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USING TECHNO-ECONOMIC ASSESSMENTS TO DETERMINE THE DEGREE OF CENTRALIZATION IN MUNICIPAL WASTEWATER INFRASTRUCTURE IN THE CONTEXT OF URBAN ENVIRONMENTS

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USING TECHNO-ECONOMIC ASSESSMENTS TO DETERMINE THE DEGREE OF CENTRALIZATION IN MUNICIPAL WASTEWATER INFRASTRUCTURE IN THE CONTEXT OF URBAN ENVIRONMENTS

A THESIS APPROVED FOR THE
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

BY THE COMMITTEE CONSISTING OF

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To friends and family for their unwavering support throughout the years
and to the many mentors who showed me that my biggest obstacle was self-doubt,
I dedicate this thesis.

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ABSTRACT

Rapid urbanization, aging infrastructure, high energy demand, and water scarcity challenge the strong reliance and sustainability of centralized municipal wastewater infrastructure. On the other hand, decentralized wastewater treatment systems (DWWTS) have gained popularity as a potential cost-effective alternative compared to costly (capital, operational, and maintenance) centralized wastewater treatment systems (CWWTS). However, determining the extent to which a municipal wastewater infrastructure should be centralized remains a daunting task. Previous studies have attempted to numerically characterize the degree of centralization within areas that have existing infrastructure. Unfortunately, no study has been conducted to determine the degree of centralization for areas without extensive existing infrastructure.

This research aims to assess the viability of various decentralized treatment systems, in the context of urban cities with high population densities and potential of water scarcity, by comparing their economic and environmental performances to centralized wastewater infrastructure. Using two wastewater modeling and simulation softwares (GPS-X and CapdetWorks), the technical and economic performance of DWWTs are compared to that of CWWTs. Both suspended and attached growth treatment processes were analyzed. Examples of suspended growth treatment processes include conventional activated sludge (CAS), sequencing batch reactors (SBR) and membrane bioreactor (MBR). Examples of attached growth treatment processes analyzed included trickling filter (TF), rotating biological contactor (RBC) and integrated fixed-film activated sludge (IFAS). This research's main conclusion is that when keeping the technical performance constant, it is cost prohibitive to decentralize municipal wastewater infrastructure. This is primarily because when the influent flow is halved, the total treatment cost is not halved. It takes almost the same treatment unit ops to treat half of the flow as it would take to treat the full flow.

CHAPTER 1: INTRODUCTION

1.0 Introduction

Providing access to improved sanitation to each global citizen is undoubtedly one of the greatest challenges of the 21st century. According to a recent study by the World Bank Group, titled “Reducing Inequalities in Water Supply, Sanitation, and Hygiene in the Era of the Sustainable Development Goals”, globally about 4.5 billion people lack access to safely managed sanitation, and 2.1 billion to safely managed water (World Bank Group 2017). To tackle this problem, the World Bank estimates that $ 100 billion per year of investment is needed. This is a significant amount of money given that the majority of the people without access to safe drinking water and sanitation services for those who live in low-income countries. Thus, there is an urgent need for researchers, innovators and engineers to find alternatives to traditional means of delivering water and sanitation services that are economically affordable and sustainable.

Taking Rwanda as a study site of a low-income country, this chapter discusses some of the current wastewater management practices in Kigali (the capital city of Rwanda). Rwanda could also represent the other East African Countries (Uganda, Kenya, Tanzania and Burundi). These countries share the same income bracket and treat less than 20% of the municipal wastewater prior to discharging to the environment. Additionally, these countries have the same demographic characteristics. Therefore, understanding what is happening in one country paints the picture of what is currently happening in the region.

This chapter ends by discussing that a paradigm shift in municipal wastewater management is desperately needed if the United Nations’ sustainable development goal of ensuring that each global citizen has access to improved sanitation services is to be achieved by 2030.

1.1 Kigali-Rwanda Overview

Kigali, the capital city of Rwanda, has a population of approximately 1.3 million (Rwanda Population 2019 (Demographics, Maps, Graphs) n.d.) with a total surface area of 281.9 square miles, making it one of the most densely populated cities in Africa. However, it does not have a centralized modern wastewater treatment plant (Kazora and Mourad 2018). Most residential and commercial wastewater is treated using small treatment units (package plants) on site or directly discharged to the environment without treatment. This pollutes the sources of water supply causing the spread of waterborne diseases. Because the city is experiencing rapid population growth (mostly rural-urban migration), more stress is being put on the existing, inadequate sanitary sewer infrastructure. Currently, the most commonly used sanitary facilities in many residential neighborhoods are pit latrines and septic tank systems (Tsinda et al. 2013).

Pit latrines are an inexpensive way "to handle human waste and require little maintenance; however, they provide limited comfort, attract flies and spread diseases such as diarrhea and dysentery through contamination of the environment" (Tsinda et al., 2013). These systems do not only fail to protect the public health and the environment, but also are not sustainable. Unsuitable soil conditions and high-water table make pit latrines shallow, generally 2-3 meters deep. Moreover, large families cause these shallow pit latrines to quickly reach capacity. It is typical for a full latrine to be abandoned because they are too expensive to be emptied. In addition, some pit latrines are inaccessible due to narrow paths and steep slopes.

Furthermore, it can be argued that pit latrines and septic systems are not economically advantageous for private developers and business owners. Investment costs are high when business-owners are forced to provide their own on-site wastewater treatment systems. High population settlement, rapid population growth and inadequate sanitation facilities call for a robust and sustainable sanitary sewer infrastructure. This research will serve as a preliminary feasibility study of centralized and decentralized wastewater treatment facilities to help Kigali develop a sustainable sanitary infrastructure plan.

To provide improved sanitation services to its residents, Kigali's policymakers are considering a number of different solutions including centralized wastewater treatment facilities, commonly used in the western world (Rwirahira, 2018). However, these facilities come with a substantial cost to construct and maintain. Additionally, shortage of skilled personnel, imported technology and materials make the implementation and sustainability of centralized wastewater treatment systems (CWWTS) questionable.

On the other hand, given Kigali's terrain complexity and high population settlement, decentralized wastewater treatment systems (DWWTS) could be viable alternatives to costly CWWTS. DWWTS involve the collection and treatment of wastewater on the site or near the site wastewater is generated. There is a plethora of decentralized treatment schemes. Capital, operational and maintenance costs, as well as effluent quality govern the treatment technology of choice. However, there is not a single detailed study of economic feasibility of DWWTS. Therefore, policymakers cannot make informed decisions about whether a centralized or decentralized wastewater treatment system will be the best choice for a specific area. A techno-economic assessment of DWWTS means analysis of total annuity costs for various treatment and collection system configurations. This study would determine whether decentralizing or centralizing wastewater infrastructure would be a viability for Kigali, Rwanda.

Adapting a decentralized sanitary sewer infrastructure implies that schools, hospitals, commercial areas, industrial parks and residential neighborhoods could have their own small treatment plants, while in a centralized wastewater infrastructure all municipal wastewater is collected and treated at one central location. While there is robust data on technical and economic performance of CWWTS, the opposite is true for DWWTS although theoretically, the existing suggests that decentralized treatment systems could be comparable, if not sustainable alternatives to centralized treatment systems. However, not enough research has been done to assess environmental and economic performance of DWWTS especially in the context of urban environments with high population densities and rapid urbanization growth.

Previous studies have identified that there might be a direct correlation between degree of centralization and investment costs. However, quantifying the extent to which a centralized infrastructure should be adapted remains a complex task, primarily because the degree of centralization arguably depends on population settlement, the urban sprawl towards the city's open greenfield, the terrain complexity, the available wastewater discharge options, the demand of implementing water reuse, and availability of monetary funds dedicated towards municipal wastewater management. All these factors considerably vary from one city to another and thus make the task of determining the degree of centralization very challenging.

Moreover, providing comprehensive assessment and comparison of techno-economic performances of DWWTS to a conventional centralized activated sludge would equip the policy makers and urban planners of developing countries to make informed decisions about the most viable wastewater management strategy to adapt.

1.2 Motivation

1.2.1 Kigali’s Sewage Escalating Problem

The lack of proper wastewater management strategies in Kigali is a serious problem that deserves special attention. The majority of wastewater produced in Kigali is discharged into the environment with minimal treatment (using minimum treatment and consequently producing poor effluent quality). Pit latrines are the most commonly used sanitation facilities in many low-income neighborhoods. “Low-cost, simplicity of construction, little or no water usage, and ease in operation and maintenance, the ability to cope with bulky varied anal cleansing materials and the ease for regular improvement of the facility makes it convenient and easily taken up” (Nakagiri et al. 2016). However, pit latrines have a short lifespan, odor nuisance and provide minimal protection for the public and environment. In a highly populated cities, like Kigali, the use of pit latrines is unstainable, and the risk of disease transmission is high with the public health concern only likely to worsen with increasing population. In case of natural disasters such as earthquakes or heavy rainstorms, the majority of Kigali’s residents could face significant public-health concerns.

In most low-income residential areas, greywater (wastewater from kitchen related activities, bathing and laundry) are directly discharged to waterbodies through open channels without any treatment Allowing this practice to continue means a large amount of organic substances and other toxic chemicals will end up in our rivers and lakes creating unhealthy environment for the public and critically endangering aquatic biosystems. Polluted waterbodies are not only detrimental to the public health and environment, but also to the economy. For example, economic activities such as fishing and recreational activities (swimming, surfing, rafting, kayaking etc.) diminish when rivers and lakes contain excessive amount of harmful contaminants.

In a few affluent neighborhoods, domestic wastewater is treated to a minimal level through the use of on-site treatment systems. Additionally, new subdivision development as well as intuitional buildings such as hotels, banks, schools, and hospitals are mandated to install a wastewater management system. Due to lack of environmental regulations and effluent quality standards, the treatment choice is often left to the property owner to decide. Consequently, property owners tend to select the most affordable treatment options which are not necessarily the best available treatment technologies nor the most sustainable.

Commonly used on-site treatment include septic tanks and occasionally activated sludge treatment systems. Although septic tank systems, if well maintained, have potential to protect public health and the environment, these systems are not suitable in high-density areas with high water table and sensitive soils. It should be noted that septic tanks are limited to affluent communities.

1.2.4 Sustainable Sanitation Solutions

The Agenda 2030 for Sustainable Development adopted by all United Nations members' serves as a roadmap towards a peaceful and prosperous planet (Weststrate et al., 2018). For example, goal 6 of the 17 Sustainable Development Goals (SDGs) aims to ensure availability and sustainable management of water and improved sanitation for all global citizens by 2030. However, this ambitious goal is in jeopardy, primarily because many developing countries lack financial capacities to address sanitation needs for their citizens. To make this goal a reality, the World Bank estimates that annul investment of $ 100 billion is needed. It is, however, not clear where this money will come from. Developing countries would have to either borrow heavily, this is unsustainable practice because it puts burden to repay debts to future generations, in order to install centralized wastewater treatment systems, commonly used in wealthy countries, or engineer new innovative approaches to urban wastewater management.

The existing literature suggests that DWWTS are the only option for developing countries to provide the desperately needed improved sanitation (Daigger 2009). However, there are various decentralized treatment approaches with a varying degree of technologies. Furthermore, decentralization does not necessarily mean sustainability. For example, Kigali’s current sanitation facilities can be considered decentralized and yet far away from being sustainable. “To qualify as sustainable sanitation, a sanitation system has to be economically viable, socially acceptable, technically and institutionally appropriate, and protect the environment and natural resources.”(Schroeder n.d.)

It is therefore crucial to investigate the innovative ways to efficiently and sustainably treat wastewater. Several researchers have pointed out DWWTS could be an alternative option to CWWTS. Yet the effectiveness, technical and economic performances of DWWTS remains largely unaddressed, making it difficult to implement them. Providing a detailed cost-benefit analysis of DWWTS will be the primary purpose of this research.

CHAPTER 2: CRITICAL LITERATURE REVIEW

2.0 Introduction

This chapter presents a critical review of the most recent publications on the topic of centralization and decentralization of municipal wastewater infrastructure. It begins by exploring key factors that are influencing the decision for decentralized treatment systems, followed by a brief summary of computer modeling tools that have been developed to determine the degree of centralization.

2.1 Key Push Factors for Decentralization of Municipal Wastewater

Centralized wastewater treatment systems have advanced collection and treatment processes that collect, treat, and discharge large quantities of wastewater. They are commonly used throughout industrialized countries. However, these systems' high capital, operational, and maintenance costs make them economically infeasible for many developing countries. Many communities in developing countries do not have any sanitary sewer infrastructure in place due to high capital, operational and maintenance costs associated with them. Where there is a sanitary sewer infrastructure, "restricted local budgets, lack of expertise, and lack of funding result in inadequate operation and maintenance" (Massoud et al., 2009). The high capital, operational and maintenance costs associated with centralized treatment systems challenge their sustainability and adaptability in developing world.

Moreover, most of the existing infrastructure, namely treatment plants and collection pipe networks, are approaching their design life. This calls on municipalities to replace or upgrade the existing infrastructure if they are to accommodate for their rapidly growing populations. Thus, decentralized treatment systems are increasingly thought as viable alternatives to costly and aging centralized treatment systems. As developing countries consider the implementation of decentralized wastewater treatment systems, they should consult modeling tools that facilitate the planning and implementations of these systems.

2.2 Determining the Optimal Degree of Centralization Using SNIP- a Modeling Tool

Eggimann et al. (2015) developed a planning tool called Sustainable Network Infrastructure Planning (SNIP) that determines the optimal degree of centralization in wastewater infrastructure. This tool could potentially allow engineers, planners, and municipalities to model and optimize the degree of centralization in wastewater infrastructure before issuing a recommendation for implementation. This is essentially an optimization of total system annuities. Often the number of wastewater treatment plants and length of network pipes are inversely proportional. By taking into account the economies of scale, topography, settlement dispersion and size of wastewater treatment plants, SNIP uses shortest path-finding and agglomerative clustering algorithms to determine the optimal degree of centralization (Eggimann et al., 2015).

SNIP was tested in a small community 1,500 people in Western Switzerland. "This region is hilly, sparsely populated and makes network infrastructure planning challenging because of its complex topography and settlement dispersion." (Eggimann et.al, 2015). SNIP can be a powerful analytical tool, but it is not without its limitations. For instance, the way Eggimann et al. (2015) approaches the cost analysis is problematic. SNIP mostly consider geographical factors such as terrain complexity, and population settlement. Cost-optimization is important in engineering design and practice, but other factors such as environmental goals need to be considered as well. For instance, SNIP assumes that all treatment systems will achieve the same performance. SNIP also does not take into account system sustainability. Cost can be a component in sustainability, however, there are externalities to be considered when equating cost-effectiveness with sustainability. SNIP would be a more robust planning tool for both developed and developing countries if it took into account energy consumption and effluent water quality.

While SNIP focuses on cost optimization mainly based on geography, population, and economies of scales, it does not consider the treatment technology of choice or environmental goals which can significantly influence the cost. The consideration of various treatment technologies, such as conventional activated sludge and UV disinfection is vital in order to assess the full applicability and effectiveness of decentralized wastewater treatment in developing countries

2.3 Cost Comparison Using a Three-Step Model

Jung et al. (2018) developed a three-step model to analyze different decentralized wastewater management (DWWM) configurations, using the town Alibag, India as the case study. The 2011 census estimated Alibag has a total population of 20,743with a total surface area of 1.98 km^2. Jung et al. (2018) found that “the town currently lacks a wastewater management system, untreated sewage is either collected by open drainage and discharged to the Arabian Sea, or released directly to the immediate environment.” (Jung et al., 2018)

The model’s main inputs are (1) degree of decentralization (N_C) defined as the number of wastewater treatment plants (WWTPS), (2) potential sewer paths represented by main roads, and (3) building nodes which denote wastewater generated per household (Jung et al., 2018). The number of wastewater treatment plants varied from 5 to 25, each with a capacity of treating 1,000 m^3/d and they were arbitrarily scattered throughout the community. The research team said “for each set of randomly distributed WWTP locations, a sewer network that connects each wastewater source node to a WWTP was generated using a mixed integer programming optimization model with the objective of minimizing the sum of sewer distances between the wastewater sources and their respective WWTPs" (Jung et al., 2018). After finding the optimal pipe network layout, a cost analysis of each decentralized wastewater treatment configuration was performed and compared to that of a centralized wastewater treatment plant (CWWTP). To ensure that apples were compared to apples, some environmental parameters were selected. For example, the target for Biochemical Oxygen Demand (BOD) was set at less than 30 mg/L for both systems. DWWM consists of s simplified sewer, an inspection chamber, a settling chamber, an anaerobic baffle reactor, an anaerobic filter and a planted gravel filter while CWWTP consists of a conventional gravity sewer, manholes, a settling chamber, a primary clarifier, an activated sludge bioreactor and a settling tank (Jung et al., 2018).

The research concluded that "in comparison to CWWM, DWWM has lower costs than CWWM when configured with less than 16 clusters with significantly less operation and maintenance requirement, but with high land requirement for construction" (Jung et al., 2018).

Even though the study compared the cost analysis of DWWM to CWWM while taking into account various degrees of decentralization, the study area was very small, and consequently, it is dubious whether the main findings could apply to any larger city with a population of more than a million. Secondly, the treatment schemes selected for both DWWM and CWWM were minimal. For instance, the operation and maintenance cost analysis for the disinfection units were omitted in this study. A thorough economic analysis should have advanced treatment technologies for both systems. For example, if a community has high environmental regulations or plans to reuse the reclaimed water for potable purpose, then the selected technologies in comparison must be able to meet these goals.

2.4 Sustainable Urban Water Infrastructure: Centralized, Decentralized or Hybrid Dilemma

Although existing literature theoretically favor decentralized treatment systems as a sustainable alternative to centralized treatment systems, only very few studies have been carried out to validate this claim, especially in the context of rapidly growing cities of developing countries. For instance, Poustie et al. (2014) used a multi-criteria decision analysis (MCDA) to explore whether a mixture of centralized and decentralized urban water systems is preferable for sustainable urban water infrastructure. Considering technical, economic, environmental and resilience performance, the study concluded that a hybrid infrastructure is favored. MCDA successfully considers multiple non-financial factors without requiring monetization, making it a powerful tool to represent stakeholder and policy makers' values for decision making. However, a series of questions have been left unanswered.

First, the author does not spare time to define degree of centralization. It is observed that a 50.0 % degree of centralization seems to be the optimal spot taking into account of all indicators (technical, economic, environmental and resilience performance). However, it is not clear what a 50.0 % degree of centralization may look like in practice, notably at a city-scale level. In one way, degree of centralization, could be understood in terms of number of treatment plants serving a certain population within a city (total flow to be treated). Conversely, degree of centralization could be defined based on household's levels. For example, treating wastewater generated from one individual home up to 5,000 households is considered decentralized, while anything above 5,000 households could be thought as a centralized infrastructure (Roefs et al., 2016).

Secondly, from technical and economic point of view, this research does not thoroughly explain what consist of decentralized treatment systems. Pit latrines, septic tank systems, lagoons, sequencing batch reactors, just to name a few examples of decentralized treatment systems. However, all decentralized treatment systems are not suitable in highly populated urban environments. Some of these systems perform well only in rural areas with a much open green space.

Considering economic performance alone, Poustie et al. (2014) found that decentralized treatment systems are less expensive compared to centralized treatment systems. However, it could be argued that these systems are inexpensive because they rely on simplified technology, which could be a tradeoff in terms of environmental performance. Decentralized treatment systems are economically feasible primarily because they rely on simple technology (require less capital to install, easy to operate and maintain). However, in urban environments with high population densities and high land usage, low-tech treatment solutions such as pit latrines and septic systems become impractical because of their large footprint requirements.

In the end, the dilemma remains. To decentralize or centralize, both policy makers and stakeholders will need to reach a general consensus by weighing and selecting their most pressing issues. If a community is financially constrained (most of developing countries do not possess abundant monetary funds to spend on wastewater infrastructure) simplified decentralized treatment systems might be preferred but this could be risking discharging low quality effluent to the environment. Alternatively, if environmental protection is of primary concern, centralized treatment systems could be preferable because of their strong technical performance and thus a high effluent equality.

2.5 Summary of Existing Literature

Based on the existing literature, the following conclusions can be drawn thus far:

- Theoretically, decentralized treatment systems are highly favored as sustainable alternative to costly and aging centralized treatment systems. A robust data and computer numerical models are needed to validate this popular opinion.
- The existing literature ambivalently defines decentralization. Various authors have defined decentralization in terms of: (a) flow of wastewater being treated or number of WWTPs (Jung et al., 2018), (b) the location where the waste is treatment, and (c) community on site sources separation.
- From a technical point of view, there is no clear set of decentralized treatment systems (package treatment plants, membrane bioreactors, or sequencing batch reactors) to consider, at least in the context of urban cities with high population density and potential of water scarcity.
- The level of centralization remains unknown. Eggimann et al. (2015) is the only author to our knowledge who attempted to numerically define the degree of centralization. However, his approach only determines the degree of centralization within areas that have existing infrastructure. For example, given a city with no existing sewer infrastructure, his methodology becomes ineffective. A new algorithm to determine degree of centralization without taking into account the existing infrastructure is needed.

3. GOALS, HYPOTHESES AND OBJECTIVES

About four percent of Kigali residents have in-door plumbing. The most commonly used sanitation facilities are pit latrines and septic system tanks. Due to rapid urban growth, these sanitation systems are not sustainable. Furthermore, although pit latrines are an inexpensive way to access improved sanitation services, these sanitation systems do not meet the national environmental goals or protect the public from waterborne diseases. Additionally, pit latrines provide limited comfort and low quality of life, which do not correspond to the aspirations of Kigali's rapidly growing middle class. Finally, the World Bank ranks Rwanda 39th globally and the second in Africa in terms of ease of doing business (Bizimungu, 2019). To retain a competitive business environment, both globally and regionally, the government of Rwanda needs to significantly invest in a sustainable sanitary infrastructure. Among the options Kigali policymakers are considering include centralized and decentralized wastewater infrastructure.

The goal of this research is to determine the viability of a sustainable wastewater infrastructure for Kigali City. Decentralized and centralized sanitary infrastructure are both options under consideration. Decentralized systems are typically small sanitation systems that collect and treat wastewater generated by individual homes, cluster of neighborhoods, schools, hospitals and commercial buildings. Centralized sanitary infrastructure involves large systems which collect and treat all municipal wastewater at one central location. The most preferred location is the point with the lowest elevation and closest to the discharge point (surface rivers, lakes, groundwater recharge or ocean).

Economic consideration is the primary factor in selecting any type infrastructure option. The economic consideration is comprised of both capital as well as operational and maintenance costs. The second important factor is population settlement. CWWTS are suitable for a densely populated urban environment while DWWTS are favorable in sparsely populated areas. Finally, the topography of a region influences the type of sanitary infrastructure. Kigali has a very complex terrain environment. Therefore, to implement a centralized sanitary infrastructure would require constructing many pump stations which could result in excessive capital, operational and maintenance costs. Conversely, these costs could be minimized by adapting a decentralized sanitary infrastructure. To determine the viability of decentralized wastewater infrastructure using techno-economic assessments is the primary objective of this research.

3.1 Hypothesis

Approximately 80 to 85 percent of capital cost in centralized wastewater infrastructure is attributed to collection pipe networks and pumping stations (Jung et al., 2018). Decentralized treatment systems rely on on-site treatment or require short pipe networks and often no pump stations are needed thus making them potentially less expensive to build, operate, and maintain. Therefore, *it is hypothesized that the total cost of decentralized wastewater infrastructure would be 85 percent that of centralized wastewater infrastructure*. To verify this hypothesis, a series of small wastewater treatment plants will be generated within the study area. The number of treatment plants would be determined based on topography, available discharge point and population served. The overall capital, operational and maintenance of these plant would be compared with that of a centralized wastewater treatment plant. All treatment plants achieve the same treatment efficiency.

3.2 Specific Objectives

The following objectives will be completed:

1) Evaluate different treatment technologies and compare their effluent quality limits
2) Determine the capital, operational and maintenance cost of an aerobic suspended growth and aerobic attached growth treatment processes. Treatment technology as well as environmental goals govern the overall cost of the system.
3) Determine the total system costs for a DWWM and CWWM system

4. APPROACH AND METHODS

4.0 Introduction

To thoroughly assess the techno-economic feasibility of CWWTS and DWWTS, two well-known wastewater modeling software GPS-X and CapdetWorks both developed by Hydromantis Environmental Solution Software Inc. are used. First, GPS-X is used to simulate full dynamic treatment models, both aerobic suspended and attached growth treatment processes. GPS-X is a very powerful and interactive tool which allows users to assess the performance of various treatment units. This tool helped to ensure that the environmental treatment goals are met. Second, CapdetWorks software is utilized to estimate the capital, operation and maintenance costs of each treatment process model. Third, the conveyance costs are obtained by assuming that only 30% of total costs account for transportation infrastructure (pipes and pump stations) with a DCWM and 70% for a CWWM. Fourth, the overall system costs are then calculated as the sum of treatment costs and conveyance costs. This chapter discusses each section in more details.

4.1 Using GPS-X to Assess Technical Performance of Aerobic Suspended and Attached Growth Treatment Process Models

This task begins by assuming a scenario where the municipality is looking for a sustainable way to manage its domestic wastewater. The average flow for this municipality is assumed to be 3.2 million gallons per day (MGD). Then using GPS-X various liquid and solids treatment processes are analyzed. Plant configurations used typical municipal influent and effluent wastewater characteristics that are used for this research (Table 1).

Table 1 Typical Influent and Effluent Wastewater Characteristics

Influent and Effluent Characteristics		
	Influent	Effluent
COD	378 mg/l	30 mg/l
CBOD	188 mg/l	15 mg/l
TKN	31.6 mg/l	1.47 mg/l
NH3	15.8 mg/l	4.1 mg/l
TSS	133 mg/l	30 mg/l
VSS	107 mg/l	9.0 mg/l
Alkalinity	297 mg/l	215 mg/l
pH	7.34	7.21

The influent constituents (Table 1) were utilized to characterize the influent wastewater in GPS-X. The effluent constituents were compared to model results to validate the process modeling. Further, various process models as well as physical and operational parameters are analyzed to meet the effluent targets (Table 1).

There exists a variety of treatment processes that could be considered for a DWWM system. Among the aerobic suspended growth treatment process models, a conventional activated sludge (CAS), sequencing batch reactors (SBR) and membrane bioreactors (MBR) are analyzed. These treatment processes are commonly used for domestic wastewater treatment plants and produce high effluent quality. These treatment processes have different efficiency removals and require different footprints. Systems with low removal efficiencies are not recommended if the effluent is discharged into ecologically sensitive environments. Systems with large footprint requirements are not suitable for applicability in urban areas with high population densities and limited green space.

A typical conventional activated sludge (CAS) treatment process is consisted of primary clarifier, aeration tank (plug flow) and secondary clarifier (Figure 1).

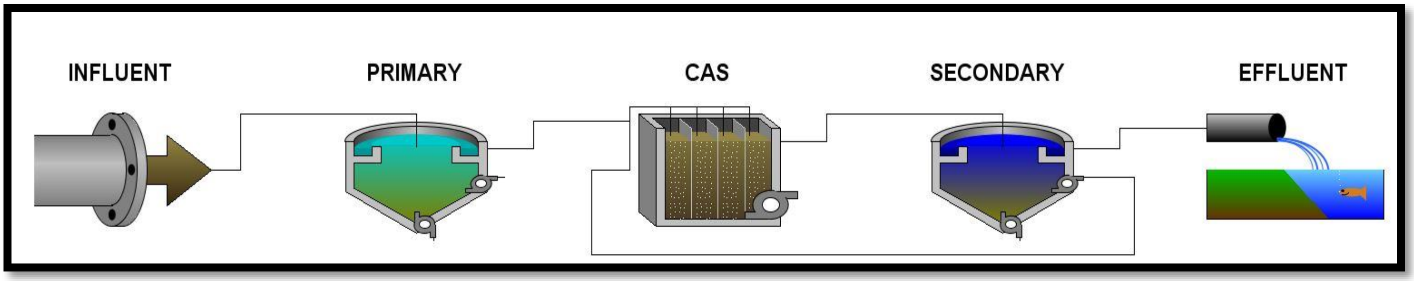

Figure 1 Liquid Treatment Processes for a Conventional Activated Sludge (CAS)

SBR systems have been successfully utilized to treat domestic wastewater. These systems are uniquely suited for wastewater treatment applications characterized by low or intermittent flow conditions. If properly designed and operated, these systems can produce effluent quality less than 10 mg/L BOD_5, 10 mg/L TSS, 5-8 mg/L TN and 1-2 mg/ L TP. Note these effluent limits are comparable to those set by most state and federal regulatory agencies. Similarly, a simplified liquid treatment process was modeled using SBR (Figure 2).

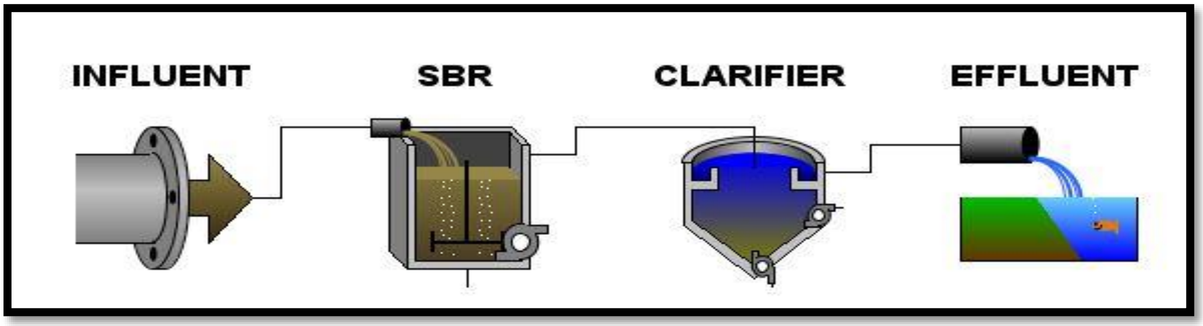

Figure 2 Liquid Treatment Processes for a Sequencing Batch Reactor (SBR)

Another commonly used aerobic suspended growth treatment process is membrane bioreactor (MBR). MBR systems are particularly suitable for wastewater treatment in high density areas with stringent environmental regulations (Figure 3). Their main advantages include improved effluent quality and minimum footprint requirement.

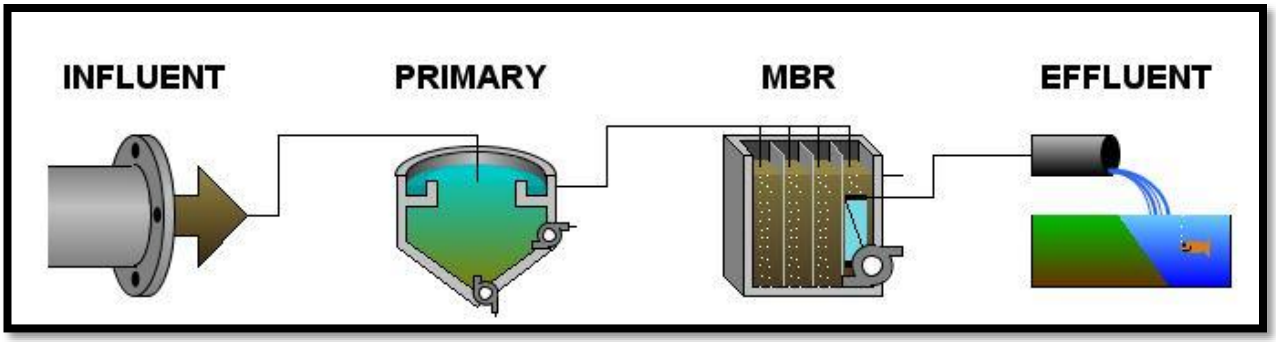

Figure 3 Liquid Treatment Processes of a Membrane Bioreactor (MBR)

In addition to aerobic suspended growth activated biological systems, aerobic attached growth systems have also been successfully used to treat domestic wastewater. The most commonly used attached growth processes include trickling filters (TFs), rotating biological contactors (RBCs) and integrated fixed-film activated sludge (IFAS). These treatment systems have different treatment removal efficiency and depending on the community's goal, some of these systems may be more appropriate than others.

TF processes have been used to treat domestic wastewater for more than a century. These systems were the most dominant secondary treatment processes in the United States by 1950. Advantage of trickling filters are their minimal energy and maintenance requirements. These systems, however, require large land areas and thus they well suited for application in areas with less population density.

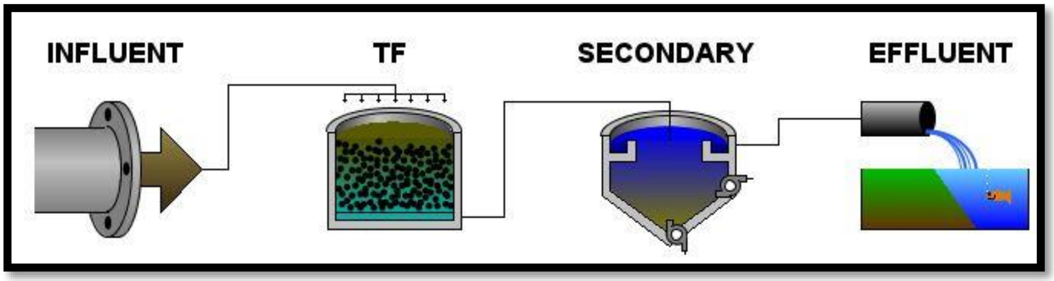

Figure 4 Liquid Treatment Processes for a Trickling Filter (TF)

In 1970s, when EPA lowered the secondary effluent standards, RBCs gained popularity as an alternative to TFs. RBCs have a higher organic removal rate and require less footprint compared to TFs.

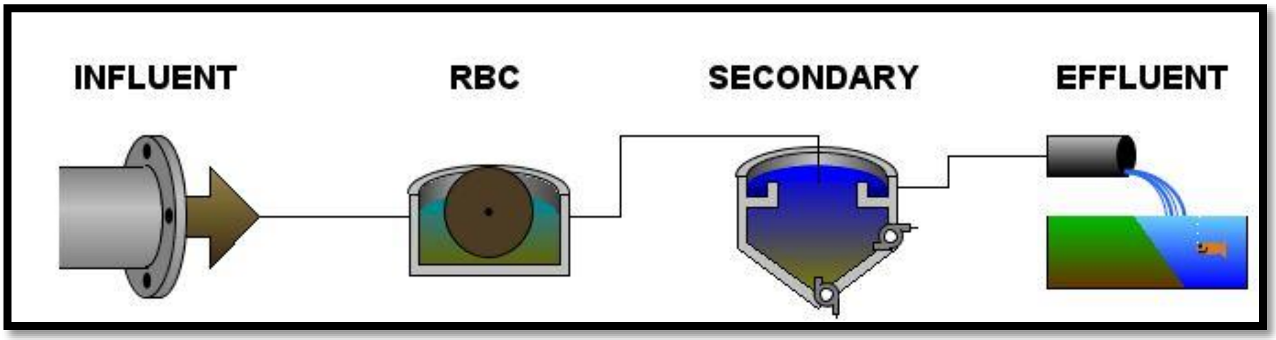

Figure 5 Liquid Treatment Processes for a Rotating Biological Contactor (RBC)

Technological advancement has led to the development of IFAS processes which can be thought as a combination of suspended and attached biomass in one bioreactor. This combination of suspended and attached biomass allows IFAS processes to have a high organic removal rate and minimize footprint requirements compared TF and RBC treatment processes. Consequently, IFAS processes are becoming popular choice as the effluent quality become more stringent. All in all, it is important to analyze different treatment processes, and compare their techno-economic performance.

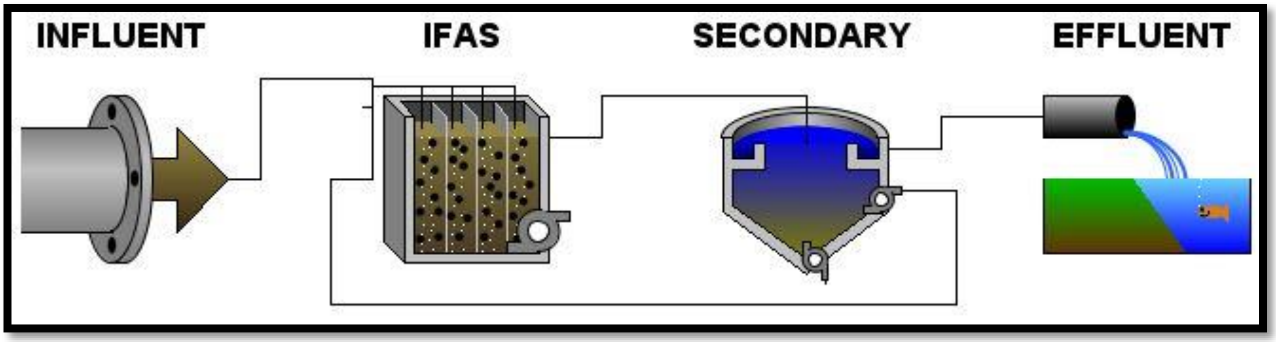

Figure 6 Liquid Treatment Processes for an Integrated Fixed-Film Activated Sludge (IFAS)

4.2 Using CapdetWorks to Estimate Capital, Operational and Maintenance Costs of WWTPs

After establishing the required physical and operational parameters and biological models of different treatment processes and ensuring that the desired effluent quality would be met, the next task focuses on determining the total treatment costs of each treatment processes. To accomplish this task a simulation software, CapdetWorks (version 4.0) developed by Hydromantis, is used. In addition to strong technical performance, cost optimization is another important factor to consider when selecting appropriate treatment technology. CapdetWorks is a very helpful tool since it allows users to rapidly estimate preliminary costs of WWTPs. Its vast library includes aerobic suspended growth and aerobic attached growth treatment processes discussed in the previous section. First, the treatment costs at different flow rates varied between 0.05-3.2 MGD are estimated. The cost per treated flow was then used to estimate the number of treatment plants that are required to treat the total flow of 3.2 MGD. For instance, a total number of 64 small treatment plants, each with a capacity of 0.05 MGD would be needed to treat a total flow of 3.2 MGD. Consequently, the total treatment cost is obtained by multiplying the cost per plant and the total number of treatment plants needed. This approach was applied to both aerobic suspended and aerobic attached growth treatment processes discussed in the section 4.1. Cost analysis was performed assuming a design life of 30 years for each treatment process.

4.3 Collection System

A collection system is used to convey wastewater generated at a household to a wastewater treatment facility. Typically, collection systems costs depend on population settlement (high density or sparsely populated), topography (hilly or flat terrain), soil conditions and ground water table location. The main components of a sanitary sewer collection system include manholes, lift-stations and pipe network. The cost of each component will separately be estimated. From previous literature, WWTP counts for approximately 70% in DWWMs and the conveyance infrastructure counts for 30% (Jung et al., 2018). The conveyance infrastructure is comprised of 20 % sewer network and 10 % manholes. This assumes that no pump stations are needed for a DWWM. On the other hand, in CWWM the total cost is broken down into 70% conveyance (sewer pipes, manholes and pump stations) and 30 % count for WWTP costs. Considering this cost breakdown, the overall total treatment costs of DWWMs and CWWMs were estimated.

5. RESULTS AND DISCUSSION

5. 1 Key Physical and Operational Parameters of Suspended Growth Treatment Processes

Using GPS-X, physical configurations and operational parameters of aeration tanks and clarifiers were modified to meet the effluent quality limits shown in Table 1. These parameters include the number and the size of primary clarifiers, aeration basins, and secondary clarifier, recycle and wastage flow rates. Tables 2-4 summarize the physical and operational parameters of suspended growth treatment processes discussed in the section 4.1. These parameters were analyzed for an average flow rate of 3.2 MGD.

Table 2 Physical and Operational Parameters of CAS

Unit Process	**Phyiscal and Operation Parameters**	**Biological Unit Model**
Primary Clarifier	1 Tank @ Surface Area : 100 m^2	Simple-1D
Aeration Tank	Volume: 1000 m^3 per tank Side Water Depth : 4.0 m Number of Tanks : 3 Aeration Method : Diffused Air Air Flow Rate 12000 m^3/d	Mantis2
Secondary Clarifier	Number of Clarifiers : 4 Surface Area : 400 m^2 per tank Side Water Depth : 3.0 m RAS : 2000 m^3/d WAS : 40.0 m^3/d Design MLSS Concentration: 3000 mg/L Sludge Blanket Threshold Concentration : 2000 mg TSS/L	Simple-1D

For a CAS system both primary and secondary clarifiers are needed to sufficiently treat the influent to the desired effluent limits (Table 2). At an average flow rate of 3.2 MGD, 1 primary clarifier, 4 aeration tanks and 4 secondary clarifiers are needed.

Table 3 Physical and Operational Parameters of SBR

Unit Process	**Phyiscal and Operation Parameters**	**Biological Unit Model**
Aeration Tank	Surface Area : 600 m^2 per tank Side Water Depth : 5.0 m Number of Tanks : 3 Cycle Time : 6 hr Mix and Fill Time : 0.5 hr Decanting Time : 0.5 hr Aeration and Fill : 1.5 hr Aeration Only : 1.5 hr Air Flow Rate 7600 m^3/d	Mantis2
Secondary Clarifier	Number of Clarifiers : 4 Surface Area : 600 m^2 per tank Side Water Depth : 3.0 m RAS : 100.0 m^3/d WAS : 40.0 m^3/d Design MLSS Concentration: 3000 mg/L Sludge Blanket Threshold Concentration : 2000 mg TSS/L	Simple-1D

For an SBR system, primary treatment is not needed to meet the desired effluent quality (Table 1). Three aeration tanks each with a surface of 600 m^2 and four secondary clarifiers each with a surface area of 600 m^2 are needed to meet the effluent target (Table 1).

Table 4 Physical and Operational Parameters of MBR

Unit Process	Phyiscal and Operation Parameters	Biological Unit Model
Primary Clarifier	1 Tank @ 100 m^2 of Surface Area	Simple-1D
Aeration Tank	Surface Area : 600 m^2 per tank Side Water Depth : 5.0 m Number of Tanks : 4 Number of Reactors /Tank : 4 Total Mebrane Surface Area : 4000 m^2 Solids Capture Rate : 99.0% Backwash Flow : 2000 m^3/d Frequency of Backwash : 15 min Duration of Backwash : 30 sec Cross Air Flow : 35000.0 m^3/d	Mantis2
Secondary Clarifier	None	

For MBR system only, one primary clarifier and four aeration tanks are required to meet the effluent (Table 1). Of the three suspended growth treatment processes analyzed, MBR requires the least amount of land area, thus making this system the most suitable treatment of choice in urban environments with population settlement with the least green space available.

5. 2 Key Physical and Operational Parameters of Attached Growth Treatment Processes

The most important physical and operational configurations of attached growth treatment processes discussed in section 4.1 were analyzed. Tables 5-7 summarize the most important factors that were used to make sure that the desired effluent limits (Table 1) were met. For each attached growth treatment process analyzed, no primary treatment was needed to achieve the desired effluent quality. Furthermore, these parameters were used to estimate the treatment costs of each treatment process.

Table 5 Physical and Operational Parameters of TF System

Unit Process	**Phyiscal and Operation Parameters**	**Biological Unit Model**
Trickling Filter	Number of Trickling Filter :3 Filter Bed Depth : 2.0 m Filter Bed Surface : 400 m^2 Density of Biofilm :1020000 mg/L Number of Horizontal Layers in Filter :6.0	Mantis2
Secondary Clarifier	Number of Clarifiers : 4 Surface Area : 600 m^2 per tank Side Water Depth : 3.0 m RAS : 100 m^3/d WAS : 40.0 m^3/d Design MLSS Concentration: 3000 mg/L Sludge Blanket Threshold Concentration : 2000 mg TSS/L	Simple-1D

Table 6 Physical and Operational Parameters of RBC System

Unit Process	**Phyiscal and Operation Parameters**	**Biological Unit Model**
Rotating Biological Contactor	RBC Liquid Volume :2000 m^3 RBC Media Volume :3000 m^3 Specific Surface Area of Media : 100m^{-1} Density of Biofilm :1020000 mg/L Submerged Fraction of Biofilm 40.0%	Mantis2
Secondary Clarifier	Number of Clarifiers : 4 Surface Area : 600 m^2 per tank Side Water Depth : 3.0 m RAS : 100 m^3/d WAS : 40.0 m^3/d Design MLSS Concentration: 3000 mg/L Sludge Blanket Threshold Concentration : 2000 mg TSS/L	Simple-1D

Table 7 Physical and Operational Parameters of IFAS System

Unit Process	**Phyiscal and Operation Parameters**	**Biological Unit Model**
Integrated Fixed-Film Activated Sludge	Number of Tanks :3 4 Aeration Rectors/Tank Tank Depth : 4 m Specific Surface Area of Media : 500m^{-1} Specific Density of Media:940000 mg/L	Mantis2
Secondary Clarifier	Number of Clarifiers : 3 Surface Area : 400 m^2 per tank Side Water Depth : 3.0 m RAS : 100 m^3/d WAS : 40.0 m^3/d Design MLSS Concentration: 3000 mg/L Sludge Blanket Threshold Concentration : 2000 mg TSS/L	Simple-1D

To sum up, GPS-X (version 7), was used to evaluate the physical, operational parameters and biological models required to meet the effluent target (Table 1) were determined. Section 5. 3 discusses the technical performance of the treatment processes discussed above. The system technical performance is assessed by comparing each removal of total suspended solids (TSS), the five-day biological oxygen demand (BOD_5), and Ammonia (NH_3).

5. 3 Technical Performance Comparison of Suspended and Attached Growth Treatment Processes

Both aerobic suspended and attached growth are used to treat domestic wastewater. Of the three suspended growth systems studied, MBRs have a high removal efficiency of total suspended solids (TSS) and require minimal land area, which make these systems highly suitable in urban environments with high densities and high effluent quality requirement (Figure7). However, MBRs significantly reduce the effluent flow, which could be a serious concern if the community intends to implement water reuse. Of the three attached growth studied, IFAS has a superior performance in removing organic constituents, nutrients and require minimal footprint (Figure 8). TFs do not perform well in reducing nutrients compared to RBC, thus they should be considered only when effluent limits are less stringent. If the treatment plant discharges the effluent into ecologically sensitive environment, more biological units are required to reduce nutrient load. Alternatively, RBCs and IFASs have a high ammonia and nutrients removal rate, thus more favorable than TFs.

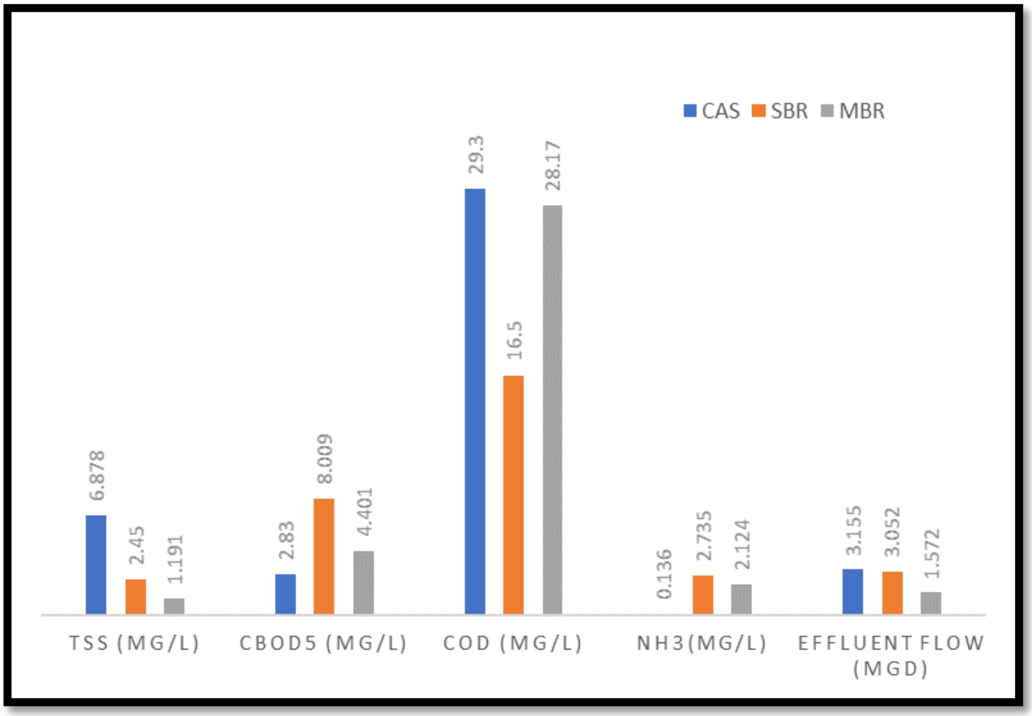

Figure 7 Technical Performance Comparison of Suspended Growth Processes (CAS, SBR, and MBR)

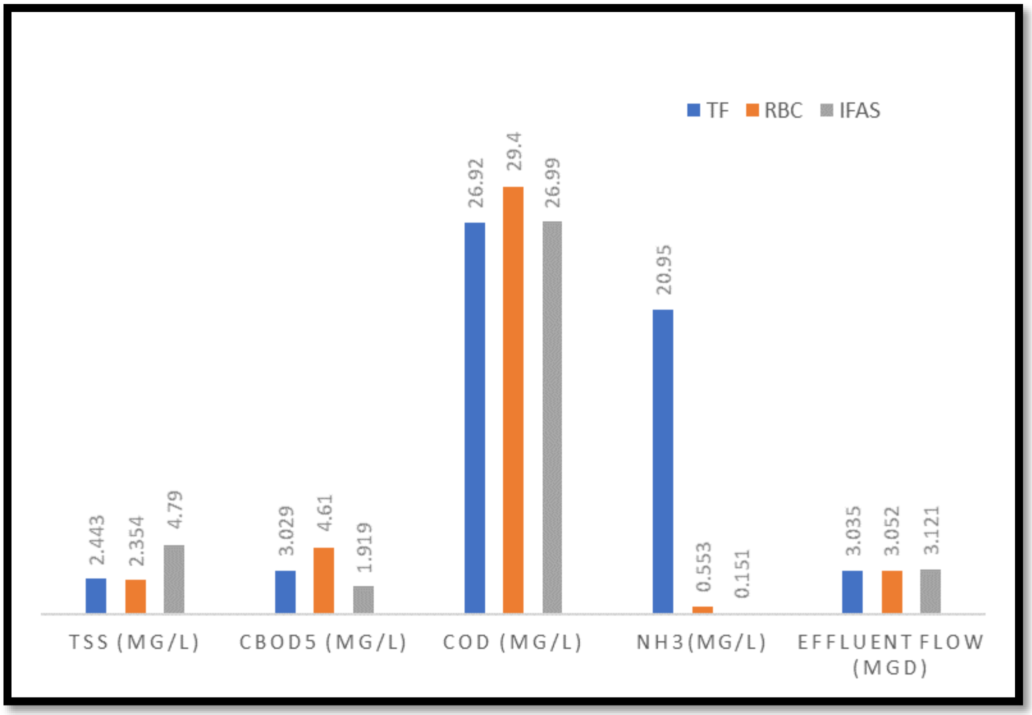

Figure 8 Technical Performance of Attached Growth Processes (TFs, RBC, and IFAS)

Overall, both aerobic suspended and aerobic attached growth processes resulted in effluent quality better than the target limits (Table 1). The exception occurred with TF which failed to meet the required ammonia limits. Additional biological units may be required if TFs are selected as treatment technology.

5.4 Treatment Costs of Suspended and Attached Growth Processes (Present Worth)

In comparing the total treatment cost and average flow rate for aerobic suspended growth treatment processes, CAS shows the highest costs, followed by SBR; MBR has the lowest cost (Figure 9). For each treatment process, the treatment cost decreases as the flow rate decreases. For example, with a CAS plant it costs approximately $27.90M (present worth value with a design life of 30 years) to treat an average flow of 3.2 MGD. If the influent flow is halved to an average capacity of 1.6 MGD, the same system would cost $19.10M. Similarly, a SBR plant rated at 3.2 MGD average capacity costs $24.60M. Reducing the influent flow to an average capacity of 1.6 MGD, would result in total treatment costs of $16.60M. An MBR plant rated at an average capacity of 3.2 MGD costs $22.5M. The same plant but with a capacity of 1.6 MGD costs $ 15.3M.

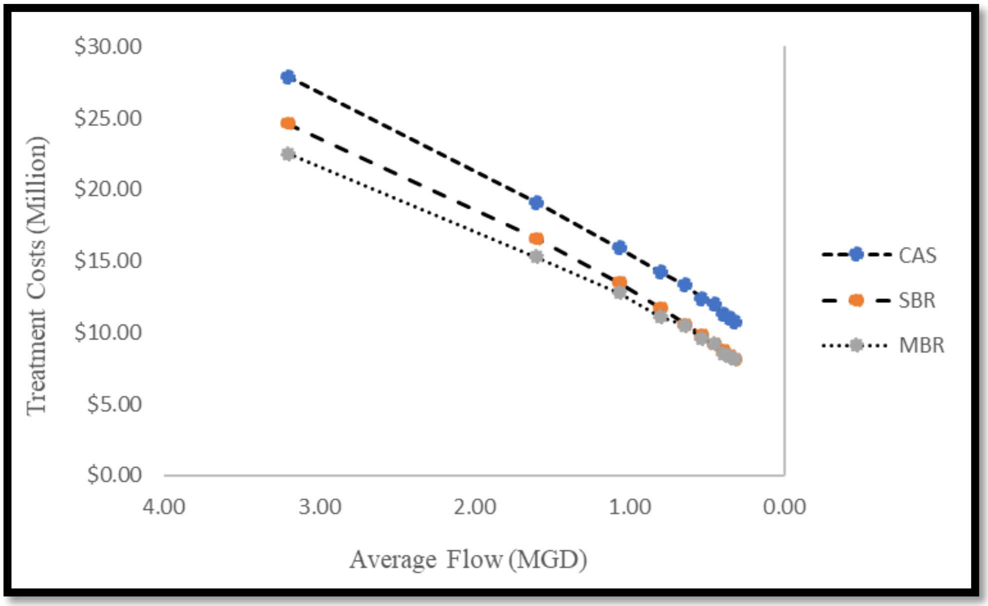

Figure 9 Treatment Costs vs Flow of Suspended Growth Processes (Present Worth)

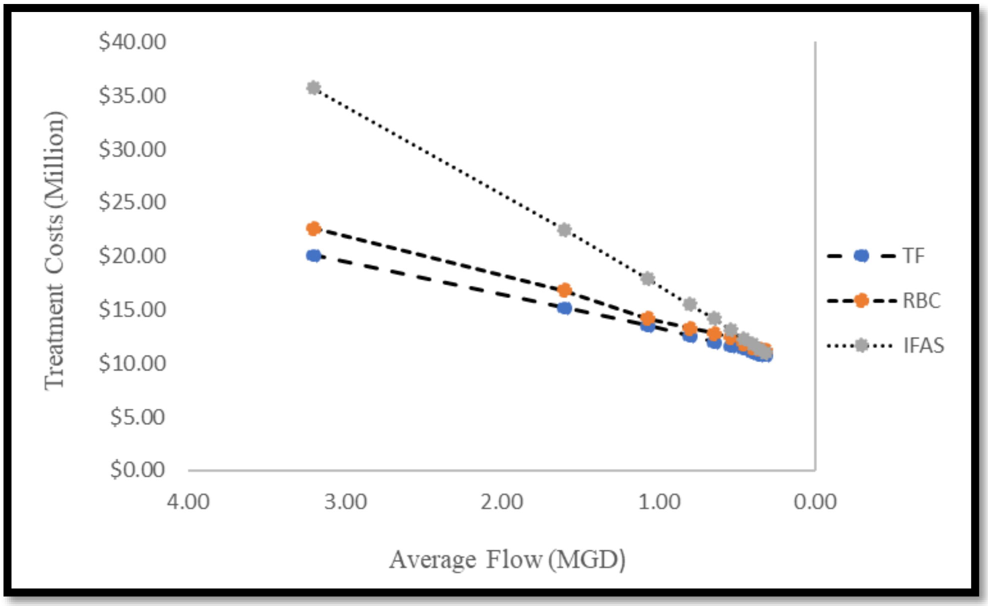

Figure 10 Treatment Costs vs Flow of Attached Growth Processes (Present Worth)

The same trend is observed with attached growth treatment processes. For instance, one TF plant with an average capacity of 3.2 MGD costs nearly $20.10M. The same plant (same unit ops) rated at an average flow of 1.60 MGD costs $15.20M. The treatment cost of installing two plants would amount to $30.40M. Comparing RBC to TF, the treatment cost is almost identical at low flow rates (less than 0.36 MGD). However, there is a significant difference between the two systems at higher flow rates (above 1.6 MGD). For example, one RBC plant rated at an average capacity of 3.2 MGD costs $22.60M, approximately $2.0M more than a TF plant. IFAS plant shows the highest treatment costs compared to TF and RBC plants. One IFAS plant costs $37.50M. Two plants cost $75M.

This suggests that, in any case, the treatment costs of running two or more plants is higher than that of running one plant. The capital costs as well as operating and maintenance costs more than doubles going from one plant to two.

5.5 Total System Costs of Suspended Growth Treatment Processes (Present Worth)

Economic analysis of suspended growth treatment processes was performed assuming a design life of 30 years. The overall system costs (treatment costs and conveyance costs) are directly proportional to the number of treatment plants (Figures 11-13). This relationship was observed in all suspended growth treatment systems.

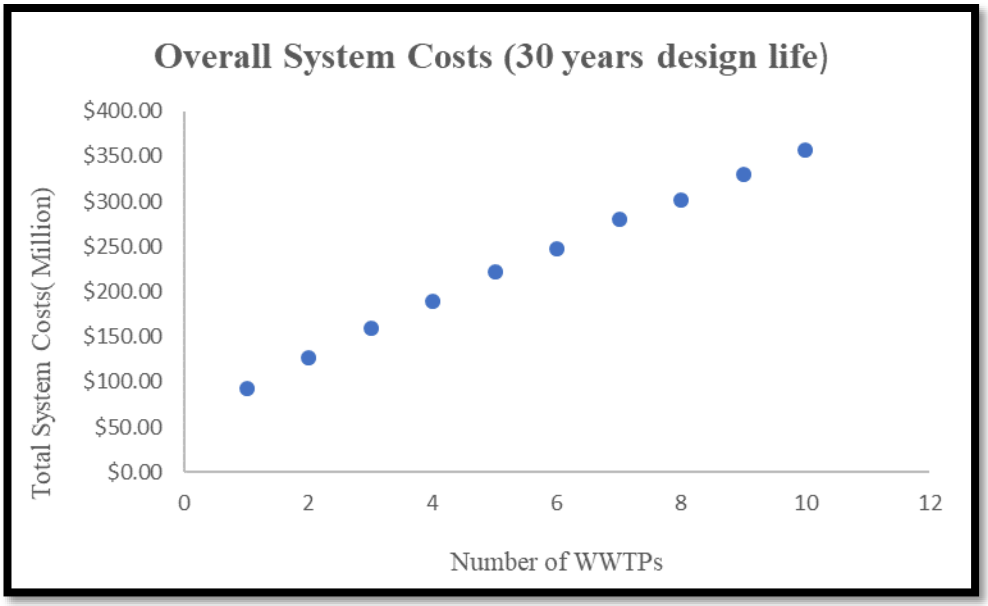

Figure 11 Total Costs of CAS System Over 30 Years Life Cycle (Flow Rate =3.20 MGD)

At an average flow rate of 3.2 MGD, the investment cost of installing one central treatment plants is approximately $93.0 M. If the number of treatment plants increases from one to two, the overall cost jumps to approximately $127.0 M. This is primarily due large footprint required to have two WWTPs running instead of one. Additional costs come from operation and maintenance. The cost of operating and maintaining two plants is significantly more than that of operating and maintaining one plant.

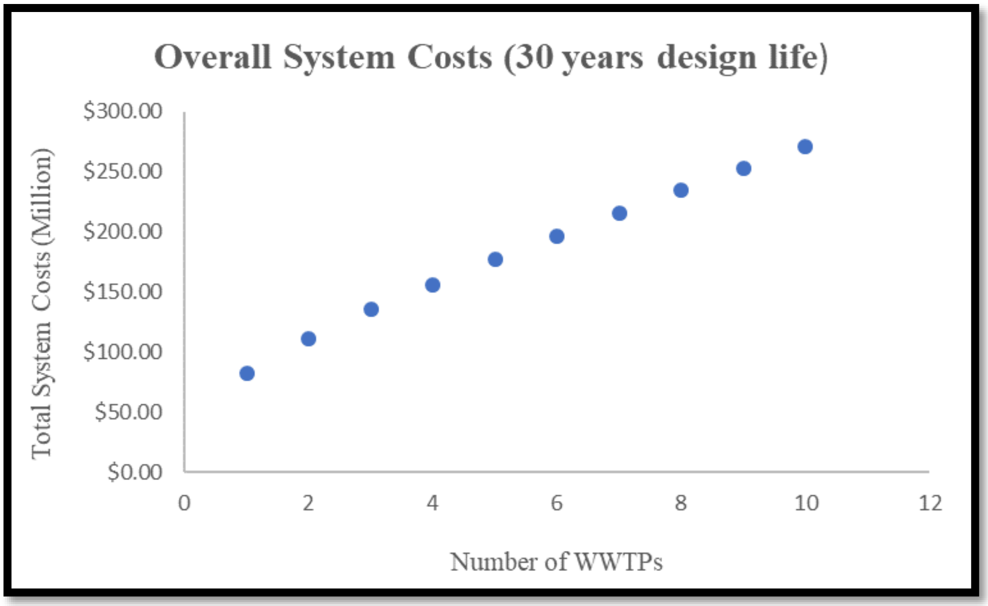

Figure 12 Total Costs of SBR System Over 30 Years Life Cycle (Flow Rate =3.20 MGD)

At the same flow rate (3.2 MGD), SBRs are more economically feasible than CASs. For instance, the investment cost of installing one central treatment plants is approximately is $82.0 versus $93.0M for the CAS system. However, similarly to CASs, the increases in number of WWTPs also increases the costs significantly. Installing two SBR WWTPs would cost nearly $110 million compared to $82.0 for just having one SBR treatment plant. This suggests it is not economically desirable to have more than one plant. Since CASs and SBRs have identical effluent quality (Figure 7), it is therefore economically more advantageous to install SBRs instead of CASs.

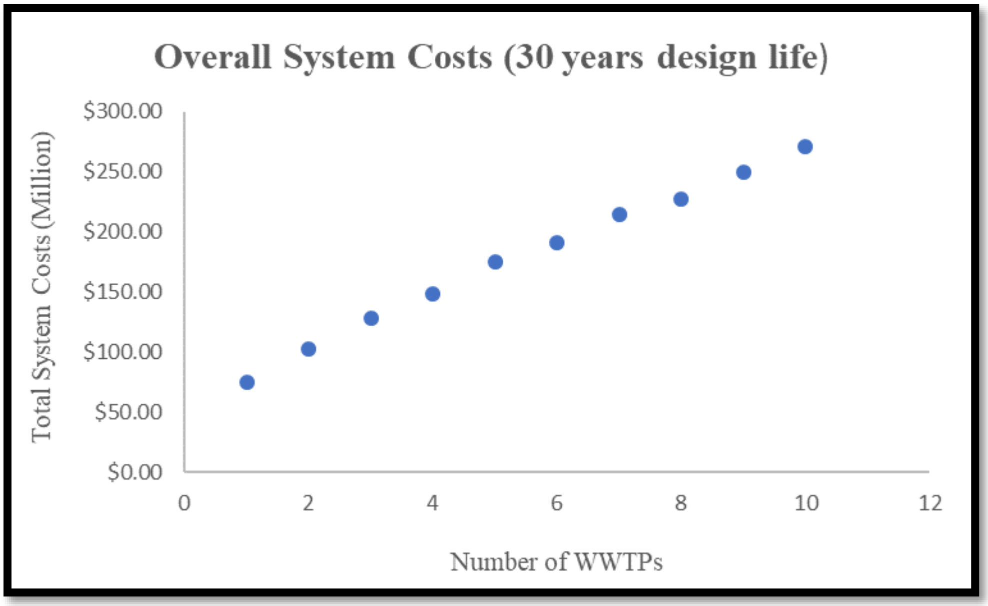

Figure 13 Total Costs of MBR System Over 30 Years Life Cycle (Flow Rate =3.20 MGD)

Like CASs and SBRs, similar trend occurs with MBRs (Figure 13). That is as the number of WWTPs increase, the total system cost also increase. At the average flow rate of 3.2 MGD, the cost of installing and running MBR treatment plant is approximately $ 75.0 million. Doubling the number of WWTPs increases the cost from $75.0 to $ 102.0 M. To sum up, of the three suspended growth treatment processes analyzed in this study, all systems indicated that it is not economically feasible to have more than one treatment plant. MBRs are the most economically affordable primarily because these systems require the least footprint compared to CASs and SBRs. This makes MBRs the ideal choice in urban areas with high population densities.

5.6 Total System Costs of Attached Growth Treatment Processes (Present Worth)

Economic analysis of attached growth treatment processes was performed assuming a design life of 30 years. The overall system cost (treatment costs and conveyance costs) are directly proportional the number of treatment plants (Figures 14-16). That is the increase in the number of wastewater treatment plants increases the overall system cost. This relationship was observed in all attached growth treatment systems. These costs analyses were performed under an average flow of 3.20 MGD.

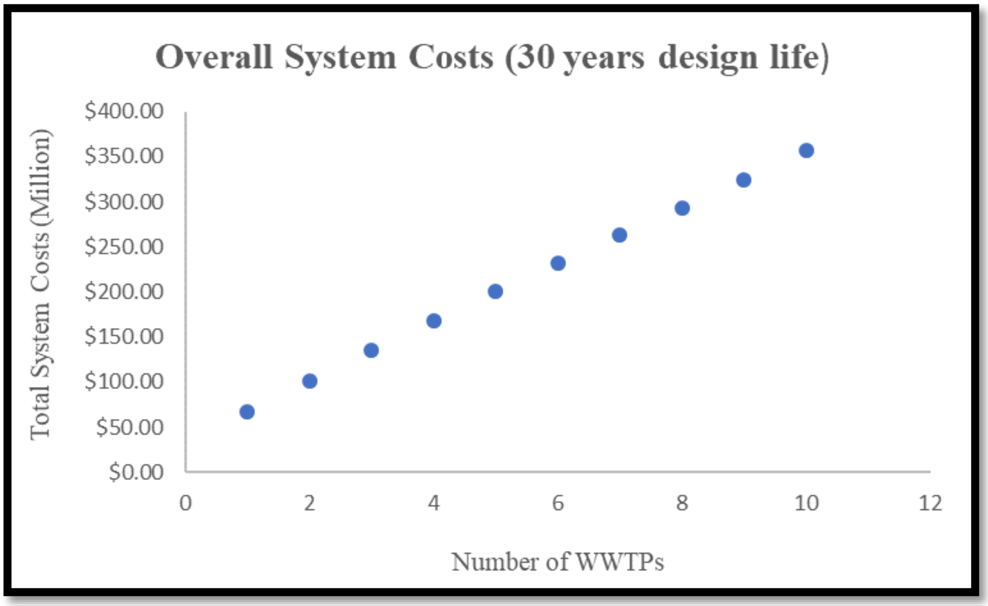

Figure 14 Total Costs of TF Over 30 Years Life Cycle (Flow Rate =3.20 MGD)

For TF plant, the overall system cost increases as the number of treatment plants increases (Figure 14). This suggests that it is not economically feasible for a community to have more than one treatment assuming that these two employ the same treatment technologies and have identical effluent flow quality. For example, the installation cost, operating and maintenance cost of TF treatment plant is approximately $ 67.0 million over an entire design life of 30 years. Doubling the number of WWTPs increases the cost to nearly $101.0 million. Thus, assuming the same level of treatment, it is economically more feasible to centralize than decentralize.

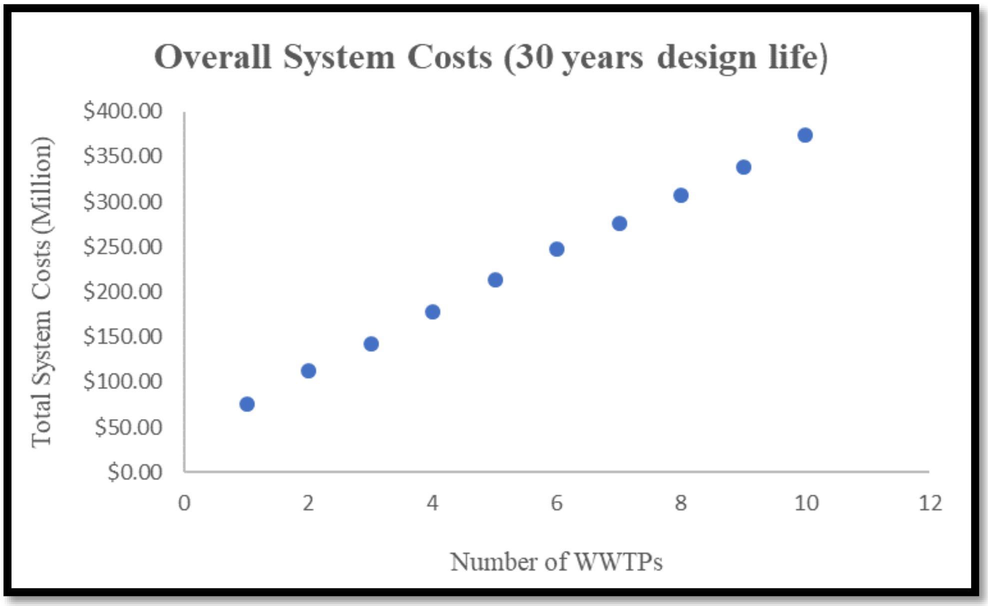

Figure 15 Total Costs of RBC System Over 30 Years of Life Cycle (Flow Rate =3.20 MGD)

Similar to TFs, installing multiple RBC treatment plants costs more than having one central treatment plant which serves the entire community (Figure 15). One RBC treatment plant costs nearly $ 75.0 million. Two RBC plants cost up to $112.0M. One of the reasons behind the increase in costs is that assuming the same technical performance (same levels of treatment), identical treatment unit ops are required to treat the full flow (3.20 MGD) and half of the flow (1.60 MGD). However, note the total cost does not halve when one goes from one plant to two. Two plants require doubling the physical land area of the plant (WWTP, administration and laboratory buildings) in addition to doubling operating and maintenance costs.

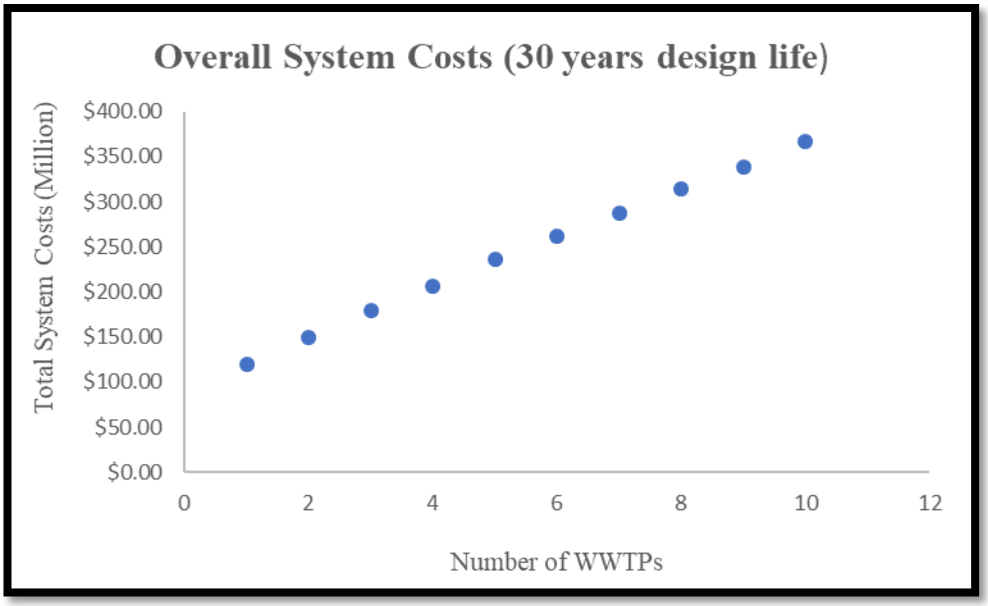

Figure 16 Total System Costs of IFAS Over 30 Years of Life Cycle (Flow rate =3.20 MGD)

The economic analysis of IFAS indicates a similar trend with other attached growth treatment processes (Figure 16). The number of WWTPs and overall system costs follow a linear relationship. That is, having multiple small WWTPs distributed over an areas of interest costs more than having one central treatment WWTP serving the entire area. For example, the cost of having one IFAS treatment plant $119M, while two IFAS plants could cost approximately $150.0 million. Therefore, it is economically more feasible to centralize municipal wastewater infrastructure than to decentralize. For all attached growth treatment processes analyzed, TFs are the least expensive, followed by RBCs and IFAS respectively.

5.7 Comparison of Amortization (costs/year) and household (HH) income per capita

The urgent demand to find the most sustainable ways to provide adequate wastewater infrastructure for millions of people living in developing countries necessitates that the affordability of various treatment technologies and configuration schemes be critically analyzed. Discussions in sections 5.4 and 5.5 established that it is cost prohibitive to decentralize municipal wastewater infrastructure in the context of urban environments with high population settlements. After showing that CWWMs are more economically feasible than DCWWMs, it is crucially important to analyze the affordability of a CWWM within a context of low-income countries like Rwanda. The affordability rule (prices) was proposed by Mcphail and Bank, who argued that if 3.5-5.0 % of household income is spent towards sanitation services, then the system is considerably affordable (Mcphail et al., 1993). Spending more than 5.0 % of total household income is considered not economically affordable. This analysis compares the affordable prices that customers are willing to pay for their infrastructure with the investment cost for several treatment facilities.

One approach to assess the affordability of any treatment system is to compare the portion of household (HH) income per capita that is spent towards sanitation services and that of amortization per capita. Taking Rwanda as an example of a low-income developing country with an average household income per capita of roughly $400 per year (Buckley & Murray 2015), the investment costs can be compared to that of household spending towards sanitation. If the Kigali's residents are willing to pay 3.5-5.0 % of their annual income, which is equivalent to approximately $14-$20 per year, then the cost of proving, operating and maintaining the required infrastructure should be maintained in that range for the community to be able to repay the debt within the life cycle of the system. However, there is a significant income disparity between rural and urban dwellers. For example, according the 2015 World Bank study on Rwanda Poverty Assessment, in 2011 the average Rwandan adult lived on $2.50/day compared to $7.60/day for those who lived in Kigali (Rwanda Poverty Assessment 2015). This indicates that the income ratio of those residing in Kigali is approximately three times that of an average citizen. Therefore, the average household income of Kigali's residents is approximately three times that of the national average which is equivalent to $1,200 per capita. Applying the same rule of affordability to residents of Kigali resulted in $42-$60 (3.5-5.0% of HH per capita). These values are then compared to amortization cost to assess the affordability of various wastewater treatment plants. The amortization costs refer to the amount that needed to be paid per year to recover the investment costs of installing, operating and maintaining a sanitary infrastructure such as a wastewater treatment plant. The amortization costs were calculated assuming an interest rate of 8% and a design life of 30 years.

The amortization costs per capita were calculated assuming an average flow rate per capita of 100 gallons per day (Figures 17-18). A WWTP plant rated at an average capacity of 3.20 MGD can serve a community of up to 30,000 people. Among the suspended growth treatment processes analyzed, if the community is willing to spend 3.5 % of their annual income towards sanitation, they can afford one SBR plant or two MBR plants. For a CAS plant, the annual repayment needed is higher than what the residents are capable or willing to pay. For example, running a CAS plant for the next 30 years requires that each connected resident pay $48.0 per year (amortization cost). However, since the minimum amount each Kigali resident can afford is roughly $42.0 per year, which suggests the community would not be able to pay off the investment loan within the design life of the treatment facility. To afford a CAS plant, the customers should spend at 5.0% of their annual income on sanitation. Overall installing smaller multiple WWTPs increases the financial burden of connected customers to repay for their infrastructure.

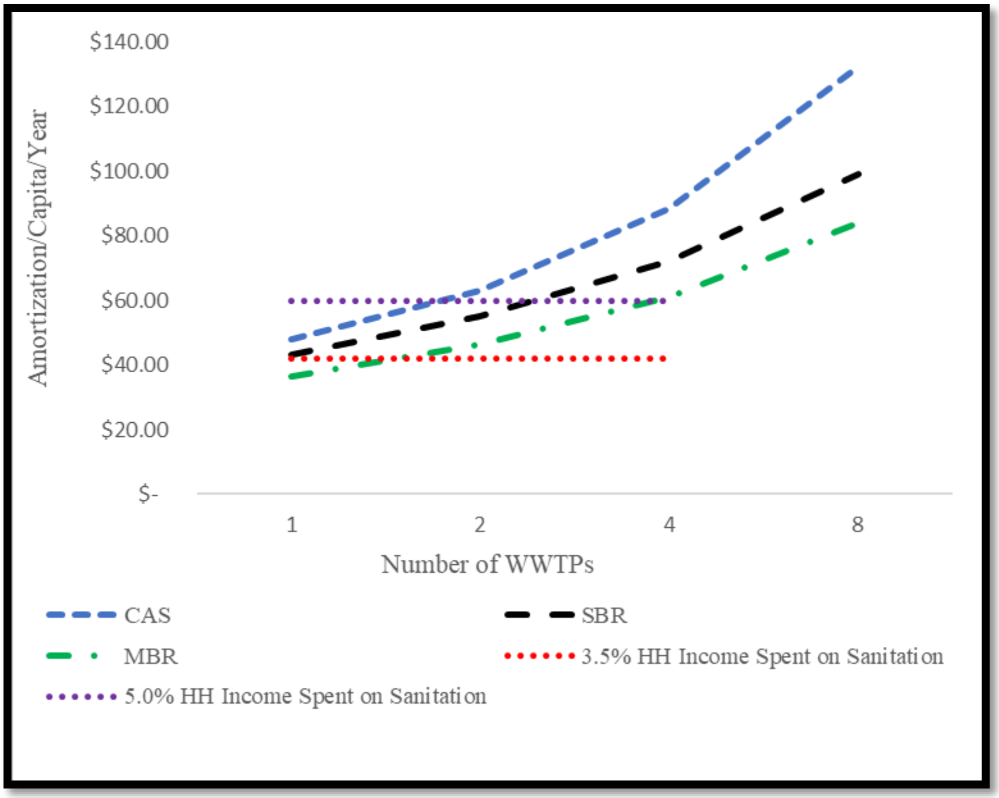

Figure 17 Comparison of Amortization Costs/Capita/Year and % of HH Income/Capita Sent on Sanitation (Suspended Growth Processes)

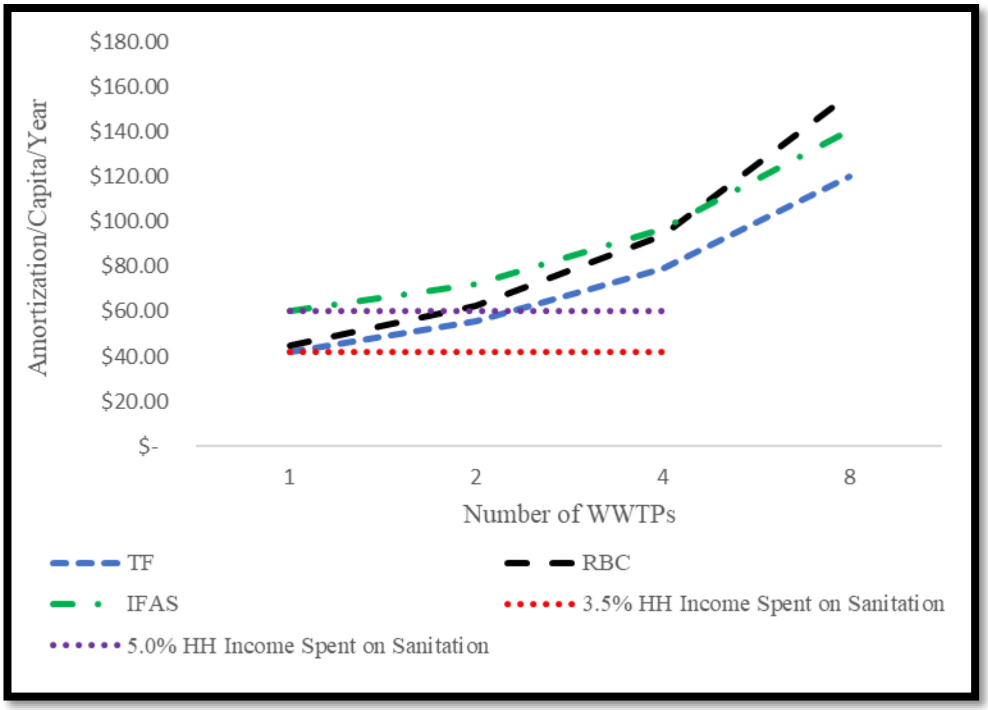

Figure 18 Comparison of Amortization Costs/Capita/Year and % of HH Income/ Capita Spent on Sanitation (Attached Growth Processes)

For attached growth treatment processes, if each resident decides to spend 3.5 % (represented by a red dashed line) of their annual income towards sanitation, the community can afford to install, operate and maintain a TF plant (Figure 18). RBC and IFAS plants have investment costs higher that what the community can afford. If, however, the community is willing to spend up to 5.0% (represented by purple dashed line) of their annual income towards sanitation services, they can afford one of any kind of the attached growth treatment plants (TF, RBC and IFAS). To sum up, the comparison of investment costs with the portion of household income that customers are willing to pay indicates that developing countries like Rwanda can afford to install, operate and maintain centralized municipal wastewater treatment facilities described in this study. For both suspended and attached growth treatment process, the optimal number of the plants the community can afford is one which strongly favors centralization instead of decentralization.

6.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

This research used techno-economic assessments to determine the degree of centralization for municipal wastewater infrastructure in the context of urban environments without existing infrastructure by using techno-economic assessment. While keeping the technical performance constant (same treatment unit ops and same effluent quality), it was observed that total system costs and number of wastewater treatment plants follow a linear relationship. This relationship holds whether aerobic suspended growth or aerobic attached growth processes are considered. The study concludes that it is cost prohibitive to decentralize municipal infrastructure beyond a degree of one. That is, it is not economically feasible to install and run more than one WWTP. For both aerobic suspended and aerobic growth systems, it is economically less expensive to centralize than decentralize. This is primarily due to loss of economies of scale and high operational and maintenance costs associated with having small treatment plants distributed over the entire area of interests.

For future studies, it is recommended to investigate the costs associated with laying out sewer collection infrastructure in regions with complex topography. Complex terrain may favor decentralization over centralization. Another crucial factor to investigate is the cost of implementing direct or indirect water reuse. DWWMs have potential to easily facilitate the implementation of water reuse because the treated effluent could be used near the sites where it is generated thus eliminating the transportation cost. On the other hand, CWWMs would mean reclaimed water has to be transported from central treatment plant to locations where there is demand of water. To estimate the cost of implementing water reuse, several locations within a city where the treated water could be used for irrigation purposes and other industrial activities could be selected and the cost to move the treated water to these locations would be estimated. These two factors, in addition to other factors discussed in this research, could be used to decide whether a municipal wastewater infrastructure should be decentralized or centralized.

Overall, decentralized wastewater treatment systems have theoretically gained popularity as a potential cost-effective alternative compared to costly centralized treatment systems. Further research is necessary to solidify the conclusions of this research.

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