
Maximum HAA5 concentration (µg/l)	***64.27 (42E) 00:00***	***67.04 (42E) 00:00***	55.86 (41E) 00:00	52.31 (150N) 19:00	59.89 (42E) 00:00	**67.04 *(42E)* *00:00***

Values in brackets present the nodes where the value occurs and the time when it occurs is shown underneath each pressure value. Bold and italic values indicate exceedance of the water quality constituent limits.

Minimum and maximum values of the water quality results are shown in Table 4-3 for the demand nodes. The values in brackets present the nodes where the value occurs and the time when it occurs is shown underneath each pressure value. Bold and italic values indicate exceedance of the water quality constituent limits.

From Table 4-3 it can be seen that no exceedances were recorded during the 24-hour simulation period. All of the nodes present favourable water quality with chlorine residuals above 0.2 mg/l; water ages below 48 hours and disinfections by-products (THM and HAA5) below the threshold of 60 µg/l.

What is interesting to note is that the minimum or maximum values occur at the same node for all solutions across all four constituents. This indicates that the optimised solutions have a central weak point in the system which is susceptible to poor water quality across all water quality constituents as they are interlinked. The nodes are usually located at the periphery of the network or immediately downstream of a tank.

This is additional support to focus on service reservoirs/tanks in water distribution networks with regards to water quality. The complex mixing mechanisms within the tanks bring variable results and hence are the focus of the water quality indices in this study.

Table 4-3: Summary of water quality analyses for the demand nodes

	PF-MOEA Solution 1	PF-MOEA Solution 2	FMO	Prasad	Walters' Solution 1	Walters' Solution 2
Maximum water age (hrs)	30.74 (7) 11:00	27.23 (6) 06:00	25.26 (16) 02:00	24.83 (16) 04:00	21.31 (7) 05:00	35.25 (5) 07:00
Minimum chlorine concentration (mg/L)	0.30 (7) 11:00	0.32 (6) 06:00	0.31 (16) 02:00	0.31 (16) 04:00	0.37 (7) 05:00	0.22 (5) 07:00
Maximum THM concentration (µg/l)	26.12 (7) 11:00	23.89 (6) 06:00	22.67 (16) 01:00	35.75 (16) 04:00	20.06 (7) 05:00	29.85 (5) 07:00
Maximum HAA5 concentration (µg/l)	34.72 (7) 11:00	31.86 (6) 06:00	29.78 (16) 02:00	28.24 (16) 04:00	26.61 (7) 05:00	39.8 (5) 07:00

Values in brackets present the nodes where the value occurs and the time when it occurs is shown underneath each pressure value. Bold and italic values indicate exceedance of the water quality constituent limits.

Additional statistical analyses were undertaken by using known statistical measures in an attempt to analyse the water quality results and compare to the water quality indices.

Two statistical measures were computed for the tanks:

- Median: The median is described in statistics as the value separating the higher half from the lower half of a data sample. The median was computed by considering hourly values of water age, chlorine concentration; THM concentration and HAA5 concentration for each tank over the last 24-hours of the simulation.
- Flow weighted mean: The flow weighted mean is simply described as the mean for the chosen water quality constituent weighted by outflow out of the tank. This is a similar approach undertaken by the United State Geological Survey (Mueller & Spahr, 2001) which is used as a statistical method to rank monitored sites across streams in the country. The flow weighted mean could be advantageous compared to the basic

mean values by weighting the outflow of the tank to the water quality value at the point in time. This takes into consideration how much water is available and how this correlates to the measured water quality constituent.

Table 4-4 shows the calculated median and flow weighted mean for each water quality constituent and tank. Values indicated in bold, and italics are values exceeding the water quality constituent limits.

Tank 55N in Walters et al. Solution 1, Tank 41E in the FMO solution and Tank 42E in both SMGA solutions exceed some of the water quality constituents based on the evaluated median. This aligns partially with the tanks shown to have poor water quality characteristics in the unprocessed water quality results. An additional approach would be to analyse the results using other statistical approaches such as determining quartiles to understand how much the exceedances vary. The median can indicatively provide an idea of the water quality within the tanks. However, it still requires analysis of each water quality constituent separately and an understanding of how the data is skewed.

The flow weighted mean is presented in Table 4-4 below alongside the median values. The flow weighted mean is surprisingly similar to the median values and produces similar water quality constituent values that exceed the limits almost identical to the median values.

Again, the flow weighted mean can indicatively provide an idea of the water quality within the tanks; however, still requires additional analyses of each water quality constituent separately which would only increase the complexity and computation steps within the optimisation of water distribution networks.

Both the median and flow weighted mean can potentially be used within the algorithms to provide designers and decision-makers with a tool to identify potential tank design problems. However, they do not fully capture extreme values. The minimum and maxima can be computed to provide a better understanding of how a network solution compared to another solution within the algorithm steps as described in Figure 2-2; however, this increases the complexity of the problem further.

At this point, the water quality indices results were compared to the results obtained here to understand if the indices are accurate and require shorter computation steps.

Table 4-4: Median and flow weighted values of water quality constituents for solution tanks

	Water Age	Chlorine	THM	HAA5	Water Age	Chlorine	THM	HAA5	Water Age	Chlorine	THM	HAA5	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L	hours	mg/L	ug/L	ug/L	hours	mg/L	ug/L	ug/L	hours	mg/L	ug/L	ug/L
PF-MOEA Solution 1																
	7N								**41E**				**42E**			
Median	31.98	0.28	45.14	41.58					17.03	0.41	28.23	30.25	24.56	0.36	36.96	57.74
Flow weighted mean	29.56	0.30	41.25	41.80	-				12.54	0.45	21.08	30.36	24.81	0.36	36.70	56.94
PF-MOEA Solution 2																
	6N								**41E**				**42E**			
Median	32.00	0.28	44.59	40.92					13.72	0.43	24.95	29.90	22.49	0.38	34.03	31.01
Flow weighted mean	31.81	0.29	43.88	40.79	-				10.70	0.43	19.11	27.80	21.29	0.39	32.24	30.51
FMO																
	150N				**170N**				**41E**				**42E**			
Median	34.23	0.25	46.80	41.15	30.98	0.27	44.51	40.72	42.02	***0.00***	58.39	***49.10***	21.18	0.38	32.87	41.57
Flow weighted mean	31.67	0.28	43.51	31.26	31.26	0.28	44.33	40.85	41.02	***0.00***	56.70	47.78	21.44	0.38	32.89	42.98
SSGA																
	150N				**170N**				**41E**				**42E**			
Median	37.22	0.22	50.42	45.00	29.72	0.29	42.10	39.36	19.82	0.39	30.95	33.93	24.15	0.35	36.26	42.88
Flow weighted mean	34.77	0.25	46.85	43.43	27.30	0.31	39.28	37.22	17.87	0.41	28.41	32.64	24.07	0.36	35.50	44.38
SMGA Solution 1																
	55N				**110N**				**41E**				**42E**			
Median	39.63	***0.19***	54.04	43.23	23.19	0.35	36.71	29.37	30.72	0.28	45.20	36.16	***60.00***	***0.00***	***70.68***	56.55

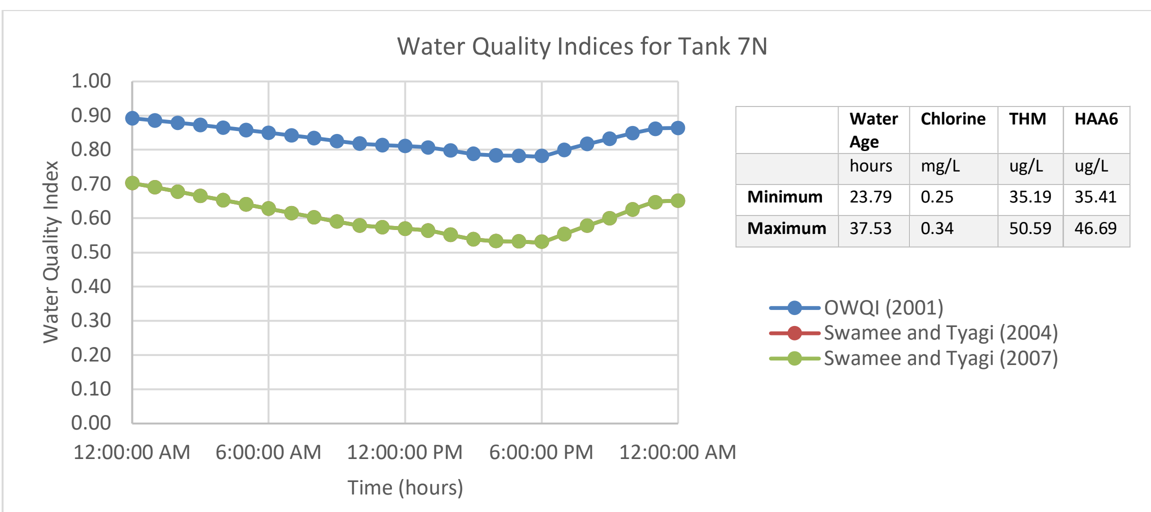
	Water Age	Chlorine	THM	HAA5	Water Age	Chlorine	THM	HAA5	Water Age	Chlorine	THM	HAA5	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L	hours	mg/L	ug/L	ug/L	hours	mg/L	ug/L	ug/L	hours	mg/L	ug/L	ug/L
Flow weighted mean	39.33	0.20	53.68	42.95	20.59	0.38	32.15	25.72	28.64	0.30	41.39	33.11	***62.62***	***0.00***	***70.87***	56.69
SMGA Solution 2																
	145N								**41E**				**42E**			
Median	34.60	0.24	49.61	39.75	-				30.38	0.29	43.64	34.98	***60.00***	***0.00***	***76.14***	***60.91***
Flow weighted mean	32.15	0.26	46.89	37.58					26.79	0.32	38.91	31.20	***56.61***	***0.00***	***73.55***	58.83

Values indicated in bold, and italics are values exceeding the water quality constituent limits

4.3 Water Quality Index Results

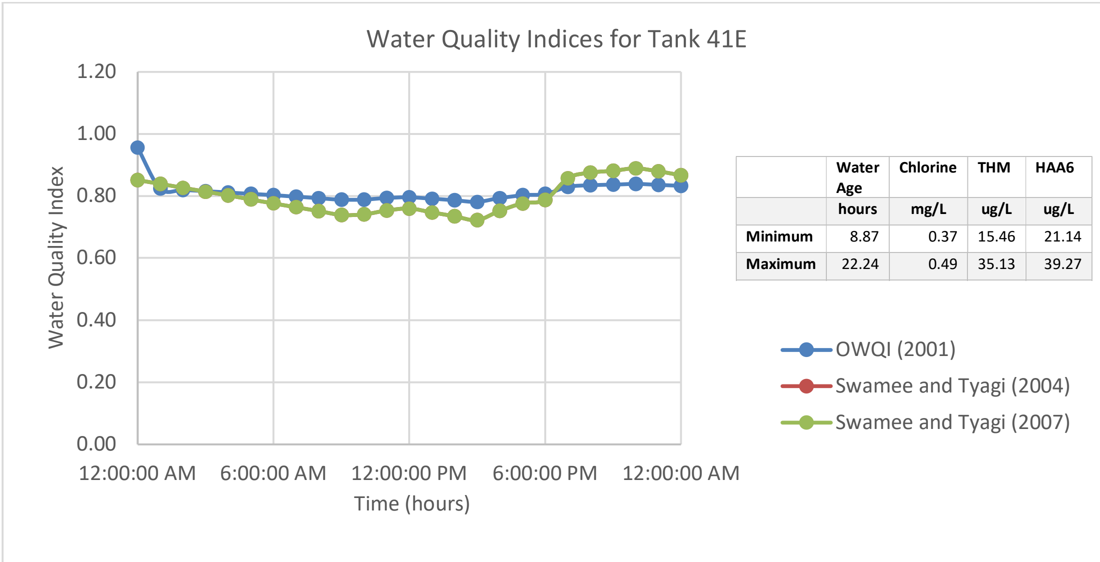
In order to test the viability of the water quality indices as compared to the produced water quality results applied in Section 4.2.1; the indices were calculated and will be discussed here. A sub-index value was calculated for water age, chlorine, THMs and HAA5 for each hour from the results of the last 24-hours of the 72-hour water quality simulation. The sub-index values were used to calculate water quality indices using equations 2.8.1 to 2.8.3 in Section 2.8. For the modified and original Canadian water quality index (equations 2.8.4 and 2.8.5); no sub-indices are required and hence the indices were calculated directly. Additionally, these indices do not have a minimum or maximum value as the index is calculated for the full set of results. Calculations for the indices are presented in Appendix B.

Figure 4-31 to Figure 4-33 present the calculated water quality indices for the PF-MOEA Solution 1 tanks alongside minimum and maximum values of the produced water quality results as a comparison. Exceedances of the minimum and maximum water quality limits are highlighted in bold. In general, the Oregon water quality index tends to rate water quality higher for the same set of results with the Swamee and Tyagi indices plotting lower on the scale. There is no clear difference between the two Swamee and Tyagi indices for tank 7N and 41E; however, there seems to be a general agreement amongst the indices for Tank 41E with most values around the 0.8 rating (a Fair to Good water quality rating). The water quality overall for all tanks could be described as good except for Tank 42E which experiences high concentrations of HAA5 towards the end of the simulation.



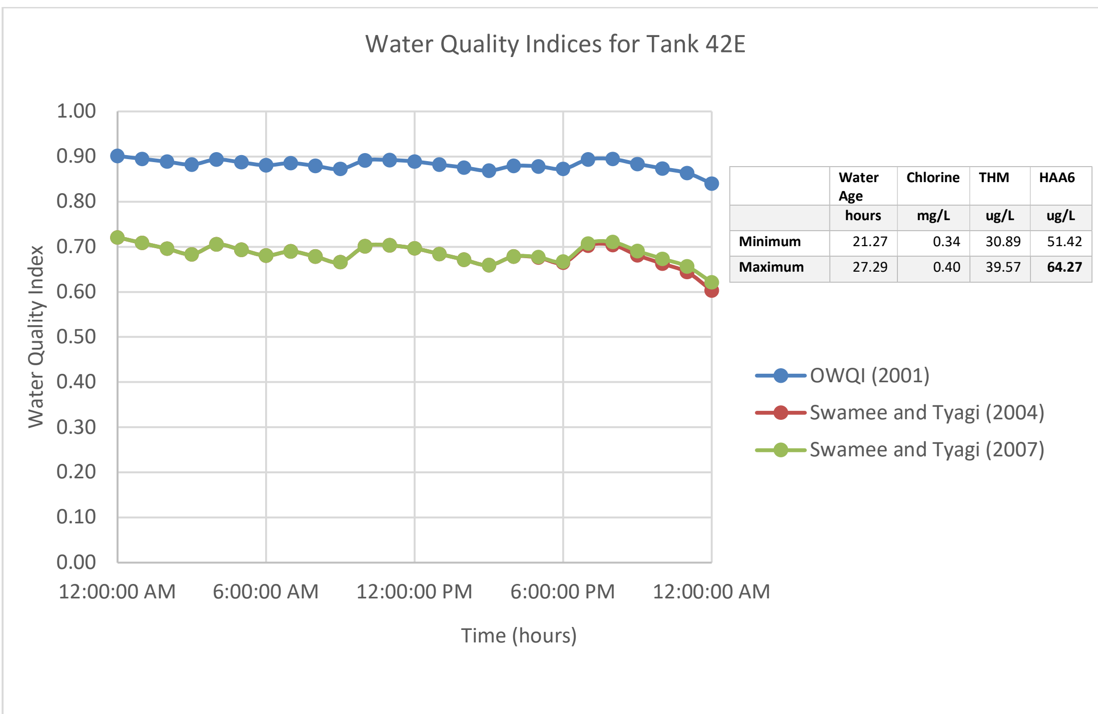
	Water Age	Chlorine	THM	HAA6
	hours	mg/L	ug/L	ug/L
Minimum	23.79	0.25	35.19	35.41
Maximum	37.53	0.34	50.59	46.69

Figure 4-31: Water quality indices for Tank 7N (PF-MOEA Solution 1)



	Water Age	Chlorine	THM	HAA6
	hours	mg/L	ug/L	ug/L
Minimum	8.87	0.37	15.46	21.14
Maximum	22.24	0.49	35.13	39.27

Figure 4-32:Water quality indices for Tank 41E (PF-MOEA Solution 1)



	Water Age	Chlorine	THM	HAA6
	hours	mg/L	ug/L	ug/L
Minimum	21.27	0.34	30.89	51.42
Maximum	27.29	0.40	39.57	**64.27**

Figure 4-33: Water quality indices for Tank 42E (PF-MOEA Solution 1)

Figure 4-34 to Figure 4-36 below present the calculated water quality indices for the PF-MOEA Solution 2 tanks alongside minimum and maximum values of the produced water quality results. Similar to the PF-MOEA solution 1; the Swamee and Tyagi indices are near identical except for Tank 41E where exceedances of the chlorine concentrations show minor differences in the indices value. It appears that the Swamee and Tyagi (2007) index deviates from the original formulation once a clear violation of the constituent limits is experienced. Again, the Oregon water quality index tends to be higher with the Swamee and Tyagi indices plotting lower on the scale. Figure 4-35 indicates how the indices mimic the produced water quality results according to the water constituent values over time. This graph is similar to the produced water quality results with the same dip in chlorine concentration for the same tank (Refer to Figure 4-15).

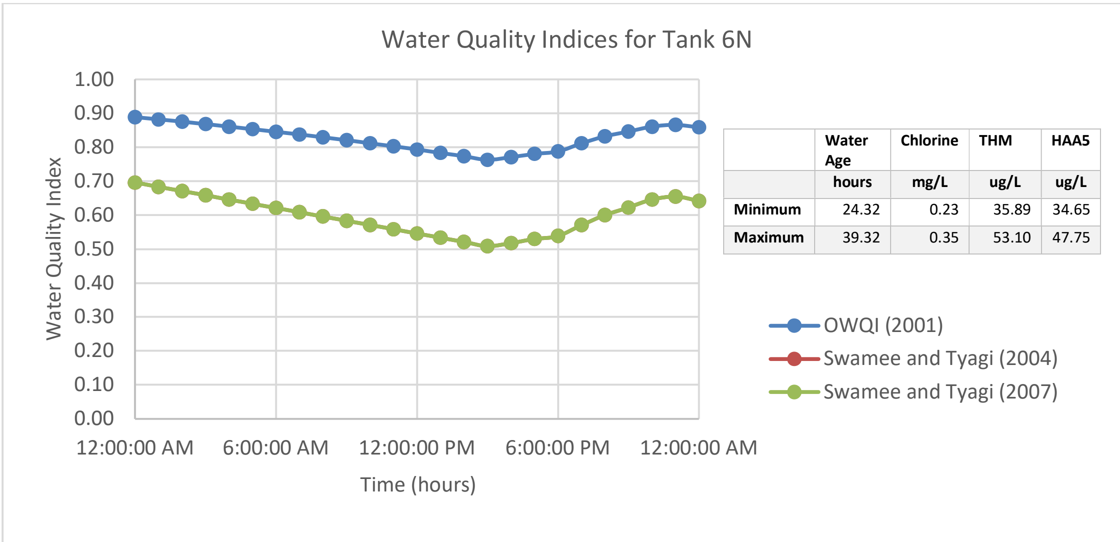


Figure 4-34: Water quality indices for Tank 6N (PF-MOEA Solution 2)

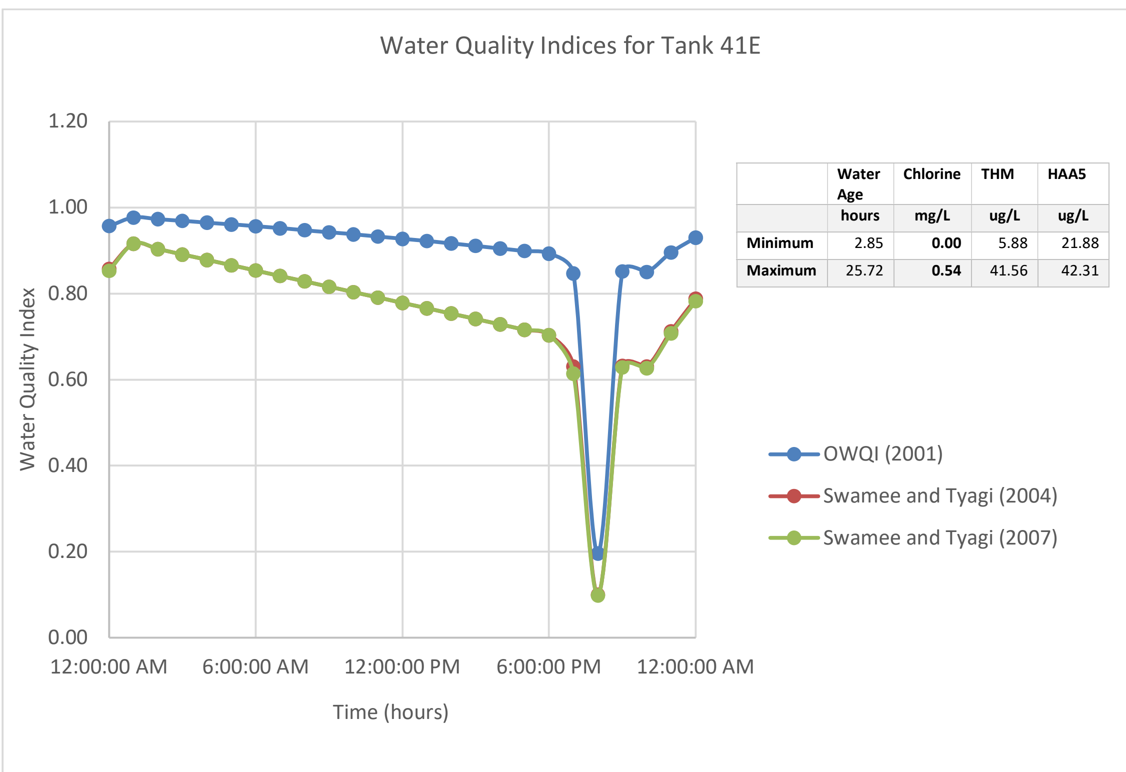


Figure 4-35: Water quality indices for Tank 41E (PF-MOEA Solution 2)

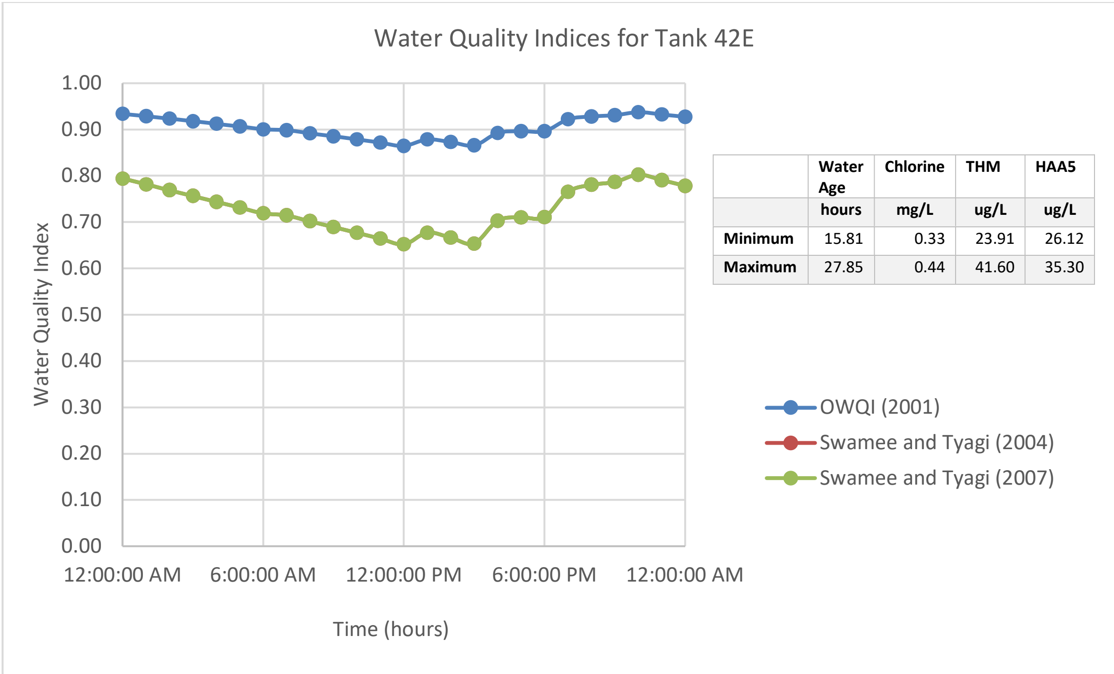
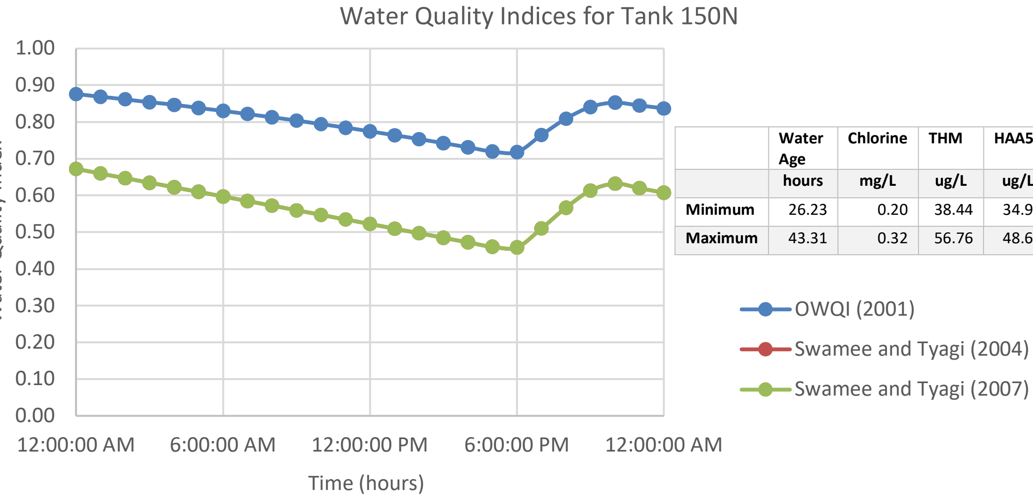


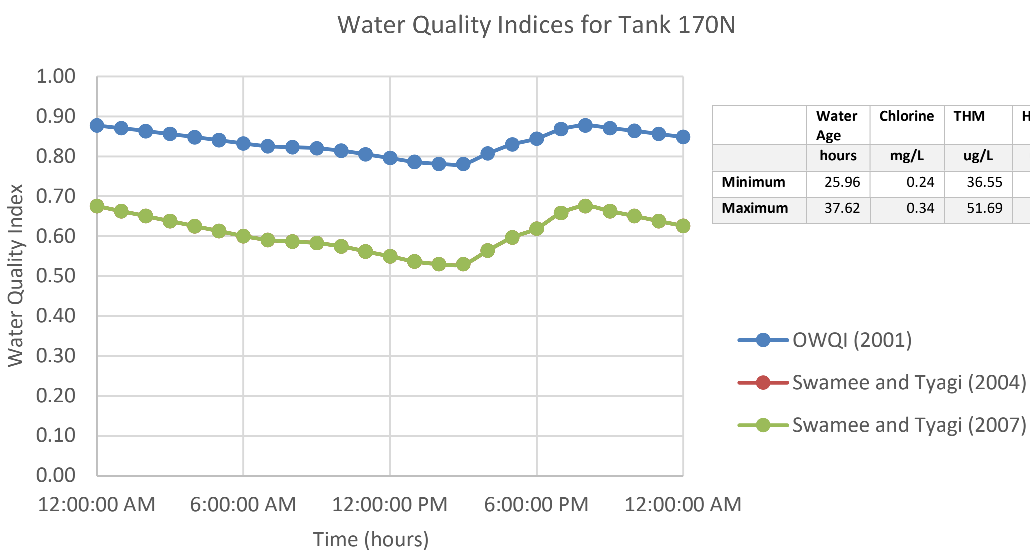
Figure 4-36: Water quality indices for Tank 42E (PF-MOEA Solution 2)

Figure 4-37 to Figure 4-40 present the water quality indices per tank for the FMO solution. The results are similar to the previous two solutions with the Oregon water quality index plotting higher on the scale and minor differences between the Swamee and Tyagi indices. For tank 41E, the water quality exceedances were captured for all water quality indices with values below 0.2 across the entire time period. The rating for each index would be Poor and Very Poor (for the OWQI) which is a good descriptor for this tank that experiences exceedances for most water quality constituents over a large portion of the simulation period.



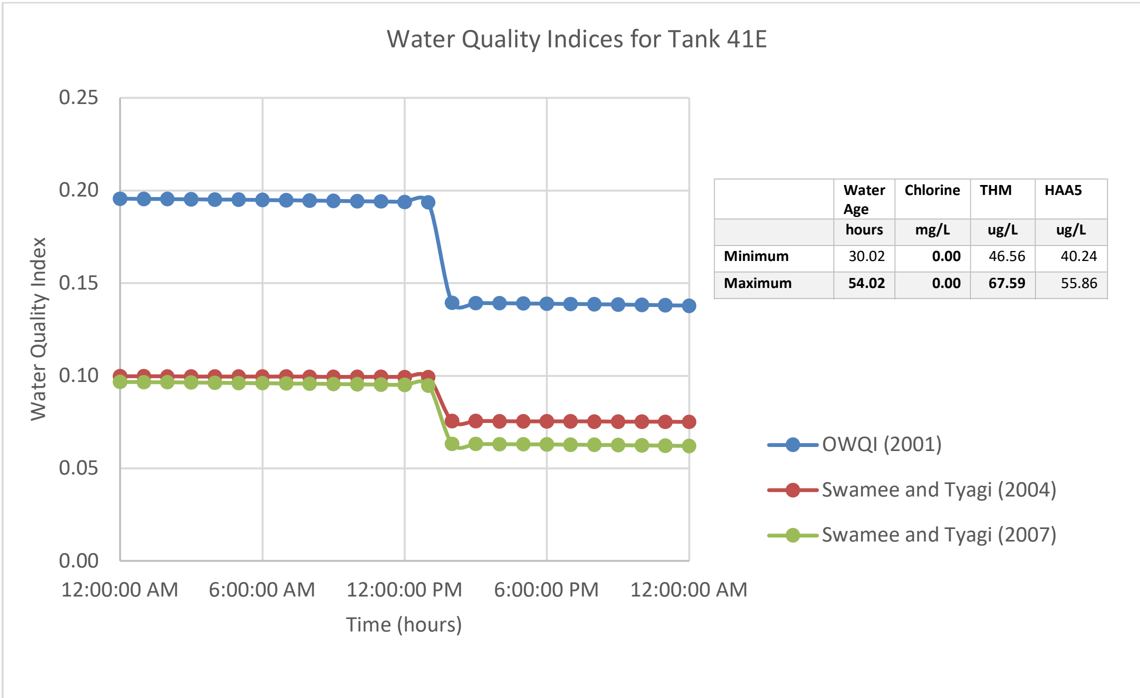
	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	26.23	0.20	38.44	34.99
Maximum	43.31	0.32	56.76	48.61

Figure 4-37: Water quality indices for Tank 150N (FMO)



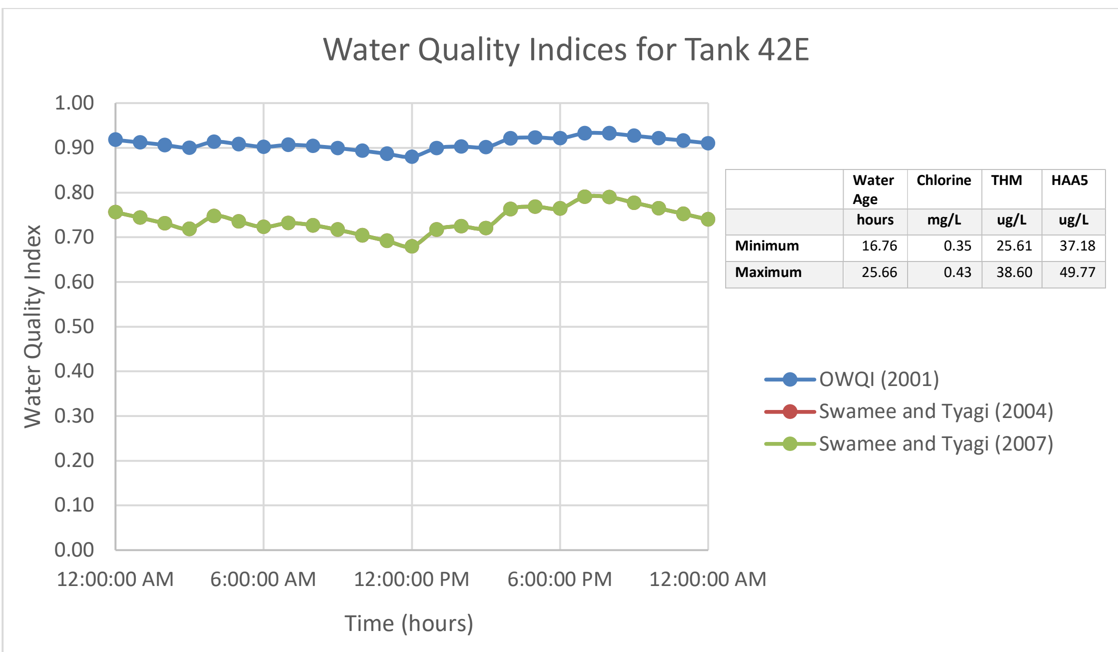
	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	25.96	0.24	36.55	35.75
Maximum	37.62	0.34	51.69	46.05

Figure 4-38: Water quality indices for Tank 170N (FMO)



	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	30.02	0.00	46.56	40.24
Maximum	54.02	0.00	67.59	55.86

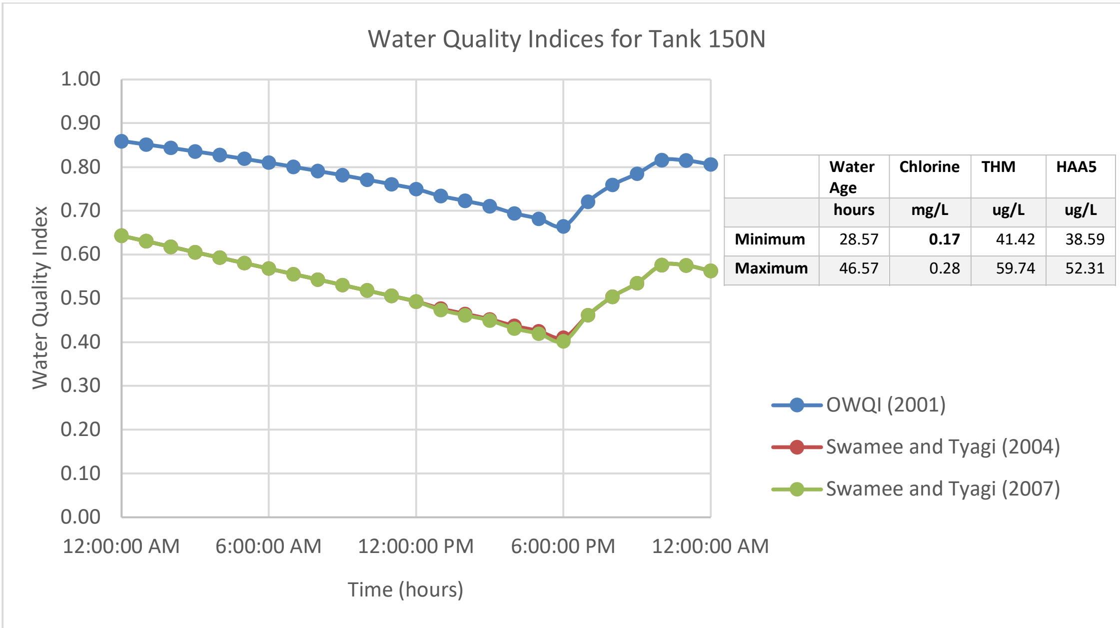
Figure 4-39: Water quality indices for Tank 41E (FMO)



	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	16.76	0.35	25.61	37.18
Maximum	25.66	0.43	38.60	49.77

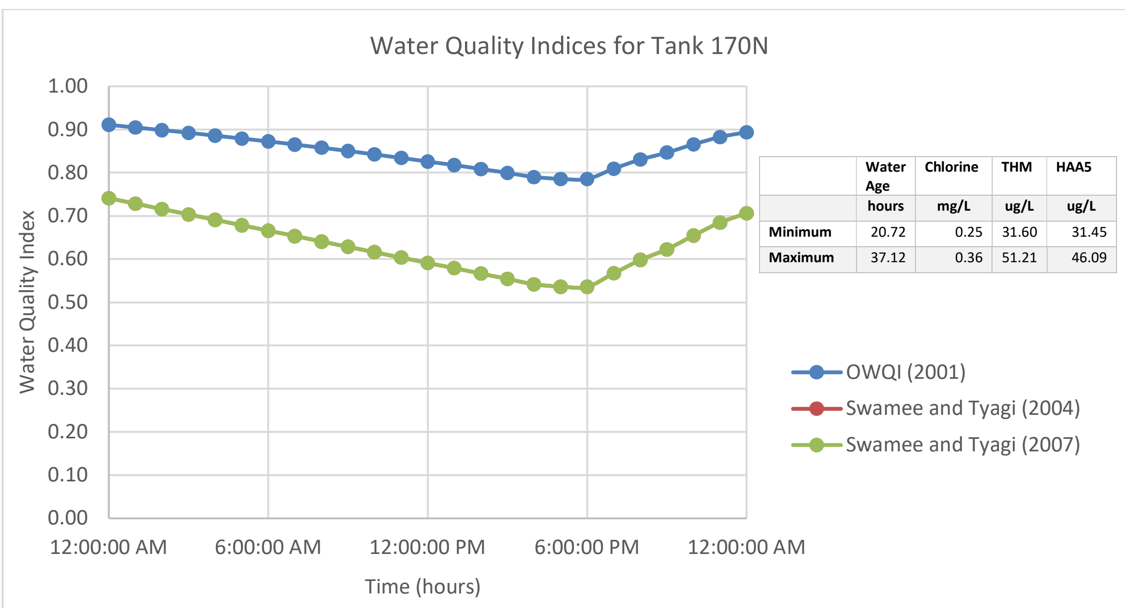
Figure 4-40: Water quality indices for Tank 42E (FMO)

Figure 4-41 to Figure 4-44 below show the indices results for the SSGA solution. This solution produces indices quite similar to previous solutions. All indices for Tank 150N capture the low concentrations of chlorine at 6pm; however, the Oregon water quality index would classify this violation as Poor water quality at a rating of 0.7 unlike the Swamee and Tyagi index which would rate the tank as Fair water quality at a rating of 0.4. The classification ratings differ widely for each index and require careful interpretation based on what the user requires.



	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	28.57	**0.17**	41.42	38.59
Maximum	46.57	0.28	59.74	52.31

Figure 4-41: Water quality indices for Tank 150N (SSGA)



	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	20.72	0.25	31.60	31.45
Maximum	37.12	0.36	51.21	46.09

Figure 4-42: Water quality indices for Tank 170N (SSGA)

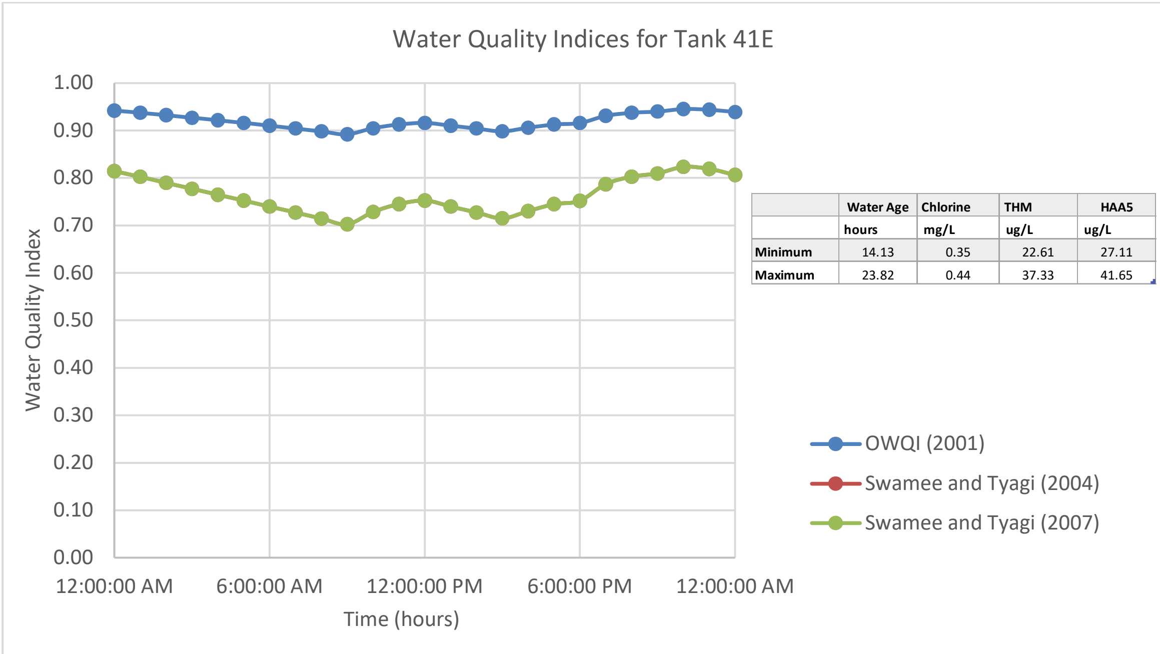


Figure 4-43: Water quality indices for Tank 41E (SSGA)

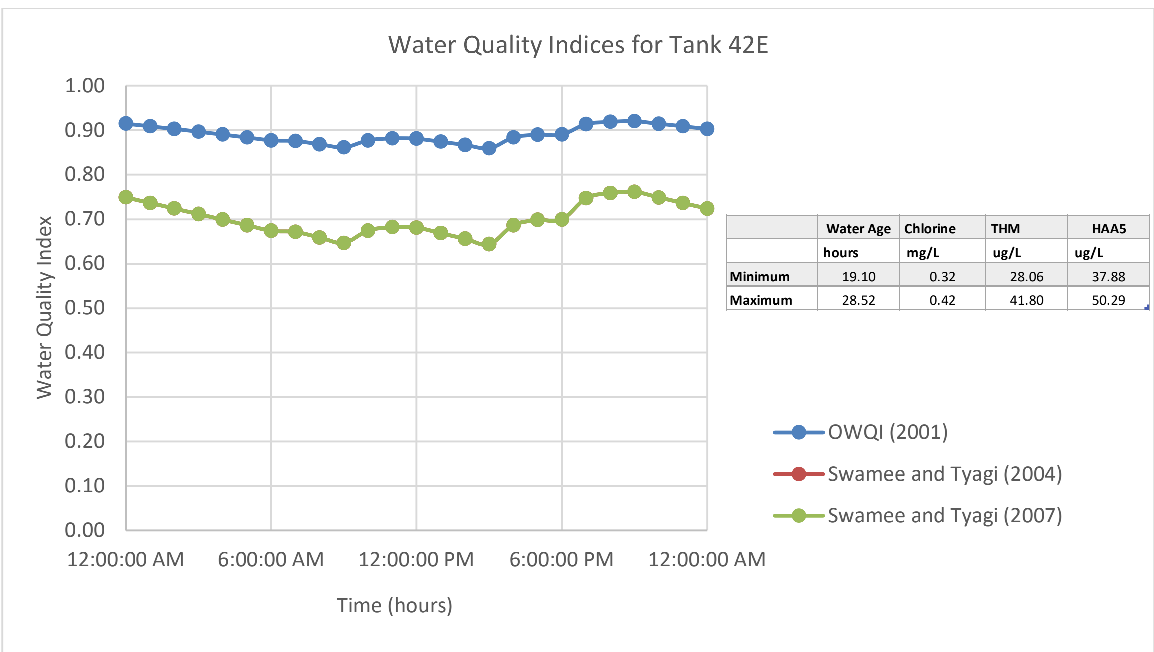
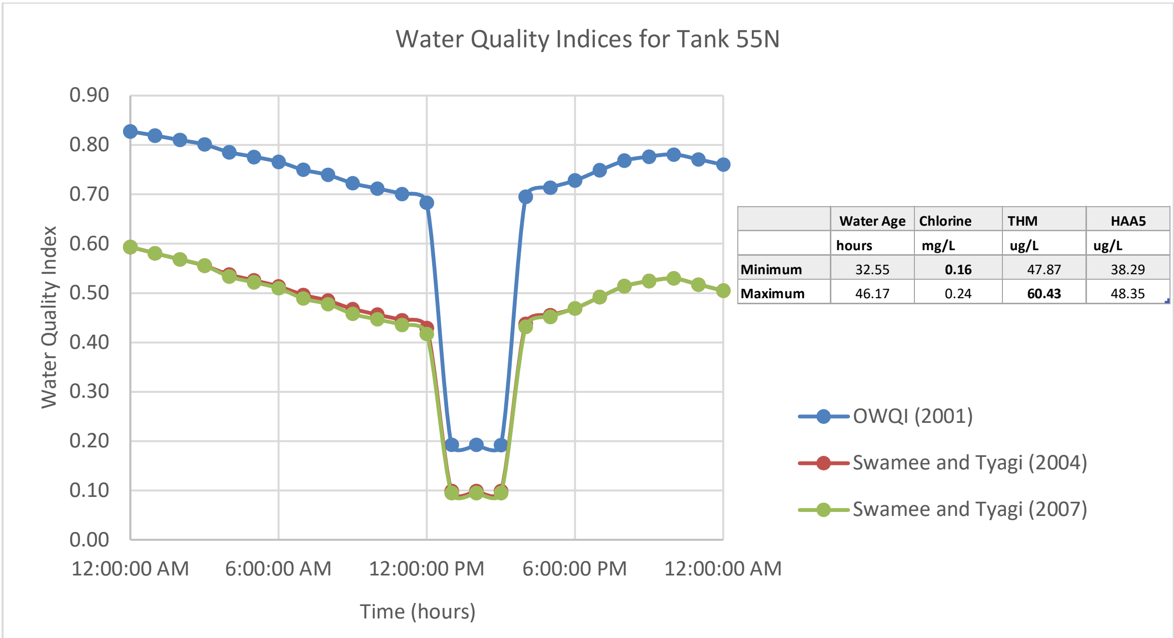


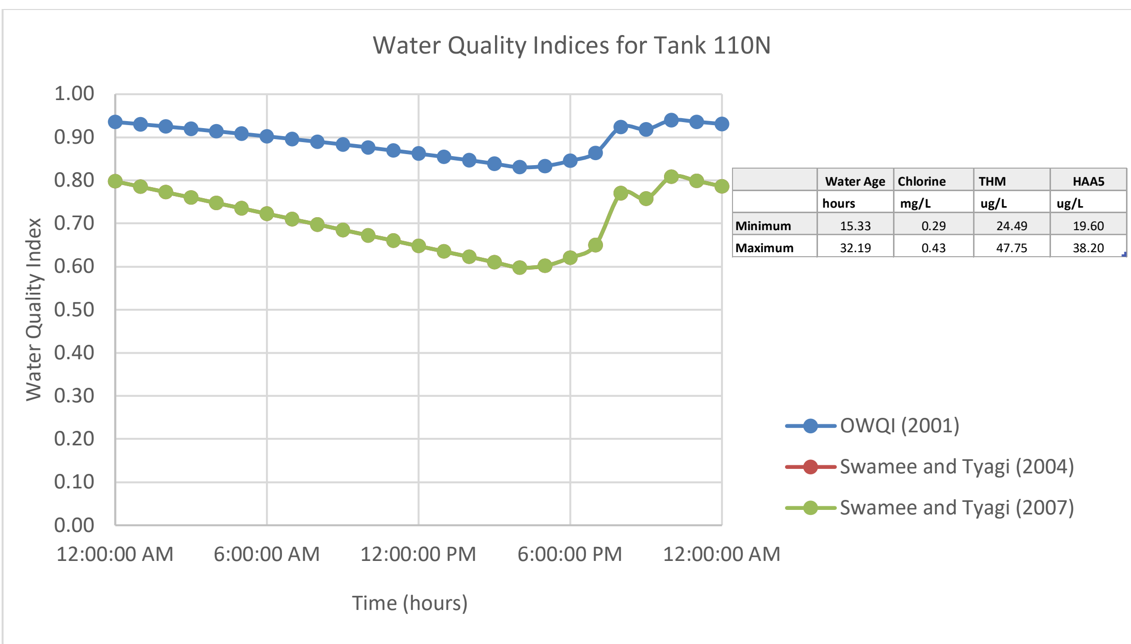
Figure 4-44: Water quality indices for Tank 42E (SSGA)

Figure 4-45 to Figure 4-51 present the calculated water quality indices for both SMGA solutions. The indices values are consistent with previous tanks and solutions. Exceedances of the constituent limits were captured by the indices throughout the 24-hour period. Tank 55N indices clearly indicate periods of Poor water quality through for all indices. Tank 42E in both solutions receives a rating of below 0.14, indicating Poor and Very Poor water quality that progressively worsens throughout the 24-hour period. The indices decrease in line with the degradation or growth of the water quality constituent.



	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	32.55	**0.16**	47.87	38.29
Maximum	46.17	0.24	**60.43**	48.35

Figure 4-45: Water quality indices for Tank 55N (SMGA Solution 1)



	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	15.33	0.29	24.49	19.60
Maximum	32.19	0.43	47.75	38.20

Figure 4-46: Water quality indices for Tank 110N (SMGA Solution 1)

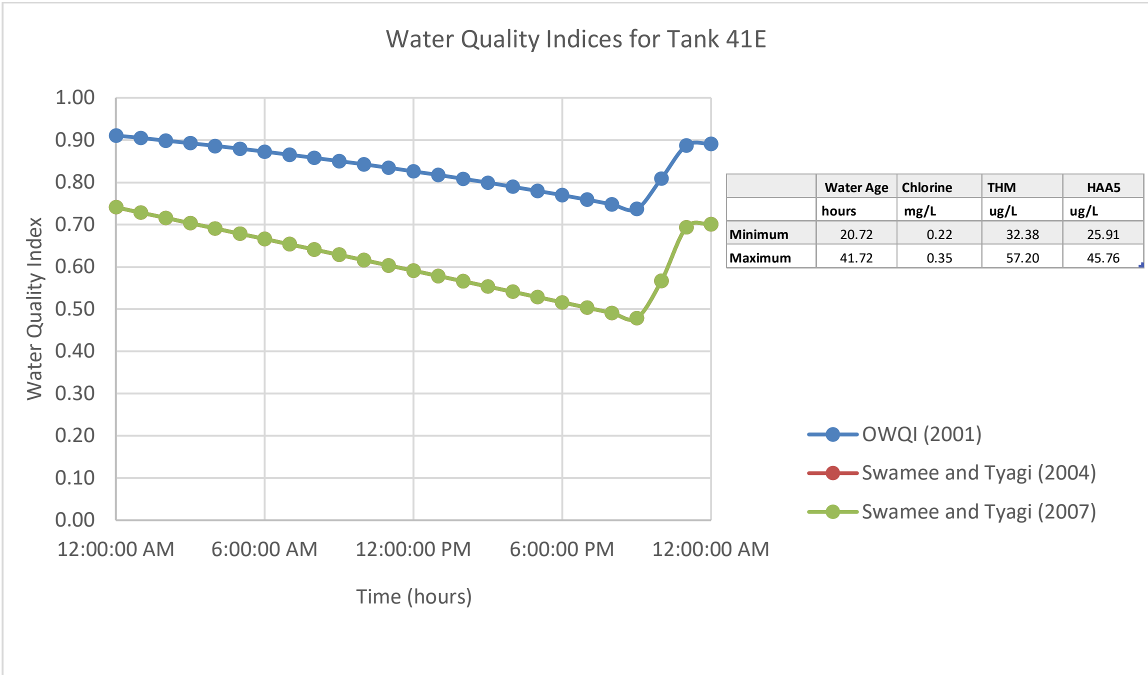


Figure 4-47: Water quality indices for Tank 41E (SMGA Solution 1)

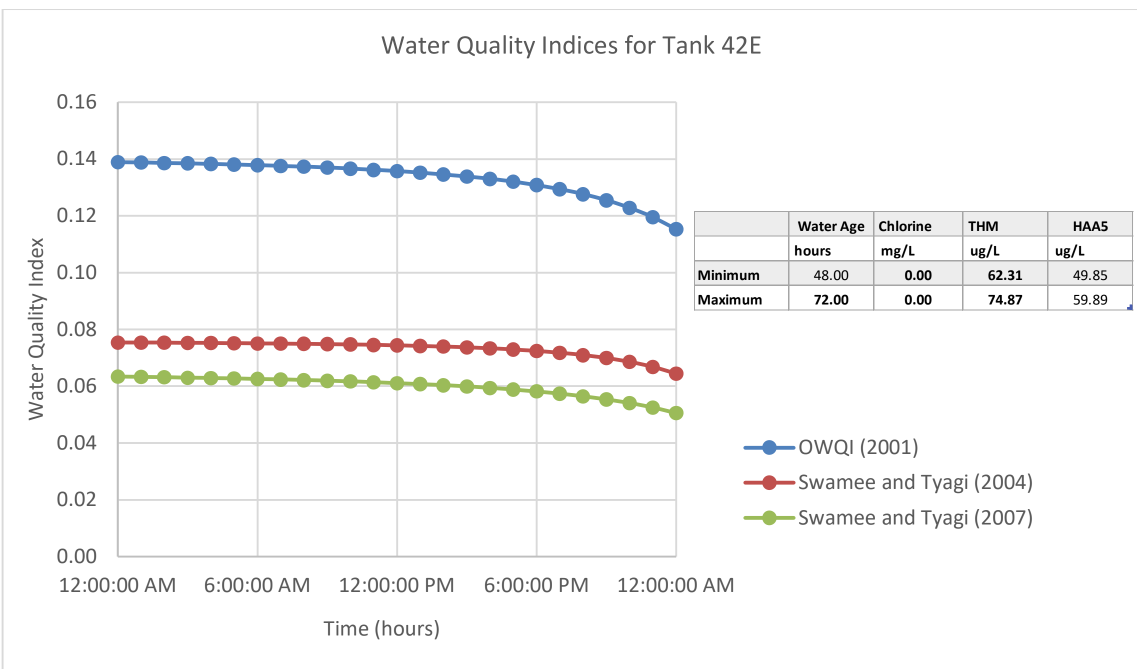
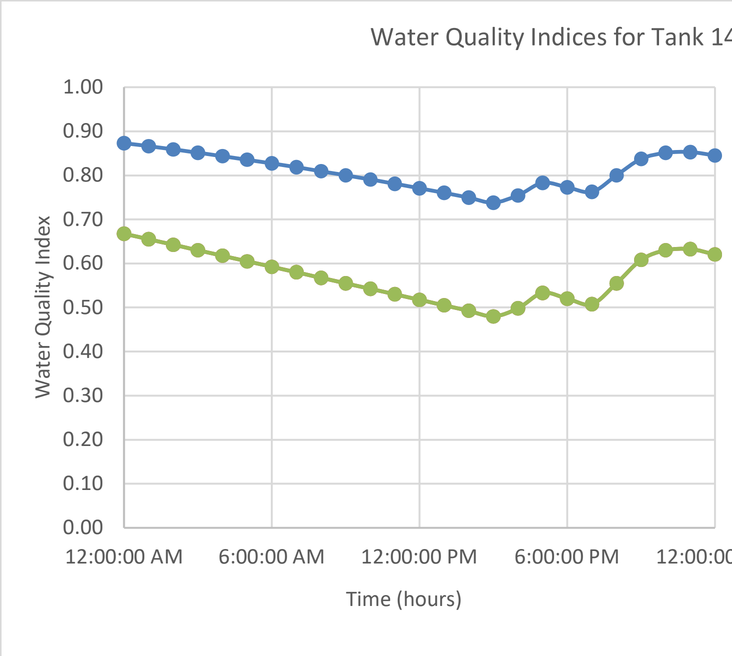
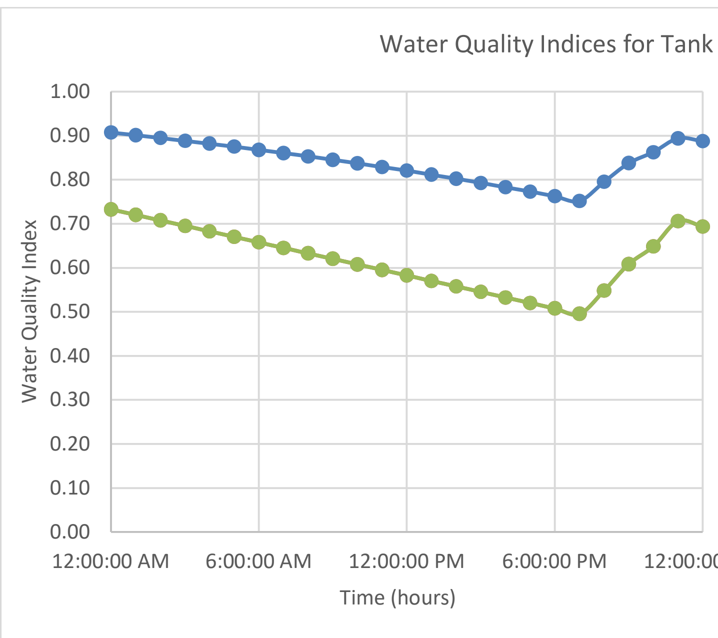


Figure 4-48: Water quality indices for Tank 42E (SMGA Solution 1)



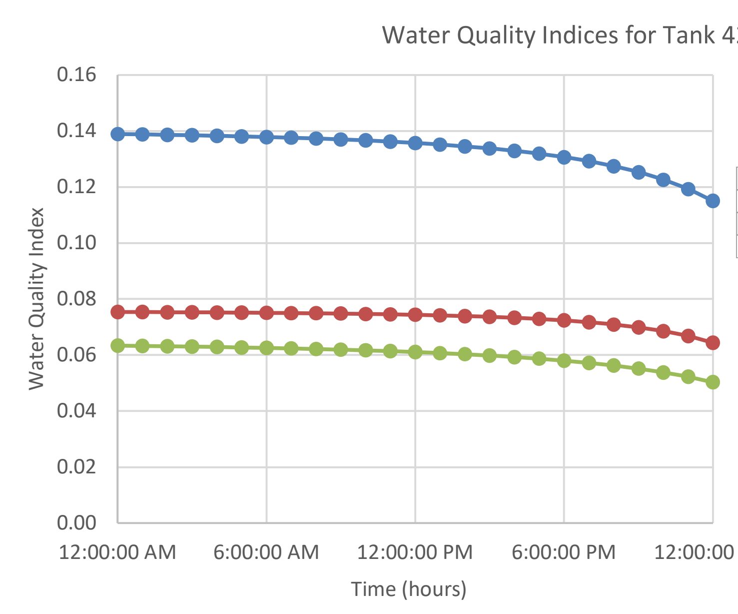
	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	26.60	0.21	41.22	33.04
Maximum	41.60	0.31	57.15	45.77

Figure 4-49: Water quality indices for Tank 145N (SMGA Solution 2)



	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	21.38	0.23	32.90	26.40
Maximum	40.38	0.37	55.24	44.24

Figure 4-50: Water quality indices for Tank 41E (SMGA Solution 2)



	Water Age	Chlorine	THM	HAA5
	hours	mg/L	ug/L	ug/L
Minimum	48.00	0.00	66.73	53.38
Maximum	72.00	0.00	83.80	67.04

Figure 4-51: Water quality indices for Tank 42E (SMGA Solution 2)

Based on the above results, the water quality indices can provide a good snapshot of all the water quality constituents in the tanks at a particular time. Tanks with hydraulic and water quality issues such as tanks 41E and 42E were highlighted through low values of water quality indices. There is a large difference between the Oregon water quality index and the Swamee and Tyagi indices that is differentiated through how the values were aggregated and the associated rating. As a further step to determining a suitable water quality index, each index was plotted for all solution tanks which also allows the modified and original Canadian water quality indices to be presented and compared. Minimum values of the water quality indices were plotted and are discussed below.

Figure 4-52 presents the minimum values calculated for the Oregon Water Quality Index. The results align well with the results shown in Section 4.2. The tanks were shown to exceed the water quality constituent limits have the lowest indices indicating poorer water quality. Existing tanks 41E and 42E obtained the lowest indices in PF-MOEA Solution 2, the FMO and both SMGA solutions.

Existing tank 41E also has the highest index value in PF-MOEA Solution 1 and the SSGA solution, while existing tank 42E achieves high indices across some of the solutions indicating acceptable operating conditions under specific network arrangements.

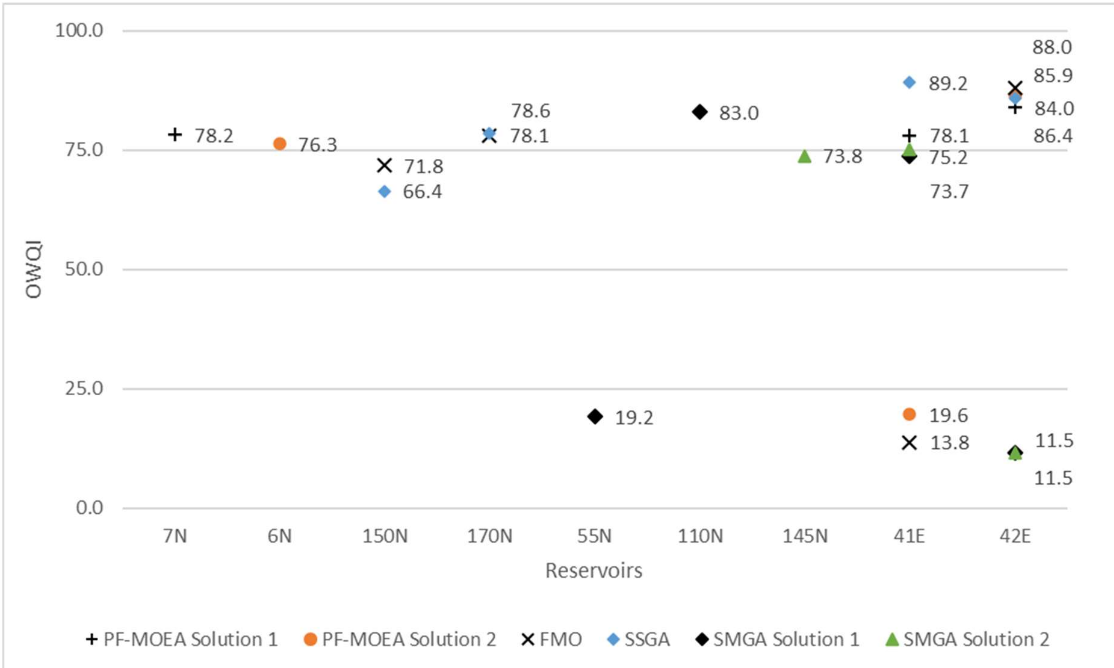


Figure 4-52: Minimum water quality index results for tanks based on the Oregon Water Quality Index (OWQI)

The Swamee and Tyagi (2004) water quality index results are shown in Figure 4-53 below. The results are similar to those produced by the Oregon water quality index with most values plotting lower on the scale. For example, Tank 7N has a rating of 53.1 compared to a rating of 78.2 using the Oregon Water Quality Index. This is similar across all solutions and hence the difference between how the two index values would be rated changes drastically. Using the Oregon Water Quality Index most of the tanks would be rated as having Very Poor to Poor water quality (0-79) while Swamee and Tyagi would rate these between Poor to Good. Potential users would need to be careful on intepereting the results depending on which index is utlised.

However, the Swamee and Tyagi water quality index mirrors the raw water quality results well with better distinguishment between the range of index values.

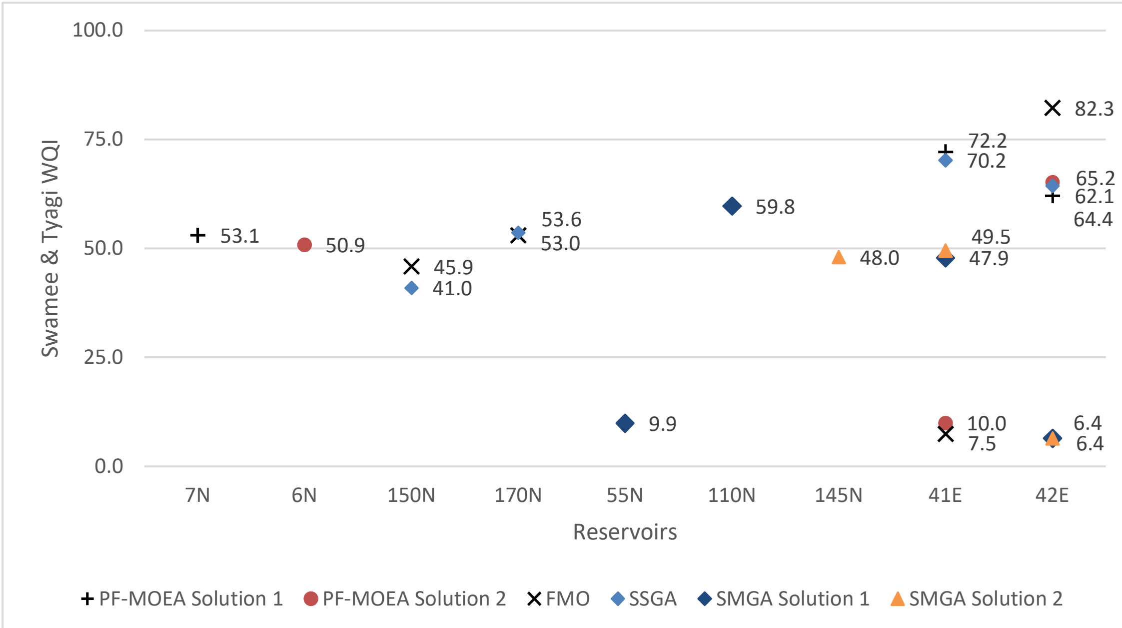


Figure 4-53: Minimum water quality index results for tanks based on the Swamee and Tyagi Water Quality Index (2000)

The modified Swamee and Tyagi water quality index (Refer to Figure 4-54) produces results similar to the original Swamee and Tyagi index. In contrast, tanks with poorer water quality have a lower value than the original index; however, the rating according to the classification is the same. This can be seen in the highest rated (Tank 42E) that scales down to 67.9 from a value greater than 80 in the indices presented so far. This index presents a higher value for Tank 41E for the PF-MOEA Solution 1 as opposed to Tank 42E for the FMO solution; which has not been the case for the other indices. This a better representation of the water quality results as although both tanks do not exceed the water quality constituent limits; Tank 41E has lower values of THMs, HAA5 and shorter water ages.

The modified Swamee and Tyagi water quality index is stated to be free from rigidity and eclipsicity which are potential reasons for these results. Violations of the water quality limits are highlighted while more favourable results are minimised. Overall, the modified Swamee and Tyagi index provides a better presentation of the raw water quality results.

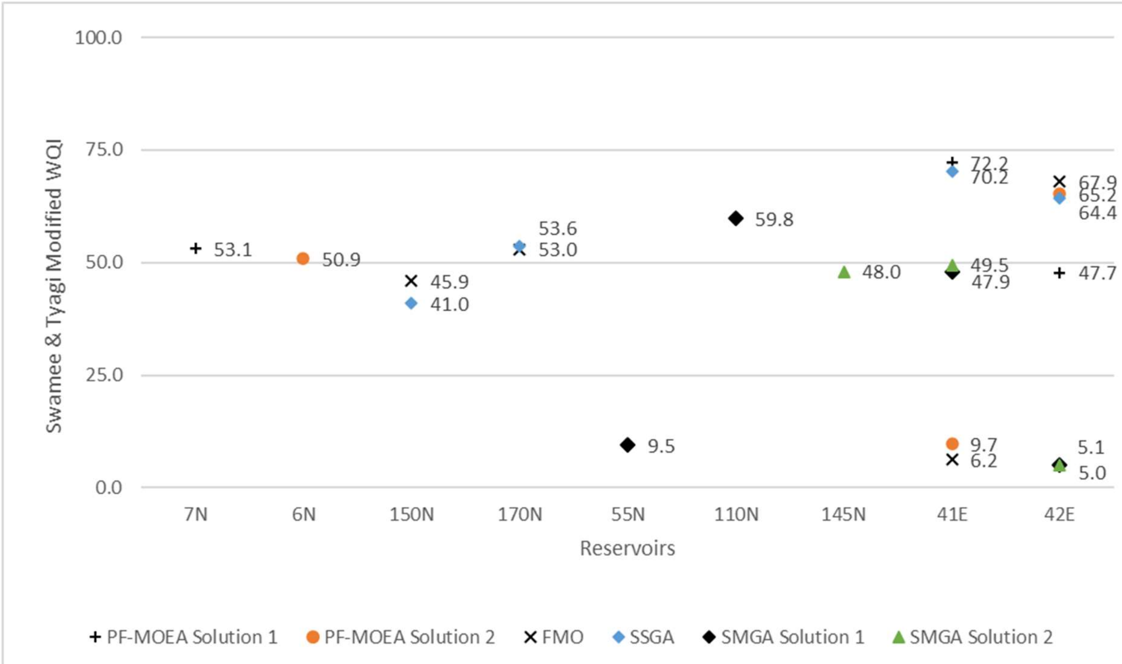


Figure 4-54: Minimum water quality index results for tanks based on the improved Swamee and Tyagi Water Quality Index (2007)

Figure 4-55 and Figure 4-56 below show results of the original and modified Canadian water quality indices. The results vary drastically from those of the previous three water quality indices. This is because the Canadian water quality index is based on indicating compliance of the data set over a certain period as opposed to transforming and aggregating a number of water quality constituents.

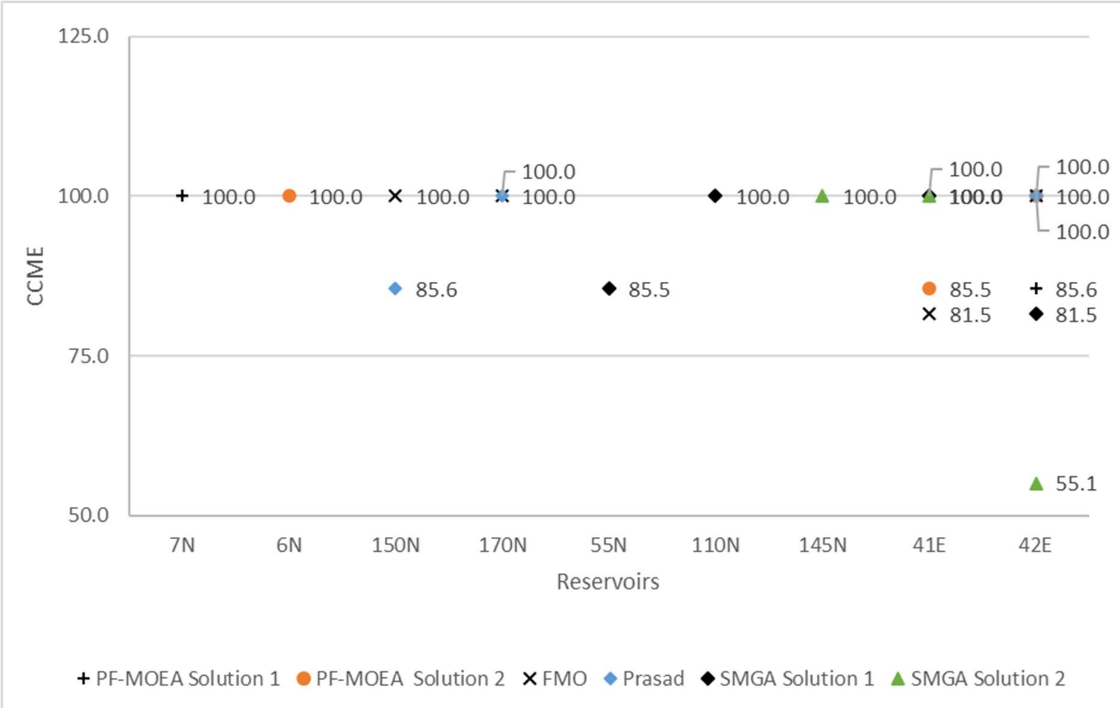


Figure 4-55: Minimum water quality index results for tanks based on the Canadian Water Quality Index (CCME)

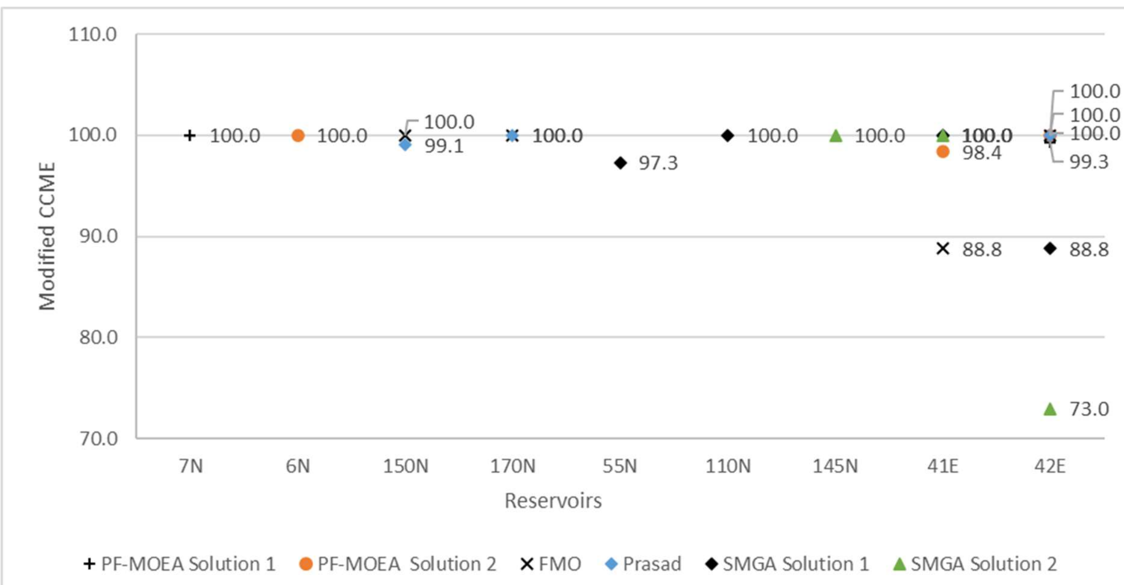


Figure 4-56: Minimum water quality index results for tanks based on the Modified Canadian Water Quality Index (MCWQI)

According to both the original and modified Canadian water quality indices; all the tanks either have Excellent or Good water quality except for Tank 42E under SMGA Solution 2. According to the original Canadian water quality index classification it would be classified as Marginal and for the modified version it would be classified as Good. This classification seems lax as this tank exceeds all the water quality constituents' limits for the entire 24-hour simulation period.

For the rest of the tanks, it provides little distinction between the tanks; which does not provide much information to the user and may cause disparity when trying to distinguish which tank is performing better when assessing water quality.

According to the raw water quality results, both the original and modified Canadian water quality indices do not mirror the results accurately for this purpose.

Overall, the water quality index seems to aggregate the raw water quality results well. The Swamee and Tyagi improved index seems to provide the most accurate results so far due to its capability of being from rigidity and eclipsicity as originally reported. The Oregon and unmodified Swamee and Tyagi water quality indices can potentially be used; however, the user will need to be aware of their limitations.

Additionally, the rating may not be of great importance in optimisation algorithms as the numerical value of the indices will likely be used in determination of the desired criteria. However; the rating may become of importance for reporting uses. In this case, the user can determine unique classification or rating systems which may be better suited to their application.

5 CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, a new and novel method to aid the inclusion of water quality into water distribution network design was explored.

The objectives of the study were:

- Understanding applicable local and international legislation; guidelines and standards surrounding drinking water quality to determine a set of water quality constituents that are well suited for water distribution systems design and optimisation. The review included investigating design and optimisation of water distribution networks and water quality indices.
- Determining an appropriate benchmark water distribution network for the purposes of the study.
- Modelling the benchmark water distribution network for the chosen water quality constituents and obtaining a set of water quality results for these constituents.
- Formulating a set of water quality indices suitable for water distribution systems.
- Aggregating the water quality indices and assessing their fitness by comparing them produced water quality results.

The literature review revealed that numerous water quality constituents can result in adverse health effects while very few will enter and remain after the water supply treatment train. Even fewer constituents are likely actively measured and used as a baseline as many of them are unlikely to enter domestic water sources or pose no to minor adverse effects unless these are at high concentrations. The South African Water Quality Guidelines and international guidelines like the World Health Organization's Guidelines for drinking water quality highlight how many water quality constituents can make their way into drinking water; what international guidelines and standards limits are for the most common constituents and how these can be managed.

The literature review also reviewed water distribution system optimisation and highlighted how current optimisation algorithms have included certain aspects of water quality. So far, most of the attempts were implicit or include one water quality constituent such as water age or chlorine concentration. It was also found that the main challenge in including water quality objectives into optimisation algorithms is the increase in complexity and computational effort as each constituent is added. The literature review also discussed several water quality indices which seemed viable for aggregating numerous water quality constituents which have different units of measurement. The water quality indices found in literature are widely used for surface water bodies and have not been applied to distribution networks. Five water quality indices were identified and chosen for use in this study. These are ; Oregon water quality index; original and modified Swamee and Tyagi index and the original and modified Canadian water quality indices.

The Anytown network problem was identified as a suitable benchmark for modelling water quality as required by the study objectives. The six most cost-effective solutions for the Anytown network which were obtained from previous optimisation studies were adopted here for modelling the water quality constituents selected for this study.

Hydraulic and water quality modelling of the network solutions was implemented in EPANET 2.0. The hydraulic models were run for the three flow scenarios as required by the original Anytown network problem. The water quality modelling was dependent on the hydraulic modelling in EPANET 2.0 and was implemented using the water quality module for water age, chlorine, tri-halomethanes and halo-acetic acids.

Water quality sub-indices charts were developed here for water age, chlorine tri-halomethanes and halo-acetic acids. The sub-indices were used to aggregate water quality indices using the water quality results. The water quality index computations were confined to the water quality in the tanks of the respective networks as tanks are critical to water quality in distribution systems.

The key findings of the analyses were:

- The water quality results indicated that even though the six solutions of the Anytown network problem were the most cost-effective and hydraulically feasible; the solutions did not always produce favourable water quality results.
- The water quality results aligned with the hydraulic modelling results which indicated that the tanks which experienced problems with emptying and filling also had problems with poor water quality.
- The nodes and tanks which experienced the worst water quality were located at the periphery of the network furthest from the treatment source or where low pressures were identified during the hydraulic modelling.
- The five water quality indices (Oregon water quality index; original and modified Swamee and Tyagi index and the original and modified Canadian water quality indices) provided variable results based on how the index was formulated.
- The modified Swamee and Tyagi index provided the best aggregation as compared to the unprocessed water quality results. The original and modified Canadian water quality indices did not provide an adequate distinction between the tanks as this index is based on indicating compliance.

The water quality indices (except for the Canadian water quality indices) seem to mirror the produced water quality results well. This suggested that they are a good indicator of the overall water quality at a point in a water distribution system which carries multiple water quality constituents.

5.2 Recommendations

Further studies are recommended to investigate in detail the use of the indices method for incorporating water quality into water distribution system optimisation. This can be done by:

- Integrating water quality indices into objective functions and constraints into water distribution system optimisation.
- Including the water quality indices at demand nodes in the analysis, as this study was confined to the water quality indices of tanks
- Refining the formulation of sub-indices and including more water quality constituents into the water quality indices

6 REFERENCES

1. Abbasi, T. & Abbasi, S., 2012. Water Quality Indices. The Netherlands: Elsevier. https://doi.org/10.1016/B978-0-444-54304-2.00016-6

2. Agapie, A. & Wright, A. H., 2014. Theoretical Analysis of Steady State Genetic Algorithms. Applications of Mathematics, Volume 59, pp. 509-525. https://doi.org/10.1007/s10492-014-0069-z

3. Alperovits, E. & Shamir, U., 1977. Design of optimal water distribution systems. Water Resources Research, 13(6), pp. 885-900. https://doi.org/10.1029/WR013i006p00885

4. American Water Works Association, 2002. Effects of Water Age on Distribution System Water Quality, Washinton, DC: United States Environmental Protection Agency.

5. Avila-Melgar, E., Cruz-Chavez, M. A., Martínez-Bahena, B. & Eraña-Díaz, M. L., 2023. Parallel evolutionary algorithm for Water Distribution Network Design, using the Masters-Students model in distributed environment. Applied Soft Computing, Volume 135. https://doi.org/10.1016/j.asoc.2023.109986

6. Barricelli, N. A., 1962. Numerical testing of evolution theories. Acta Biotheor, Volume 16, pp. 69-98. https://doi.org/10.1007/BF01556771

7. Barricelli, N. A., 1962. Numerical testing of evolution theories : Part I Theoretical introduction and basic tests. Acta Biotheoretica, Issue 16, pp. 69-98. https://doi.org/10.1007/BF01556771

8. Birkett, D. M., 2017. Water Critical Infrastructure Security and Its Dependencies. Journal of Terrorism Research, 8(2), pp. pp.1-22. https://doi.org/10.15664/jtr.1289

9. CCME, 2001. Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index, s.l.: Canadian Council of Ministers of the Environment.

10. Centers for Disease Control and Prevention, 2018. Facts about chlorine. [Online]

Available at: https://emergency.cdc.gov/agent/chlorine/basics/facts.asp

11. Cheng, R., He, C., Yaochu, J. & Yao, X., 2018. Model-based evolutionary algorithms: a short survey. Complex Intelligence Systems, pp. 283-292. https://doi.org/10.1007/s40747-018-0080-1

12. Clark, R. M., Abdesaken, F., Boulos, P. F. & Mau, R. E., 1996. Mixing in Distribution System Storage Tanks: Its Effect on Water Quality. Journal of Environmental Engineering, 122(9), pp. 814-821.
https://doi.org/10.1061/(ASCE)0733-9372(1996)122:9(814)

13. Cude, C. G., 2001. Oregon Water Quality Index: A tool for evaluating water quality management effectiveness. Journal of the American Water Resources Association, 37(1), pp. 125-137. https://doi.org/10.1111/j.1752-1688.2001.tb05480.x

14. Dao, V., Urban, W. & Hazra, S. B., 2020. Introducing the modification of Canadian Water Quality Index. Groundwater for Sustainable Development, Volume 11.
https://doi.org/10.1016/j.gsd.2020.100457

15. Das, A. & Das, H. S., 2020. Impact of Cuckoo Algorithm in Speech Processing. In: Applications of Cuckoo Search Algorithm and its Variants. s.l.:Springer Tracts in Nature-Inspired Computing, pp. 207-228. https://doi.org/10.1007/978-981-15-5163-5_9

16. Department of Water Affairs and Forestry, 1996. South African Water Quality Guidelines (second edition). s.l.:s.n.

17. Dunette, D. A., 1979. A geographically variable water quality index used in Oregon. Journal of the Water Pollution Control Federation, 51(1), pp. 53-61.

18. Farmani, R., Walters, G. & Savic, D., 2006. Evolutionary multi-objective optimization of the design and operation of water distribution network: total cost vs. reliabitiy vs. water quality. Journal of Hydroinformatics, pp. 165-179.
https://doi.org/10.2166/hydro.2006.019b

19. Figueiredo, D. M., 2014. Modelling Chlorine Decay in Drinking Water Supply Systems. Lisbon, Portugal, Instituto Superior Tecnico.

20. Fujiwara, O., Jenchaimahakoon, B. & Edirisinghe, N., 1987. A modified linear programming gradient method for optimal design of looped water distribution networks. Water Resources Research, 23(6), pp. 977-982.
https://doi.org/10.1029/WR023i006p00977

21. Gleick, P. H., 2006. Water and terrorism. Water Policy, December, 8(6), p. 481-503.
https://doi.org/10.2166/wp.2006.035

22. Horton, R. K., 1965. An index-number system for rating water quality. Journal of the Water Pollution Control Federation, Volume 37, pp. 300-306.

23. Madalina, P. & Gabriela, B. I., 2014. Water Quality Index - An Instrument for Water Resources Management. Cluj Napoca, s.n., pp. 391-398.

24. Mueller, D. K. & Spahr, N. E., 2001. Water-Quality, Streamflow, and Ancillary Data for Nutrients in Streams and Rivers Across the Nation, 1992-2001. [Online]
Available at: https://pubs.usgs.gov/ds/2005/152/htdocs/data_report_sum_stat.htm

25. Nyirenda, M. S. & Tanyimboh, T. T., 2020. Appraisal of water quality indices for service reservoirs. Water Science and Technology, 81(8), pp. 1606-1614.
https://doi.org/10.2166/wst.2020.215

26. Prasad, D. T., 2010. Design of pumped water distribution networks with Storage. Journal of Water Resources Planning and Management, 136(1), pp. 129-132.
https://doi.org/10.1061/(ASCE)0733-9496(2010)136:1(129)

27. Prasad, D. T. & Tanyimboh, T. T., 2008. Entropy based design of Anytown water distribution network. Kruger National Park, South Africa, s.n., pp. 450-461.

28. Rathnayake, U. S. & Tanyimboh, T. T., 2015. Evolutionary multi-objective optimal control of combined sewer overflows. Water Resources Management, 29(8), pp. 2715-2731.
https://doi.org/10.1007/s11269-015-0965-3

29. Rossman, L. A., 2000. EPANET Users manual. Cincinnati: National Risk Management Research Laboratory.

30. Schaake, J. C. & Lai, D., 1969. Linear Programming and Dynamic Programming Application to Water Distribution Network Design, Boston: Department of Civil Engineering, Massachusetts Institute of technology.

31. Schaake, J. & Lai, D., 1969. Linear programming and dynamic programming applications to water dstribution network design, Cambridge MA: Hydrodynamic Laboratory.

32. Seyoum, A. G., Tamyimboh, T. T. & Siew, C., 2014. Optimal Tank Design and Operation Strategy to Enhance Water Quality In Distribution Systems. New York City, CUNY Academic Works.

33. Siew, C., Tanyimboh, T. T. & Alemtsehay, S. G., 2016. Penalty-Free Multi-Objective Evolutionary Approach to Optimization of Anytown Water Distribution Network. Water Resources Management, 30(11), pp. 3671-3688.
https://doi.org/10.1007/s11269-016-1371-1

34. Swamee, P. K. & Tyagi, A., 2000. Describing water quality with aggregate index. Journal of Environmental Engineering, 126(5), pp. 451-455.
https://doi.org/10.1061/(ASCE)0733-9372(2000)126:5(451)

35. Tyagi, S. S., Singh, P. & Dobhal, R., 2013. Water quality assessment in terms of water quality index. American Journal of Water Resources, Volume 1, pp. 34-38. https://doi.org/10.12691/ajwr-1-3-3

36. UNICEF , 2018. Methodological Work - Water Quality (Multiple Indicator Surveys MICS). [Online] Available at: https://mics.unicef.org/methodological_work/3/WATER-QUALITY [Accessed 1 May 2024].

37. United Nations, 1966. Treaty Series 993. 171, General Assembly, p. 3.

38. United Nations, 2023. Sustainable Development Goals kick off with start of new year. [Online]
Available at: https://www.un.org/sustainabledevelopment/blog/2015/12/sustainable-development-goals-kick-off-with-start-of-new-year/#.

39. United States Environmental Protection Agency, 2007. Complying with the Stage 2 Disinfectant and Disinfection Byproducts Rule: Small Entity Compliance Guide. [Online] Available at: www.epa.gov/safewater

40. Vamvakeridou-Lyroudia, L. S., Walters, G. A. & Savic, D., 2005. Fuzzy Multiobjective Optimization of Water Distribution Networks. Journal of Water Resourcces Planning and Management, 131(467-476).
https://doi.org/10.1061/(ASCE)0733-9496(2005)131:6(467)

41. Van der Merwe, M., 2009. Water quality: A vital dimension of water security, Midrand: Development Planning Division, DBSA.

42. Walski, T. M., Brill, D. J. & Gessler, J., 1987. Battle of the Network Models: Epilogue. Journal of Water Resources Planning and Management, 113(2), pp. 191-203. https://doi.org/10.1061/(ASCE)0733-9496(1987)113:2(191)

43. Walters, G. A., Halhal, D., Savic, D. & Ouazr, D., 1999. Improved design of Anytown distribution network using structured messy genetic algorithms. Urban Water, pp. 23-38. https://doi.org/10.1016/S1462-0758(99)00005-9

44. World Health Organization, 2016. Protecting surface water for health. Identifying, assessing and managing drinking-water quality risks in surface-water catchments, Geneva, Switzerland: s.n.

45. World Health Organization, 2017. Guidelines for Drinking-water Quality. Fourth ed. Geneva: s.n.

46. World Health Organization, 2017. Guidelines for Drinking-water Quality: Fourth edition incorporating the first addendum, Geneva: World Health Organization.

47. Zitzler, E., Laumanns, M. & Thiele, L., 2001. SPEA2: Improving the strength pareto evolutionary algorithm, s.l.: TIK Report 103.

7 APPENDIX A: DETAILS OF THE ANYTOWN NETWORK PROBLEM

Loading Conditions

NodeID	Elevation (ft)	Average day demand (gpm)	Instantaneous peak (gpm)	Fire 1 (gpm)	Fire 2 (gpm)	Fire 3 (gpm)
1	20	500	900	650	650	650
2	50	200	360	260	260	260
3	50	200	360	260	260	260
4	50	600	1080	780	780	780
5	80	600	1080	780	1500	780
6	80	600	1080	780	1500	780
7	80	600	1080	780	1500	780
8	80	400	720	520	520	520
9	120	400	720	520	520	520
10	120	400	720	520	520	520
11	120	400	720	520	520	1000
12	50	500	900	650	650	650
13	50	500	900	650	650	650
14	50	500	900	650	650	650
15	50	500	900	650	650	650
16	120	400	720	520	520	520
17	120	1000	1800	1300	1300	1000
18	50	500	900	650	650	650
19	50	1000	1800	2500	1300	1300

Pipe Rehabilitation Costs

Pipe diameter (in)	New pipes ($/ft)	Duplicating existing pipes ($/ft)		Clean and line existing pipes ($/ft)	
		City	Residential	City	Residential
6	12.8	26.2	14.2	17.0	12.0
8	17.8	27.8	19.8	17.0	12.0
10	22.5	34.1	25.1	17.0	12.0
12	29.2	41.4	32.4	17.0	13.0
14	36.2	50.2	40.2	18.2	14.2
16	43.6	58.5	48.5	19.8	15.5
18	51.5	66.2	57.2	21.6	17.1
20	60.1	76.8	66.8	23.5	20.2
24	77.0	109.2	85.5	30.1	-
30	105.5	142.5	116.1	41.3	-

Pumping characteristics

Discharge (gpm)	Pump head (ft)	Efficiency (%) (wire to water)
0	300	0
2000	292	50
4000	270	65
6000	230	55
8000	181	40

Tank costs

Tank volume (gal)	Cost ($)
50000	115000
100000	145000
250000	325000
500000	425000
1000000	600000

8 APPENDIX B: HYDRAULIC AND WATER QUALITY RESULTS

PF-MOEA Solution 1

Time Series Table - TANK 6N

Time	Demand	Abs Demand	Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean				CCME Calculations				
																Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water	Flow weigthed mean chlorine	Flow weigthed	Flow weigthed					
Hours	GPM	GPM	ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)								Violations			
12:00:00 AM	-834.84	834.84	239.44	72.9813	17.09	23.79	0.32	35.19	41.35	0.70	1.00	1.00	1.00	5.03	0.89	0.70	0.70	19860.8	267.1	29378.0	34520.6	0	0	0	0	
1:00:00 AM	-1223.22	1223.22	236.51	72.0882	15.82	24.79	0.31	36.53	39.65	0.69	1.00	1.00	1.00	5.10	0.89	0.69	0.69	30323.6	379.2	44684.2	48500.7	0	0	0	0	
2:00:00 AM	-1310.94	1310.94	233.03	71.0275	14.31	25.79	0.31	37.83	38.31	0.68	1.00	1.00	1.00	5.18	0.88	0.68	0.68	33809.1	406.4	49592.9	50222.1	0	0	0	0	
3:00:00 AM	-1512.83	1512.83	229.44	69.9333	12.76	26.79	0.3	39.12	36.84	0.67	1.00	1.00	1.00	5.26	0.87	0.67	0.67	40528.7	453.8	59181.9	55732.7	0	0	0	0	
4:00:00 AM	-1041.8	1041.8	226.03	68.8939	11.28	27.79	0.29	40.37	35.41	0.65	1.00	1.00	1.00	5.35	0.86	0.65	0.65	28951.6	302.1	42057.5	36890.1	0	0	0	0	
5:00:00 AM	-830.98	830.98	223.52	68.1289	10.19	28.79	0.29	41.6	35.49	0.64	1.00	1.00	1.00	5.44	0.86	0.64	0.64	23923.9	241.0	34568.8	29491.5	0	0	0	0	
6:00:00 AM	-430.14	430.14	221.4	67.4827	9.27	29.79	0.28	42.81	36.42	0.63	1.00	1.00	1.00	5.54	0.85	0.63	0.63	12813.9	120.4	18414.3	15665.7	0	0	0	0	
7:00:00 AM	-265.61	265.61	220.49	67.2054	8.88	30.79	0.28	43.99	37.32	0.62	1.00	1.00	1.00	5.64	0.84	0.62	0.62	8178.1	74.4	11684.2	9912.6	0	0	0	0	
8:00:00 AM	0	0	220.41	67.181	8.84	31.79	0.27	45.14	38.21	0.60	1.00	1.00	1.00	5.75	0.83	0.60	0.60	0.0	0.0	0.0	0.0	0	0	0	0	
9:00:00 AM	0	0	220.41	67.181	8.84	32.79	0.26	46.27	39.08	0.59	1.00	1.00	1.00	5.87	0.83	0.59	0.59	0.0	0.0	0.0	0.0	0	0	0	0	
10:00:00 AM	111.79	111.79	220.54	67.2206	8.9	33.67	0.26	47.22	39.93	0.58	1.00	1.00	1.00	5.98	0.82	0.58	0.58	3764.0	29.1	5278.7	4463.8	0	0	0	0	
11:00:00 AM	158.56	158.56	220.92	67.3364	9.06	34.1	0.26	47.56	40.77	0.57	1.00	1.00	1.00	6.04	0.81	0.57	0.57	5406.9	41.2	7541.1	6464.5	0	0	0	0	
12:00:00 PM	286.1	286.1	221.37	67.4736	9.26	34.44	0.26	47.77	41.58	0.57	1.00	1.00	1.00	6.08	0.81	0.57	0.57	9853.3	74.4	13667.0	11896.0	0	0	0	0	
1:00:00 PM	12.96	12.96	221.73	67.5833	9.41	34.91	0.26	48.16	42.38	0.56	1.00	1.00	1.00	6.15	0.81	0.56	0.56	452.4	3.4	624.2	549.2	0	0	0	0	
2:00:00 PM	-89.51	89.51	221.59	67.5406	9.36	35.91	0.25	49.23	43.16	0.55	1.00	1.00	1.00	6.29	0.80	0.55	0.55	3214.3	22.4	4406.6	3863.3	0	0	0	0	
3:00:00 PM	91.14	91.14	221.32	67.4583	9.24	36.91	0.25	50.27	43.93	0.54	1.00	1.00	1.00	6.45	0.79	0.54	0.54	3364.0	22.8	4581.6	4003.8	0	0	0	0	
4:00:00 PM	196.29	196.29	221.74	67.5864	9.42	37.35	0.25	50.59	44.7	0.53	1.00	1.00	1.00	6.52	0.78	0.53	0.53	7331.4	49.1	9930.3	8774.2	0	0	0	0	
5:00:00 PM	224.2	224.2	222.32	67.7631	9.67	37.46	0.25	50.48	44.82	0.53	1.00	1.00	1.00	6.54	0.78	0.53	0.53	8398.5	56.1	11317.6	10048.6	0	0	0	0	
6:00:00 PM	613.18	613.18	222.94	67.9521	9.94	37.53	0.25	50.33	44.52	0.53	1.00	1.00	1.00	6.55	0.78	0.53	0.53	23012.6	153.3	30861.3	27298.8	0	0	0	0	
7:00:00 PM	837.05	837.05	224.96	68.5678	10.81	35.71	0.27	47.81	45.25	0.55	1.00	1.00	1.00	6.26	0.80	0.55	0.55	29891.1	226.0	40019.4	37876.5	0	0	0	0	
8:00:00 PM	994.22	994.22	227.39	69.3085	11.87	33.78	0.29	45.22	45.98	0.58	1.00	1.00	1.00	6.00	0.82	0.58	0.58	33584.8	288.3	44958.6	45714.2	0	0	0	0	
9:00:00 PM	1235	1235	230.1	70.1345	13.04	31.98	0.31	42.87	46.69	0.60	1.00	1.00	1.00	5.78	0.83	0.60	0.60	39495.3	382.9	52944.5	57662.2	0	0	0	0	
10:00:00 PM	1274.33	1274.33	233.54	71.183	14.53	29.99	0.32	40.32	46.4	0.63	1.00	1.00	1.00	5.56	0.85	0.63	0.63	38217.2	407.8	51381.0	59128.9	0	0	0	0	
11:00:00 PM	1360.6	1360.6	237.28	72.3229	16.15	28.27	0.34	38.19	46.3	0.65	1.00	1.00	1.00	5.39	0.86	0.65	0.65	38464.2	462.6	51961.3	62995.8	0	0	0	0	
12:00:00 AM	-834.84	834.84	239.44	72.9813	17.09	27.9	0.34	37.78	44.96	0.65	1.00	1.00	1.00	5.36	0.86	0.65	0.65	23292.0	283.8	31540.3	37534.4	0	0	0	0	
					min	23.79	0.25	35.19	35.41					min	0.78	0.53	0.53	**29.6**	**0.3**	**41.3**	**41.8**		0	0	0	0
					max	37.53	0.34	50.59	46.69					max	0.89	0.70	0.70									
					q1	28.085	0.26	39.72	38.26					q1	0.80	0.56	0.56					F1	=		0	
					q2	35.31	0.31	47.985	44.89					q2	0.86	0.65	0.65					F2	=		0	
					median	31.98	0.28	45.14	41.58					median	0.83	0.60	0.60					nse	=		0	
																						F3	=		0	
																						CCME WQI	=		100	
																						MCWQI	=		100	

Time Series Table - Tank 41E

Time	Demand	Abs Demand	Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean				CCME Calculations				
																Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6					
Hours	GPM	GPM	ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)								Violations			
48:00:00	-1425.11	1425.11	250	76.2	15.17	11.89	0.45	20.35	27.42	0.85	1.00	1.00	1.00	4.38	0.96	0.85	0.85	16944.6	641.3	29001.0	39076.5	0	0	0	0	
49:00:00	-964.36	964.36	238.65	72.7405	10.25	12.89	0.44	21.99	23.62	0.84	1.00	1.00	1.00	4.42	0.82	0.84	0.84	12430.6	424.3	21206.3	22778.2	0	0	0	0	
50:00:00	-702.06	702.06	230.76	70.3356	6.83	13.89	0.43	23.6	22.46	0.83	1.00	1.00	1.00	4.46	0.82	0.83	0.83	9751.6	301.9	16568.6	15768.3	0	0	0	0	
51:00:00	0	0	225	68.58	4.33	14.89	0.42	25.17	21.14	0.81	1.00	1.00	1.00	4.51	0.82	0.81	0.81	0.0	0.0	0.0	0.0	0	0	0	0	
52:00:00	0	0	225	68.58	4.33	15.89	0.42	26.72	22.37	0.80	1.00	1.00	1.00	4.56	0.81	0.80	0.80	0.0	0.0	0.0	0.0	0	0	0	0	
53:00:00	0	0	225	68.58	4.33	16.89	0.41	28.23	23.56	0.79	1.00	1.00	1.00	4.61	0.81	0.79	0.79	0.0	0.0	0.0	0.0	0	0	0	0	
54:00:00	0	0	225	68.58	4.33	17.89	0.4	29.71	24.74	0.78	1.00	1.00	1.00	4.66	0.80	0.78	0.78	0.0	0.0	0.0	0.0	0	0	0	0	
55:00:00	0	0	225	68.58	4.33	18.89	0.39	31.16	25.89	0.76	1.00	1.00	1.00	4.71	0.80	0.76	0.76	0.0	0.0	0.0	0.0	0	0	0	0	
56:00:00	0	0	225	68.58	4.33	19.89	0.38	32.58	27.01	0.75	1.00	1.00	1.00	4.77	0.79	0.75	0.75	0.0	0.0	0.0	0.0	0	0	0	0	
57:00:00	0	0	225	68.58	4.33	20.89	0.37	33.97	28.12	0.74	1.00	1.00	1.00	4.83	0.79	0.74	0.74	0.0	0.0	0.0	0.0	0	0	0	0	
58:00:00	78.43	78.43	225.49	68.7294	4.55	20.74	0.38	33.54	29.2	0.74	1.00	1.00	1.00	4.82	0.79	0.74	0.74	1626.6	29.8	2630.5	2290.2	0	0	0	0	
59:00:00	77.88	77.88	226.27	68.9671	4.88	19.75	0.39	31.86	30.25	0.75	1.00	1.00	1.00	4.76	0.79	0.75	0.75	1538.1	30.4	2481.3	2355.9	0	0	0	0	
60:00:00	-27.87	27.87	226.95	69.1744	5.18	19.24	0.39	30.94	31.29	0.76	1.00	1.00	1.00	4.73	0.80	0.76	0.76	536.2	10.9	862.3	872.1	0	0	0	0	
61:00:00	-138.03	138.03	225.99	68.8818	4.76	20.24	0.39	32.37	32.3	0.75	1.00	1.00	1.00	4.79	0.79	0.75	0.75	2793.7	53.8	4468.0	4458.4	0	0	0	0	
62:00:00	-145.68	145.68	225	68.58	4.33	21.24	0.38	33.76	33.29	0.73	1.00	1.00	1.00	4.85	0.79	0.73	0.73	3094.2	55.4	4918.2	4849.7	0	0	0	0	
63:00:00	84.48	84.48	225	68.58	4.33	22.24	0.37	35.13	34.27	0.72	1.00	1.00	1.00	4.92	0.78	0.72	0.72	1878.8	31.3	2967.8	2895.1	0	0	0	0	
64:00:00	112.64	112.64	226.01	68.8878	4.77	19.78	0.39	31.31	35.34	0.75	1.00	1.00	1.00	4.76	0.79	0.75	0.75	2228.0	43.9	3526.8	3980.7	0	0	0	0	
65:00:00	98.26	98.26	227.03	69.1987	5.21	17.91	0.41	28.47	34.18	0.78	1.00	1.00	1.00	4.66	0.80	0.78	0.78	1759.8	40.3	2797.5	3358.5	0	0	0	0	
66:00:00	649.68	649.68	227.88	69.4578	5.58	17.03	0.42	27.16	35.14	0.79	1.00	1.00	1.00	4.61	0.81	0.79	0.79	11064.1	272.9	17645.3	22829.8	0	0	0	0	
67:00:00	531.84	531.84	233.61	71.2043	8.06	11.43	0.47	18.83	36.07	0.86	1.00	1.00	1.00	4.36	0.83	0.86	0.86	6078.9	250.0	10014.5	19183.5	0	0	0	0	
68:00:00	507.66	507.66	238.26	72.6216	10.08	9.97	0.48	16.8	36.99	0.88	1.00	1.00	1.00	4.31	0.83	0.88	0.88	5061.4	243.7	8528.7	18778.3	0	0	0	0	
69:00:00	875.07	875.07	242.35	73.8683	11.85	9.52	0.48	16.3	37.97	0.88	1.00	1.00	1.00	4.29	0.84	0.88	0.88	8330.7	420.0	14263.6	33226.4	0	0	0	0	
70:00:00	519.72	519.72	248.87	75.8556	14.68	8.87	0.49	15.46	39.27	0.89	1.00	1.00	1.00	4.26	0.84	0.89	0.89	4609.9	254.7	8034.9	20409.4	0	0	0	0	
71:00:00	0	0	250	76.2	15.17	9.63	0.48	16.83	37.18	0.88	1.00	1.00	1.00	4.29	0.84	0.88	0.88	0.0	0.0	0.0	0.0	0	0	0	0	
72:00:00	-1425.11	1425.11	250	76.2	15.17	10.63	0.47	18.55	25.81	0.87	1.00	1.00	1.00	4.33	0.83	0.87	0.87	15148.9	669.8	26435.8	36782.1	0	0	0	0	
					min	8.87	0.37	15.46	21.14					min	0.78	0.72	0.72	**12.5**	**0.5**	**21.1**	**30.4**		0	0	0 0	
					max	22.24	0.49	35.13	39.27					max	0.96	0.89	0.89									
					q1	11.66	0.39	19.59	25.275					q1	0.79	0.75	0.75					F1	=		0	
					q2	19.835	0.46	32.115	35.24					q2	0.83	0.85	0.85					F2	=		0	
					median	17.03	0.41	28.23	30.25					median	0.81	0.79	0.79					nse	=		0	
																						F3	=		0	
																						CCME WQI	=		100	
																						MCWQI	=		100	

Time Series Table - Tank 42E

Time	Demand	Abs Demand	Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean				CCME Calculations				
																Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6					
Hours	GPM	GPM	ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)								Violations			
48:00:00	-854.48	854.48	250	76.2	15.17	22.34	0.37	34.42	51.42	0.72	1.00	1.00	1.00	4.92	0.90	0.72	0.72	19089.1	316.2	29411.2	43937.4	0	0	0	0	
49:00:00	-498.81	498.81	243.99	74.3682	12.56	23.34	0.36	35.78	51.45	0.71	1.00	1.00	1.00	4.99	0.90	0.71	0.71	11642.2	179.6	17847.4	25663.8	0	0	0	0	
50:00:00	-382.47	382.47	239.82	73.0971	10.76	24.34	0.35	37.1	52.05	0.70	1.00	1.00	1.00	5.07	0.89	0.70	0.70	9309.3	133.9	14189.6	19907.6	0	0	0	0	
51:00:00	692.65	692.65	236.4	72.0547	9.27	25.34	0.35	38.4	52.63	0.68	1.00	1.00	1.00	5.14	0.88	0.68	0.68	17551.8	242.4	26597.8	36454.2	0	0	0	0	
52:00:00	48.87	48.87	239.42	72.9752	10.58	23.6	0.36	35.68	53.2	0.71	1.00	1.00	1.00	5.01	0.89	0.71	0.71	1153.3	17.6	1743.7	2599.9	0	0	0	0	
53:00:00	-104.78	104.78	238.92	72.8228	10.36	24.56	0.36	36.96	53.75	0.69	1.00	1.00	1.00	5.08	0.89	0.69	0.69	2573.4	37.7	3872.7	5631.9	0	0	0	0	
54:00:00	369.48	369.48	237.84	72.4936	9.9	25.56	0.35	38.26	54.3	0.68	1.00	1.00	1.00	5.16	0.88	0.68	0.68	9443.9	129.3	14136.3	20062.8	0	0	0	0	
55:00:00	84.18	84.18	239.74	73.0728	10.72	24.83	0.36	37.03	54.83	0.69	1.00	1.00	1.00	5.10	0.89	0.69	0.69	2090.2	30.3	3117.2	4615.6	0	0	0	0	
56:00:00	-83.64	83.64	238.85	72.8015	10.33	25.74	0.35	38.21	55.36	0.68	1.00	1.00	1.00	5.17	0.88	0.68	0.68	2152.9	29.3	3195.9	4630.3	0	0	0	0	
57:00:00	710.72	710.72	238.27	72.6247	10.08	26.74	0.34	39.48	56.15	0.67	1.00	1.00	1.00	5.26	0.87	0.67	0.67	19004.7	241.6	28059.2	39906.9	0	0	0	0	
58:00:00	243.46	243.46	242.6	73.9445	11.96	23.92	0.37	35.3	56.64	0.70	1.00	1.00	1.00	5.03	0.89	0.70	0.70	5823.6	90.1	8594.1	13789.6	0	0	0	0	
59:00:00	91.54	91.54	244.07	74.3925	12.6	23.77	0.37	35	57.16	0.70	1.00	1.00	1.00	5.02	0.89	0.70	0.70	2175.9	33.9	3203.9	5232.4	0	0	0	0	
60:00:00	-973.4	973.4	244.69	74.5815	12.87	24.29	0.37	35.67	57.74	0.70	1.00	1.00	1.00	5.06	0.89	0.70	0.70	23643.9	360.2	34721.2	56204.1	0	0	0	0	
61:00:00	-327.97	327.97	238.98	72.8411	10.39	25.29	0.36	37	58.2	0.68	1.00	1.00	1.00	5.14	0.88	0.68	0.68	8294.4	118.1	12134.9	19087.9	0	0	0	0	
62:00:00	-118.38	118.38	236.98	72.2315	9.52	26.29	0.36	38.29	58.66	0.67	1.00	1.00	1.00	5.22	0.88	0.67	0.67	3112.2	42.6	4532.8	6944.2	0	0	0	0	
63:00:00	413.43	413.43	236.27	72.0151	9.22	27.29	0.35	39.57	59.33	0.66	1.00	1.00	1.00	5.30	0.87	0.66	0.66	11282.5	144.7	16359.4	24528.8	0	0	0	0	
64:00:00	157.9	157.9	238.77	72.7771	10.3	25.73	0.36	37.26	59.76	0.68	1.00	1.00	1.00	5.17	0.88	0.68	0.68	4062.8	56.8	5883.4	9436.1	0	0	0	0	
65:00:00	83.21	83.21	239.87	73.1124	10.77	25.66	0.36	37.07	60.2	0.68	1.00	1.00	0.99	5.19	0.88	0.68	0.68	2135.2	30.0	3084.6	5009.2	0	0	0		0.00333
66:00:00	926.78	926.78	240.53	73.3135	11.06	26.04	0.36	37.51	60.62	0.67	1.00	1.00	0.97	5.26	0.87	0.67	0.66	24133.4	333.6	34763.5	56181.4	0	0	0		0.01033
67:00:00	472.09	472.09	246.86	75.2429	13.81	22.13	0.4	32.04	61.05	0.72	1.00	1.00	0.95	5.01	0.89	0.71	0.70	10447.4	188.8	15125.8	28821.1	0	0	0		0.01750
68:00:00	0	0	250	76.2	15.17	21.27	0.4	30.89	61.45	0.73	1.00	1.00	0.93	5.00	0.89	0.71	0.70	0.0	0.0	0.0	0.0	0	0	0		0.02417
69:00:00	0	0	250	76.2	15.17	22.27	0.39	32.31	62	0.72	1.00	1.00	0.91	5.13	0.88	0.69	0.68	0.0	0.0	0.0	0.0	0	0	0		0.03333
70:00:00	0	0	250	76.2	15.17	23.27	0.39	33.71	62.38	0.71	1.00	1.00	0.89	5.24	0.87	0.67	0.66	0.0	0.0	0.0	0.0	0	0	0		0.03967
71:00:00	0	0	250	76.2	15.17	24.27	0.38	35.08	62.78	0.70	1.00	1.00	0.87	5.37	0.86	0.66	0.64	0.0	0.0	0.0	0.0	0	0	0		0.04633
72:00:00	-854.48	854.48	250	76.2	15.17	25.27	0.37	36.41	64.27	0.68	1.00	1.00	0.81	5.67	0.84	0.62	0.60	21592.7	316.2	31111.6	54917.4	0	0	0		0.07117
					min	21.27	0.34	30.89	51.42					min	0.84	0.62	0.60	**24.8**	**0.4**	**36.7**	**56.9**		0	0	0	8
					max	27.29	0.4	39.57	64.27					max	0.90	0.72	0.72									
					q1	23.47	0.355	35.04	54.025					q1	0.87	0.67	0.67					F1	=		25	
					q2	25.695	0.37	37.86	60.835					q2	0.89	0.70	0.70					F2	=		0.08	
					median	24.56	0.36	36.96	57.74					median	0.88	0.68	0.68					nse	=		0.00245833	
																						F3	=		0.24523048	
																						CCME WQI	=		85.5650515	

PF-MOEA Solution 2

Time Series Table - Tank 7N

Time	Demand	Abs Dema	Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean				CCME Calculations			
Hours	GPM	GPM	ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	Violations			
12:00:00 AM	0	0	239.44	72.9813	17.09	24.32	0.32	35.89	34.65	0.70	1.00	1.00	1.00	5.06	0.89	0.70	0.70	0.0	0.0	0.0	0.0	0	0	0	0
1:00:00 AM	-427.34	427.34	238.74	72.768	16.79	25.32	0.31	37.21	35.6	0.68	1.00	1.00	1.00	5.14	0.88	0.68	0.68	10820.2	132.5	15901.3	15213.3	0	0	0	0
2:00:00 AM	-513.49	513.49	237.43	72.3687	16.22	26.32	0.3	38.5	36.52	0.67	1.00	1.00	1.00	5.22	0.88	0.67	0.67	13515.1	154.0	19769.4	18752.7	0	0	0	0
3:00:00 AM	-736.16	736.16	236.01	71.9358	15.6	27.32	0.3	39.77	37.43	0.66	1.00	1.00	1.00	5.31	0.87	0.66	0.66	20111.9	220.8	29277.1	27554.5	0	0	0	0
4:00:00 AM	-890.93	890.93	233.7	71.2318	14.6	28.32	0.29	41.01	38.32	0.65	1.00	1.00	1.00	5.40	0.86	0.65	0.65	25231.1	258.4	36537.0	34140.4	0	0	0	0
5:00:00 AM	-851.45	851.45	231.32	70.5063	13.57	29.32	0.28	42.23	39.19	0.63	1.00	1.00	1.00	5.49	0.85	0.63	0.63	24964.5	238.4	35956.7	33368.3	0	0	0	0
6:00:00 AM	-551.51	551.51	229.11	69.8327	12.62	30.32	0.28	43.42	40.04	0.62	1.00	1.00	1.00	5.59	0.85	0.62	0.62	16721.8	154.4	23946.6	22082.5	0	0	0	0
7:00:00 AM	-301.2	301.2	228.05	69.5096	12.15	31.32	0.27	44.59	40.92	0.61	1.00	1.00	1.00	5.70	0.84	0.61	0.61	9433.6	81.3	13430.5	12325.1	0	0	0	0
8:00:00 AM	-242.75	242.75	227.32	69.2871	11.84	32.32	0.27	45.73	41.73	0.60	1.00	1.00	1.00	5.82	0.83	0.60	0.60	7845.7	65.5	11101.0	10130.0	0	0	0	0
9:00:00 AM	-78.3	78.3	226.71	69.1012	11.57	33.32	0.26	46.85	42.54	0.58	1.00	1.00	1.00	5.94	0.82	0.58	0.58	2609.0	20.4	3668.4	3330.9	0	0	0	0
10:00:00 AM	-723.93	723.93	225.48	68.7263	11.04	34.32	0.26	47.95	43.32	0.57	1.00	1.00	1.00	6.07	0.81	0.57	0.57	24845.3	188.2	34712.4	31360.6	0	0	0	0
11:00:00 AM	-760.14	760.14	223.4	68.0923	10.14	35.32	0.25	49.02	44.09	0.56	1.00	1.00	1.00	6.21	0.80	0.56	0.56	26848.1	190.0	37262.1	33514.6	0	0	0	0
12:00:00 PM	-439.23	439.23	221.41	67.4858	9.28	36.32	0.25	50.07	44.83	0.55	1.00	1.00	1.00	6.35	0.79	0.55	0.55	15952.8	109.8	21992.2	19690.7	0	0	0	0
1:00:00 PM	-103.1	103.1	220.83	67.309	9.03	37.32	0.24	51.1	45.56	0.53	1.00	1.00	1.00	6.51	0.78	0.53	0.53	3847.7	24.7	5268.4	4697.2	0	0	0	0
2:00:00 PM	-63.88	63.88	220.62	67.245	8.93	38.32	0.24	52.11	46.31	0.52	1.00	1.00	1.00	6.68	0.77	0.52	0.52	2447.9	15.3	3328.8	2958.3	0	0	0	0
3:00:00 PM	210.48	210.48	220.46	67.1962	8.86	39.32	0.23	53.1	47.01	0.51	1.00	1.00	1.00	6.87	0.76	0.51	0.51	8276.1	48.4	11176.5	9894.7	0	0	0	0
4:00:00 PM	465.9	465.9	221.5	67.5132	9.32	38.59	0.24	51.87	47.75	0.52	1.00	1.00	1.00	6.73	0.77	0.52	0.52	17979.1	111.8	24166.2	22246.7	0	0	0	0
5:00:00 PM	446.75	446.75	222.76	67.8972	9.86	37.61	0.25	50.36	45.83	0.53	1.00	1.00	1.00	6.56	0.78	0.53	0.53	16802.3	111.7	22498.3	20474.6	0	0	0	0
6:00:00 PM	807.78	807.78	223.92	68.2508	10.36	36.92	0.26	49.26	45	0.54	1.00	1.00	1.00	6.45	0.79	0.54	0.54	29823.2	210.0	39791.2	36350.1	0	0	0	0
7:00:00 PM	1135.1	1135.1	226.69	69.0951	11.57	34.36	0.29	45.85	42.9	0.57	1.00	1.00	1.00	6.07	0.81	0.57	0.57	39002.0	329.2	52044.3	48695.8	0	0	0	0
8:00:00 PM	1169.4	1169.4	229.86	70.0613	12.94	32	0.31	42.77	40.04	0.60	1.00	1.00	1.00	5.78	0.83	0.60	0.60	37420.8	362.5	50015.2	46822.8	0	0	0	0
9:00:00 PM	1319.92	1319.92	232.99	71.0154	14.3	30.2	0.32	40.47	38.8	0.62	1.00	1.00	1.00	5.58	0.85	0.62	0.62	39861.6	422.4	53417.2	51212.9	0	0	0	0
10:00:00 PM	1440.08	1440.08	236.81	72.1797	15.95	28.34	0.34	38.13	36.88	0.65	1.00	1.00	1.00	5.40	0.86	0.65	0.65	40811.9	489.6	54910.3	53110.2	0	0	0	0
11:00:00 PM	0	0	239.44	72.9813	17.09	27.64	0.35	37.3	36.28	0.65	1.00	1.00	1.00	5.33	0.87	0.65	0.65	0.0	0.0	0.0	0.0	0	0	0	0
12:00:00 AM	0	0	239.44	72.9813	17.09	28.64	0.34	38.6	37.19	0.64	1.00	1.00	1.00	5.43	0.86	0.64	0.64	0.0	0.0	0.0	0.0	0	0	0	0
					min	24.32	0.23	35.89	34.65					min	0.76	0.51	0.51	**31.8**	**0.3**	**43.9**	**40.8**	0	0	0	0
					max	39.32	0.35	53.1	47.75					max	0.89	0.70	0.70								
					q1	28.33	0.25	39.185	37.31					q1	0.79	0.54	0.54					F1	=	0	
					q2	36.62	0.31	49.665	44.915					q2	0.86	0.65	0.65					F2	=	0	
					median	32	0.28	44.59	40.92					median	0.83	0.60	0.60					nse	=	0	
																						F3	=	0	
																						CCME WQI	=	100	
																						MCWQI	=	100	

Time Series Table - Tank 41E

Time	Demand	Abs Dema	Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean				CCME Calculations			
Hours	GPM	GPM	ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	Violations			
48:00:00	-924.28	924.28	250	76.2	15.17	5.72	0.51	11.34	21.88	0.93	0.91	1.00	1.00	4.37	0.96	0.86	0.85	5286.9	471.4	10481.3	20223.2	0	0.02000	0	0
49:00:00	-642.28	642.28	242.5	73.914	11.92	6.72	0.5	13.17	23.09	0.92	1.00	1.00	1.00	4.19	0.98	0.92	0.92	4316.1	321.1	8458.8	14830.2	0		0	0
50:00:00	-439.03	439.03	237.38	72.3534	9.7	7.72	0.49	14.96	24.28	0.90	1.00	1.00	1.00	4.23	0.97	0.90	0.90	3389.3	215.1	6567.9	10659.6	0		0	0
51:00:00	-543.58	543.58	233.83	71.2714	8.16	8.72	0.48	16.71	25.44	0.89	1.00	1.00	1.00	4.26	0.97	0.89	0.89	4740.0	260.9	9083.2	13828.7	0		0	0
52:00:00	-421.97	421.97	229.19	69.8571	6.15	9.72	0.47	18.43	26.58	0.88	1.00	1.00	1.00	4.30	0.96	0.88	0.88	4101.5	198.3	7776.9	11216.0	0		0	0
53:00:00	-323.91	323.91	225.64	68.7751	4.61	10.72	0.46	20.11	27.69	0.87	1.00	1.00	1.00	4.33	0.96	0.87	0.87	3472.3	149.0	6513.8	8969.1	0		0	0
54:00:00	-115.78	115.78	225	68.58	4.33	11.72	0.45	21.76	28.78	0.85	1.00	1.00	1.00	4.37	0.96	0.85	0.85	1356.9	52.1	2519.4	3332.1	0		0	0
55:00:00	-105.38	105.38	225	68.58	4.33	12.72	0.44	23.37	29.9	0.84	1.00	1.00	1.00	4.41	0.95	0.84	0.84	1340.4	46.4	2462.7	3150.9	0		0	0
56:00:00	-120.42	120.42	225	68.58	4.33	13.72	0.43	24.95	30.94	0.83	1.00	1.00	1.00	4.46	0.95	0.83	0.83	1652.2	51.8	3004.5	3725.8	0		0	0
57:00:00	-264.06	264.06	225	68.58	4.33	14.72	0.42	26.5	31.96	0.82	1.00	1.00	1.00	4.50	0.94	0.82	0.82	3887.0	110.9	6997.6	8439.4	0		0	0
58:00:00	0	0	225	68.58	4.33	15.72	0.41	28.02	32.96	0.80	1.00	1.00	1.00	4.55	0.94	0.80	0.80	0.0	0.0	0.0	0.0	0		0	0
59:00:00	0	0	225	68.58	4.33	16.72	0.41	29.5	33.94	0.79	1.00	1.00	1.00	4.60	0.93	0.79	0.79	0.0	0.0	0.0	0.0	0		0	0
60:00:00	0	0	225	68.58	4.33	17.72	0.4	30.96	34.9	0.78	1.00	1.00	1.00	4.65	0.93	0.78	0.78	0.0	0.0	0.0	0.0	0		0	0
61:00:00	0	0	225	68.58	4.33	18.72	0.39	32.38	35.84	0.77	1.00	1.00	1.00	4.70	0.92	0.77	0.77	0.0	0.0	0.0	0.0	0		0	0
62:00:00	0	0	225	68.58	4.33	19.72	0.38	33.77	36.75	0.75	1.00	1.00	1.00	4.76	0.92	0.75	0.75	0.0	0.0	0.0	0.0	0		0	0
63:00:00	0	0	225	68.58	4.33	20.72	0.37	35.14	37.65	0.74	1.00	1.00	1.00	4.82	0.91	0.74	0.74	0.0	0.0	0.0	0.0	0		0	0
64:00:00	5.49	5.49	225	68.58	4.33	21.72	0.37	36.48	38.54	0.73	1.00	1.00	1.00	4.88	0.90	0.73	0.73	119.2	2.0	200.3	211.6	0		0	0
65:00:00	48.06	48.06	225.3	68.6714	4.46	22.72	0.36	37.79	39.4	0.72	1.00	1.00	1.00	4.95	0.90	0.72	0.72	1091.9	17.3	1816.2	1893.6	0		0	0
66:00:00	626.05	626.05	225.83	68.833	4.69	23.72	0.34	39.07	40.29	0.70	1.00	1.00	1.00	5.02	0.89	0.70	0.70	14849.9	212.9	24459.8	25223.6	0		0	0
67:00:00	518.15	518.15	231.46	70.549	7.13	24.72	0.16	40.33	42.31	0.69	0.82	1.00	1.00	5.58	0.85	0.63	0.61	12808.7	82.9	20897.0	21922.9	0	0.25000	0	0
68:00:00	389.25	389.25	235.75	71.8566	8.99	25.72	0	41.56	28.95	0.68	0.10	1.00	1.00	104.17	0.20	0.10	0.10	10011.5	0.0	16177.2	11268.8	0	1.00000	0	0
69:00:00	612.7	612.7	239.1	72.8777	10.44	2.85	0.54	5.88	28.37	0.96	0.64	1.00	1.00	5.52	0.85	0.63	0.63	1746.2	330.9	3602.7	17382.3	0	0.08000	0	0
70:00:00	485.75	485.75	244.42	74.4992	12.75	3.33	0.54	6.83	22.97	0.96	0.64	1.00	1.00	5.53	0.85	0.63	0.63	1617.5	262.3	3317.7	11157.7	0	0.08000	0	0
71:00:00	0	0	250	76.2	15.17	3.95	0.53	8.03	21.9	0.95	0.73	1.00	1.00	4.98	0.90	0.71	0.71	0.0	0.0	0.0	0.0	0	0.06000	0	0
72:00:00	-924.28	924.28	250	76.2	15.17	4.95	0.52	9.93	23.11	0.94	0.82	1.00	1.00	4.62	0.93	0.79	0.78	4575.2	480.6	9178.1	21360.1	0	0.04000	0	0
					min	2.85	0	5.88	21.88					min	0.20	0.10	0.10	**10.7**	**0.4**	**19.1**	**27.8**	0	7	0	0
					max	25.72	0.54	41.56	42.31					max	0.98	0.92	0.92								
					q1	7.22	0.375	14.065	24.86					q1	0.90	0.71	0.71					F1	=	25	
					q2	20.22	0.495	34.455	36.295					q2	0.96	0.86	0.85					F2	=	0.07	
					median	13.72	0.43	24.95	29.9					median	0.93	0.79	0.78					nse	=	0.0153	
																						F3	=	1.5069438	
																						CCME WQI	=	85.539565	
																						MCWQI	=	98.376069	

Time Series Table - Node 42

Time	Demand	Abs Dema	Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean				CCME Calculations			
Hours	GPM	GPM	ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	Violations			
48:00:00	-759.23	759.23	250	76.2	15.17	16.49	0.41	26.12	30.08	0.79	1.00	1.00	1.00	4.59	0.93	0.79	0.79	12519.7	311.3	19831.1	22837.6	0	0	0	0
49:00:00	-230.1	230.1	245.92	74.9564	13.4	17.49	0.41	27.65	31.12	0.78	1.00	1.00	1.00	4.64	0.93	0.78	0.78	4024.4	94.3	6362.3	7160.7	0	0	0	0
50:00:00	-153.42	153.42	244.18	74.4261	12.64	18.49	0.4	29.14	32.22	0.77	1.00	1.00	1.00	4.69	0.92	0.77	0.77	2836.7	61.4	4470.7	4943.2	0	0	0	0
51:00:00	-558.71	558.71	242.82	74.0115	12.05	19.49	0.39	30.6	33.22	0.76	1.00	1.00	1.00	4.75	0.92	0.76	0.76	10889.3	217.9	17096.5	18560.3	0	0	0	0
52:00:00	-245.06	245.06	239.44	72.9813	10.59	20.49	0.38	32.03	34.35	0.74	1.00	1.00	1.00	4.81	0.91	0.74	0.74	5021.3	93.1	7849.3	8417.8	0	0	0	0
53:00:00	-198.06	198.06	237.37	72.3504	9.69	21.49	0.37	33.43	35.3	0.73	1.00	1.00	1.00	4.87	0.91	0.73	0.73	4256.3	73.3	6621.1	6991.5	0	0	0	0
54:00:00	286.64	286.64	235.7	71.8414	8.97	22.49	0.37	34.8	29.97	0.72	1.00	1.00	1.00	4.94	0.90	0.72	0.72	6446.5	106.1	9975.1	8590.6	0	0	0	0
55:00:00	-17.8	17.8	236.47	72.0761	9.3	22.85	0.36	35.19	31.01	0.71	1.00	1.00	1.00	4.96	0.90	0.71	0.71	406.7	6.4	626.4	552.0	0	0	0	0
56:00:00	-40.1	40.1	236.15	71.9785	9.16	23.85	0.36	36.52	27.02	0.70	1.00	1.00	1.00	5.03	0.89	0.70	0.70	956.4	14.4	1464.5	1083.5	0	0	0	0
57:00:00	-1055.13	1055.13	235.78	71.8657	9	24.85	0.35	37.83	28.12	0.69	1.00	1.00	1.00	5.10	0.89	0.69	0.69	26220.0	369.3	39915.6	29670.3	0	0	0	0
58:00:00	-350.68	350.68	230.22	70.1711	6.59	25.85	0.34	39.12	29.2	0.68	1.00	1.00	1.00	5.18	0.88	0.68	0.68	9065.1	119.2	13718.6	10239.9	0	0	0	0
59:00:00	-190.97	190.97	227.86	69.4517	5.57	26.85	0.34	40.37	30.41	0.66	1.00	1.00	1.00	5.27	0.87	0.66	0.66	5127.5	64.9	7709.5	5807.4	0	0	0	0
60:00:00	445.21	445.21	226.19	68.9427	4.85	27.85	0.33	41.6	31.43	0.65	1.00	1.00	1.00	5.35	0.86	0.65	0.65	12399.1	146.9	18520.7	13993.0	0	0	0	0
61:00:00	33.03	33.03	227.81	69.4365	5.55	25.83	0.35	38.47	32.6	0.68	1.00	1.00	1.00	5.18	0.88	0.68	0.68	853.2	11.6	1270.7	1076.8	0	0	0	0
62:00:00	-8.17	8.17	227.86	69.4517	5.57	26.7	0.34	39.55	33.58	0.67	1.00	1.00	1.00	5.25	0.87	0.67	0.67	218.1	2.8	323.1	274.3	0	0	0	0
63:00:00	594.16	594.16	227.76	69.4212	5.53	27.7	0.34	40.8	34.95	0.65	1.00	1.00	1.00	5.34	0.87	0.65	0.65	16458.2	202.0	24241.7	20765.9	0	0	0	0
64:00:00	176.55	176.55	230.9	70.3783	6.89	23.76	0.37	35.03	31.95	0.70	1.00	1.00	1.00	5.02	0.89	0.70	0.70	4194.8	65.3	6184.5	5640.8	0	0	0	0
65:00:00	96.44	96.44	232.09	70.741	7.41	23.18	0.38	34.14	32.82	0.71	1.00	1.00	1.00	4.98	0.90	0.71	0.71	2235.5	36.6	3292.5	3165.2	0	0	0	0
66:00:00	947.66	947.66	232.94	71.0001	7.77	23.15	0.38	34.03	31.65	0.71	1.00	1.00	1.00	4.98	0.90	0.71	0.71	21938.3	360.1	32248.9	29993.4	0	0	0	0
67:00:00	416.23	416.23	238.74	72.768	10.29	18.77	0.42	27.82	26.12	0.77	1.00	1.00	1.00	4.71	0.92	0.77	0.77	7812.6	174.8	11579.5	10871.9	0	0	0	0
68:00:00	308.86	308.86	242.14	73.8043	11.76	17.57	0.43	26.2	27.24	0.78	1.00	1.00	1.00	4.64	0.93	0.78	0.78	5426.7	132.8	8092.1	8413.3	0	0	0	0
69:00:00	694.07	694.07	244.86	74.6333	12.94	17.07	0.43	25.6	28.44	0.79	1.00	1.00	1.00	4.62	0.93	0.79	0.79	11847.8	298.5	17768.2	19739.4	0	0	0	0
70:00:00	414.58	414.58	249.83	76.1482	15.09	15.81	0.44	23.91	29.03	0.80	1.00	1.00	1.00	4.55	0.94	0.80	0.80	6554.5	182.4	9912.6	12035.3	0	0	0	0
71:00:00	0	0	250	76.2	15.17	16.75	0.44	25.39	29.45	0.79	1.00	1.00	1.00	4.60	0.93	0.79	0.79	0.0	0.0	0.0	0.0	0	0	0	0
72:00:00	-759.23	759.23	250	76.2	15.17	17.75	0.43	26.93	30.5	0.78	1.00	1.00	1.00	4.65	0.93	0.78	0.78	13476.3	326.5	20446.1	23156.5	0	0	0	0
					min	15.81	0.33	23.91	26.12					min	0.86	0.65	0.65	**21.3**	**0.4**	**32.2**	**30.5**	0	0	0	0
					max	27.85	0.44	41.6	35.3					max	0.94	0.80	0.80								
					q1	17.66	0.35	27.29	29.115					q1	0.88	0.68	0.68					F1	=	0	
					q2	25.34	0.415	38.15	32.71					q2	0.93	0.78	0.78					F2	=	0	
					median	22.49	0.38	34.03	31.01					median	0.90	0.72	0.72					nse	=	0	
																						F3	=	0	
																						CCME WQI	=	100	
																						MCWQI	=	100	

FMO

Time Series Table - Tank 150N

Time Hours	Demand GPM	Abs Dema GPM	Head ft	Head m	Pressure psi	Age hours	Chlorine mg/L	THM ug/L	HAA6 ug/L	Calculated sub-indices: Water age	Chlorine	THM	HAA6		Water quality indices: OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weighted mean: Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	CCME Calculations		Violations	
12:00:00 AM	-543.47	543.47	243	74.0664	12.13	26.23	0.29	38.44	34.99	0.67	1.00	1.00	1.00	5.21	0.88	0.67	0.67	14255.2	157.6	20891.0	19016.0	0	0	0	0
1:00:00 AM	-878.03	878.03	240.24	73.2252	10.94	27.23	0.28	39.71	35.92	0.66	1.00	1.00	1.00	5.30	0.87	0.66	0.66	23908.8	245.8	34866.6	31538.8	0	0	0	0
2:00:00 AM	-965.45	965.45	236.75	72.1614	9.42	28.23	0.27	40.96	36.84	0.65	1.00	1.00	1.00	5.39	0.86	0.65	0.65	27254.7	260.7	39544.8	35567.2	0	0	0	0
3:00:00 AM	-931.67	931.67	233.15	71.0641	7.87	29.23	0.27	42.17	37.74	0.63	1.00	1.00	1.00	5.48	0.85	0.63	0.63	27232.7	251.6	39288.5	35161.2	0	0	0	0
4:00:00 AM	-522.7	522.7	230.6	70.2869	6.76	30.23	0.26	43.37	38.61	0.62	1.00	1.00	1.00	5.58	0.85	0.62	0.62	15801.2	135.9	22669.5	20181.4	0	0	0	0
5:00:00 AM	0	0	230.5	70.2564	6.72	31.23	0.26	44.53	39.48	0.61	1.00	1.00	1.00	5.69	0.84	0.61	0.61	0.0	0.0	0.0	0.0	0	0	0	0
6:00:00 AM	0	0	230.5	70.2564	6.72	32.23	0.25	45.68	40.32	0.60	1.00	1.00	1.00	5.80	0.83	0.60	0.60	0.0	0.0	0.0	0.0	0	0	0	0
7:00:00 AM	0	0	230.5	70.2564	6.72	33.23	0.25	46.8	41.15	0.58	1.00	1.00	1.00	5.93	0.82	0.58	0.58	0.0	0.0	0.0	0.0	0	0	0	0
8:00:00 AM	0	0	230.5	70.2564	6.72	34.23	0.24	47.89	41.96	0.57	1.00	1.00	1.00	6.06	0.81	0.57	0.57	0.0	0.0	0.0	0.0	0	0	0	0
9:00:00 AM	0	0	230.5	70.2564	6.72	35.23	0.24	48.97	42.75	0.56	1.00	1.00	1.00	6.19	0.80	0.56	0.56	0.0	0.0	0.0	0.0	0	0	0	0
10:00:00 AM	0	0	230.5	70.2564	6.72	36.23	0.23	50.02	43.53	0.55	1.00	1.00	1.00	6.34	0.79	0.55	0.55	0.0	0.0	0.0	0.0	0	0	0	0
11:00:00 AM	0	0	230.5	70.2564	6.72	37.23	0.23	51.05	44.29	0.53	1.00	1.00	1.00	6.50	0.78	0.53	0.53	0.0	0.0	0.0	0.0	0	0	0	0
12:00:00 PM	0	0	230.5	70.2564	6.72	38.23	0.22	52.06	45.03	0.52	1.00	1.00	1.00	6.67	0.77	0.52	0.52	0.0	0.0	0.0	0.0	0	0	0	0
1:00:00 PM	0	0	230.5	70.2564	6.72	39.23	0.22	53.05	45.75	0.51	1.00	1.00	1.00	6.85	0.76	0.51	0.51	0.0	0.0	0.0	0.0	0	0	0	0
2:00:00 PM	0	0	230.5	70.2564	6.72	40.23	0.21	54.02	46.47	0.50	1.00	1.00	1.00	7.05	0.75	0.50	0.50	0.0	0.0	0.0	0.0	0	0	0	0
3:00:00 PM	0	0	230.5	70.2564	6.72	41.23	0.21	54.97	47.17	0.48	1.00	1.00	1.00	7.26	0.74	0.48	0.48	0.0	0.0	0.0	0.0	0	0	0	0
4:00:00 PM	0	0	230.5	70.2564	6.72	42.23	0.2	55.89	47.85	0.47	1.00	1.00	1.00	7.49	0.73	0.47	0.47	0.0	0.0	0.0	0.0	0	0	0	0
5:00:00 PM	58.67	58.67	230.55	70.2716	6.74	43.2	0.2	56.76	48.52	0.46	1.00	1.00	1.00	7.73	0.72	0.46	0.46	2534.5	11.7	3330.1	2846.7	0	0	0	0
6:00:00 PM	390.38	390.38	230.91	70.3814	6.89	43.31	0.2	56.57	48.61	0.46	1.00	1.00	1.00	7.75	0.72	0.46	0.46	16907.4	78.1	22083.8	18976.4	0	0	0	0
7:00:00 PM	788.81	788.81	233.24	71.0916	7.9	39.18	0.24	51.23	45.67	0.51	1.00	1.00	1.00	6.84	0.76	0.51	0.51	30905.6	189.3	40410.7	36025.0	0	0	0	0
8:00:00 PM	1051.5	1051.5	236.56	72.1035	9.34	34.65	0.28	45.53	40.41	0.57	1.00	1.00	1.00	6.11	0.81	0.57	0.57	36434.5	294.4	47874.8	42491.1	0	0	0	0
9:00:00 PM	1256.23	1256.23	240.4	73.2739	11.01	30.93	0.31	40.97	37.04	0.61	1.00	1.00	1.00	5.66	0.84	0.61	0.61	38855.2	389.4	51467.7	46530.8	0	0	0	0
10:00:00 PM	0	0	243	74.0664	12.13	29.43	0.32	39.22	36.13	0.63	1.00	1.00	1.00	5.50	0.85	0.63	0.63	0.0	0.0	0.0	0.0	0	0	0	0
11:00:00 PM	0	0	243	74.0664	12.13	30.43	0.32	40.47	37.04	0.62	1.00	1.00	1.00	5.60	0.84	0.62	0.62	0.0	0.0	0.0	0.0	0	0	0	0
12:00:00 AM	-543.47	543.47	243	74.0664	12.13	31.43	0.31	41.7	37.94	0.61	1.00	1.00	1.00	5.71	0.84	0.61	0.61	17081.3	168.5	22662.7	20619.3	0	0	0	0
					min	26.23	0.2	38.44	34.99					**min**	0.72	0.46	0.46	**31.7**	**0.3**	**43.5**	**39.0**	0	0	0	0
					max	43.31	0.32	56.76	48.61					**max**	0.88	0.67	0.67								
					q1	30.33	0.22	41.335	37.39					**q1**	0.76	0.51	0.51					F1	=		0
					q2	39.205	0.28	52.555	45.71					**q2**	0.85	0.62	0.62					F2	=		0
					median	34.23	0.25	46.8	41.15					**median**	0.81	0.57	0.57					nse	=		0
																						F3	=		0
																						CCME WC =			100
																						MCWQI =			100

Time Series Table - Tank 170N

Time Hours	Demand GPM	Abs Dema GPM	Head ft	Head m	Pressure psi	Age hours	Chlorine mg/L	THM ug/L	HAA6 ug/L	Calculated sub-indices: Water age	Chlorine	THM	HAA6		Water quality indices: OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weighted mean: Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	CCME Calculations		Violations	
48:00:00	-4.68	4.68	229.7	70.0126	11.27	25.98	0.29	39.09	37.05	0.68	1.00	1.00	1.00	5.19	0.88	0.68	0.68	121.6	1.4	182.9	173.4	0	0	0	0
49:00:00	-153.82	153.82	228.84	69.7504	10.89	26.98	0.29	40.35	37.95	0.66	1.00	1.00	1.00	5.28	0.87	0.66	0.66	4150.1	44.6	6206.6	5837.5	0	0	0	0
50:00:00	-223.4	223.4	226.96	69.1774	10.08	27.98	0.28	41.58	38.82	0.65	1.00	1.00	1.00	5.37	0.86	0.65	0.65	6250.7	62.6	9289.0	8672.4	0	0	0	0
51:00:00	-315.6	315.6	224.61	68.4611	9.06	28.98	0.27	42.78	39.68	0.64	1.00	1.00	1.00	5.46	0.86	0.64	0.64	9146.1	85.2	13501.4	12523.0	0	0	0	0
52:00:00	-123.96	123.96	222.73	67.8881	8.25	29.98	0.27	43.96	40.51	0.63	1.00	1.00	1.00	5.56	0.85	0.63	0.63	3716.3	33.5	5449.3	5021.6	0	0	0	0
53:00:00	-136.13	136.13	221.36	67.4705	7.65	30.98	0.26	45.12	41.34	0.61	1.00	1.00	1.00	5.66	0.84	0.61	0.61	4217.3	35.4	6142.2	5627.6	0	0	0	0
54:00:00	-19.27	19.27	220.12	67.0926	7.11	31.98	0.26	46.25	42.14	0.60	1.00	1.00	1.00	5.78	0.83	0.60	0.60	616.3	5.0	891.2	812.0	0	0	0	0
55:00:00	37.8	37.8	220.28	67.1413	7.18	32.77	0.25	47.08	42.93	0.59	1.00	1.00	1.00	5.87	0.83	0.59	0.59	1238.7	9.5	1779.6	1622.8	0	0	0	0
56:00:00	45.61	45.61	220.7	67.2694	7.37	33.08	0.25	47.28	43.76	0.59	1.00	1.00	1.00	5.91	0.82	0.59	0.59	1508.8	11.4	2156.4	1995.9	0	0	0	0
57:00:00	100.82	100.82	221.13	67.4004	7.55	33.37	0.26	47.44	43.78	0.58	1.00	1.00	1.00	5.94	0.82	0.58	0.58	3364.4	26.2	4782.9	4413.9	0	0	0	0
58:00:00	-87.33	87.33	221.04	67.373	7.51	34.05	0.25	48.11	43.07	0.57	1.00	1.00	1.00	6.03	0.81	0.57	0.57	2973.6	21.8	4201.4	3761.3	0	0	0	0
59:00:00	-219.17	219.17	219.54	66.9158	6.86	35.05	0.25	49.18	43.84	0.56	1.00	1.00	1.00	6.17	0.81	0.56	0.56	7681.9	54.8	10778.8	9608.4	0	0	0	0
60:00:00	-110.38	110.38	217.21	66.2056	5.85	36.05	0.24	50.23	44.59	0.55	1.00	1.00	1.00	6.31	0.80	0.55	0.55	3979.2	26.5	5544.4	4921.8	0	0	0	0
61:00:00	5.89	5.89	216.81	66.0837	5.68	37.05	0.24	51.26	45.33	0.54	1.00	1.00	1.00	6.47	0.79	0.54	0.54	218.2	1.4	301.9	267.0	0	0	0	0
62:00:00	37.99	37.99	217.05	66.1568	5.79	37.58	0.24	51.69	46.05	0.53	1.00	1.00	1.00	6.56	0.78	0.53	0.53	1427.7	9.1	1963.7	1749.4	0	0	0	0
63:00:00	141.62	141.62	217.47	66.2849	5.97	37.62	0.24	51.51	45.61	0.53	1.00	1.00	1.00	6.56	0.78	0.53	0.53	5327.7	34.0	7294.8	6459.3	0	0	0	0
64:00:00	212.97	212.97	219.31	66.8457	6.76	34.87	0.26	47.91	43.79	0.56	1.00	1.00	1.00	6.14	0.81	0.56	0.56	7426.3	55.4	10203.4	9326.0	0	0	0	0
65:00:00	210.97	210.97	221.42	67.4888	7.68	32.26	0.28	44.51	40.72	0.60	1.00	1.00	1.00	5.81	0.83	0.60	0.60	6805.9	59.1	9390.3	8590.7	0	0	0	0
66:00:00	341.53	341.53	223.37	68.0832	8.52	30.47	0.3	42.19	39.32	0.62	1.00	1.00	1.00	5.61	0.84	0.62	0.62	10406.4	102.5	14409.2	13429.0	0	0	0	0
67:00:00	386.4	386.4	227.03	69.1987	10.11	27.34	0.33	38.24	36.96	0.66	1.00	1.00	1.00	5.31	0.87	0.66	0.66	10564.2	127.5	14775.9	14281.3	0	0	0	0
68:00:00	0	0	229.7	70.0126	11.27	25.96	0.34	36.55	35.75	0.68	1.00	1.00	1.00	5.19	0.88	0.68	0.68	0.0	0.0	0.0	0.0	0	0	0	0
69:00:00	0	0	229.7	70.0126	11.27	26.96	0.33	37.86	36.67	0.66	1.00	1.00	1.00	5.27	0.87	0.66	0.66	0.0	0.0	0.0	0.0	0	0	0	0
70:00:00	0	0	229.7	70.0126	11.27	27.96	0.32	39.14	37.57	0.65	1.00	1.00	1.00	5.36	0.86	0.65	0.65	0.0	0.0	0.0	0.0	0	0	0	0
71:00:00	0	0	229.7	70.0126	11.27	28.96	0.32	40.39	38.45	0.64	1.00	1.00	1.00	5.46	0.86	0.64	0.64	0.0	0.0	0.0	0.0	0	0	0	0
72:00:00	-4.68	4.68	229.7	70.0126	11.27	29.96	0.31	41.62	39.32	0.63	1.00	1.00	1.00	5.56	0.85	0.63	0.63	140.2	1.5	194.8	184.0	0	0	0	0
					min	25.96	0.24	36.55	35.75					min	0.78	0.53	0.53	**31.3**	**0.3**	**44.3**	**40.8**	0	0	0	0
					max	37.62	0.34	51.69	46.05					max	0.88	0.68	0.68								
					q1	27.97	0.25	40.37	38.2					q1	0.81	0.57	0.57					F1	=		0
					q2	34.46	0.305	48.01	43.785					q2	0.86	0.65	0.65					F2	=		0
					median	30.98	0.27	44.51	40.72					median	0.84	0.61	0.61					nse	=		0
																						F3	=		0
																						CCME WC =			100
																						MCWQI =			100

Time Series Table - Tank 41E

Time Hours	Demand GPM	Abs Dema GPM	Head ft	Head m	Pressure psi	Age hours	Chlorine mg/L	THM ug/L	HAA6 ug/L	Calculated sub-indices: Water age	Chlorine	THM	HAA6		Water quality indices: OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weighted mean: Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	CCME Calculations: Violations
48:00:00	-1454.53	1454.53	250	76.2	15.17	30.02	0	46.56	40.24	0.62	0.10	1.00	1.00	104.56	0.20	0.10	0.10	43665.0	0.0	67722.9	58530.3	1.00000
49:00:00	-972.83	972.83	238.46	72.6826	10.17	31.02	0	47.67	41.07	0.61	0.10	1.00	1.00	104.67	0.20	0.10	0.10	30177.2	0.0	46374.8	39954.1	1.00000
50:00:00	-658.97	658.97	230.79	70.3448	6.84	32.02	0	48.74	41.88	0.60	0.10	1.00	1.00	104.78	0.20	0.10	0.10	21100.2	0.0	32118.2	27597.7	1.00000
51:00:00	-367.44	367.44	225.34	68.6836	4.48	33.02	0	49.8	42.67	0.59	0.10	1.00	1.00	104.90	0.20	0.10	0.10	12132.9	0.0	18298.5	15678.7	1.00000
52:00:00	-281.33	281.33	225	68.58	4.33	34.02	0	50.84	43.44	0.57	0.10	1.00	1.00	105.03	0.20	0.10	0.10	9570.8	0.0	14302.8	12221.0	1.00000
53:00:00	-444.65	444.65	225	68.58	4.33	35.02	0	51.85	44.2	0.56	0.10	1.00	1.00	105.16	0.20	0.10	0.10	15571.6	0.0	23055.1	19653.5	1.00000
54:00:00	-194.68	194.68	225	68.58	4.33	36.02	0	52.84	44.95	0.55	0.10	1.00	1.00	105.31	0.19	0.10	0.10	7012.4	0.0	10286.9	8750.9	1.00000
55:00:00	-111.47	111.47	225	68.58	4.33	37.02	0	53.82	45.68	0.54	0.10	1.00	1.00	105.46	0.19	0.10	0.10	4126.6	0.0	5999.3	5091.9	1.00000
56:00:00	-84.49	84.49	225	68.58	4.33	38.02	0	54.77	46.39	0.52	0.10	1.00	1.00	105.63	0.19	0.10	0.10	3212.3	0.0	4627.5	3919.5	1.00000
57:00:00	-171.07	171.07	225	68.58	4.33	39.02	0	55.7	47.09	0.51	0.10	1.00	1.00	105.81	0.19	0.10	0.10	6675.2	0.0	9528.6	8055.7	1.00000
58:00:00	-467.5	467.5	225	68.58	4.33	40.02	0	56.61	47.78	0.50	0.10	1.00	1.00	106.00	0.19	0.10	0.10	18709.4	0.0	26465.2	22337.2	1.00000
59:00:00	0	0	225	68.58	4.33	41.02	0	57.51	48.45	0.49	0.10	1.00	1.00	106.21	0.19	0.10	0.10	0.0	0.0	0.0	0.0	1.00000

60:00:00	0	0	225	68.58	4.33	42.02	0	58.39	49.1	0.47	0.10	1.00	1.00	106.44	0.19	0.10	0.10	0.0	0.0	0.0	0.0		1.00000		
61:00:00	0	0	225	68.58	4.33	43.02	0	59.24	49.75	0.46	0.10	1.00	1.00	106.68	0.19	0.10	0.09	0.0	0.0	0.0	0.0		1.00000		
62:00:00	0	0	225	68.58	4.33	44.02	0	60.08	50.38	0.45	0.10	1.00	1.00	106.95	0.19	0.10	0.09	0.0	0.0	0.0	0.0		1.00000		
63:00:00	0	0	225	68.58	4.33	45.02	0	60.91	51	0.44	0.10	0.96	1.00	107.32	0.19	0.10	0.09	0.0	0.0	0.0	0.0		1.00000		
64:00:00	168.21	168.21	225.97	68.8757	4.75	46.02	0	61.71	51.6	0.42	0.10	0.92	1.00	107.72	0.19	0.10	0.09	7741.0	0.0	10380.2	8679.6		1.00000		
65:00:00	157.02	157.02	227.64	69.3847	5.48	47.02	0	62.5	52.1	0.41	0.10	0.89	1.00	108.15	0.19	0.10	0.09	7383.1	0.0	9813.8	8180.7		1.00000		
66:00:00	688.11	688.11	228.92	69.7748	6.03	48.02	0	63.28	52.62	0.40	0.10	0.85	1.00	108.63	0.19	0.10	0.09	33043.0	0.0	43543.6	36208.3		1.00000		
67:00:00	421.09	421.09	234.12	71.3598	8.29	49.02	0	64.03	53.19	0.39	0.10	0.82	1.00	109.16	0.19	0.10	0.09	20641.8	0.0	26962.4	22397.8		1.00000		
68:00:00	495.47	495.47	238.28	72.6277	10.09	50.02	0	64.77	53.75	0.37	0.10	0.79	1.00	109.74	0.19	0.10	0.09	24783.4	0.0	32091.6	26631.5		1.00000		
69:00:00	839.72	839.72	242.41	73.8866	11.88	51.02	0	65.5	54.29	0.36	0.10	0.75	1.00	110.39	0.19	0.10	0.09	42842.5	0.0	55001.7	45588.4		1.00000		
70:00:00	0	0	250	76.2	15.17	52.02	0	66.21	54.82	0.35	0.10	0.72	1.00	111.10	0.19	0.10	0.09	0.0	0.0	0.0	0.0		1.00000		
71:00:00	0	0	250	76.2	15.17	53.02	0	66.91	55.35	0.34	0.10	0.69	1.00	111.90	0.19	0.10	0.09	0.0	0.0	0.0	0.0		1.00000		
72:00:00	-1454.53	1454.53	250	76.2	15.17	54.02	0	67.59	55.86	0.32	0.10	0.66	1.00	112.79	0.19	0.10	0.09	78573.7	0.0	98311.7	81250.0		1.00000		
					min	30.02	0	46.56	40.24					min	0.19	0.10	0.09	**41.0**	**0.0**	**56.7**	**47.8**	0	25	0	0
					max	54.02	0	67.59	55.86					max	0.20	0.10	0.10								
					q1	35.52	0	52.345	44.575					q1	0.19	0.10	0.09					F1	=		25
					q2	48.52	0	63.655	52.905					q2	0.19	0.10	0.10					F2	=		0.25
					median	42.02	0	58.39	49.1					median	0.19	0.10	0.10					nse	=		0.25
																						F3	=		20
																						CCME WC	=		81.5147
																						MCWQI	=		88.8197

Time Series Table - Tank 42E

Time	Demand	Abs Dema	Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean					CCME Calculations		
Hours	GPM	GPM	ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6		Violations		
48:00:00	-896.47	896.47	250	76.2	15.17	19.51	0.39	30.89	38.08	0.76	1.00	1.00	1.00	4.75	0.92	0.76	0.76	17490.1	349.6	27692.0	34137.6	0	0	0	0
49:00:00	-471.12	471.12	243.87	74.3316	12.51	20.51	0.38	32.32	38.96	0.74	1.00	1.00	1.00	4.81	0.91	0.74	0.74	9662.7	179.0	15226.6	18354.8	0	0	0	0
50:00:00	-348.32	348.32	240.02	73.1581	10.84	21.51	0.37	33.71	39.81	0.73	1.00	1.00	1.00	4.87	0.91	0.73	0.73	7492.4	128.9	11741.9	13866.6	0	0	0	0
51:00:00	1074.23	1074.23	236.98	72.2315	9.52	22.51	0.36	35.08	40.65	0.72	1.00	1.00	1.00	4.94	0.90	0.72	0.72	24180.9	386.7	37684.0	43667.4	0	0	0	0
52:00:00	151.75	151.75	241.63	73.6488	11.54	20.23	0.39	31.53	41.57	0.75	1.00	1.00	1.00	4.79	0.91	0.75	0.75	3069.9	59.2	4784.7	6308.2	0	0	0	0
53:00:00	-91.95	91.95	240.46	73.2922	11.03	21.18	0.38	32.87	42.37	0.74	1.00	1.00	1.00	4.85	0.91	0.74	0.74	1947.5	34.9	3022.4	3895.9	0	0	0	0
54:00:00	457.03	457.03	239.8	73.091	10.75	22.18	0.37	34.26	43.16	0.72	1.00	1.00	1.00	4.91	0.90	0.72	0.72	10136.9	169.1	15657.8	19725.4	0	0	0	0
55:00:00	139.86	139.86	242.38	73.8774	11.86	21.46	0.38	33.06	44.14	0.73	1.00	1.00	1.00	4.87	0.91	0.73	0.73	3001.4	53.1	4623.8	6173.4	0	0	0	0
56:00:00	47.77	47.77	243.2	74.1274	12.22	21.87	0.38	33.58	44.88	0.73	1.00	1.00	1.00	4.89	0.90	0.73	0.73	1044.7	18.2	1604.1	2143.9	0	0	0	0
57:00:00	-1265.65	1265.65	243.5	74.2188	12.35	22.66	0.37	34.64	45.62	0.72	1.00	1.00	1.00	4.95	0.90	0.72	0.72	28679.6	468.3	43842.1	57739.0	0	0	0	0
58:00:00	-423.01	423.01	236.07	71.9541	9.13	23.66	0.37	35.99	46.34	0.70	1.00	1.00	1.00	5.02	0.89	0.70	0.70	10008.4	156.5	15224.1	19602.3	0	0	0	0
59:00:00	-410.83	410.83	231.54	70.5734	7.17	24.66	0.36	37.31	47.04	0.69	1.00	1.00	1.00	5.09	0.89	0.69	0.69	10131.1	147.9	15328.1	19325.4	0	0	0	0
60:00:00	491.01	491.01	228.64	69.6895	5.91	25.66	0.35	38.6	47.72	0.68	1.00	1.00	1.00	5.17	0.88	0.68	0.68	12599.3	171.9	18953.0	23431.0	0	0	0	0
61:00:00	203.01	203.01	231.75	70.6374	7.26	22.66	0.38	34.1	48.6	0.72	1.00	1.00	1.00	4.95	0.90	0.72	0.72	4600.2	77.1	6922.6	9866.3	0	0	0	0
62:00:00	94.83	94.83	233.1	71.0489	7.84	22.07	0.39	33.19	49.43	0.72	1.00	1.00	1.00	4.91	0.90	0.72	0.72	2092.9	37.0	3147.4	4687.4	0	0	0	0
63:00:00	810.88	810.88	233.77	71.2531	8.13	22.35	0.38	33.53	49.77	0.72	1.00	1.00	1.00	4.93	0.90	0.72	0.72	18123.2	308.1	27188.8	40357.5	0	0	0	0
64:00:00	314.15	314.15	238.72	72.7619	10.28	19	0.41	28.68	39.97	0.76	1.00	1.00	1.00	4.72	0.92	0.76	0.76	5968.9	128.8	9009.8	12556.6	0	0	0	0
65:00:00	146.92	146.92	240.88	73.4202	11.22	18.54	0.42	28.06	40.81	0.77	1.00	1.00	1.00	4.69	0.92	0.77	0.77	2723.9	61.7	4122.6	5995.8	0	0	0	0
66:00:00	922.55	922.55	241.95	73.7464	11.68	18.87	0.42	28.59	41.67	0.76	1.00	1.00	1.00	4.71	0.92	0.76	0.76	17408.5	387.5	26375.7	38442.7	0	0	0	0
67:00:00	410.95	410.95	247.84	75.5416	14.23	16.76	0.43	25.61	37.18	0.79	1.00	1.00	1.00	4.60	0.93	0.79	0.79	6887.5	176.7	10524.4	15279.1	0	0	0	0
68:00:00	0	0	250	76.2	15.17	16.83	0.43	25.81	38.07	0.79	1.00	1.00	1.00	4.60	0.93	0.79	0.79	0.0	0.0	0.0	0.0	0	0	0	0
69:00:00	0	0	250	76.2	15.17	17.83	0.42	27.34	38.94	0.78	1.00	1.00	1.00	4.66	0.93	0.78	0.78	0.0	0.0	0.0	0.0	0	0	0	0
70:00:00	0	0	250	76.2	15.17	18.83	0.42	28.83	39.79	0.76	1.00	1.00	1.00	4.71	0.92	0.76	0.76	0.0	0.0	0.0	0.0	0	0	0	0
71:00:00	0	0	250	76.2	15.17	19.83	0.41	30.3	40.63	0.75	1.00	1.00	1.00	4.77	0.92	0.75	0.75	0.0	0.0	0.0	0.0	0	0	0	0
72:00:00	-896.47	896.47	250	76.2	15.17	20.83	0.4	31.74	41.45	0.74	1.00	1.00	1.00	4.83	0.91	0.74	0.74	18673.5	358.6	28454.0	37158.7	0	0	0	0
					min	16.76	0.35	25.61	37.18					min	0.88	0.68	0.679	**21.4**	**0.4**	**32.9**	**43.0**	0	0	0	0
					max	25.66	0.43	38.6	49.77					max	0.93	0.79	0.79								
					q1	18.935	0.37	28.755	39.8					q1	0.90	0.72	0.72					F1	=		0
					q2	22.43	0.415	34.18	45.98					q2	0.92	0.76	0.76					F2	=		0
					median	21.18	0.38	32.87	41.57					median	0.91	0.74	0.74					nse	=		0
																						F3	=		0
																						CCME WC	=		100
																						MCWQI	=		100

SSGA

Time Series Table - Tank 150N

Time Hours	Demand GPM	Abs Dema GPM	Head ft	Head m	Pressure psi	Age hours	Chlorine mg/L	THM ug/L	HAA6 ug/L	Calculated sub-indices: Water age	Chlorine	THM	HAA6		Water quality indices: OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	CCME Calculations	Violations			
12:00:00 AM	-822.16	822.16	243.9	74.34072	15.56	28.57	0.25	41.42	38.59	0.64	1.00	1.00	1.00	5.42	0.86	0.64	0.64	23489.1	205.5	34053.9	31727.2	0	0	0	0	
1:00:00 AM	-687.39	687.39	240.52	73.3105	14.09	29.57	0.25	42.63	39.45	0.63	1.00	1.00	1.00	5.52	0.85	0.63	0.63	20326.1	171.8	29303.4	27117.5	0	0	0	0	
2:00:00 AM	-585.22	585.22	237.65	72.43572	12.85	30.57	0.24	43.81	40.3	0.62	1.00	1.00	1.00	5.62	0.84	0.62	0.62	17890.2	140.5	25638.5	23584.4	0	0	0	0	
3:00:00 AM	-780.15	780.15	235.24	71.70115	11.8	31.57	0.24	44.97	41.12	0.61	1.00	1.00	1.00	5.73	0.84	0.61	0.61	24629.3	187.2	35083.3	32079.8	0	0	0	0	
4:00:00 AM	-743.42	743.42	231.76	70.64045	10.3	32.57	0.23	46.11	41.93	0.59	1.00	1.00	1.00	5.84	0.83	0.59	0.59	24213.2	171.0	34279.1	31171.6	0	0	0	0	
5:00:00 AM	0	0	229.43	69.93026	9.29	33.57	0.23	47.22	42.72	0.58	1.00	1.00	1.00	5.97	0.82	0.58	0.58	0.0	0.0	0.0	0.0	0	0	0	0	
6:00:00 AM	0	0	229.43	69.93026	9.29	34.57	0.22	48.3	43.5	0.57	1.00	1.00	1.00	6.10	0.81	0.57	0.57	0.0	0.0	0.0	0.0	0	0	0	0	
7:00:00 AM	0	0	229.43	69.93026	9.29	35.57	0.22	49.37	44.26	0.56	1.00	1.00	1.00	6.24	0.80	0.56	0.56	0.0	0.0	0.0	0.0	0	0	0	0	
8:00:00 AM	0	0	229.43	69.93026	9.29	36.57	0.21	50.42	45	0.54	1.00	1.00	1.00	6.39	0.79	0.54	0.54	0.0	0.0	0.0	0.0	0	0	0	0	
9:00:00 AM	0	0	229.43	69.93026	9.29	37.57	0.21	51.44	45.73	0.53	1.00	1.00	1.00	6.55	0.78	0.53	0.53	0.0	0.0	0.0	0.0	0	0	0	0	
10:00:00 AM	0	0	229.43	69.93026	9.29	38.57	0.21	52.44	46.45	0.52	1.00	1.00	1.00	6.73	0.77	0.52	0.52	0.0	0.0	0.0	0.0	0	0	0	0	
11:00:00 AM	0	0	229.43	69.93026	9.29	39.57	0.2	53.42	47.15	0.51	1.00	1.00	1.00	6.92	0.76	0.51	0.51	0.0	0.0	0.0	0.0	0	0	0	0	
12:00:00 PM	0	0	229.43	69.93026	9.29	40.57	0.2	54.38	47.83	0.49	1.00	1.00	1.00	7.12	0.75	0.49	0.49	0.0	0.0	0.0	0.0	0	0	0	0	
1:00:00 PM	0	0	229.43	69.93026	9.29	41.57	0.19	55.32	48.5	0.48	0.96	1.00	1.00	7.43	0.73	0.48	0.47	0.0	0.0	0.0	0.0	0	0.05263	0	0	
2:00:00 PM	0	0	229.43	69.93026	9.29	42.57	0.19	56.24	49.15	0.47	0.96	1.00	1.00	7.66	0.72	0.46	0.46	0.0	0.0	0.0	0.0	0	0.05263	0	0	
3:00:00 PM	0	0	229.43	69.93026	9.29	43.57	0.19	57.14	49.8	0.46	0.96	1.00	1.00	7.92	0.71	0.45	0.45	0.0	0.0	0.0	0.0	0	0.05263	0	0	
4:00:00 PM	0	0	229.43	69.93026	9.29	44.57	0.18	58.03	50.43	0.44	0.91	1.00	1.00	8.31	0.69	0.44	0.43	0.0	0.0	0.0	0.0	0	0.11111	0	0	
5:00:00 PM	0	0	229.43	69.93026	9.29	45.57	0.18	58.89	51.04	0.43	0.91	1.00	1.00	8.61	0.68	0.42	0.42	0.0	0.0	0.0	0.0	0	0.11111	0	0	
6:00:00 PM	419.18	419.18	229.43	69.93026	9.29	46.57	0.17	59.74	51.64	0.42	0.87	1.00	1.00	9.06	0.66	0.41	0.40	19521.2	71.3	25041.8	21646.5	0	0.17647	0	0	
7:00:00 PM	667.08	667.08	232.04	70.72579	10.42	43.08	0.21	55.27	52.31	0.46	1.00	1.00	1.00	7.70	0.72	0.46	0.46	28737.8	140.1	36869.5	34895.0	0	0	0	0	
8:00:00 PM	682.01	682.01	235.12	71.66458	11.75	39.69	0.23	51.07	47.64	0.50	1.00	1.00	1.00	6.94	0.76	0.50	0.50	27069.0	156.9	34830.3	32491.0	0	0	0	0	
9:00:00 PM	834.89	834.89	238.11	72.57593	13.05	37.22	0.26	48.07	44.93	0.53	1.00	1.00	1.00	6.50	0.78	0.53	0.53	31074.6	217.1	40133.2	37511.6	0	0	0	0	
10:00:00 PM	978.75	978.75	242.71	73.97801	15.04	33.94	0.28	44.22	41.75	0.58	1.00	1.00	1.00	6.02	0.82	0.58	0.58	33218.8	274.1	43280.3	40862.8	0	0	0	0	
11:00:00 PM	0	0	243.9	74.34072	15.56	33.99	0.28	44.29	42.14	0.58	1.00	1.00	1.00	6.02	0.81	0.58	0.58	0.0	0.0	0.0	0.0	0	0	0	0	
12:00:00 AM	-822.16	822.16	243.9	74.34072	15.56	34.99	0.28	45.44	42.93	0.56	1.00	1.00	1.00	6.16	0.81	0.56	0.56	28767.4	230.2	37359.0	35295.3	0	0	0	0	
					min	28.57	0.17	41.42	38.59					min	0.66	0.41	0.40	**34.8**	**0.2**	**46.9**	**43.4**		0	6	0	0
					max	46.57	0.28	59.74	52.31					max	0.86	0.64	0.64									
					q1	33.755	0.195	45.205	42.035					q1	0.73	0.47	0.47					F1	=		25	
					q2	42.07	0.245	55.295	48.825					q2	0.82	0.58	0.58					F2	=		0.06	
					median	37.22	0.22	50.42	45					median	0.78	0.53	0.53					nse	=		0.005566	
																						F3	=		0.553507	
																						CCME WQ	=		85.56224	
																						MCWQI	=		99.08881	

Time Series Table - Tank 170N

Time Hours	Demand GPM	Abs Dema GPM	Head ft	Head m	Pressure psi	Age hours	Chlorine mg/L	THM ug/L	HAA6 ug/L	Calculated sub-indices: Water age	Chlorine	THM	HAA6		Water quality indices: OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weighted mean: Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	CCME Calculations	Violations			
48:00:00	-168.41	168.41	236.29	72.02119	11.82	20.72	0.34	31.6	31.45	0.74	1.00	1.00	1.00	4.82	0.91	0.74	0.74	3489.5	57.3	5321.8	5296.5	0	0	0	0	
49:00:00	-183.28	183.28	235.15	71.67372	11.33	21.72	0.34	33.01	32.46	0.73	1.00	1.00	1.00	4.88	0.90	0.73	0.73	3980.8	62.3	6050.1	5949.3	0	0	0	0	
50:00:00	-200.12	200.12	233.9	71.29272	10.79	22.72	0.33	34.39	33.45	0.72	1.00	1.00	1.00	4.95	0.90	0.72	0.72	4546.7	66.0	6882.1	6694.0	0	0	0	0	
51:00:00	-287.81	287.81	232.55	70.88124	10.2	23.72	0.32	35.74	34.42	0.70	1.00	1.00	1.00	5.02	0.89	0.70	0.70	6826.9	92.1	10286.3	9906.4	0	0	0	0	
52:00:00	-332.37	332.37	230.5	70.2564	9.32	24.72	0.32	37.07	35.37	0.69	1.00	1.00	1.00	5.09	0.89	0.69	0.69	8216.2	106.4	12321.0	11755.9	0	0	0	0	
53:00:00	-447.07	447.07	228.12	69.53098	8.29	25.72	0.31	38.37	36.3	0.68	1.00	1.00	1.00	5.17	0.88	0.68	0.68	11498.6	138.6	17154.1	16228.6	0	0	0	0	
54:00:00	-353.51	353.51	225.13	68.61962	6.99	26.72	0.3	39.64	37.21	0.67	1.00	1.00	1.00	5.25	0.87	0.67	0.67	9445.8	106.1	14013.1	13154.1	0	0	0	0	
55:00:00	-235.46	235.46	223.34	68.07403	6.21	27.72	0.3	40.88	38.1	0.65	1.00	1.00	1.00	5.34	0.87	0.65	0.65	6527.0	70.6	9625.6	8971.0	0	0	0	0	
56:00:00	-199.31	199.31	221.93	67.64426	5.6	28.72	0.29	42.1	38.97	0.64	1.00	1.00	1.00	5.43	0.86	0.64	0.64	5724.2	57.8	8391.0	7767.1	0	0	0	0	
57:00:00	0	0	220.9	67.33032	5.16	29.72	0.28	43.3	39.83	0.63	1.00	1.00	1.00	5.53	0.85	0.63	0.63	0.0	0.0	0.0	0.0	0	0	0	0	
58:00:00	0	0	220.9	67.33032	5.16	30.72	0.28	44.46	40.66	0.62	1.00	1.00	1.00	5.64	0.84	0.62	0.62	0.0	0.0	0.0	0.0	0	0	0	0	
59:00:00	0	0	220.9	67.33032	5.16	31.72	0.27	45.61	41.48	0.60	1.00	1.00	1.00	5.75	0.83	0.60	0.60	0.0	0.0	0.0	0.0	0	0	0	0	
60:00:00	44.9	44.9	220.9	67.33032	5.16	32.72	0.27	46.73	42.29	0.59	1.00	1.00	1.00	5.86	0.83	0.59	0.59	1469.1	12.1	2098.2	1898.8	0	0	0	0	
61:00:00	0	0	220.9	67.33032	5.16	33.67	0.26	47.77	43.09	0.58	1.00	1.00	1.00	5.98	0.82	0.58	0.58	0.0	0.0	0.0	0.0	0	0	0	0	
62:00:00	0	0	220.9	67.33032	5.16	34.67	0.26	48.84	43.86	0.57	1.00	1.00	1.00	6.11	0.81	0.57	0.57	0.0	0.0	0.0	0.0	0	0	0	0	
63:00:00	0	0	220.9	67.33032	5.16	35.67	0.25	49.9	44.61	0.55	1.00	1.00	1.00	6.26	0.80	0.55	0.55	0.0	0.0	0.0	0.0	0	0	0	0	
64:00:00	20.95	20.95	220.93	67.33946	5.17	36.67	0.25	50.93	45.35	0.54	1.00	1.00	1.00	6.41	0.79	0.54	0.54	768.2	5.2	1067.0	950.1	0	0	0	0	
65:00:00	51.07	51.07	221.17	67.41262	5.27	37.09	0.25	51.21	46.09	0.54	1.00	1.00	1.00	6.48	0.79	0.54	0.54	1894.2	12.8	2615.3	2353.8	0	0	0	0	
66:00:00	191.2	191.2	221.56	67.53149	5.44	37.12	0.25	51	45.94	0.54	1.00	1.00	1.00	6.48	0.79	0.54	0.54	7097.3	47.8	9751.2	8783.7	0	0	0	0	
67:00:00	260.51	260.51	223.07	67.99174	6.1	34.61	0.27	47.62	43.94	0.57	1.00	1.00	1.00	6.11	0.81	0.57	0.57	9016.3	70.3	12405.5	11446.8	0	0	0	0	
68:00:00	283.03	283.03	224.85	68.53428	6.87	32.17	0.29	44.38	41.22	0.60	1.00	1.00	1.00	5.80	0.83	0.60	0.60	9105.1	82.1	12560.9	11666.5	0	0	0	0	
69:00:00	350.24	350.24	226.72	69.10426	7.68	30.17	0.31	41.77	39.36	0.62	1.00	1.00	1.00	5.58	0.85	0.62	0.62	10566.7	108.6	14629.5	13785.4	0	0	0	0	
70:00:00	418.66	418.66	229.45	69.93636	8.86	27.65	0.33	38.55	36.95	0.65	1.00	1.00	1.00	5.34	0.87	0.65	0.65	11575.9	138.2	16139.3	15469.5	0	0	0	0	
71:00:00	557.33	557.33	232.84	70.96963	10.33	25.23	0.35	35.51	34.5	0.68	1.00	1.00	1.00	5.13	0.88	0.68	0.68	14061.4	195.1	19790.8	19227.9	0	0	0	0	
72:00:00	-168.41	168.41	236.29	72.02119	11.82	23.49	0.36	33.36	33.26	0.71	1.00	1.00	1.00	5.00	0.89	0.71	0.71	3956.0	60.6	5618.2	5601.3	0	0	0	0	
					min	20.72	0.25	31.6	31.45					min	0.79	0.54	0.54	**27.3**	**0.3**	**39.3**	**37.2**		0	0	0	0
					max	37.12	0.36	51.21	46.09					max	0.91	0.74	0.74									
					q1	24.975	0.265	36.405	34.935					q1	0.81	0.57	0.57					F1	=		0	
					q2	34.14	0.325	47.695	43.475					q2	0.88	0.69	0.69					F2	=		0	
					median	29.72	0.29	42.1	39.36					median	0.85	0.63	0.63					nse	=		0	
																						F3	=		0	
																						CCME WQ	=		100	
																						MCWQI	=		100	

Time Series Table - Tank 41E

Time Hours	Demand GPM	Abs Dema GPM	Head ft	Head m	Pressure psi	Age hours	Chlorine mg/L	THM ug/L	HAA6 ug/L	Calculated sub-indices: Water age	Chlorine	THM	HAA6		Water quality indices: OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weighted mean: Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6	CCME Calculations	Violations		
48:00:00	-537.8	537.8	250	76.2	15.17	14.82	0.42	24.41	27.73	0.81	1.00	1.00	1.00	4.51	0.94	0.81	0.81	7970.2	225.9	13127.7	14913.2	0	0	0	0
49:00:00	-401.39	401.39	245.54	74.84059	13.23	15.82	0.42	25.97	28.82	0.80	1.00	1.00	1.00	4.55	0.94	0.80	0.80	6350.0	168.6	10424.1	11568.1	0	0	0	0
50:00:00	-313.58	313.58	242.14	73.80427	11.76	16.82	0.41	27.49	29.88	0.79	1.00	1.00	1.00	4.60	0.93	0.79	0.79	5274.4	128.6	8620.3	9369.8	0	0	0	0
51:00:00	-417.99	417.99	239.43	72.97826	10.59	17.82	0.4	28.99	30.93	0.78	1.00	1.00	1.00	4.66	0.93	0.78	0.78	7448.6	167.2	12117.5	12928.4	0	0	0	0
52:00:00	-355.17	355.17	235.73	71.8505	8.98	18.82	0.39	30.45	31.95	0.76	1.00	1.00	1.00	4.71	0.92	0.76	0.76	6684.3	138.5	10814.9	11347.7	0	0	0	0
53:00:00	-458.78	458.78	232.17	70.76542	7.44	19.82	0.38	31.89	32.95	0.75	1.00	1.00	1.00	4.77	0.92	0.75	0.75	9093.0	174.3	14630.5	15116.8	0	0	0	0
54:00:00	-150.41	150.41	228.14	69.53707	5.69	20.82	0.37	33.29	33.93	0.74	1.00	1.00	1.00	4.83	0.91	0.74	0.74	3131.5	55.7	5007.1	5103.4	0	0	0	0
55:00:00	-88.15	88.15	227.04	69.20179	5.22	21.82	0.37	34.67	34.89	0.73	1.00	1.00	1.00	4.89	0.90	0.73	0.73	1923.4	32.6	3056.2	3075.6	0	0	0	0
56:00:00	-62.3	62.3	226.33	68.98538	4.91	22.82	0.36	36.01	35.83	0.71	1.00	1.00	1.00	4.96	0.90	0.71	0.71	1421.7	22.4	2243.4	2232.2	0	0	0	0
57:00:00	185.17	185.17	225.78	68.81774	4.67	23.82	0.35	37.33	36.75	0.70	1.00	1.00	1.00	5.03	0.89	0.70	0.70	4410.7	64.8	6912.4	6805.0	0	0	0	0
58:00:00	187.59	187.59	227.61	69.37553	5.46	21.74	0.37	34.02	37.77	0.73	1.00	1.00	1.00	4.89	0.90	0.73	0.73	4078.2	69.4	6381.8	7085.3	0	0	0	0

59:00:00	157.07	157.07	229.27	69.8815	6.18	20.41	0.39	31.91	39.08	0.74	1.00	1.00	1.00	4.80	0.91	0.74	0.74	3205.8	61.3	5012.1	6138.3	0	0	0	0	
60:00:00	-16.85	16.85	230.61	70.28993	6.77	19.81	0.39	30.95	36.78	0.75	1.00	1.00	1.00	4.77	0.92	0.75	0.75	333.8	6.6	521.5	619.7	0	0	0	0	
61:00:00	-144.76	144.76	229.7	70.01256	6.37	20.81	0.38	32.37	37.68	0.74	1.00	1.00	1.00	4.83	0.91	0.74	0.74	3012.5	55.0	4685.9	5454.6	0	0	0	0	
62:00:00	-163.27	163.27	228.18	69.54926	5.71	21.81	0.38	33.77	38.56	0.73	1.00	1.00	1.00	4.89	0.90	0.73	0.73	3560.9	62.0	5513.6	6295.7	0	0	0	0	
63:00:00	112.32	112.32	226.68	69.09206	5.06	22.81	0.37	35.14	39.42	0.71	1.00	1.00	1.00	4.96	0.90	0.71	0.71	2562.0	41.6	3946.9	4427.7	0	0	0	0	
64:00:00	177.14	177.14	228.17	69.54622	5.71	21.57	0.38	33.22	40.35	0.73	1.00	1.00	1.00	4.87	0.91	0.73	0.73	3820.9	67.3	5884.6	7147.6	0	0	0	0	
65:00:00	161.01	161.01	229.82	70.04914	6.42	20.42	0.39	31.49	41.65	0.74	1.00	1.00	1.00	4.80	0.91	0.74	0.74	3287.8	62.8	5070.2	6706.1	0	0	0	0	
66:00:00	503.29	503.29	231.21	70.47281	7.03	19.85	0.4	30.64	39.45	0.75	1.00	1.00	1.00	4.77	0.92	0.75	0.75	9990.3	201.3	15420.8	19854.8	0	0	0	0	
67:00:00	428.35	428.35	235.68	71.83526	8.96	17.05	0.42	26.58	33.92	0.79	1.00	1.00	1.00	4.62	0.93	0.79	0.79	7303.4	179.9	11385.5	14529.6	0	0	0	0	
68:00:00	357.03	357.03	239.44	72.98131	10.59	15.78	0.43	24.8	30.76	0.80	1.00	1.00	1.00	4.55	0.94	0.80	0.80	5633.9	153.5	8854.3	10982.2	0	0	0	0	
69:00:00	490.13	490.13	242.58	73.93838	11.95	15.24	0.44	24.12	29.68	0.81	1.00	1.00	1.00	4.53	0.94	0.81	0.81	7469.6	215.7	11821.9	14547.1	0	0	0	0	
70:00:00	483.12	483.12	248.01	75.59345	14.3	14.13	0.44	22.61	27.11	0.82	1.00	1.00	1.00	4.48	0.95	0.82	0.82	6826.5	212.6	10923.3	13097.4	0	0	0	0	
71:00:00	0	0	250	76.2	15.17	14.48	0.44	23.25	27.91	0.82	1.00	1.00	1.00	4.49	0.94	0.82	0.82	0.0	0.0	0.0	0.0	0	0	0	0	
72:00:00	-537.8	537.8	250	76.2	15.17	15.48	0.43	24.83	28.99	0.81	1.00	1.00	1.00	4.54	0.94	0.81	0.81	8325.1	231.3	13353.6	15590.8	0	0	0	0	
					min	14.13	0.35	22.61	27.11					min	0.89	0.70	0.70	**17.9**	**0.4**	**28.4**	**32.6**		0	0	0	0
					max	23.82	0.44	37.33	41.65					max	0.95	0.82	0.82									
					q1	15.8	0.375	25.4	29.78					q1	0.91	0.73	0.73					F1	=		0	
					q2	21.655	0.42	33.53	38.165					q2	0.94	0.80	0.80					F2	=		0	
					median	19.82	0.39	30.95	33.93					median	0.92	0.75	0.75					nse	=		0	
																						F3	=		0	
																						CCME WQ	=		100	
																						MCWQI	=		100	

Time Series Table - Tank 42E

Time	Demand	Abs Dema	Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean				CCME Calculations				
Hours	GPM	GPM	ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6		Violations			
48:00:00	-107.93	107.93	250	76.2	15.17	20.09	0.38	31.13	37.88	0.75	1.00	1.00	1.00	4.78	0.91	0.75	0.75	2168.3	41.0	3359.9	4088.4	0	0	0	0	
49:00:00	-180.42	180.42	248.5	75.7428	14.52	21.09	0.37	32.55	38.76	0.74	1.00	1.00	1.00	4.84	0.91	0.74	0.74	3805.1	66.8	5872.7	6993.1	0	0	0	0	
50:00:00	-179.98	179.98	246.76	75.21245	13.76	22.09	0.36	33.94	39.62	0.72	1.00	1.00	1.00	4.91	0.90	0.72	0.72	3975.8	64.8	6108.5	7130.8	0	0	0	0	
51:00:00	-498.5	498.5	245.07	74.69734	13.03	23.09	0.35	35.3	40.46	0.71	1.00	1.00	1.00	4.98	0.90	0.71	0.71	11510.4	174.5	17597.1	20169.3	0	0	0	0	
52:00:00	-280.27	280.27	241.56	73.62749	11.51	24.09	0.35	36.64	41.28	0.70	1.00	1.00	1.00	5.05	0.89	0.70	0.70	6751.7	98.1	10269.1	11569.5	0	0	0	0	
53:00:00	-494	494	238.37	72.65518	10.13	25.09	0.34	37.94	42.09	0.69	1.00	1.00	1.00	5.12	0.88	0.69	0.69	12394.5	168.0	18742.4	20792.5	0	0	0	0	
54:00:00	213.87	213.87	234.77	71.5579	8.57	26.09	0.33	39.22	42.88	0.67	1.00	1.00	1.00	5.20	0.88	0.67	0.67	5579.9	70.6	8388.0	9170.7	0	0	0	0	
55:00:00	11.96	11.96	235.57	71.80174	8.91	26.3	0.33	39.34	43.77	0.67	1.00	1.00	1.00	5.22	0.88	0.67	0.67	314.5	3.9	470.5	523.5	0	0	0	0	
56:00:00	-29.18	29.18	235.45	71.76516	8.86	27.29	0.33	40.57	44.52	0.66	1.00	1.00	1.00	5.30	0.87	0.66	0.66	796.3	9.6	1183.8	1299.1	0	0	0	0	
57:00:00	412.28	412.28	234.89	71.59447	8.62	28.29	0.32	41.8	45.26	0.65	1.00	1.00	1.00	5.39	0.86	0.65	0.65	11663.4	131.9	17233.3	18659.8	0	0	0	0	
58:00:00	214.47	214.47	237.78	72.47534	9.87	26.07	0.34	38.41	46.17	0.67	1.00	1.00	1.00	5.20	0.88	0.67	0.67	5591.2	72.9	8237.8	9902.1	0	0	0	0	
59:00:00	125.38	125.38	239.36	72.95693	10.56	25.44	0.35	37.38	46.99	0.68	1.00	1.00	1.00	5.15	0.88	0.68	0.68	3189.7	43.9	4686.7	5891.6	0	0	0	0	
60:00:00	-717.11	717.11	240.33	73.25258	10.97	25.52	0.35	37.36	46.64	0.68	1.00	1.00	1.00	5.16	0.88	0.68	0.68	18300.6	251.0	26791.2	33446.0	0	0	0	0	
61:00:00	-340.34	340.34	235.71	71.84441	8.97	26.52	0.34	38.65	47.34	0.67	1.00	1.00	1.00	5.24	0.87	0.67	0.67	9025.8	115.7	13154.1	16111.7	0	0	0	0	
62:00:00	-197.85	197.85	233.22	71.08546	7.89	27.52	0.34	39.92	48.01	0.66	1.00	1.00	1.00	5.32	0.87	0.66	0.66	5444.8	67.3	7898.2	9498.8	0	0	0	0	
63:00:00	498.85	498.85	231.67	70.61302	7.22	28.52	0.33	41.16	48.68	0.64	1.00	1.00	1.00	5.41	0.86	0.64	0.64	14227.2	164.6	20532.7	24284.0	0	0	0	0	
64:00:00	250.01	250.01	235.15	71.67372	8.73	25.09	0.36	36.26	49.55	0.69	1.00	1.00	1.00	5.12	0.88	0.69	0.69	6272.8	90.0	9065.4	12388.0	0	0	0	0	
65:00:00	140.77	140.77	236.95	72.22236	9.51	24.15	0.37	34.89	50.29	0.70	1.00	1.00	1.00	5.05	0.89	0.70	0.70	3399.6	52.1	4911.5	7079.3	0	0	0	0	
66:00:00	975.66	975.66	238.05	72.55764	9.99	24.06	0.37	34.74	49.45	0.70	1.00	1.00	1.00	5.05	0.89	0.70	0.70	23474.4	361.0	33894.4	48246.4	0	0	0	0	
67:00:00	434.97	434.97	244.27	74.4535	12.68	20.25	0.41	29.46	39.8	0.75	1.00	1.00	1.00	4.79	0.91	0.75	0.75	8808.1	178.3	12814.2	17311.8	0	0	0	0	
68:00:00	282.21	282.21	247.59	75.46543	14.12	19.33	0.41	28.27	40.37	0.76	1.00	1.00	1.00	4.74	0.92	0.76	0.76	5455.1	115.7	7978.1	11392.8	0	0	0	0	
69:00:00	682.63	682.63	249.99	76.19695	15.16	19.1	0.42	28.06	39.41	0.76	1.00	1.00	1.00	4.73	0.92	0.76	0.76	13038.2	286.7	19154.6	26902.4	0	0	0	0	
70:00:00	0	0	250	76.2	15.17	20.1	0.41	29.53	40.25	0.75	1.00	1.00	1.00	4.78	0.91	0.75	0.75	0.0	0.0	0.0	0.0	0	0	0	0	
71:00:00	0	0	250	76.2	15.17	21.1	0.4	30.99	41.08	0.74	1.00	1.00	1.00	4.84	0.91	0.74	0.74	0.0	0.0	0.0	0.0	0	0	0	0	
72:00:00	-107.93	107.93	250	76.2	15.17	22.1	0.39	32.41	41.89	0.72	1.00	1.00	1.00	4.91	0.90	0.72	0.72	2385.3	42.1	3498.0	4521.2	0	0	0	0	
					min	19.1	0.32	28.06	37.88					min	0.86	0.64	0.64	**24.1**	**0.4**	**35.5**	**44.4**		0	0	0	0
					max	28.52	0.42	41.8	50.29					max	0.92	0.76	0.76									
					q1	21.095	0.34	31.77	40.31					q1	0.88	0.67	0.67					F1	=		0	
					q2	26.195	0.385	38.935	47.165					q2	0.91	0.74	0.74					F2	=		0	
					median	24.15	0.35	36.26	42.88					median	0.89	0.70	0.70					nse	=		0	
																						F3	=		0	
																						CCME WQ	=		100	
																						MCWQI	=		100	

SMGA Solution 1

Time Series Table - Tank 55N

Time	Demand		Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean						CCME Calculations		
Hours	GPM		ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6			Violations		
12:00:00 AM	0	0	204	62.1792	15.17	32.55	0.21	47.87	38.29	0.59	1.00	1.00	1.00	5.84	0.83	0.59	0.59	0.0	0.0	0.0	0.0	0	0	0	0	
1:00:00 AM	-160.43	160.43	204	62.1792	15.17	33.55	0.21	48.95	39.16	0.58	1.00	1.00	1.00	5.97	0.82	0.58	0.58	5382.4	33.7	7853.0	6282.4	0	0	0	0	
2:00:00 AM	-445.2	445.2	203.48	62.0207	14.94	34.55	0.2	50.02	40.01	0.57	1.00	1.00	1.00	6.10	0.81	0.57	0.57	15381.7	89.0	22268.9	17812.5	0	0	0	0	
3:00:00 AM	-769.49	769.49	201.95	61.5544	14.28	35.55	0.2	51.05	40.84	0.56	1.00	1.00	1.00	6.24	0.80	0.56	0.56	27355.4	153.9	39282.5	31426.0	0	0	0	0	
4:00:00 AM	-1059.8	1059.8	199.65	60.8533	13.28	36.55	0.19	52.07	41.66	0.54	0.96	1.00	1.00	6.49	0.79	0.54	0.53	38735.7	201.4	55183.8	44151.3	0		0.05263 0	0	
5:00:00 AM	-1712.41	1712.41	194.97	59.4269	11.25	37.55	0.19	53.07	42.45	0.53	0.96	1.00	1.00	6.65	0.78	0.53	0.52	64301.0	325.4	90877.6	72691.8	0		0.05263 0	0	
6:00:00 AM	-944.51	944.51	189.85	57.8663	9.03	38.55	0.19	54.04	43.23	0.52	0.96	1.00	1.00	6.82	0.77	0.51	0.51	36410.9	179.5	51041.3	40831.2	0		0.05263 0	0	
7:00:00 AM	0	0	189	57.6072	8.67	39.55	0.18	55	44	0.51	0.91	1.00	1.00	7.12	0.75	0.50	0.49	0.0	0.0	0.0	0.0	0		0.11111 0	0	
8:00:00 AM	0	0	189	57.6072	8.67	40.55	0.18	55.93	44.75	0.49	0.91	1.00	1.00	7.32	0.74	0.48	0.48	0.0	0.0	0.0	0.0	0		0.11111 0	0	
9:00:00 AM	0	0	189	57.6072	8.67	41.55	0.17	56.85	45.48	0.48	0.87	1.00	1.00	7.67	0.72	0.47	0.46	0.0	0.0	0.0	0.0	0		0.17647 0	0	
10:00:00 AM	0	0	189	57.6072	8.67	42.55	0.17	57.75	46.2	0.47	0.87	1.00	1.00	7.90	0.71	0.46	0.45	0.0	0.0	0.0	0.0	0		0.17647 0	0	
11:00:00 AM	0	0	189	57.6072	8.67	43.55	0.17	58.63	46.9	0.46	0.87	1.00	1.00	8.15	0.70	0.44	0.44	0.0	0.0	0.0	0.0	0		0.17647 0	0	
12:00:00 PM	144.09	144.09	189	57.6072	8.67	44.55	0.16	59.49	47.59	0.44	0.82	1.00	1.00	8.58	0.68	0.43	0.42	6419.2	23.1	8571.9	6857.2	0		0.25000 0	0	
1:00:00 PM	134.64	134.64	189.43	57.7383	8.85	45.55	0.16	60.35	48.28	0.43	0.82	0.98	1.00	8.91	0.67	0.4171	0.4046	6132.9	21.5	8125.5	6500.4	0		0.25000 0	0	
2:00:00 PM	125.8	125.8	189.83	57.8602	9.03	45.83	0.16	60.36	48.28	0.43	0.82	0.98	1.00	9.00	0.67	0.4139	0.4016	5765.4	20.1	7593.3	6073.6	0		0.25000 0	0	
3:00:00 PM	542.98	542.98	190.21	57.976	9.19	46.17	0.16	60.43	48.35	0.42	0.82	0.98	1.00	9.12	0.66	0.4100	0.3976	25069.4	86.9	32812.3	26253.1	0		0.25000 0	0	
4:00:00 PM	496.04	496.04	191.84	58.4728	9.9	44.5	0.18	58.28	46.63	0.44	0.91	1.00	1.00	8.29	0.69	0.44	0.43	22073.8	89.3	28909.2	23130.3	0		0.11111 0	0	
5:00:00 PM	473.59	473.59	193.32	58.9239	10.54	43.34	0.19	56.79	45.43	0.46	0.96	1.00	1.00	7.86	0.71	0.46	0.45	20525.4	90.0	26895.2	21515.2	0		0.05263 0	0	
6:00:00 PM	821.71	821.71	194.74	59.3568	11.15	42.48	0.2	55.7	44.56	0.47	1.00	1.00	1.00	7.55	0.73	0.47	0.47	34906.2	164.3	45769.2	36615.4	0	0	0	0	
7:00:00 PM	965.91	965.91	197.2	60.1066	12.22	40.66	0.22	53.62	42.9	0.49	1.00	1.00	1.00	7.14	0.75	0.49	0.49	39273.9	212.5	51792.1	41437.5	0	0	0	0	
8:00:00 PM	702.9	702.9	200.09	60.9874	13.47	38.88	0.23	51.7	41.36	0.51	1.00	1.00	1.00	6.79	0.77	0.51	0.51	27328.8	161.7	36339.9	29071.9	0	0	0	0	
9:00:00 PM	1169.29	1169.29	202.23	61.6397	14.4	38.06	0.24	50.81	40.65	0.52	1.00	1.00	1.00	6.64	0.78	0.52	0.52	44503.2	280.6	59411.6	47531.6	0	0	0	0	
10:00:00 PM	0	0	204	62.1792	15.17	37.63	0.24	50.31	40.25	0.53	1.00	1.00	1.00	6.57	0.78	0.53	0.53	0.0	0.0	0.0	0.0	0	0	0	0	
11:00:00 PM	0	0	204	62.1792	15.17	38.63	0.24	51.34	41.07	0.52	1.00	1.00	1.00	6.74	0.77	0.52	0.52	0.0	0.0	0.0	0.0	0	0	0	0	
12:00:00 AM	0	0	204	62.1792	15.17	39.63	0.23	52.35	41.88	0.50	1.00	1.00	1.00	6.93	0.76	0.50	0.50	0.0	0.0	0.0	0.0	0	0	0	0	
					min	32.55	0.16	47.87	38.29					min	0.66	0.41	0.40	**39.3**	**0.2**	**53.7**	**42.9**		0	14	0	0
					max	46.17	0.24	60.43	48.35					max	0.83	0.59	0.59									
					q1	37.59	0.17	51.195	40.955					q1	0.71	0.45	0.44					F1	=		25	
					q2	43.445	0.215	58.015	46.415					q2	0.78	0.53	0.53					F2	=		0.14	
					median	39.63	0.19	54.04	43.23					median	0.75	0.50	0.49					nse	=		0.0207327	
																						F3	=		2.03116	
																						CCME WQI	=		85.518033	
																						MCWQI	=		97.333718	

Time Series Table - Tank 110N

Time	Demand		Head	Head	Pressure	Age	Chlorine	THM	HAA6		Calculated sub-indices				Water quality indices			Flow weighted mean						CCME Calculations		
Hours	GPM		ft	m	psi	hours	mg/L	ug/L	ug/L	age	Chlorine	THM	HAA6		(2001)	Tyagi (2004)	and Tyagi	weigthed	weigthed	weigthed	weigthed			Violations		
48:00:00	0	0	251	76.5048	6.07	16.19	0.4	26.68	21.34	0.80	1.00	1.00	1.00	4.57	0.94	0.80	0.80	0.0	0.0	0.0	0.0	0	0	0	0	
49:00:00	-1330.51	1330.51	251	76.5048	6.07	17.19	0.4	28.21	22.57	0.79	1.00	1.00	1.00	4.62	0.93	0.79	0.79	22871.5	532.2	37533.7	30029.6	0	0	0	0	
50:00:00	-944.85	944.85	247.87	75.5508	4.71	18.19	0.39	29.7	23.76	0.77	1.00	1.00	1.00	4.68	0.92	0.77	0.77	17186.8	368.5	28062.0	22449.6	0	0	0	0	
51:00:00	-1095.53	1095.53	245.09	74.7034	3.5	19.19	0.38	31.16	24.93	0.76	1.00	1.00	1.00	4.73	0.92	0.76	0.76	21023.2	416.3	34136.7	27311.6	0	0	0	0	
52:00:00	-1868.98	1868.98	242.46	73.9018	2.37	20.19	0.37	32.59	26.07	0.75	1.00	1.00	1.00	4.79	0.91	0.75	0.75	37734.7	691.5	60910.1	48724.3	0	0	0	0	
53:00:00	0	0	241	73.4568	1.73	21.19	0.36	33.99	27.19	0.74	1.00	1.00	1.00	4.85	0.91	0.74	0.74	0.0	0.0	0.0	0.0	0	0	0	0	
54:00:00	0	0	241	73.4568	1.73	22.19	0.36	35.37	28.29	0.72	1.00	1.00	1.00	4.92	0.90	0.72	0.72	0.0	0.0	0.0	0.0	0	0	0	0	
55:00:00	0	0	241	73.4568	1.73	23.19	0.35	36.71	29.37	0.71	1.00	1.00	1.00	4.98	0.90	0.71	0.71	0.0	0.0	0.0	0.0	0	0	0	0	
56:00:00	0	0	241	73.4568	1.73	24.19	0.34	38.03	30.42	0.70	1.00	1.00	1.00	5.05	0.89	0.70	0.70	0.0	0.0	0.0	0.0	0	0	0	0	
57:00:00	0	0	241	73.4568	1.73	25.19	0.33	39.32	31.45	0.69	1.00	1.00	1.00	5.13	0.88	0.69	0.69	0.0	0.0	0.0	0.0	0	0	0	0	
58:00:00	0	0	241	73.4568	1.73	26.19	0.33	40.58	32.46	0.67	1.00	1.00	1.00	5.21	0.88	0.67	0.67	0.0	0.0	0.0	0.0	0	0	0	0	
59:00:00	0	0	241	73.4568	1.73	27.19	0.32	41.82	33.45	0.66	1.00	1.00	1.00	5.29	0.87	0.66	0.66	0.0	0.0	0.0	0.0	0	0	0	0	
60:00:00	0	0	241	73.4568	1.73	28.19	0.31	43.03	34.42	0.65	1.00	1.00	1.00	5.38	0.86	0.65	0.65	0.0	0.0	0.0	0.0	0	0	0	0	
61:00:00	0	0	241	73.4568	1.73	29.19	0.31	44.22	35.37	0.64	1.00	1.00	1.00	5.48	0.85	0.64	0.64	0.0	0.0	0.0	0.0	0	0	0	0	
62:00:00	0	0	241	73.4568	1.73	30.19	0.3	45.38	36.3	0.62	1.00	1.00	1.00	5.58	0.85	0.62	0.62	0.0	0.0	0.0	0.0	0	0	0	0	
63:00:00	196.1	196.1	241	73.4568	1.73	31.19	0.3	46.52	37.21	0.61	1.00	1.00	1.00	5.69	0.84	0.61	0.61	6116.4	58.8	9122.6	7296.9	0	0	0	0	
64:00:00	96	96	241.47	73.6001	1.94	32.19	0.29	47.75	38.2	0.60	1.00	1.00	1.00	5.80	0.83	0.60	0.60	3090.2	27.8	4584.0	3667.2	0	0	0	0	
65:00:00	202.2	202.2	241.7	73.6702	2.04	31.86	0.29	47.04	37.63	0.60	1.00	1.00	1.00	5.76	0.83	0.60	0.60	6442.1	58.6	9511.5	7608.8	0	0	0	0	
66:00:00	327.86	327.86	242.18	73.8165	2.25	30.34	0.31	44.78	35.82	0.62	1.00	1.00	1.00	5.60	0.85	0.62	0.62	9947.3	101.6	14681.6	11743.9	0	0	0	0	
67:00:00	2118.56	2118.56	242.97	74.0573	2.59	28	0.33	41.48	33.18	0.65	1.00	1.00	1.00	5.37	0.86	0.65	0.65	59319.7	699.1	87877.9	70293.8	0	0	0	0	
68:00:00	-892.85	892.85	248.04	75.6026	4.78	18.41	0.4	28.65	22.92	0.77	1.00	1.00	1.00	4.69	0.92	0.77	0.77	16437.4	357.1	25580.2	20464.1	0	0	0	0	
69:00:00	3183.05	3183.05	246.23	75.0509	4	19.41	0.39	30.14	24.11	0.76	1.00	1.00	1.00	4.74	0.92	0.76	0.76	61783.0	1241.4	95937.1	76743.3	0	0	0	0	
70:00:00	1818.86	1818.86	250.72	76.4195	5.94	15.33	0.43	24.49	19.6	0.81	1.00	1.00	1.00	4.53	0.94	0.81	0.81	27883.1	782.1	44543.9	35649.7	0	0	0	0	
71:00:00	0	0	251	76.5048	6.07	16.1	0.42	25.74	20.59	0.80	1.00	1.00	1.00	4.57	0.94	0.80	0.80	0.0	0.0	0.0	0.0	0	0	0	0	
72:00:00	0	0	251	76.5048	6.07	17.1	0.41	27.28	21.82	0.79	1.00	1.00	1.00	4.62	0.93	0.79	0.79	0.0	0.0	0.0	0.0	0	0	0	0	
					min	15.33	0.29	24.49	19.6					min	0.83	0.60	0.60	**20.6**	**0.4**	**32.1**	**25.7**		0	0	0	0
					max	32.19	0.43	47.75	38.2					max	0.94	0.81	0.81									
					q1	18.3	0.31	29.175	23.34					q1	0.86	0.64	0.64					F1	=		0	
					q2	28.69	0.395	43.625	34.895					q2	0.92	0.77	0.77					F2	=		0	
					median	23.19	0.35	36.71	29.37					median	0.90	0.71	0.71					nse	=		0	
																						F3	=		0	
																						CCME WQI	=		100	
																						MCWQI	=		100	

Time Series Table - Tank 41E

Time	Demand		Head	Head	Pressure	Age	Chlorine	THM	HAA6		Calculated sub-indices				Water quality indices			Flow weighted mean						CCME Calculations		
Hours	GPM		ft	m	psi	hours	mg/L	ug/L	ug/L	age	Chlorine	THM	HAA6		(2001)	Tyagi (2004)	and Tyagi	weigthed	weigthed	weigthed	weigthed			Violations		
48:00:00	-1279.92	1279.92	250	76.2	15.17	20.72	0.34	32.38	25.91	0.74	1.00	1.00	1.00	4.82	0.91	0.74	0.74	26519.9	435.2	41443.8	33162.7	0	0	0	0	
49:00:00	-1407.3	1407.3	237.74	72.4632	9.85	21.72	0.33	33.79	27.03	0.73	1.00	1.00	1.00	4.88	0.90	0.73	0.73	30566.6	464.4	47552.7	38039.3	0	0	0	0	
50:00:00	0	0	225	68.58	4.33	22.72	0.33	35.17	28.14	0.72	1.00	1.00	1.00	4.95	0.90	0.72	0.72	0.0	0.0	0.0	0.0	0	0	0	0	
51:00:00	0	0	225	68.58	4.33	23.72	0.32	36.51	29.21	0.70	1.00	1.00	1.00	5.02	0.89	0.70	0.70	0.0	0.0	0.0	0.0	0	0	0	0	
52:00:00	0	0	225	68.58	4.33	24.72	0.31	37.84	30.27	0.69	1.00	1.00	1.00	5.09	0.89	0.69	0.69	0.0	0.0	0.0	0.0	0	0	0	0	
53:00:00	0	0	225	68.58	4.33	25.72	0.31	39.12	31.3	0.68	1.00	1.00	1.00	5.17	0.88	0.68	0.68	0.0	0.0	0.0	0.0	0	0	0	0	
54:00:00	0	0	225	68.58	4.33	26.72	0.3	40.39	32.31	0.67	1.00	1.00	1.00	5.25	0.87	0.67	0.67	0.0	0.0	0.0	0.0	0	0	0	0	
55:00:00	0	0	225	68.58	4.33	27.72	0.29	41.63	33.3	0.65	1.00	1.00	1.00	5.34	0.87	0.65	0.65	0.0	0.0	0.0	0.0	0	0	0	0	
56:00:00	0	0	225	68.58	4.33	28.72	0.29	42.85	34.28	0.64	1.00	1.00	1.00	5.43	0.86	0.64	0.64	0.0	0.0	0.0	0.0	0	0	0	0	
57:00:00	0	0	225	68.58	4.33	29.72	0.28	44.04	35.23	0.63	1.00	1.00	1.00	5.53	0.85	0.63	0.63	0.0	0.0	0.0	0.0	0	0	0	0	
58:00:00	0	0	225	68.58	4.33	30.72	0.28	45.2	36.16	0.62	1.00	1.00	1.00	5.64	0.84	0.62	0.62	0.0	0.0	0.0	0.0	0	0	0	0	
59:00:00	0	0	225	68.58	4.33	31.72	0.27	46.34	37.07	0.60	1.00	1.00	1.00	5.75	0.83	0.60	0.60	0.0	0.0	0.0	0.0	0	0	0	0	
60:00:00	0	0	225	68.58	4.33	32.72	0.26	47.46	37.97	0.59	1.00	1.00	1.00	5.86	0.83	0.59	0.59	0.0	0.0	0.0	0.0	0	0	0	0	
61:00:00	0	0	225	68.58	4.33	33.72	0.26	48.56	38.84	0.58	1.00	1.00	1.00	5.99	0.82	0.58	0.58	0.0	0.0	0.0	0.0	0	0	0	0	
62:00:00	0	0	225	68.58	4.33	34.72	0.25	49.63	39.7	0.57	1.00	1.00	1.00	6.12	0.81	0.57	0.57	0.0	0.0	0.0	0.0	0	0	0	0	
63:00:00	0	0	225	68.58	4.33	35.72	0.25	50.68	40.54	0.55	1.00	1.00	1.00	6.26	0.80	0.55	0.55	0.0	0.0	0.0	0.0	0	0	0	0	
64:00:00	0	0	225	68.58	4.33	36.72	0.24	51.7	41.36	0.54	1.00	1.00	1.00	6.42	0.79	0.54	0.54	0.0	0.0	0.0	0.0	0	0	0	0	
65:00:00	0	0	225	68.58	4.33	37.72	0.24	52.71	42.17	0.53	1.00	1.00	1.00	6.58	0.78	0.53	0.53	0.0	0.0	0.0	0.0	0	0	0	0	
66:00:00	0	0	225	68.58	4.33	38.72	0.23	53.7	42.96	0.52	1.00	1.00	1.00	6.76	0.77	0.52	0.52	0.0	0.0	0.0	0.0	0	0	0	0	
67:00:00	593.47	593.47	225	68.58	4.33	39.72	0.23	54.66	43.73	0.50	1.00	1.00	1.00	6.94	0.76	0.50	0.50	23572.6	136.5	32439.1	25952.4	0	0	0	0	
68:00:00	-338.07	338.07	230.69	70.3143	6.8	40.72	0.22	56.29	45.03	0.49	1.00	1.00	1.00	7.15	0.75	0.49	0.49	13766.2	74.4	19030.0	15223.3	0	0	0	0	
69:00:00	1111.37	1111.37	227.86	69.4517	5.57	41.72	0.22	57.2	45.76	0.48	1.00	1.00	1.00	7.37	0.74	0.48	0.48	46366.4	244.5	63570.4	50856.3	0	0	0	0	
70:00:00	917.42	917.42	235.48	71.7743	8.87	34.63	0.27	48.79	39.03	0.57	1.00	1.00	1.00	6.11	0.81	0.57	0.57	31770.3	247.7	44760.9	35806.9	0	0	0	0	
71:00:00	1168.46	1168.46	247.21	75.3496	13.96	24.53	0.35	35.57	28.46	0.69	1.00	1.00	1.00	5.08	0.89	0.69	0.69	28662.3	409.0	41562.1	33254.4	0	0	0	0	
72:00:00	-1279.92	1279.92	250	76.2	15.17	23.96	0.35	34.92	27.93	0.70	1.00	1.00	1.00	5.04	0.89	0.70	0.70	30666.9	448.0	44694.8	35748.2	0	0	0	0	
					min	20.72	0.22	32.38	25.91					min	0.74	0.48	0.48	**28.6**	**0.3**	**41.4**	**33.1**		0	0	0	0
					max	41.72	0.35	57.2	45.76					max	0.91	0.74	0.74									
					q1	24.625	0.245	37.175	29.74					q1	0.79	0.55	0.55					F1	=		0	
					q2	36.22	0.315	51.19	40.95					q2	0.89	0.69	0.69					F2	=		0	

median	30.72	0.28	45.2	36.16	median	0.84	0.62	0.62

nse	=	0
F3	=	0
CCME WQI	=	100
MCWQI	=	100

Time Series Table - Node 165

Time Hours	Demand GPM		Head ft	Head m	Pressure psi	Age hours	Chlorine mg/L	THM ug/L	HAA6 ug/L	Calculated sub-indices: age	Chlorine	THM	HAA6
48:00:00	-2246.7	2246.7	250	76.2	15.17	48	0	62.31	49.85	0.40	0.10	0.90	1.00
49:00:00	123.73	123.73	228.48	69.6407	5.84	49	0	63.1	50.48	0.39	0.10	0.86	1.00
50:00:00	-1070.45	1070.45	228.98	69.7931	6.06	50	0	63.82	51.06	0.38	0.10	0.83	1.00
51:00:00	-1335.16	1335.16	225	68.58	4.33	51	0	64.57	51.66	0.36	0.10	0.79	1.00
52:00:00	0	0	225	68.58	4.33	52	0	65.31	52.25	0.35	0.10	0.76	1.00
53:00:00	0	0	225	68.58	4.33	53	0	66.03	52.83	0.34	0.10	0.73	1.00
54:00:00	0	0	225	68.58	4.33	54	0	66.74	53.39	0.33	0.10	0.70	1.00
55:00:00	0	0	225	68.58	4.33	55	0	67.43	53.94	0.31	0.10	0.67	1.00
56:00:00	0	0	225	68.58	4.33	56	0	68.11	54.49	0.30	0.10	0.64	1.00
57:00:00	0	0	225	68.58	4.33	57	0	68.77	55.02	0.29	0.10	0.61	1.00
58:00:00	0	0	225	68.58	4.33	58	0	69.42	55.54	0.28	0.10	0.58	1.00
59:00:00	0	0	225	68.58	4.33	59	0	70.06	56.05	0.26	0.10	0.55	1.00
60:00:00	0	0	225	68.58	4.33	60	0	70.68	56.55	0.25	0.10	0.52	1.00
61:00:00	0	0	225	68.58	4.33	61	0	71.29	57.04	0.24	0.10	0.49	1.00
62:00:00	0	0	225	68.58	4.33	62	0	71.89	57.51	0.23	0.10	0.46	1.00
63:00:00	-27.52	27.52	225	68.58	4.33	63	0	72.48	57.98	0.21	0.10	0.44	1.00
64:00:00	92.64	92.64	225	68.58	4.33	64	0	73.05	58.44	0.20	0.10	0.41	1.00
65:00:00	-14.58	14.58	225.89	68.8513	4.72	65	0	73.6	58.88	0.19	0.10	0.39	1.00
66:00:00	1335.55	1335.55	225.75	68.8086	4.66	66	0	74.15	59.32	0.18	0.10	0.36	1.00
67:00:00	-1412.46	1412.46	238.54	72.707	10.2	67	0	74.22	59.37	0.16	0.10	0.36	1.00
68:00:00	2696.28	2696.28	225.01	68.583	4.34	68	0	74.75	59.8	0.15	0.10	0.34	1.00
69:00:00	-2634.93	2634.93	248.92	75.8708	14.7	69	0	73.59	58.87	0.14	0.10	0.39	1.00
70:00:00	-42.79	42.79	245.02	74.6821	13.01	70	0	73.92	59.14	0.13	0.10	0.37	1.00
71:00:00	0	0	250	76.2	15.17	71	0	74.34	59.47	0.11	0.10	0.35	1.00
72:00:00	-2246.7	2246.7	250	76.2	15.17	72	0	74.87	59.89	0.10	0.10	0.33	1.00
					min	48	0	62.31	49.85				
					max	72	0	74.87	59.89				
					q1	53.5	0	66.385	53.11				
					q2	66.5	0	73.76	59.01				
					median	60	0	70.68	56.55				

Time Hours		Water quality indices: (2001)	Tyagi (2004)	and Tyagi	Flow weighted mean: weigthed	weigthed	weigthed	weigthed		CCME Calculations: Violations			
48:00:00	108.50	0.19	0.10	0.09	107841.6	0.0	139991.9	111998.0	0	1.00000	0	0	
49:00:00	109.01	0.19	0.10	0.09	6062.8	0.0	7807.4	6245.9	0	1.00000	0	0	
50:00:00	109.57	0.19	0.10	0.09	53522.5	0.0	68316.1	54657.2	0	1.00000	0	0	
51:00:00	110.19	0.19	0.10	0.09	68093.2	0.0	86211.3	68974.4	0	1.00000	0	0	
52:00:00	110.89	0.19	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
53:00:00	111.66	0.19	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
54:00:00	112.53	0.19	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
55:00:00	113.50	0.19	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
56:00:00	114.59	0.19	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
57:00:00	115.83	0.19	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
58:00:00	117.24	0.18	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
59:00:00	118.85	0.18	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
60:00:00	120.71	0.18	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
61:00:00	122.86	0.18	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0	
62:00:00	125.38	0.18	0.09	0.08	0.0	0.0	0.0	0.0	0	1.00000	0	0	
63:00:00	128.35	0.18	0.09	0.08	1733.8	0.0	1994.6	1595.6	0	1.00000	0	0	
64:00:00	131.87	0.17	0.09	0.08	5929.0	0.0	6767.4	5413.9	0	1.00000	0	0	
65:00:00	136.09	0.17	0.09	0.08	947.7	0.0	1073.1	858.5	0	1.00000	0	0	
66:00:00	141.23	0.17	0.09	0.08	88146.3	0.0	99031.0	79224.8	0	1.00000	0	0	
67:00:00	146.58	0.17	0.09	0.08	94634.8	0.0	104832.8	83857.8	0	1.00000	0	0	
68:00:00	154.29	0.16	0.09	0.07	183347.0	0.0	201546.9	161237.5	0	1.00000	0	0	
69:00:00	160.52	0.16	0.09	0.07	181810.2	0.0	193904.5	155118.3	0	1.00000	0	0	
70:00:00	172.16	0.15	0.08	0.07	2995.3	0.0	3163.0	2530.6	0	1.00000	0	0	
71:00:00	187.96	0.15	0.08	0.07	0.0	0.0	0.0	0.0	0	1.00000	0	0	
72:00:00	210.14	0.14	0.08	0.06	161762.4	0.0	168210.4	134554.9	0	1.00000	0	0	
	min	0.14	0.08	0.06	**62.6**	**0.0**	**70.9**	**56.7**	0	25		0	0
	max	0.19	0.10	0.09									
	q1	0.17	0.09	0.08									
	q2	0.19	0.10	0.09									
	median	0.18	0.10	0.09									

F1	=	25
F2	=	0.25
nse	=	0.25
F3	=	20
CCME WQI	=	81.514667
MCWQI	=	88.81966

SMGA Solution 2

Time Series Table - Tank 145N

Time	Demand		Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean					CCME Calculations		
Hours	GPM		ft	m	psi	hours	mg/L	ug/L	ug/L	Water age	Chlorine	THM	HAA6		OWQI (2001)	Swamee and Tyagi (2004)	Swamee and Tyagi (2007)	Flow weigthed mean water age	Flow weigthed mean chlorine	Flow weigthed mean THM	Flow weigthed mean HAA6			Violations	
12:00:00 AM	0	0	240	73.152	13	26.6	0.28	41.22	33.04	0.67	1.00	1.00	1.00	5.24	0.87	0.67	0.67	0.0	0.0	0.0	0.0	0	0	0	0
1:00:00 AM	-5896.59	5896.59	240	73.152	13	27.6	0.28	42.44	34.02	0.66	1.00	1.00	1.00	5.33	0.87	0.66	0.66	162745.9	1651.0	250251.3	200602.0	0	0	0	0
2:00:00 AM	-5488.29	5488.29	237.29	72.326	11.82	28.6	0.27	43.64	34.98	0.64	1.00	1.00	1.00	5.42	0.86	0.64	0.64	156965.1	1481.8	239509.0	191980.4	0	0	0	0
3:00:00 AM	-5025.4	5025.4	234.4	71.4451	10.57	29.6	0.27	44.81	35.92	0.63	1.00	1.00	1.00	5.52	0.85	0.63	0.63	148751.8	1356.9	225188.2	180512.4	0	0	0	0
4:00:00 AM	-5414.8	5414.8	231.11	70.4423	9.15	30.6	0.26	45.96	36.83	0.62	1.00	1.00	1.00	5.62	0.84	0.62	0.62	165692.9	1407.8	248864.2	199427.1	0	0	0	0
5:00:00 AM	1009.62	1009.62	225.29	68.6684	6.62	31.6	0.26	47.08	37.73	0.61	1.00	1.00	1.00	5.73	0.84	0.61	0.61	31904.0	262.5	47532.9	38093.0	0	0	0	0
6:00:00 AM	315.08	315.08	222.82	67.9155	5.55	32.6	0.25	48.21	38.63	0.59	1.00	1.00	1.00	5.85	0.83	0.59	0.59	10271.6	78.8	15190.0	12171.5	0	0	0	0
7:00:00 AM	-817.78	817.78	221.3	67.4522	4.9	33.6	0.24	49.28	39.48	0.58	1.00	1.00	1.00	5.97	0.82	0.58	0.58	27477.4	196.3	40300.2	32286.0	0	0	0	0
8:00:00 AM	0	0	220	67.056	4.33	34.6	0.24	50.33	40.32	0.57	1.00	1.00	1.00	6.11	0.81	0.57	0.57	0.0	0.0	0.0	0.0	0	0	0	0
9:00:00 AM	0	0	220	67.056	4.33	35.6	0.23	51.37	41.15	0.56	1.00	1.00	1.00	6.25	0.80	0.56	0.56	0.0	0.0	0.0	0.0	0	0	0	0
10:00:00 AM	0	0	220	67.056	4.33	36.6	0.23	52.38	41.96	0.54	1.00	1.00	1.00	6.40	0.79	0.54	0.54	0.0	0.0	0.0	0.0	0	0	0	0
11:00:00 AM	0	0	220	67.056	4.33	37.6	0.23	53.37	42.75	0.53	1.00	1.00	1.00	6.56	0.78	0.53	0.53	0.0	0.0	0.0	0.0	0	0	0	0
12:00:00 PM	0	0	220	67.056	4.33	38.6	0.22	54.34	43.53	0.52	1.00	1.00	1.00	6.73	0.77	0.52	0.52	0.0	0.0	0.0	0.0	0	0	0	0
1:00:00 PM	164.16	164.16	220	67.056	4.33	39.6	0.22	55.29	44.29	0.51	1.00	1.00	1.00	6.92	0.76	0.51	0.51	6500.7	36.1	9076.4	7270.6	0	0	0	0
2:00:00 PM	-213.87	213.87	220.21	67.12	4.42	40.6	0.21	56.24	45.04	0.49	1.00	1.00	1.00	7.12	0.75	0.49	0.49	8683.1	44.9	12028.0	9632.7	0	0	0	0
3:00:00 PM	648.08	648.08	220.15	67.1017	4.4	41.6	0.21	57.15	45.77	0.48	1.00	1.00	1.00	7.34	0.74	0.48	0.48	26960.1	136.1	37037.8	29662.6	0	0	0	0
4:00:00 PM	1182.22	1182.22	220.97	67.3517	4.75	40.13	0.22	55.16	44.18	0.50	1.00	1.00	1.00	7.03	0.75	0.50	0.50	47442.5	260.1	65211.3	52230.5	0	0	0	0
5:00:00 PM	-290.9	290.9	222.46	67.8058	5.4	37.38	0.24	51.81	41.51	0.53	1.00	1.00	1.00	6.52	0.78	0.53	0.53	10873.8	69.8	15071.5	12075.3	0	0	0	0
6:00:00 PM	3619.2	3619.2	222.09	67.693	5.24	38.38	0.24	52.81	42.31	0.52	1.00	1.00	1.00	6.69	0.77	0.52	0.52	138904.9	868.6	191130.0	153128.4	0	0	0	0
7:00:00 PM	2537.16	2537.16	226.65	69.0829	7.22	39.38	0.23	53.94	43.21	0.51	1.00	1.00	1.00	6.88	0.76	0.51	0.51	99913.4	583.5	136854.4	109630.7	0	0	0	0
8:00:00 PM	3985.75	3985.75	229.85	70.0583	8.6	35.62	0.26	49.61	39.75	0.55	1.00	1.00	1.00	6.25	0.80	0.55	0.55	141972.4	1036.3	197733.1	158433.6	0	0	0	0
9:00:00 PM	1108.78	1108.78	234.88	71.5914	10.78	31.34	0.29	44.74	35.87	0.61	1.00	1.00	1.00	5.70	0.84	0.61	0.61	34749.2	321.5	49606.8	39771.9	0	0	0	0
10:00:00 PM	2864.92	2864.92	238.23	72.6125	12.23	29.62	0.3	42.74	34.27	0.63	1.00	1.00	1.00	5.52	0.85	0.63	0.63	84858.9	859.5	122446.7	98180.8	0	0	0	0
11:00:00 PM	0	0	240	73.152	13	29.39	0.31	42.51	34.08	0.63	1.00	1.00	1.00	5.50	0.85	0.63	0.63	0.0	0.0	0.0	0.0	0	0	0	0
12:00:00 AM	0	0	240	73.152	13	30.39	0.3	43.71	35.04	0.62	1.00	1.00	1.00	5.60	0.85	0.62	0.62	0.0	0.0	0.0	0.0	0	0	0	0
					min	26.6	0.21	41.22	33.04					min	0.74	0.48	0.48	**32.1**	**0.3**	**46.9**	**37.6**	0	0	0	0
					max	41.6	0.31	57.15	45.77					max	0.87	0.67	0.67								
					q1	30.005	0.23	44.225	35.455					q1	0.77	0.52	0.52					F1	=		0
					q2	38.49	0.275	53.655	42.98					q2	0.85	0.62	0.62					F2	=		0
					median	34.6	0.24	49.61	39.75					median	0.81	0.57	0.57					nse	=		0
					std	4.5569	0.02954	4.99926	3.99246					std	0.04113	0.05696	0.05696					F3	=		0
					mean	33.9948	0.24997	48.9591	39.2302					mean	0.80833	0.56865	0.56865					CCME WC =			100
																						MCWQI	=		100

Time Series Table - Tank 41E

Time	Demand		Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean					CCME Calculations		
Hours	GPM		ft	m	psi	hours	mg/L	ug/L	ug/L	age	Chlorine	THM	HAA6		(2001)	and	and	weigthe	weigthe	weigthe	weigthe			Violations	
48:00:00	-1371.11	1371.11	250	76.2	15.17	21.38	0.34	32.9	26.4	0.73	1.00	1.00	1.00	4.86	0.91	0.73	0.73	29314.3	466.2	45109.5	36197.3	0	0	0	0
49:00:00	-896.3	896.3	236.86	72.1949	9.47	22.38	0.33	34.3	27.51	0.72	1.00	1.00	1.00	4.93	0.90	0.72	0.72	20059.2	295.8	30743.1	24657.2	0	0	0	0
50:00:00	-556.46	556.46	231.51	70.5642	7.15	23.38	0.33	35.66	28.6	0.71	1.00	1.00	1.00	5.00	0.89	0.71	0.71	13010.0	183.6	19843.4	15914.8	0	0	0	0
51:00:00	-716.02	716.02	228.58	69.6712	5.88	24.38	0.32	36.99	29.67	0.70	1.00	1.00	1.00	5.07	0.89	0.70	0.70	17456.6	229.1	26485.6	21244.3	0	0	0	0
52:00:00	0	0	225	68.58	4.33	25.38	0.31	38.3	30.71	0.68	1.00	1.00	1.00	5.15	0.88	0.68	0.68	0.0	0.0	0.0	0.0	0	0	0	0
53:00:00	0	0	225	68.58	4.33	26.38	0.31	39.58	31.73	0.67	1.00	1.00	1.00	5.23	0.87	0.67	0.67	0.0	0.0	0.0	0.0	0	0	0	0
54:00:00	0	0	225	68.58	4.33	27.38	0.3	40.83	32.73	0.66	1.00	1.00	1.00	5.31	0.87	0.66	0.66	0.0	0.0	0.0	0.0	0	0	0	0
55:00:00	0	0	225	68.58	4.33	28.38	0.29	42.06	33.71	0.65	1.00	1.00	1.00	5.40	0.86	0.65	0.65	0.0	0.0	0.0	0.0	0	0	0	0
56:00:00	0	0	225	68.58	4.33	29.38	0.29	43.26	34.67	0.63	1.00	1.00	1.00	5.50	0.85	0.63	0.63	0.0	0.0	0.0	0.0	0	0	0	0
57:00:00	0	0	225	68.58	4.33	30.38	0.28	44.44	35.62	0.62	1.00	1.00	1.00	5.60	0.85	0.62	0.62	0.0	0.0	0.0	0.0	0	0	0	0
58:00:00	0	0	225	68.58	4.33	31.38	0.27	45.6	36.54	0.61	1.00	1.00	1.00	5.71	0.84	0.61	0.61	0.0	0.0	0.0	0.0	0	0	0	0
59:00:00	0	0	225	68.58	4.33	32.38	0.27	46.73	37.45	0.60	1.00	1.00	1.00	5.82	0.83	0.60	0.60	0.0	0.0	0.0	0.0	0	0	0	0
60:00:00	0	0	225	68.58	4.33	33.38	0.26	47.84	38.33	0.58	1.00	1.00	1.00	5.94	0.82	0.58	0.58	0.0	0.0	0.0	0.0	0	0	0	0
61:00:00	0	0	225	68.58	4.33	34.38	0.26	48.93	39.2	0.57	1.00	1.00	1.00	6.08	0.81	0.57	0.57	0.0	0.0	0.0	0.0	0	0	0	0
62:00:00	0	0	225	68.58	4.33	35.38	0.25	49.99	40.05	0.56	1.00	1.00	1.00	6.21	0.80	0.56	0.56	0.0	0.0	0.0	0.0	0	0	0	0
63:00:00	0	0	225	68.58	4.33	36.38	0.25	51.03	40.88	0.55	1.00	1.00	1.00	6.36	0.79	0.55	0.55	0.0	0.0	0.0	0.0	0	0	0	0
64:00:00	0	0	225	68.58	4.33	37.38	0.24	52.05	41.69	0.53	1.00	1.00	1.00	6.52	0.78	0.53	0.53	0.0	0.0	0.0	0.0	0	0	0	0
65:00:00	0	0	225	68.58	4.33	38.38	0.24	53.05	42.49	0.52	1.00	1.00	1.00	6.69	0.77	0.52	0.52	0.0	0.0	0.0	0.0	0	0	0	0
66:00:00	615.67	615.67	225	68.58	4.33	39.38	0.23	54.03	43.27	0.51	1.00	1.00	1.00	6.88	0.76	0.51	0.51	24245.1	141.6	33264.7	26640.0	0	0	0	0
67:00:00	314.62	314.62	230.9	70.3783	6.89	40.38	0.23	55.24	44.24	0.50	1.00	1.00	1.00	7.08	0.75	0.50	0.50	12704.4	72.4	17379.6	13918.8	0	0	0	0
68:00:00	445.42	445.42	233.91	71.2958	8.19	36.13	0.26	49.74	39.85	0.55	1.00	1.00	1.00	6.33	0.80	0.55	0.55	16093.0	115.8	22155.2	17750.0	0	0	0	0
69:00:00	320.91	320.91	238.18	72.5973	10.04	31.33	0.3	43.64	34.98	0.61	1.00	1.00	1.00	5.70	0.84	0.61	0.61	10054.1	96.3	14004.5	11225.4	0	0	0	0
70:00:00	348.67	348.67	242.32	73.8591	11.84	28.12	0.33	39.53	31.7	0.65	1.00	1.00	1.00	5.38	0.86	0.65	0.65	9804.6	115.1	13782.9	11052.8	0	0	0	0
71:00:00	0	0	250	76.2	15.17	23.51	0.37	33.56	26.93	0.71	1.00	1.00	1.00	5.01	0.89	0.71	0.71	0.0	0.0	0.0	0.0	0	0	0	0
72:00:00	-1371.1	1371.1	250	76.2	15.17	24.51	0.36	34.95	28.04	0.69	1.00	1.00	1.00	5.08	0.89	0.69	0.69	33605.7	493.6	47919.9	38445.6	0	0	0	0
					min	21.38	0.23	32.9	26.4					min	0.75	0.50	0.50	**26.8**	**0.3**	**38.9**	**31.2**	0	0	0	0
					max	40.38	0.37	55.24	44.24					max	0.91	0.73	0.73								
					q1	24.945	0.255	37.645	30.19					q1	0.80	0.55	0.55					F1	=		0
					q2	35.755	0.325	49.865	39.95					q2	0.88	0.69	0.69					F2	=		0
					median	30.38	0.29	43.64	34.98					median	0.85	0.62	0.62					nse	=		0
																						F3	=		0
																						CCME WC =			100
																						MCWQI	=		100

Time Series Table - Tank 42E

Time	Demand		Head	Head	Pressure	Age	Chlorine	THM	HAA6	Calculated sub-indices					Water quality indices			Flow weighted mean					CCME Calculations		
Hours	GPM		ft	m	psi	hours	mg/L	ug/L	ug/L	age	Chlorine	THM	HAA6		(2001)	and	and	weigthe	weigthe	weigthe	weigthe			Violations	
48:00:00	-1867.34	1867.34	250	76.2	15.17	48	0	66.73	53.38	0.40	0.10	0.70	1.00	109.31	0.19	0.10	0.09	89632.3	0.0	124607.6	99678.6	0	1.00000	0	0
49:00:00	4369.35	4369.35	232.11	70.7471	7.41	49	0	67.42	53.94	0.39	0.10	0.67	1.00	109.91	0.19	0.10	0.09	214098.2	0.0	294581.6	235682.7	0	1.00000	0	0
50:00:00	3739.14	3739.14	231.78	70.6465	7.27	50	0	68.39	54.71	0.38	0.10	0.62	1.00	110.69	0.19	0.10	0.09	186957.0	0.0	255719.8	204568.3	0	1.00000	0	0
51:00:00	2588.56	2588.56	231.72	70.6283	7.24	51	0	69.4	55.52	0.36	0.10	0.58	1.00	111.61	0.19	0.10	0.09	132016.6	0.0	179646.1	143716.9	0	1.00000	0	0
52:00:00	2538.58	2538.58	228.35	69.6011	5.78	52	0	70.35	56.28	0.35	0.10	0.53	1.00	112.67	0.19	0.10	0.09	132006.2	0.0	178589.1	142871.3	0	1.00000	0	0
53:00:00	-4430.56	4430.56	244.24	74.4444	12.67	53	0	71.74	57.39	0.34	0.10	0.47	1.00	114.27	0.19	0.10	0.09	234819.7	0.0	317848.4	254269.8	0	1.00000	0	0
54:00:00	-2422.03	2422.03	234.22	71.3903	8.33	54	0	72.72	58.18	0.33	0.10	0.43	1.00	115.94	0.19	0.10	0.09	130789.6	0.0	176130.0	140913.7	0	1.00000	0	0
55:00:00	-1009.94	1009.94	227.73	69.4121	5.52	55	0	73.5	58.8	0.31	0.10	0.39	1.00	117.73	0.18	0.10	0.09	55546.7	0.0	74230.6	59384.5	0	1.00000	0	0
56:00:00	0	0	225	68.58	4.33	56	0	74.05	59.24	0.30	0.10	0.37	1.00	119.51	0.18	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0
57:00:00	0	0	225	68.58	4.33	57	0	74.59	59.67	0.29	0.10	0.34	1.00	121.58	0.18	0.10	0.09	0.0	0.0	0.0	0.0	0	1.00000	0	0
58:00:00	0	0	225	68.58	4.33	58	0	75.12	60.09	0.28	0.10	0.32	1.00	124.02	0.18	0.10	0.08	0.0	0.0	0.0	0.0	0	1.00000	0	0.00150
59:00:00	0	0	225	68.58	4.33	59	0	75.63	60.51	0.26	0.10	0.30	0.98	126.92	0.18	0.09	0.08	0.0	0.0	0.0	0.0	0	1.00000	0	0.00850
60:00:00	110.73	110.73	225	68.58	4.33	60	0	76.14	60.91	0.25	0.10	0.27	0.96	130.44	0.18	0.09	0.08	6643.8	0.0	8431.0	6744.6	0	1.00000	0	0.01517
61:00:00	-105.42	105.42	226.06	68.9031	4.79	61	0	76.83	61.47	0.24	0.10	0.24	0.93	135.86	0.17	0.09	0.08	6430.6	0.0	8099.4	6480.2	0	1.00000	0	0.02450
62:00:00	314.47	314.47	225.05	68.5952	4.36	62	0	77.32	61.85	0.23	0.10	0.22	0.92	141.49	0.17	0.09	0.08	19497.1	0.0	24314.8	19450.0	0	1.00000	0	0.03083
63:00:00	300.74	300.74	226.22	68.9519	4.86	63	0	78.05	62.44	0.21	0.10	0.19	0.89	151.78	0.16	0.09	0.07	18946.6	0.0	23472.8	18778.2	0	1.00000	0	0.04067
64:00:00	-369.03	369.03	229.1	69.8297	6.11	64	0	78.88	63.11	0.20	0.10	0.15	0.86	170.56	0.15	0.08	0.07	23617.9	0.0	29109.1	23289.5	0	1.00000	0	0.05183
65:00:00	1236.27	1236.27	225.57	68.7537	4.58	65	0	79.32	63.46	0.19	0.10	0.13	0.84	188.48	0.15	0.08	0.06	80357.6	0.0	98060.9	78453.7	0	1.00000	0	0.05767
66:00:00	-162.37	162.37	237.41	72.3626	9.71	66	0	80.66	64.53	0.18	0.10	0.10	0.80	234.23	0.13	0.07	0.06	10716.4	0.0	13096.8	10477.7	0	1.00000	0.00825	0.07550
67:00:00	1202.55	1202.55	235.86	71.8901	9.04	67	0	81.07	64.85	0.16	0.10	0.10	0.78	239.51	0.13	0.07	0.06	80570.9	0.0	97490.7	77985.4	0	1.00000	0.01337	0.08083
68:00:00	-1119.97	1119.97	247.38	75.4014	14.03	68	0	82.06	65.65	0.15	0.10	0.10	0.75	246.24	0.13	0.07	0.06	76158.0	0.0	91904.7	73526.0	0	1.00000	0.02575	0.09417
69:00:00	3259.66	3259.66	236.65	72.1309	9.38	69	0	82.43	65.95	0.14	0.10	0.10	0.73	254.76	0.13	0.07	0.06	224916.5	0.0	268693.8	214974.6	0	1.00000	0.03038	0.09917
70:00:00	791.64	791.64	247.74	75.5112	14.19	70	0	83.07	66.46	0.13	0.10	0.10	0.71	265.99	0.12	0.07	0.05	55414.8	0.0	65761.5	52612.4	0	1.00000	0.03837	0.10767
71:00:00	0	0	250	76.2	15.17	71	0	83.45	66.76	0.11	0.10	0.10	0.70	281.08	0.12	0.07	0.05	0.0	0.0	0.0	0.0	0	1.00000	0.04313	0.11267
72:00:00	-1867.35	1867.35	250	76.2	15.17	72	0	83.8	67.04	0.10	0.10	0.10	0.68	302.14	0.12	0.06	0.05	134449.2	0.0	156483.9	125187.1	0	1.00000	0.04750	0.11733
					min	48	0	66.73	53.38					min	0.12	0.06	0.05	**56.6**	**0.0**	**73.5**	**58.8**	0	25	7	15
					max	72	0	83.8	67.04					max	0.19	0.10	0.09								
					q1	53.5	0	72.23	57.785					q1	0.13	0.07	0.06					F1	=		75
					q2	66.5	0	80.865	64.69					q2	0.19	0.10	0.09					F2	=		0.47
					median	60	0	76.14	60.91					median	0.18	0.09	0.08					nse	=		0.26125
																						F3	=		20.7134
																						CCME WC =			55.0755
																						MCWQI	=		72.9787