

**Developing a Conceptual Solution for Domestic
Wastewater Management in Developing Countries:
Kumasi (Ghana) as a Case Study**

A thesis approved by the Faculty of Environment and Natural Sciences
at the Brandenburg University of Technology Cottbus – Senftenberg
in partial fulfilment of the requirement for the award of the academic degree
of Doctor of Philosophy (Ph.D.) in Environmental Sciences

by

Master of Science

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Day of the oral examination: 18.01.2017

Declaration

I, Kwaku Boakye Apau, hereby declare that this PhD thesis is an accurate and original account of my work done under the framework of the Environmental and Resource Management doctoral program offered by the Brandenburg University of Technology, Cottbus -Senftenberg. It includes objective discussion of results, accurate representation of underlining data and detailed referencing of all sources and tools used.

Kwaku Boakye Apau

Cottbus, August 2016

Acknowledgements

Many institutions and individuals have contributed in diverse ways to the realization of this research. I would therefore like to express my profound gratitude to each one of them. First, I really appreciate the opportunity given to me by the Brandenburg University of Technology, Cottbus – Senftenberg to pursue my post-graduate studies.

Secondly, I would like to express my sincere gratitude to my supervisor Professor Dr. Marion Martienssen for her patience, motivation and supervision. Her guidance and advice helped me a great deal during the course of this research and writing of this thesis. I also appreciate the supporting supervisory role played by Professor Dr. Frank Watzold whose insightful questions posed guided me in widening this research.

I am thankful to the Waste Management Department of the Kumasi Metropolitan Assembly in Ghana for giving me access to treatment facilities in the city of Kumasi and their provision of assistance during data collection and field work. A special thanks also goes to members of the Constructed Wetland Association of the UK, Dr. Jasmine Seggiger and Dr. Caterina Dalla Torre of SANDEC (Department of Water and Sanitation in Developing Countries) at the Swiss Federal Institute of Science and Technology and Professor Dr. Heidrun Steinmetz and Mr. Carsten Meyer of the EXPOVAL project for their direction and assistance during the data gathering part of this research.

I am highly indebted to the General Board of Global Ministries (GBGM) of The United Methodist Church for their immense financial assistance. This study would not have been possible without such assistance. My sincere thanks also go to Ms. Liza Katzenstein (Executive Secretary, Justice & Discipleship) at GBGM for her encouragement and support during this research.

Last but not the least, I would like to thank my parents, Mr. Kwadwo Boakye Apau and Ms. Faustina Kwakye, my siblings Mr. Kwadwo Boakye Yiadom and Ms. Rita Bokye Yiadom for their patience, encouragement and financial support throughout my education in Germany.

Dedication

To Skyler Boakye Apau

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List of abbreviations

AHP	Analytical Hierarchy Process
BOD	Biochemical Oxygen Demand
CPI	Consumer Price Index
CW	Constructed Wetlands
CWfs	Constructed Wetlands free water surface
CWrb	Constructed Wetlands reed bed
DSS	Decision Support System
DWF	Dry Weather Flow
EPA	Environmental Protection Agency
HC	Historical Cost
MADM	Multi-Attribute Decision Making
MCDM	Multi-Criteria Decision Making
MODM	Multi-Objective Decision Making
MWWTPs	Municipal Wastewater Treatment Plants
O & M	Operation and Maintenance
PURC	Public Utility Regulatory Commission
PV	Present Value
SAW	Simple Additive Weighting
TF	Trickling Filter
TN	Total Nitrogen
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TP	Total Phosphorus
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WMD–KMA	Waste Management Department of the Kumasi Metropolitan Assembly
WSP	Waste Stabilization Pond

Abstract

Wastewater treatment systems abound as a result of technological improvements in treatment processes. Therefore in the selection of a wastewater treatment system for a particular wastewater treatment situation there are many alternatives to choose from. Despite this development municipal wastewater treatment in communities in developing countries are not always sustainable due to the application of inappropriate treatment systems. The question is how can an appropriate treatment system be identified for a certain location? The answer to this question is of importance to developing countries where wastewater treatment is usually not sustainable.

In this study a framework for assessing wastewater treatment systems was developed. First, a comprehensive set of indicators representing parameters of treatment systems and properties of the study area that impacts on wastewater treatment were identified. Secondly, assessment of these indicators were carried out through expert and community survey to identify a final set of indicators whose composition consist of efficiency, reliability and simplicity of treatment systems and resource constraint, resource recovery and environmental concerns of the study area. Thirdly, four wastewater treatment systems, namely: Waste Stabilization Ponds, Trickling Filter, reed bed and free water surface Constructed Wetlands considered to be feasible for the study area were evaluated by the application of the identified indicators. Finally, a decision matrix produced was processed by multi-attribute decision making methods using two indicator weights to identify the most appropriate treatment system among the four alternatives.

Results of the study show that in a scenario where equal indicator weights are assumed, reed bed is identified as the most appropriate with stabilization ponds being ranked as the least appropriate. In a more practical scenario where the weights of the indicators are allocated to reflect conditions of the study area, free water surface is ranked as the most appropriate. This outcome is at variance with stabilization pond technologies currently installed at communities in the study area. The performance of constructed wetlands is at the midpoint as far as most of the high to medium weighted assessment indicators are concern. It therefore represents a compromising solution between waste stabilization pond and trickling filter. The study also shows a change in variants of constructed wetland with a change in indicator weights. An

indication that the decision situation determines the appropriateness of a treatment system and not the treatment system itself.

The selection framework employed in this study can be said to be reliable and capable of identifying a treatment system that can be appropriate for a particular location. This is because the choice of a constructed wetland for the study area fits the definition of appropriate treatment system defined by the final indicators identified in this study.

Keywords: Wastewater treatment, treatment efficiency, land requirement, multi-attribute decision making, assessment indicators

1 Introduction

1.1 Background

The pollution of waterbodies by municipal wastewater in most developed countries is well controlled to the extent that the focus of wastewater treatment has now shifted to the removal of specific compounds and the impacts of emerging contaminants on aquatic ecosystems. Conversely, in developing countries wastewater treatment is a challenge. The collection and conveyance of wastewater out of urban neighbourhoods is not yet a service provided to the entire population, and only a small portion of the collected wastewater is adequately treated, usually less than 10 percent of the municipal wastewater generated (Corcoran et al., 2010; Libhaber and Orozco-Jaramillo, 2012). As a result, polluted water courses and rivers occasioned by the discharge of untreated or poorly treated effluents is commonplace. This poses a substantial risk to health and the health impact statistics are stark. According to the 2008 World Health Organization (WHO) report on the Global Burden of Disease, 1.8 million children under age of five years die annually due to water related diseases and a greater percentage of this health burden is primarily borne by populations in developing countries. For the improvement in sanitation and consequently a reduction in the spread of water borne diseases, developing countries need to focus on the abatement of gross pollution, and the importance of wastewater treatment systems in ensuring it cannot be overemphasized.

Recent significant technological improvements in wastewater treatment processes that have brought in its wake many treatment options indicate that the technologies to address pollution from wastewater are available. These treatment options range from the highly mechanized conventional systems such as activated sludge, trickling filter, upflow anaerobic sludge blanket etc. and their variants to natural or nature-related treatment systems such as waste stabilization ponds, constructed wetlands, etc. (Metcalf and Eddy, 2003; Horan, 1993). With this background, the question that arises is, why have the implementation of treatment systems in localities in most developing countries not been successful in municipal wastewater treatment to prevent environmental degradation?

The installation of a treatment system in a community is not in itself sufficient. It should be appropriate to the conditions of the community that impact on its operational sustainability.

The main causes of the selection of treatment systems that are not suitable to the local context are threefold;

In the implementation of new or expansion of old treatment systems, the tendency in developing countries sometimes is the selection of treatment plants based on cutting edge technologies (Libhaber and Orozco-Jaramillo, 2012). Lacking the expertise and financial resources for operation and maintenance (O & M), it is not uncommon to see in developing countries complex treatment systems that have deteriorated rapidly and abandoned within a short time.

Secondly, sometimes attempts are made not to select more expensive conventional treatment systems. But rather than performance requirements, efficiency, environmental, public health and sustainability considerations forming part of the selection procedures, too much emphasis is placed on cost and the wherewithal of recipient communities. The result is the selection of treatment systems with minimum construction, O & M costs as the most appropriate (Musiyarira et al., 2012). In reality, this selection approach overlooks the importance of the local context which must be considered to ensure the sustainability of wastewater treatment.

Lastly, in some instances treatment system selection decisions are centered on past experience or by the adoption of a treatment system successfully implemented in a similar location. This selection approach is not based on a community by community basis and departs from the basic definition of appropriate technology concept which suggests that the appropriateness of a technology is contextual and situational. This also indicates that a treatment system can be appropriate for a given situation or location depending on the technological level of the community, labour and resource availability (Kalbar et al., 2012). As a result, treatment systems selected through this approach have not been appropriate for their communities.

As the norm in most developing countries, urban communities in Ghana have poor wastewater treatment coverage due to the failure of most of their treatment facilities. With about 70 mostly decentralized wastewater and faecal sludge treatment plants in the country, less than 10 are currently operating effectively (Murray and Drechsel, 2011). The city of Kumasi particularly has very few functioning treatment systems. Out of the four municipal wastewater treatment plants (mostly waste stabilization ponds), only one is working

optimally (as at the time of field work). As a result, the discharge of untreated wastewater into recipient water bodies is common in Kumasi.

According to the Waste Management Department of the Kumasi Metropolitan Assembly (WMD-KMA), factors accounting for the poor state of existing treatment plants in Kumasi can be divided into three main groups; technical, institutional and financial issues. Damage, wear and tear on physical components of plants, unreliably power supply, blocked sewer lines, overloading due to population growth constitute the technical issues. Factors related to institutional issues include lack of qualified personnel, inability to maintain and rehabilitate plants, low operation and maintenance activities, etc. Financial issues are mainly about the lack of adequate funds for treatment plant activities such as maintenance, expansion and construction of new plants.

By these known factors, when sustainability is considered in relation to domestic wastewater treatment in Kumasi, two issues are evident;

- Highly mechanized treatment systems characterized by high construction, O & M cost and high energy consumption are not appropriate.
- There is the need to incorporate the above listed factors into a decision making process geared towards identifying appropriate treatment systems for communities within the city.

This background shows that there is the need for a decision making tool to aid in the selection of appropriate treatment system. Such a tool must allow decision-makers to take into account the availability of local resources and limitations of local conditions.

Several types of decision support systems (DSS) and methodologies have been developed to assess the appropriateness of treatment systems. Their modelizations are based on different formats such as mathematical programming, checklists, decision matrix and flow diagrams. The nature of the models renders some of these DSS limited in their capacity to solve real-world decision problems. For instance, SANEX produced specifically for selecting sanitation systems for developing countries is based on mathematical programming models making it complex for non-experts to apply (Loetscher and Keller, 2002). Some selection

methodologies do not consider entire wastewater treatment systems but rather focus on the various units within the system (Gomez-Lopez et al., 2009; Huang et al., 2015). Other DSS such as those developed by Tang and Ellis (1994) and Muga and Mihelcic (2008) employ a comprehensive list of technical, economic, environmental and socio-cultural indicators to rank treatment systems. But the ranking is done on an indicator by indicator basis and not aggregated, making it difficult to identify the most appropriate treatment system. Therefore a selection method that assesses treatment systems and ranks their appropriateness based on their performance on all the indicators combined is what is needed.

1.2 Research objectives

Having considered the background problems, the overall objective of this research is to present a framework for decision support system that will assist planners and municipal authorities in charge of wastewater management in developing countries to identify appropriate treatment systems for their particular treatment situation. To achieve this objective, the following specific objectives have been set:

- Identification of indicators capable of being used to assess treatment systems with the aim of identifying the most appropriate one.
- Performance assessment of some selected treatment systems with the identified indicators.
- Aggregation of the resultant decision matrix from the performance assessment with a multi-attribute decision making method to identify the most appropriate treatment system.

It must be emphasized that the findings of this research is contributing to decision making methods as far as treatment system selection in developing countries is concern.

The study is based on a case study and therefore the results would be peculiar to the study area. The generalization to developing countries is because most developing countries have similarities in terms of the availability of resources and limitations of local conditions that impact on wastewater treatment. Also since the study is presenting a concept, the

generalization to other developing countries with different context to Ghana could be valid if the assessment indicators are changed to reflect that of the geographical area where it needs to be applied.

2 Literature review

2.1 Wastewater treatment in developing countries

2.1.1 Treatment issues of concern in developing countries

The need for wastewater treatment systems in developing countries is enormous. A 2012 water and sanitation report by the WHO estimates that sanitation coverage in many countries of sub-Saharan Africa and Southern Asia is below 50 percent. As a result, the quality of water resources is highly degraded and huge sections of the population in these regions are at risk of water-borne diseases.

There are several reasons for the lack of treatment infrastructure and consequently low wastewater treatment in developing countries. These include the low priority assigned to sanitation problems, adoption of inappropriate treatment technologies occasioned by not taking into consideration the local conditions of the targeted communities, low institutional capacity including low technical capacity, lack of funds, lack of public awareness, etc.

Sanitation problems features low on the number and kind of problems (such as healthcare, food supply, education) requiring urgent attention in most developing countries (Zhang et al., 2014). Even in the water sector, the focus on water projects has largely been on the provision of potable water before wastewater management due to the perception of wastewater treatment being less important. The less attention given to wastewater treatment is also due to the often high cost involved in implementing such projects. In instances where efforts are made to manage municipal wastewater, economics had been the deciding factor on the type of technology to adopt (Libralato, 2012; Massoud, 2009). The result of this practice is the selection of a treatment technology that is economically affordable but inappropriate for its location.

Adoption of treatment systems employed in developed countries without taking into consideration the local conditions of developing countries accounts for a considerable number of wastewater management project failures. Given the huge differences between developed and developing countries in terms of environmental priorities, technological advancement and financial resources, there are different priorities between them in terms of wastewater treatment as shown on Table 1.

Table 1: Important factors in the selection of wastewater treatment technologies in developed and developing countries (von Sperling, 1996).

Factor	Developed countries		Developing countries	
	Critical	Important	Critical	Important
Efficiency	X			X
Reliability	X			X
Sludge disposal	X			X
Land requirements	X			X
Environmental impacts		X		X
Operational costs		X	X	
Construction costs		X	X	
Sustainability		X	X	
Simplicity		X	X	

This consideration is often not taken into account in the selection of treatment systems in developing countries leading to complete replication of systems such as centralized technologies that have proved efficient in solving sanitation problems in developed countries but invariably proves to be cost-prohibitive and not feasible for developing countries (Kivaisi, 2001).

According to Klarkson et al., (2010), sustainable wastewater treatment systems for developing countries should focus on meeting local needs, being less-sophisticated to operate and requiring minimal investment. In addition to this, the sustainability of treatment systems depends on the availability of appropriate institutions and technical capacity to troubleshoot operational problems and ensure maximum efficiency. Even the longevity of the most advanced treatment technology cannot be ensured without the presence of the required expertise. And it is such expertise among other things that are frequently overlooked in the selection and implementation of treatment systems in most developing countries.

Lastly, public opposition to sanitation projects in developing countries is common especially when such infrastructures are sited close to communities. The failure of many treatment systems can be attributed to this (Massoud et al., 2009). Reason for this is that, public

awareness with respect to adverse health impacts due to absence of sanitation infrastructures is minimal.

The consequence of overlooking the above explained issues in the selection of treatment systems is the common practice of discharging untreated wastewater directly into waterbodies in developing countries (Senzai et al., 2003; Shrestha et al., 2001). Therefore for the identification of appropriate treatment systems for developing countries, the above discussed issues need to be addressed.

2.1.2 Wastewater treatment options in developing countries

Many treatment systems have been developed for the purposes of treating municipal and industrial wastewater streams. As a result, there are many options to choose from for the implementation of treatment system in a community. For the purposes of this study, the review of treatment systems being carried out in this section is limited to those frequently applied to municipal wastewater treatment and those with the potential of application in developing countries. Also it is not meant to be exhaustive in describing the options available, but to give some idea of the diversity, flexibility, capacity and utility of the treatment technologies.

Classification of municipal wastewater treatment systems can be done based on various properties of treatment systems. Treatment options may be classified into groups of processes according to the function they perform and their complexity into primary, secondary and tertiary treatment methods. They can also be classified into land-based and water-based systems. By their location of application they can also be classified into on-site and off-site treatment systems. Natural or nature-related and conventional treatment systems are two groups of classification based on nature of treatment. Conventional treatment systems can further be divided into mechanical and biological.

Of these classifications, locational dimension is usually considered. Deciding on the type of treatment system, whether on-site or off-site depends on the size and density of the settlement. On-site and off-site treatment systems are further examined in this review.

2.1.2.1 On-site treatment systems

On-site wastewater treatment systems are widely utilized for the treatment of wastewater from single households or a group of households in areas where centralized treatment facilities are unavailable. Table 2 below presents the properties of some common on-site treatment systems. Among these, septic tanks, ventilated improved pit latrine and composting toilets are the most popularly utilized due to their low construction cost, simple design and low requirement for operation and maintenance.

Septic tank is the most commonly used on-site wastewater treatment system. It is made up of a watertight rectangular, oval or cylindrical vessel which is usually buried. This vessel usually receives wastewater from a pour or cistern flush toilet. Septic tanks provide primary treatment by the removal of suspended solids, limited digestion of settled solids and some form of peak flow attenuation. In spite of its widespread application among onsite treatment systems, the septic tank is not without drawbacks. In communities with high septic density, there is the potential of leachate from septic systems contaminating domestic water wells (Bremer and Harter, 2012). In addition to contaminating by conventional pollutants such as coliform bacteria, nitrates and phosphorus, septic systems are also a source of organic wastewater compounds such as pharmaceuticals, personal care products and organophosphate flame retardants (Conn et al., 2010; Shaider et al., 2016). Generally, effluent quality from septic tanks is not usually high for safe discharge and requires further treatment. Imhoff tank is an upgrade version of the septic tank developed to overcome a major problem of the septic tank. In its structural design, Imhoff tank is composed of two chambers, one inside the other, to enhance proper sedimentation that separates the settled sludge from influent wastewater. Unlike septic tanks, composting toilets are more common in areas that have limited water resources for toilet flushing and as such more utilized in developing countries. They are designed to store and compost human waste by aerobic bacteria digestion. To enhance digestion, supplemental additions of food waste are added.

Table 2: Properties of some selected on-site treatment systems

Treatment technology	Community or Household application	Construction cost	Complexity of construction	Operator skill requirement	Maintenance requirement	Energy requirement	Spatial requirement	Value added by-products
Ventilated improved pit latrine (VIP)	Mainly community but can be applied at household level	Low	Easy to construct except in high groundwater table	Low	Medium	None	Low	Soil humus
Vermicompost toilet	Both	Medium to high	Medium to high	Low	Medium	Some variants require less electricity	Low	Soil humus
Composting toilet	Household level but can be expanded for entire community	Low	High	Low	Medium	None	Low	Compost
Pour flush toilet	Mainly household but suitable for medium density communities	Low to medium	Low to moderate	Low	High	None	Low	-
Septic tanks (including Imhoff tanks)	Household, suitable for low to medium density areas	High	High, Skilled labour required	Low	High	None	Low	-

Compiled from sources: Sharma et al., 2016; Gunady et al., 2015; Residential On-site Wastewater Treatment Systems – Design Handbook 2012.

Generally, on-site systems usually act as primary treatment units removing mostly settleable fraction of the organic matter. It is able to remove about 30 – 40 % of the organic load from domestic wastewater (Sharma et al., 2016). This draw back necessitates further treatment by offsite treatment facilities in order to render effluents harmless for disposal. The feasibility of on-site treatment systems is not universal to every location or project. On-site treatment systems are usually implemented in communities with limited sewerage network coverage such as rural areas. It is also suitable for areas with poor urbanization patterns where poor city planning will not permit for the proper sewerage of entire communities. However, in high population density areas where excessive volumes of effluents are generated they may not be appropriate. Also environmental considerations with respect to ground water or surface water pollution and their public health impacts make on-site treatment systems not suitable for areas with high soil permeability and low stability (Sharma et al., 2014).

2.1.2.2 Off-site treatment systems

Off-site treatment systems are used in communities in a decentralized manner or for entire cities in a centralized manner. The decentralized wastewater treatment systems are designed to operate at small scale. They are particularly more preferable for communities with improper zoning and also scattered low-density populated rural and urban areas. Decentralized systems allow for flexibility in management and a combination of a series of processes to meet treatment goals and address environmental and public health protection requirements. Treatment systems usually used in a decentralized manner are mostly the low mechanized or natural systems.

Centralized wastewater treatment systems involve advanced processes that collect, treat and discharge large quantities of wastewater. More often than not, the treatment technology involve in centralized treatment are conventional and highly mechanized. It is mostly the wastewater management approach for densely populated areas with limited land space. Constructing a centralized treatment system for small communities or peri-urban areas in low income countries will result in burden of debts for the populace.

Off-site systems can be divided into technical and natural treatment systems. Within these two sub-divisions, further partitioning can be done based on whether the treatment process is aerobic or anaerobic. Table 3 describes the common treatment systems usually employed for

the off-site treatment of municipal wastewater. It must be emphasized that the treatment options have been limited to those more suitable or usually used in developing countries.

Table 3: Common options for off-site wastewater treatment

Treatment system	Description	Key features
Conventional systems–Aerobic processes		
Activated sludge process(AS)	Aerobic degradation of pollutants is achieved by mechanically supplying oxygen to aerobic bacteria which feed on organic material and provide treatment.	A complex process with many mechanical and electrical parts. Requires skilled personnel for construction, O & M. High cost, produces large quantities of sludge for disposal but provides high degree of treatment.
Aerated lagoons	Waste stabilization pond equipped with mechanical aeration.	Oxygen supply mostly from aeration devices making it more complex to operate with higher O & M costs.
Oxidation ditch	Similar to stabilization pond but oval-shaped channel with aeration provided.	Higher energy requirement but less land requirement than stabilization pond. Requires less expertise for operation.
Trickling filter	Made up of a loose bed of stones or other coarse material over which sewage passes and the biofilm on the surface of the bed degrade organic material in the sewage.	Oxygen requirement of biofilm is supplied by the atmosphere. Has moving parts which often breaks down in developing countries.
Rotating biological contactor (biodisk)	Made up of series of thin vertical plates providing surface area for bacteria growth.	Plates are exposed to air and wastewater by rotation with about 30 % immersion in wastewater. High efficiency but with frequent break downs.
Anaerobic processes		
Upflow anaerobic sludge blanket (UASB)	Anaerobic process using blanket of bacteria to absorb polluting load	Suited to hot climates. Produces little sludge, no oxygen requirement or power requirement. Usually requires an additional treatment to polish off effluent.

Treatment system	Description	Key features
Natural treatment processes		
Waste stabilization ponds (WSP)	A series of large surface area ponds connecting each other. Ponds have different depths for different purposes.	Treatment is essential by the action of sunlight, encouraging algal growth which provides the oxygen requirement of bacteria to oxidize organic material. Large land area requirement and particularly suited to developing countries due to low construction, O & M costs and hot climates. Also highly suitable for treating pathogenic material.
Constructed wetlands (CW)	Artificial treatment system designed and constructed to replicate the biological processes found in natural wetland ecosystems. It simulates the ecosystem's biochemical functions such as filtration and cleansing.	Treatment is by action of soil matrix, particularly soil – root interface of the plants. No oxygenation is required by mechanical devices. Hence suitable for developing countries. Takes long to establish optimum treatment capacities.
Land treatment (soil aquifer treatment - SAT)	Sewage is supplied in controlled conditions to a soil media.	Soil matrix has a high capacity for treatment of normal domestic wastewater as long as the capacity is not exceeded. Not effective for all pollutants. Eg. Phosphorus. Heightened risk of soil, groundwater and plant contamination.

Compiled from several sources: Zhang et al., 2014; Massoud et al., 2009

2.2 Parameters to consider in the identification of appropriate treatment systems

In the implementation of treatment systems in developing countries, the norm had mostly been the adoption of systems employed for wastewater treatment in developed countries. The operation of these treatment systems had not been entirely sustainable because they are mostly mechanical treatment systems that require a constant supply of energy and regular maintenance. Two conditions which are not usually available in developing countries. To correct this method of treatment system implementation, the tendencies among communities in developing countries have been to adopt natural or nature-related treatment systems that have been successfully implemented in other developing countries. Again, many have not been successful because they had been simply transplanted without considering the differences in properties of such communities and the appropriateness of the system. This indicates that the appropriateness of a treatment system is contextual and situational (Murphy et al., 2009). For instance, a certain type of treatment system can be appropriate for a given location and or situation provided the technological level of that location, labour and resource availability provide the installation, operation and maintenance needs of the system. If the conditions are not present or cannot be replicated in a different location which intends to install the same system, implementation might not be successful. The challenge therefore is to select a treatment system that will operate as intended within the given conditions of the host community – appropriate treatment system.

According to the appropriate wastewater treatment technology concept as explained by Libhaber and Orozco-Jaramillo (2012) and Massoud et al. (2009), a system made up of simple treatment processes of proven technology, capable of providing any required effluent quality at low construction, operation and maintenance costs with minimal impact on the environment and acceptable to users is considered as appropriate for a particular community. This highlights the need to assess treatment systems not only on their technical properties but also on the environmental, economic and socio-cultural properties of the host community as illustrated in Figure 1. The various factors defining an appropriate treatment system outlined in Figure 1 are general and do not pertain to any particular community. Due to the differences in geography, demographic conditions and treatment objectives between communities, the listed factors can vary from one community to the other.

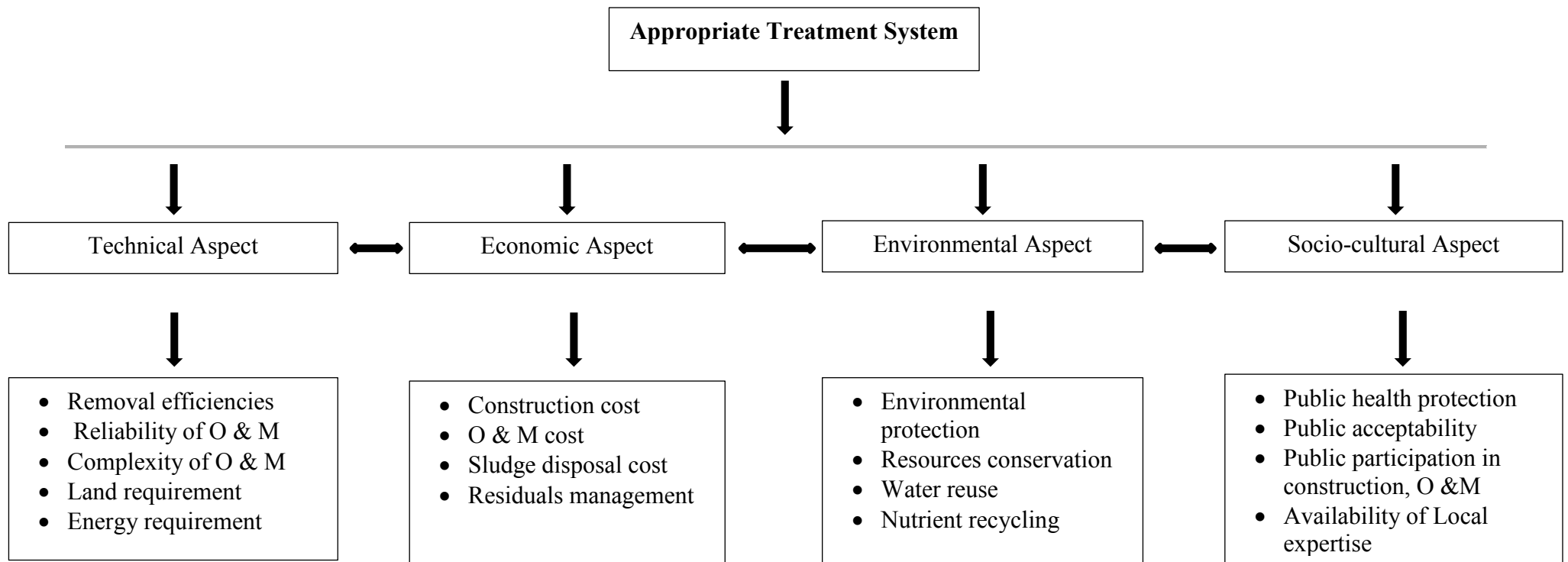


Figure 1: Characteristics of an appropriate wastewater treatment system (Adopted from Massoud et al., 2009)

Several approaches have been made to develop indicators to assess treatment systems. For the objective of identifying a sustainable treatment system, Lundin et al. (1999) and Balkema et al. (2002) developed and applied indicators intended to evaluate environmental stressors. Tillman et al. (1998) applied indicators derived from Life Cycle Assessment to gain information on the environmental performance of treatment systems. An attempt to measure the environmental performance and economic issues associated with treatment systems were made by Tsagarakis et al. (2002) and Dixon et al. (2003). The common thread that runs through these studies is that, they tend to give a limited or one sided assessment of treatment systems and do not offer a comprehensive assessment that will evaluate the technical, environmental and socio-economic components in an integrated manner which is required for the identification of an appropriate treatment system.

Therefore a comprehensive set of indicators that offer not only the technical insight but an understanding of the human and environmental activities surrounding treatment systems needs to be derived. To this effect, the 4 broad aspects of wastewater management that defines an appropriate treatment system; technical properties of treatment systems, environmental, economic and socio-cultural properties of the community needs to be discussed.

2.2.1 Technical aspects

The evaluation of treatment systems based on their technical properties is intended to identify their effectiveness in pollution prevention, consistency in contaminant removal, their complexity or simplicity of installation, operation and maintenance and their usage of resources in construction and operation. In other words, technical indicators determine the effectiveness of the treatment system and the conditions that need to be provided for successful implementation and operation.

Efficiency of the treatment system is measured in terms of the removal of contaminants associated with wastewater and consequently the quality of the effluent and its variability which must be consistent with local discharge standards. Contaminants in domestic wastewater usually monitored by regulatory bodies include Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), coliforms, Total Nitrogen (TN) and Total Phosphorus (TP). Effluent quality of treatment systems are assessed on these contaminants for the

prevention of eutrophication and oxygen depletion of water courses as well as the protection of environmental and public health. The discharge standards set on these contaminants depend on the end use of the effluent. Coupled with the major differences in the removal efficiencies of various treatment systems, assessment is required to identify the most effective treatment system.

The consistency of a treatment system in contaminant removal – reliability, is a critical issue when the effluent is reused or discharged into water courses. According to Oliveira and von Sperling (2008), the reliability of a system can be defined as the probability of achieving adequate performance for a specified period of time under specified conditions. It is also an indication of how easily the system can adapt to changing situations. As a result, the long and short term reliability needs to be evaluated. The long-term reliability assessment seeks to answer questions such as how often effluent consistently meets discharge standards, frequency of system break downs, capacity for expansion, etc. On the other hand, short-term reliability assesses treatment system performance in situations of extreme variations in flow rate, organic load, weather variations, etc. For a developing country context, consistency in operation and minimum system problems is an important attribute of a treatment system since expertise for troubleshooting problems are usually not available.

Generally, treatment systems that are simple in construction, operation and maintenance are suitable for developing countries due to the unavailability of operator services. To prevent the consequences of inadequate operation and maintenance, the complexity of the treatment systems is usually considered in the assessment process.

If the treatment system is being selected for a community in an urban area, the potential land requirement is also considered in the assessment process. Generally, the land size requirement of a conventional treatment system is less than that of a natural treatment system of equal design capacity (Brissaud, 2007). With the exception of the type of treatment system, the land size is determined by the level of treatment required and design capacity (Tsagarakis et al., 2002). Due to population growth and urbanization, land is usually a constraint and the cost of large expanse of lands usually required for the installation of treatment systems can be substantial.

2.2.2 Economic aspects

The importance of taking economic factors into account in the selection of municipal treatment systems especially in developing countries cannot be overemphasized. It is decisive on the type of treatment system to be selected, whether conventional or nature-related. The objective of assessing the economics of treatment systems is to identify a system that the community in question can finance its implementation, operation and maintenance including the capital expenditure required in the future for improvement and the necessary long-term expansion, repairs and replacements (Ho, 2005). As a result the economic aspects of treatment systems usually evaluated are construction, operation and maintenance cost.

Construction cost refers to the monetary expense required for the construction of the treatment system. It involves several costly items such as land, construction, machinery and equipment, facilities and piping works. Operation and maintenance cost on the other hand is related to the management of the system, and they include the following cost items: energy, staff, reagents, maintenance and waste management such as sludge disposal cost (Panjeshahi and Ataei, 2008). Generally, the cost components for conventional treatment systems are higher than natural systems as shown on Table 4 below. This is due to the incorporation of mechanical systems and the requirement of energy for operation in conventional systems.

Table 4: Comparison of cost components between conventional treatment system and CW

	Design capacity (m ³ d ⁻¹)	Unit capital cost (US\$m ⁻³)	Treatment cost (US\$m ⁻³)	O & M cost (US\$m ⁻³)	Energy cost (US\$m ⁻³)
Conventional WWTP		246 – 657	0.7717	0.12 – 0.25	0.1036
CWs in					
Dongying, Shandon, China	100,000	82		0.012	
Bogota Savannah, Colombia	65	225.72		0.0134	
Longdao River, China	200	163.08	0.0223	0.014	

Compiled from several sources: Wang et al., 2005; Liu et al., 2008; Chen et al., 2008; Arias and Brown, 2009; Hernandez-Sancho and Sala Garrido, 2008.

Natural treatment systems are therefore more suitable for developing countries where the ability to pay for wastewater treatment services is usually low (Singhirunnusorn, and Stenstrom, 2010). Aside the type of treatment system, the construction, operation and

maintenance costs components are determined by design flow or population equivalent, actual flow, quality of effluent required and quality of raw sewage to be treated (Tsagarakis et al., 2002; Friedler and Pisanty, 2006; Hernandez-Sancho and Sala-Garrido, 2008).

2.2.3 Environmental aspects

As stated by Castillo et al., (2016) the importance of assessing the environmental friendliness of wastewater treatment plants stems from public awareness regarding water scarcity and pollution. Also the realization of global warming potential (emission of greenhouse gases such as N₂O, CH₄, CO₂ etc.) of wastewater treatment plants and the quest to reduce the carbon footprint of such infrastructures makes their environmental assessment relevant (Larsen, 2015). Therefore, for a system to be environmentally sustainable, it should preserve environmental quality, conserve resources, produce effluent fit for reuse and ensure the recycling of nutrients (Ho, 2005).

The suitability of a certain wastewater treatment system for a certain environment can be ascertained if the potential environmental impacts or protection and potential resource recovery or consumption is known. As such, the impacts of treatment systems on the various environmental components such as surface and groundwater, aquatic and land-based ecosystems, soil quality, air quality and energy use should be evaluated. In terms of resource recovery, energy recovery by way of biogas production potential can be assessed. Is the effluent quality high enough to be used for groundwater recharge or reuse for irrigation and can the biosolids be recycled for use as fertilizer? These are some of the questions that environmental assessment of the treatment system seeks to answer. Table 5 presents a summary of the potential environmental and aesthetic impacts of three groups of treatment systems, namely; land application, constructed wetlands and stabilization ponds.

Table 5: Summary of potential environmental and aesthetic impacts

Land application	Constructed wetlands	Ponds
Negative impacts		
<ul style="list-style-type: none"> • Wetting and clogging of soils • Changes in vegetation type • Salinity impacts on vegetation • Surface water eutrophication • Groundwater contamination • May cause erosion • Odours 	<ul style="list-style-type: none"> • Pollutant accumulation in biota • Rodents, mosquitoes, birds • Spreading of water hyacinth, etc. • Contamination with wildlife excreta • Limited phosphorus binding capacity • Limited salinity removal • Groundwater contamination 	<ul style="list-style-type: none"> • Large area requirements • Flooding risks • Sludge accumulation • Contamination with wildlife excreta • Pollutant accumulation in wildlife • Limited phosphorus binding capacity • Toxic algal blooms
Positive impacts		
<ul style="list-style-type: none"> • Increase in soil microbial activity • Increase in fertility and productivity • Recycling of phosphorus • Immobilization of metals • Less wastewater transportation 	<ul style="list-style-type: none"> • Wastewater reuse by irrigation • Groundwater replenishment • Recreational values • Ecosystem and habitat restoration • Flood and erosion control • Surface runoff control 	<ul style="list-style-type: none"> • Utilization of solar energy • Utilization of biogas • Water reservoir • Salinity removal • Wastewater volume reduction • Algal consumption of CO₂

Source: Isosaari, 2010

Treatment plants can be a source of objectionable odour as a by-product of treatment processes. Controlling odours is now a major consideration in the selection of treatment systems, especially with respect to public acceptance. Several studies have concluded that complaints of inhabitants due to the odours from poorly maintained treatment plants have led to their closure or unwillingness for such facilities to be situated in close proximity to their communities (Stellacci et al., 2010).

Sludge is a by-product of treatment process within treatment systems. The processing of sludge for reuse as an organic amendment or disposal presents one of the most complex problems facing the establishment of treatment systems (Metcalf and Eddy, 2003). Therefore treatment systems should be evaluated by taking into consideration the amount of sludge produced by their core treatment processes.

2.2.4 Socio-cultural aspects

Socio-cultural variations are likely to influence the type of technology that is appropriate for a specific country, community, or tribal context (Long and Oleson, 1980). It relates to the local factors that have the potential of impacting on the installation, operation and maintenance of a treatment system. And these factors include, but are not limited to public acceptance of the treatment system, public participation in the construction, operation and maintenance and institutional capacity available to monitor the operation of the treatment system.

Acceptability is crucial to the implementation as well as the long term operational sustainability. It takes into account the opinion of the public as far as the implementation of the treatment system is concerned. It describes the phenomenon of social opposition to the construction of such facilities known as “not in my back yard” (Molinos-Senante et al., 2015). The lack of public acceptance has been the cause of failure for many waste management programmes in developing countries especially in the operational phase. This is due to the environmental impacts that sometimes result from poorly maintained waste treatment facilities. As a by-product of wastewater collection and treatment processes, the occasional release of odourous emissions from even well maintained treatment plants present an aesthetic problem to surrounding communities. Cognizant of this, the public usually resist the siting of treatment facilities within or near their communities. Public support for

wastewater treatment systems can be garnered by the creation of public awareness through educating communities about the role of waste management programmes in ensuring public health safety.

Securing public acceptance can transform into public participation in system planning, construction and operation. Public participation is often a neglected aspect when selecting the most appropriate wastewater treatment technology for a particular community. While some regulations designate a specific technology through a “best technology” process, the perceptions and preferences of the public toward the selection and implementation of a particular technology is important if the technology is to be integrated with local and broader sustainability concerns (Muga and Mihelcic, 2008). The cost of installation can be reduced by the active involvement of the public during the construction phase. It also has the added advantage of creating a sense of ownership of the project among the community which will go a long way in ensuring its sustainability.

Does the community or municipal authority have the capacity or required competence to monitor the installation, operation and maintenance phases of the treatment system? Institutional capacity and competence availability is a measure of governmental agencies preparedness to adequately manage treatment systems. It is also a measure of appropriate technical and managerial expertise available to manage wastewater in the community. Institutional capacity assessment is important in determining the type of wastewater treatment system that can be successfully implemented in a community. More complex and sophisticated treatment processes require higher level of competence than less mechanized treatment systems (USEPA, 2004). Therefore the availability of competent operators within the facility can reduce the risk of process failure and troubleshoot operational problems when they arise.

As explained in this section, the selection of a treatment system should not be based only on the technical capacities but should also consider or adapt to the environmental and human activities that surround it. The failure to do so had resulted in the non-operation of most municipal wastewater treatment systems. Others have also been unsustainable as a result of being adopted without making adjustments to suit local conditions. This therefore indicates that, the selection of an appropriate treatment system for a particular location is multi-factor or multi-criteria decision making problem.

2.3 Methods of wastewater treatment selection

For the identification of the appropriate treatment system for a community, the discussions from the previous sections show that there are many treatment options to choose from. But the question is how can the selection be done since there are many diverse factors to consider? This section presents a review of some of the methods that have been applied for the selection of treatment technologies.

2.3.1 Optimization methods

Optimization methods of treatment system selection or design are mostly mathematical-based and focus largely on technical aspects. It applies integer, linear, non-linear and mixed programming models as well as heuristic algorithms to outline an objective function (Hamouda et al., 2009). As illustrated by Bozkurt et al., (2015), mathematical-based optimization usually solves treatment system selection problem such that an objective decision-making is achieved.

It usually deals with a single objective function such as cost reduction. At best, optimization deals with two objectives in the selection process such as identification of a treatment system that maximizes efficiency and minimizes cost. In such a situation, the least cost treatment system selected may be appropriate in terms of cost but may not be optimum when other factors recommended for consideration by the appropriate treatment technology concept are included. This feature of the optimization models has created a doubt whether mathematical programming is capable of solving real world selection problems such as identifying appropriate wastewater treatment system.

Also, at the core of optimization methods are complex mathematical models that are likely to be complicated to be applied by lay persons such as local planners and municipal authorities in charge of wastewater management in developing countries.

Optimization methods of selection usually deal with numeric or quantitative indicators and find it challenging to quantify qualitative indicators for incorporation into the selection process. This presents a drawback as far as the selection of an appropriate treatment system is concern because a considerable number of factors under socio-cultural and environmental aspects are qualitative in nature.

In spite of these weaknesses, a number of Decision Support Systems (DSS) based on programming models have been developed to aid in the design and selection of water and wastewater treatment systems. Table 6 presents some of these DSS and the models used.

Table 6: Summary of some decision support systems derived from optimization methods

DSS name	Scope	Objective function	Programming technique	Purpose & comments	Reference
-	Wastewater treatment	Technical & economic	Process modelling, mathematical programming	Solves mass balance on treatment systems. Graphical display of designs	Kao et al., 1993
-	Wastewater treatment	Technical & economic	Case-based reasoning, heuristic search	Defines cost per unit removal of contaminant	Krovvidy & Wee, 1993
WASDA	Wastewater treatment	Technical design	Rule-based, design equations	Identifies the least cost alternative and assesses risk. Community specific data considered in the decision.	Finney & Gerheart, 2004
WADO	Industrial wastewater treatment	Technical & economic	Rule-based, mixed integer, non-linear programming	Investigates treatment options of industrial wastewater	Ullmer et al., 2005
WTRNet	Wastewater treatment	Technical & economic	Modelling & simulation, linear & non-linear programming, genetic algorithm	Provides user guidance for treatment system selection through an expert approach	Joksimovic et al., 2006

Note: Contents of the table is reviewed by Hamouda et al., 2009

2.3.2 Artificial intelligence methods

In response to some of the challenges posed by the sophisticated mathematical programming methods and their derived DSS for the selection of treatment systems in developing countries, simpler, less mathematical and computer-based models have also been developed. These were developed to help communities with limited resources and skills to select treatment systems that suit their particular wastewater treatment needs. Two of such selection methods are expert systems and case-based reasoning.

Expert systems are sometimes referred to as knowledge-based systems. They are usually modeled along the lines of human reasoning methods using knowledge within a particular discipline. In its basic description, knowledge of treatment problems and solutions by way of treatment systems are gathered, organized and documented in the form of decision trees. Decision trees are then converted to selection rules by traversing each branch from the root to the leaf. Rules extracted from decision trees are codified and applied as a benchmark against which alternative treatment systems must satisfy to be selected as appropriate for a particular locality (Comas et al., 2003). Expert system is limited in application in developing countries or localities with limited wastewater treatment expertise. This is because expert knowledge is vital in the establishment of the knowledge base (Sairan et al., 2004).

Communities sometimes decide on the implementation of a particular treatment system alternative based on the successful implementation of a similar treatment system in a similar location. This method of selection forms the basis of case-based reasoning. The rationale according to Hamouda et al., 2009 is that, starting from a solution of relevant previous case will more likely put the selection process on the optimal path to a solution. A database of relevant treatment problems and their solutions are set up. It is continually updated with new cases to improve the obtained solution. Case-based systems require a large number of cases in its database to be able to produce acceptable solutions and the challenge is determining or identifying such large number of similar situations. This makes case-based reasoning limited in its application.

From the concept of appropriate wastewater treatment, the selection of a treatment system for a particular location would not be successful unless an integrated approach to problem analysis and solution is adopted. The implication is that, not only should the technical

properties of treatment systems be evaluated but all aspects of the local environment with the potential of impacting on the treatment system implementation should also be assessed. The review of literature in the previous section indicates that these local aspects are made up of qualitative and quantitative variables. Consequently, the selection method applied must be able to aggregate these variables. It should also be flexible to allow the incorporation of characteristics of local conditions. And lastly, the selection method should be easy to apply and interpret with minimum expert involvement.

Based on these conditions and the various limitations of the 2 main groups of selection methods (optimization and artificial intelligence) outlined above, this study employs a multi-criteria decision making (MCDM) approach to evaluate a number of treatment system alternatives in order to identify the most appropriate one. This is because the problem of selecting an appropriate treatment system presented in this study exhibits the characteristics of a MCDM problem.

2.3.3 Concept of multi-criteria decision making (MCDM)

Making a decision implies that there are alternative choices to be considered, and in such a case the decision maker seeks not only to identify as many of these alternatives as possible but to choose the one that has the highest probability of effectiveness and also best fits the purposes of which the decision is being made. Usually the alternatives have to be selected based on some benchmarks which reflect the values and preferences of the decision maker. These benchmarks are referred to as the criteria of the decision making. A simple and straight forward rare case of decision making involves just a single or very few criteria against which the alternatives will be evaluated. But more often than not, most practical decision making cases consist of a number of alternatives being evaluated by a set of conflicting criteria at the same time. Such a decision making scenario becomes complex and it is referred to as Multi-Criteria Decision Making (MCDM).

Problems of multi-criteria nature are wide spread and are encountered regularly on many environmental protection or remediation projects. As a result, many municipal authorities and government departments in charge of environmental projects at some point is confronted with the evaluation of a set of alternative solutions with a set of decision criteria to environmental problems. In the context of this study, choosing or recommending a treatment technology for

a certain community may be characterized in terms of treatment efficiency, capital and operating cost, manageability, ease of operation, etc. These are the decision criteria and the various municipal wastewater treatment technologies suitable for implementation represent the alternatives.

This illustration is as a result of the differences in performances of the alternative treatment technologies as far as the treatment criteria are concern. In other words, rarely do any two treatment systems perform at the same level as far as the performance criteria are concern.

In addition, some conflicts or trade-offs usually exist in the decision criteria. For example, options that are more beneficial are also usually more costly. Costs and benefits typically conflict, but so can short-term benefits compared to long-term ones (Multi-criteria analysis: a manual, 2009). The need therefore arises for a decision maker to choose the alternative that best satisfies most of the decision criteria. MCDM is the tool that has been developed to aid the decision maker to make a decision on a multi-criteria problem.

MCDM is both an approach and a set of techniques, with the aim of establishing an overall ranking of alternatives being considered to satisfy certain criteria. Unlike traditional operations research optimization problems, which deal with a single objective function to be optimized over a set of feasible solutions, MCDM refers to making decisions in the presence of multiple, usually conflicting and non-commensurable criteria (Zanakis et al., 1998). It is a way of looking at complex problems that are characterized by non-commensurable criteria, of disaggregating a complex problem, of measuring the extent to which alternatives achieve criteria, of weighting the criteria and of reassembling the pieces to present a coherent overall picture to decision makers (Multi-criteria analysis: a manual, 2009). Although MCDM problems could be very different in context, they share the following common features;

- Existence of multiple criteria
- Conflict among criteria
- Criteria being non-commensurable
- Combination of qualitative and quantitative criteria
- Combination of deterministic and probabilistic criteria

Generally, MCDM methods are categorized into two main subgroups: Multi-attribute decision making (MADM) and Multi-objective decision making (MODM) methods. Discrete MCDM problems characterized by a finite number of well-defined alternatives are handled by MADM methods. Continuous decision problems involving an infinite number of feasible alternatives are handled by MODM. That is under MODM, there are no pre-defined alternatives to select from but it is the MODM method that is used to build alternatives. Since the problem of selecting an appropriate treatment technology fits the description of an MADM problem (it is characterized by a finite set of treatment system alternatives), further classification that focuses on MADM will be reviewed.

2.3.3.1 Classification of Multi-Attribute Decision Making (MADM) methods

Many MADM methods have been developed and applied in various fields. They range from simple to highly sophisticated ranking systems. To select the appropriate decision making method for any type of problem, understanding the decision making classification is vital. There are many ways to classify MADM methods but one of the most commonly used is the classification and review conducted by Hwang and Yoon (1981). According to this classification there are two types of MADM methods, namely, compensatory and non-compensatory as illustrated in Figure 2: and this classification is based on how the attribute information is to be processed. Non-compensatory methods do not permit tradeoffs between attributes or indicators. An unfavourable value in one attribute cannot be offset by a favourable value in other attributes. Each attribute must stand on its own. Hence comparisons are made on an attribute-by-attribute basis. The MADM methods in this category are credited for their simplicity. Examples of these methods include dominance, maximin, maximax, conjunctive constraint and disjunctive constraint methods.

Compensatory methods on the other hand permit tradeoffs between attributes. A weakness in one attribute is acceptable if it is compensated by some enhancement in one or more of the other attributes. Compensatory methods are complex but may lead to outcomes that are closer to the ideal solution than non-compensatory methods (Yoon and Hwang, 1995).

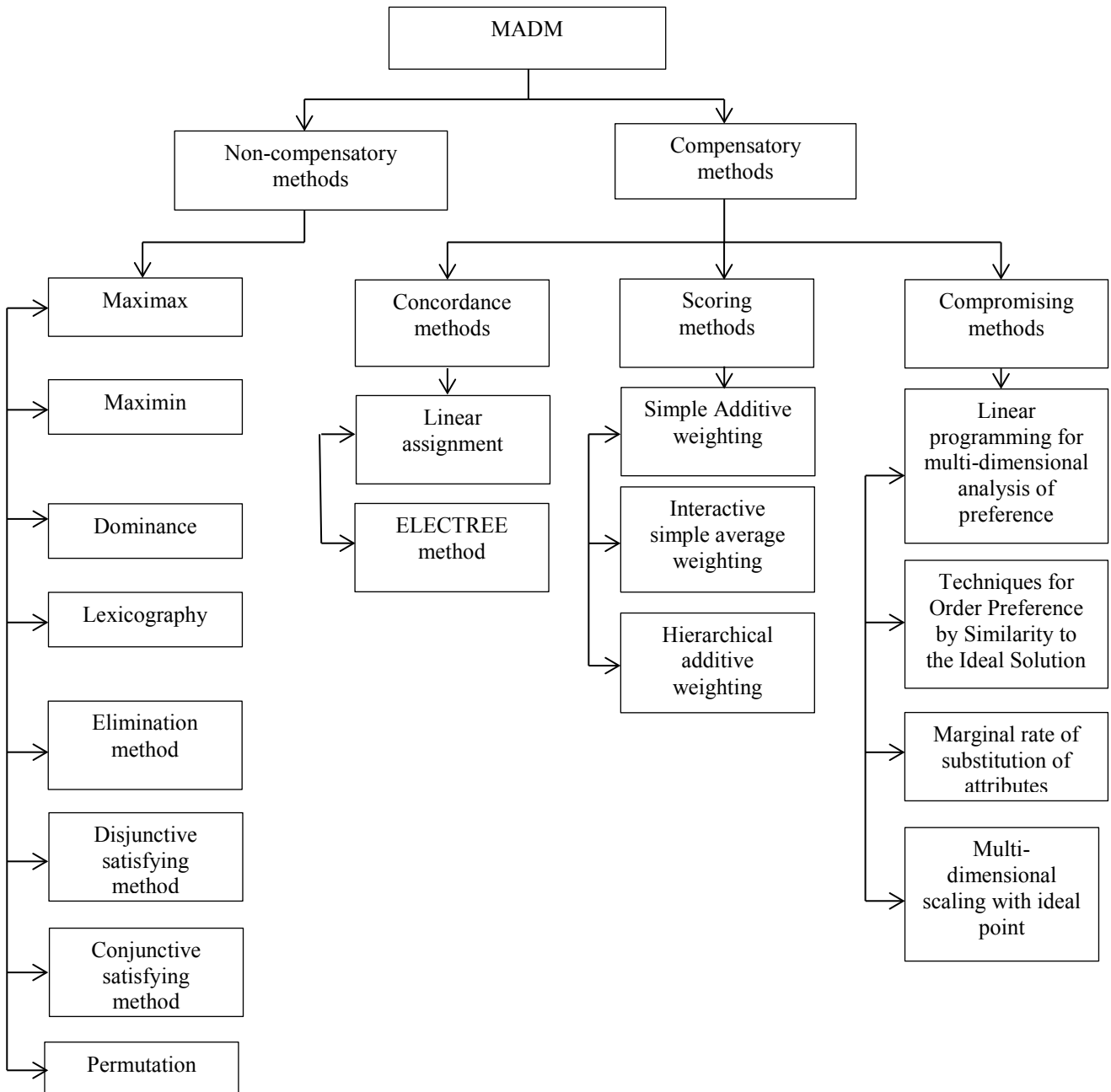


Figure 2: Classification of MADM methods of decision making

Compensatory methods can be further classified into the following 3 subgroups:

Scoring methods

Selects an alternative with the highest score or utility considering all of the attributes together simultaneously. Examples of methods under this category are Simple Additive Weighting (SAW) and the Analytical Hierarchy Process (AHP).

Compromising methods

This method selects an alternative that is closest to the ideal solution. A very popular method that belongs to this category is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method.

Concordance methods

Generate a preference ranking which best satisfies a given concordance measure. An example under this group is the Linear Assignment Method.

Among these methods TOPSIS is selected as the most suitable for the decision making problem of this study because of its logical way of solving a discrete MADM problem. The basic principle behind TOPSIS is that, the most appropriate alternative must have the shortest distance to the positive ideal solution and farthest distance to the negative ideal solution (Hwang and Yoon, 1981; Garcia-Cascales and Lamata, 2007). TOPSIS can be implemented computationally (programmed into a spreadsheet) and made available for end users as a decision support tool due to its simple and logical mathematical algorithm. And as a result of this simplicity, it is one of the most widely used MADM methods for the development of environmental decision support systems. By way of recent examples, the works of Cheng et al., (2003); Shih et al., (2007); Li et al., (2009); KandaKoglu et al., (2009) and Kalbar et al., (2012); all applied TOPSIS as an environmental decision making method.

Inherent in most decision making models with a minimal degree of subjectivity is the tendency to produce slightly different results when applied to resolve the same decision problem. To eliminate this weakness as much as possible, Simple Additive Weighting (SAW), which is usually applied as a benchmark to compare the results obtained from other discrete MADM methods is also applied. The step by step exposition and mathematical algorithms that characterizes TOPSIS and SAW are outlined in the methodology section.

3 Methodology

3.1 Description of the study area

The city of Kumasi is the second largest in Ghana and located at about 300 km northwest of Accra, the capital city of Ghana. It roughly lies in the center of Ghana and covers an area of approximately 150 km² (Figure 3). It is between latitude 6.35° to 6.40° and longitude 1.30° to 1.35° with an elevation that ranges between 250 to 300 m. The climate of Kumasi is wet, semi-equatorial. It has an annual rainfall of approximately 1350 mm with minimum and maximum temperatures around 21 °C and 30 °C respectively.

Currently, Kumasi is being inhabited by about 2 million people with an annual growth rate of approximately 5.47 % (Ghana statistical service, 2010). Being an inland city, it has a very limited industrial activity with about 4 major industries; 2 breweries, soft drink bottling plant and the Kumasi abattoir. There are also other minor industries such as saw milling, furniture manufacturing, light engineering, vehicle repair and metal fabrication.

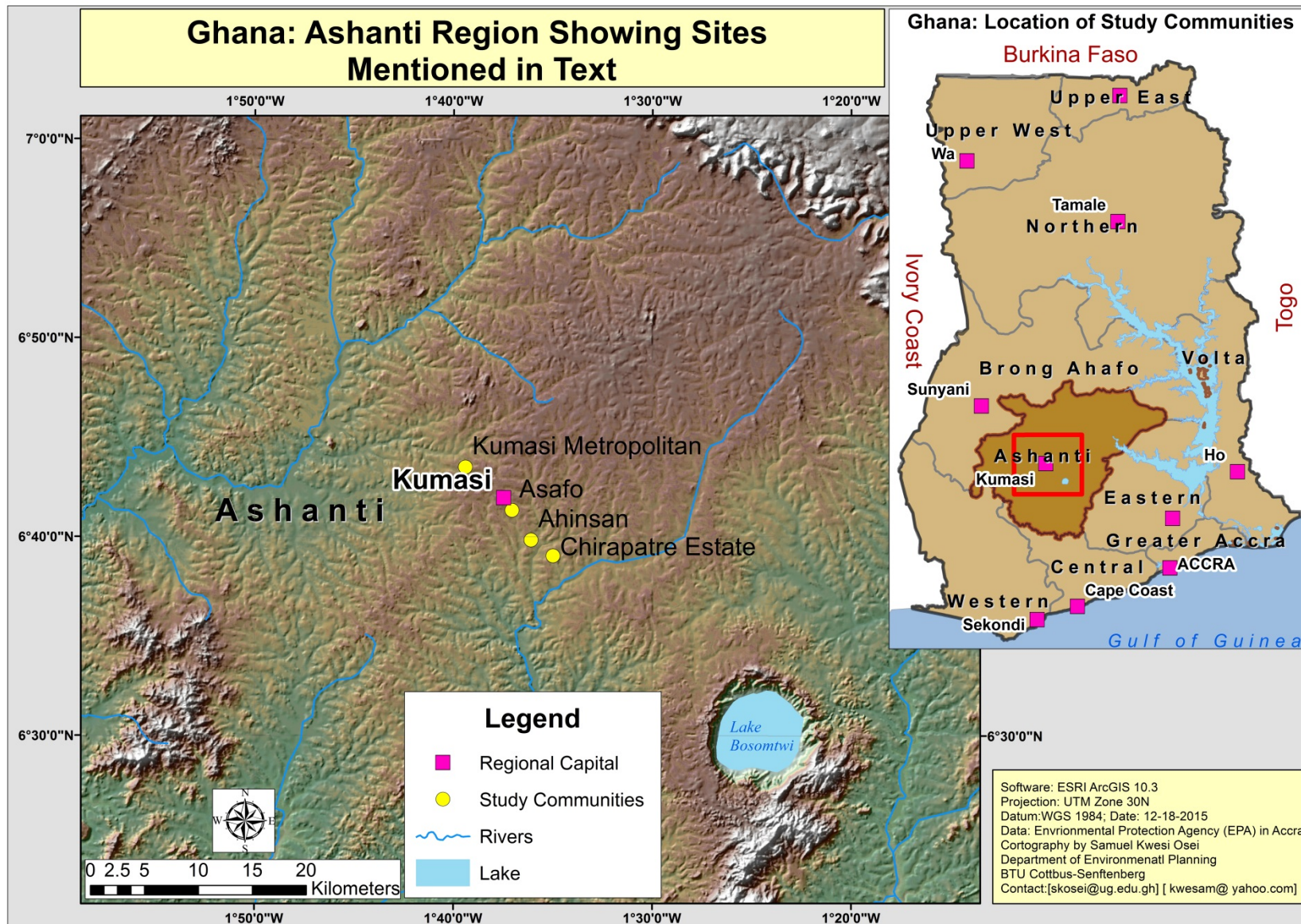


Figure 3: Map of Kumasi showing study communities

3.1.1 The wastewater situation of Kumasi

With limited industrial activity in Kumasi, the city's effluent is mainly of domestic origin. Assessment by the Waste Management Department of the Kumasi Metropolitan Assembly (WMD-KMA) in 2003 for the purposes of planning waste management intervention programmes showed that approximately 20,000 m³ of wastewater is generated in the metropolis every day. Of this figure 1510 m³ per day comes from industrial sources. It is further estimated that of this, less than 10 % is collected for treatment before disposal. This is because, in line with cities in most developing countries, infrastructure for wastewater treatment in Kumasi is not well developed. It is characterized by very limited number of treatment systems, some of which are out of service and others partially operational due to many problems ranging from overloading due to population growth in some communities, inability to maintain and rehabilitate plants, low operation and maintenance activities and lack of funds for maintenance and expansion. Currently, a series of stabilization ponds at the outskirts of the city (Kaase) with a capacity of 500 m³ is responsible for the treatment of faecal sludge for most parts of the city.

As a result of the volumes of effluent generated in the city daily, the limited capacity of the Kaase stabilization ponds, limited number and inefficient treatment from other treatment plants in some communities, the efficient treatment and disposal of the city's faecal waste have become a critical problem. Faecal waste from households ends up in the city's main water bodies. Open sewers and storm drains also discharge untreated wastewater into the main streams flowing through the city. These water bodies are polluted and pose health risks as they represent water sources for downstream communities. With population growth and the consequent increase in wastewater generated daily, the environmental pollution is set to be worse.

In an effort to redress this environmental impact, the Kumasi Metropolitan Assembly in conjunction with the United Nations Development Programme / World Bank Water & Sanitation Programme has produced a Strategic Sanitation Plan for Kumasi (SSP-Kumasi). SSP-Kumasi identifies facilities required for the provision of comprehensive sanitation services, their implementation and feasible financing options. Among these facilities are treatment systems. It recommends a decentralize form of wastewater treatment with community-based treatment plants due to the abuse of the city's layout. It also recommends

private establishments such as larger hotels to have their own treatment plants. It is against this background that this research seeks to find treatment systems that will be appropriate for the various communities.

3.2 Identification of study communities

Given the wide expanse of the city of Kumasi and the following compelling factors, it became necessary to focus the study on some selected communities within the city.

- In line with the approach of this research which advocates for a decentralized wastewater treatment system for the city of Kumasi due to its dense population, heavily built up areas, the practice of development preceding planning and consequently improper zoning which will make implementation of a centralized system for the entire city less feasible, a decision was made to focus the household survey at the community level.
- Again since this research is about a concept development, the results from the selected communities will be applicable to the other communities due to the homogenous nature of the city. But in the event of communities having marked differences in environmental and socio-cultural properties, the concept can still be useful by adjusting corresponding indicators to reflect the conditions in the communities not focused on. This lends further validity to this research being applicable to the entire city.
- Also considering the limited research timeframe and budget, and the huge cost of data collection that would have been incurred if samples had been drawn from each community within the city, the survey was confined to few communities.

Once the need to focus the community survey on some communities was established, the next step was to determine which communities to carry out the survey. Three communities, namely, Asafo sub-metro, Ahinsan estates and Chirapatre estates were selected based on the criteria outlined in Table 7 below.

Table 7: Criteria for selecting communities for household survey

Criteria	Description of criteria
Accessibility	Easy access to the area during survey.
Availability of data	Data on households, community population estimates, volumes of wastewater generation and other socio-cultural parameters.
Community stability	The community not likely to be altered or developed during the survey.
Prior participation in a sewerage management scheme	Questionnaire requires respondents to have had an experience of a community wastewater treatment scheme and therefore have a fair view of what the survey is about.

3.2.1 Description of study communities

3.2.1.1 Asafo sub-metro community

Asafo is almost at the center of Kumasi and part of the main business district. Being part of central Kumasi, the community is made up of tenements and business entities. It is a high-density area mostly characterized by 2 – 3 storey buildings interspersed with single storey buildings. Most of the houses have 20 – 30 rooms shared by 10 – 20 families (40 – 100 persons). Plot sizes are about 30 m by 30 m and the housing type is predominantly compound houses. Population densities in the tenement area are between 300 to 600 persons / hectare. Water supply is mainly obtained from the public water works but a growing number of houses are converting to groundwater abstraction due to the unreliability of the main water distribution system. Flush toilet is a common feature in most houses but there are a number of public toilets (mostly water closets) serving households without toilets.

Currently most of the residential dwellings are being converted into commercial buildings because of population growth and the expansion of the central business district of Kumasi.

Implementing the recommendation of the SSP-Kumasi for community-based treatment plants, the Asafo Pilot Sewerage Scheme was launched in the mid-1990s. It is composed of underground sewers that convey faecal waste to a treatment plant located at one end of the community. The plant is a stabilization pond made up of a grit chamber, two anaerobic ponds, a facultative pond and two maturation ponds (Figure 4). It is constructed for the

treatment of faecal waste from 320 households in the community before discharge into the Subin River.



Figure 4: Asafo waste stabilization pond (Field photograph, 2014)

Data gathered from field interviews of personnel of WMD-KMA indicates that Asafo was selected for the pilot project due to;

- the community's master plan layout being relatively intact (not heavily abused by the construction of illegal structures).
- availability of land suitable for the treatment system.
- high population density (to service more people).
- to phase-out bucket latrines for the city's poor and to reduce pollution of the Subin River by faecal waste.

Data gathered from field interviews indicates that the Asafo treatment plant is operating below capacity (active users less than the 320 households) mainly because of the cost for using the plant and the difficulties in making connections in the heavily built-up surroundings.

3.2.1.2 Ahinsan and Chirapatre sub-metro

Ahinsan and Chirapatre communities are low cost housing estates that were constructed in the late 1970s. Compared to Asafo, the communities of Ahinsan and Chirapatre can be described to be on the outskirts of the city of Kumasi. They are among the few areas in Kumasi with underground sewer network systems. The sewer systems were initially conveying effluents to communal septic tanks and filter beds but have been converted into stabilization ponds (Figure 5) due to operational problems occasioned by lack of maintenance.



Figure 5: Stabilization ponds for the Ahinsan and Chirapatre communities (Field photograph, 2014)

There are two types of houses in both communities; the earlier estate houses that are connected to the treatment plants and latest private houses that are equipped with septic tanks that are de-sludged periodically. Faecal wastes from the estates are treated by the stabilization ponds before discharge into nearby streams. Most houses are equipped with flush toilets and water is obtained from a combination of the public water works and groundwater abstraction.

The Ahinsan WSP system is made up of 5 chambers; a grit, screening, influent and two inspection chambers and four treatment ponds; anaerobic, facultative and two maturation ponds.

3.3 Criteria and indicators development

Factors that must be considered in the selection of wastewater treatment technologies have been widely researched into and as a result a wide body of literature exist that list these

important factors. These factors mostly represent the technical criteria that the design and construction of treatment systems must satisfy to ensure longevity and satisfactory operation.

Most often, factors that account for the operational failures of treatment systems and the discontinuity of wastewater treatment in developing countries are not part of these technical factors. They usually fall into one of these criteria; environmental, economic and socio-cultural. Appropriate treatment technologies being simple treatment processes of proven technology, capable of providing any required effluent quality (technical criteria) at low investment, operation and maintenance costs (economic criteria) with minimal impact on the environment (environmental criteria) and acceptable to users (socio-cultural criteria) are required to overcome the challenges of wastewater treatment and management in developing countries.

Therefore the economic, environmental and socio-cultural concerns of communities need to be taken into account for the design and construction of appropriate treatment systems. But to a larger extent, environmental and socio-cultural properties and to a lesser extent economic properties present an engineering challenge because they are conceptual variables (ideas or constructs). They are difficult to be objectively measured and incorporated into the technical criteria used for the design and construction of treatment systems. They can be used as benchmarks against which treatment systems can be evaluated for the purposes of selecting the most appropriate. This can be possible only when the conceptual variables are translated into specific measures or indicators that can be used to collect data (operational variables). The following steps have therefore been taken to develop the initial criteria and indicators required for the assessment of treatment systems;

1. Identify the ideas or conceptual variables from the appropriate wastewater treatment technology concept;

Based on literature review about the definition and understanding of appropriate treatment technology, an initial set of criteria for the assessment of the treatment technologies have been identified (column 1 of Table 1 in Appendix A). These variables are comprehensive and not specific to be applied for data collection.

2. Identify the dimension of interests in each conceptual variable;

These represent the sub-criteria (column 2 of Table 1 in Appendix A). These are also not specific enough for data collection.

3. Transformation of sub-criteria into indicators for data collection and measurements i.e. Operational variables for measurements (column 3 of Table 1 in Appendix A).

This involves creation of questions to elicit data needed to determine the importance of indicators.

These constitute the initial indicators that have been developed for this research. Assessment of these by local wastewater treatment experts, municipal personnel in charge of wastewater management and households of the selected communities was used to decide on the final set of criteria and indicators. A two-step process of the assessment is as follows;

1. Indicators were used to create a questionnaire for a survey requiring respondents to rank the relative importance of each indicator in relation to the overall selection of appropriate wastewater treatment technology.
2. Result of the survey was used to prioritize the indicators by selecting those of high relative importance and eliminating those of low importance.

3.4 Assessing the importance of criteria and indicators

3.4.1 Expert survey

This survey was done to elicit information from a diverse group of local experts representing academics, private and public consultants, plant operators and managers and public officials in charge of wastewater treatment and management. Information gathered forms the basis for assessing the relevance of the initial criteria and indicators developed for identifying appropriate treatment technologies for the study area.

With the help of the waste management department of Kumasi Metropolitan Authority (Municipal Authority), local experts who are consulted or contracted for the planning, design, construction, operation and maintenance of the city's treatment plants were identified. These experts were further used to identify other people in Ghana in their field of expertise. In all 43

experts were identified. Each one of them was contacted and subsequently sent a detailed structured questionnaire requesting them to apply a quantitative scale of measurement to rank and give their remarks on a range of indicators considered useful for the assessment and selection of appropriate treatment systems.

Also a request was made for completed questionnaires to be sent by email to the researcher. Several follow up visitations were made for collection from those who did not mail their completed questionnaires and those who were given hard copies. Responses of 27 respondents representing academicians, city authorities and consultants and plant designers were collated. Figure 6 below illustrates the proportion of each group of respondents in the total questionnaire receipts.

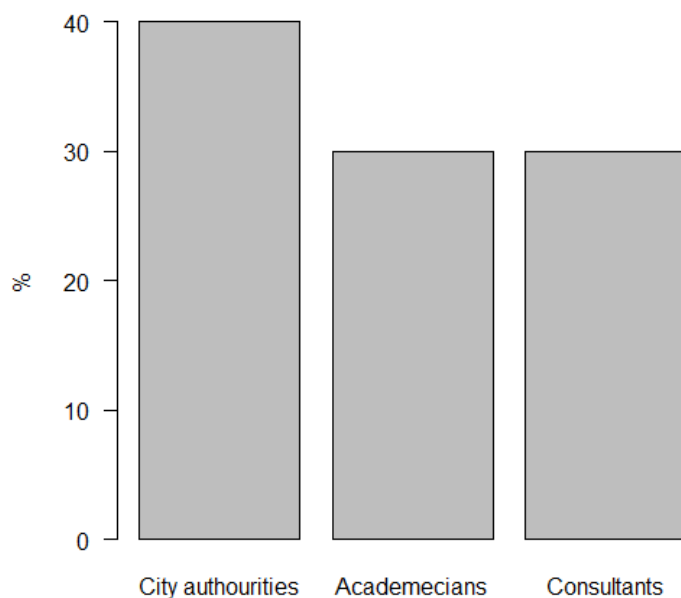


Figure 6: Types of respondents in expert survey

The advantage of this kind of survey is to have acknowledged experts approving the proposed selection criteria and indicators and to eliminate subjectivity on the part of the researcher.

3.4.1.1 Sampling criteria for expert survey

The number of experts in the field of wastewater treatment and management in Ghana is highly limited. It was therefore not feasible or practical to carry out a random sampling. Non-

probabilistic sampling alternatives were considered to be more suitable and since a specific predefined group, being wastewater treatment and management experts are being sought, purposive sampling methods were applied.

In an expert survey sampling, the contacts of a handful of experts were assembled through information gathered from the waste management department of KMA and relevant literature concerning wastewater treatment and management in Ghana. On reaching the identified experts, a snowball sampling procedure was applied by asking them to recommend others who they may know also meet the criteria for inclusion. These purposive sampling methods made it easy to reach potential respondents who were inaccessible or difficult to find.

3.4.2 Community survey

The purpose of this survey was to identify the peculiarities of local socio-cultural and environmental conditions that will impact on the adoption and implementation of treatment systems. A 3 part questionnaire that gives the background information of this research and request representatives of households (respondents) to apply a quantitative scale of measurement to rank proposed indicators in order of their importance was applied in collecting data pertaining to the local situation. Interviewers made visitations to selected households to seek answers to questions in the questionnaire or to explain and present questionnaires to households for completion. Further visitations were made to collect completed questionnaires. A total of 307 houses consisting of private residences, schools, polytechnic, lorry stations, guest houses, hotels and offices out of a total population of 695 houses in the 3 communities participated in this survey.

3.4.2.1 Sampling criteria for community survey

Unlike the expert survey where certain expertise was sought for data collection, every household within the study communities was a potential respondent in this survey. As a result, probability sampling methods were applied. Probability sampling methods utilizes some form of random selection and it ensures that the different units in the sampling frame of the population under study have equal probabilities of being chosen.

A multi-stage sampling method consisting of two levels of random sampling - stratified and systematic, were applied at the Asafo community. Households were stratified into 3 homogenous non-overlapping sub-groups (strata) on the basis of their house numbers. The 3 different strata are as follows;

AA – Amakom Aburotia

NA – New Amakom

BH – Bimpa Hill

Being in close proximity to the center of Kumasi, Asafo has a significant proportion of households that are not residential but serves other purposes such as hotels and lodgings, offices, educational institutions and lorry stations. All these “housing units” are connected to the treatment plant. They were therefore deemed to be potential respondents to the household survey. Consequently, they were placed in a 4th sub-group, such that the total number of households or housing units in all the 4 sub-groups equals the household population in the community. That is;

$$N_1 + N_2 + N_3 + \dots + N_i = N$$

Having established the minimum sample size required from each sub-group, the systematic random sampling method was applied to draw samples from each sub-group in the following steps;

- Acquisition of data on population size (N) and household numbers
- Deciding on sample size (n) required
- Calculating the interval size ($k = N/n$)
- Randomly selecting an integer between 1 to k
- After that, selecting every kth unit

Two man survey teams made visitations to interview members of selected households preferably the landlord or caretaker concerning factors that should be considered in the selection of a wastewater treatment plant in their respective communities. The household

population of the Asafo sewerage scheme is 250, but the accessible population (sampling frame) is 189, this is the total number of households for all the 4 sub-groups.

The systematic random sampling technique was also applied in the communities of Ahinsan and Chirapatre estates to draw representative samples for the survey.

3.5 Methods of indicators quantification

After establishing the indicators that reflect the technical aspects of municipal wastewater treatment systems, environmental, socio-cultural and economic concerns of the Kumasi metropolitan area that the implementation of treatment systems needs to be cognizant of in the first step of this study, the next step is the quantification of these indicators against each of the wastewater treatment systems considered to be feasible for the study area. That is the assessment of alternative treatment systems by the derived indicators. The indicators are quantitative and qualitative in nature and the methods for their quantification are as follows.

3.5.1 Quantification of quantitative indicators

3.5.1.1 Removal efficiencies

Indicators representing the removal efficiencies of the various pollutants such as BOD, TN, TSS, etc. were quantified by adopting values considered to be typical removal efficiencies by technical literature of the different wastewater treatment technologies.

3.5.1.2 Land size requirement

The total land requirement or size of a treatment system is a function of;

- Treatment level required
- Type of treatment system or processes
- Design capacity or flow (m^3/d)

But analysis of land requirement and cost properties of municipal wastewater treatment plants (MWWTPs) indicates that there is a strong correlation between the land requirement and design capacity or flow. Design capacity or flow (m^3/d) on the other hand, is a function of the

average wastewater generated per person per day and the population size served. Therefore to determine the land size requirements of the treatment system alternatives being considered, the exact relationship between land requirements and design capacities of similar operating MWWTPs with effluent quality within the limits of Ghana discharge standards needs to be established. That is, a predictive model needs to be derived. For this, a survey of municipal wastewater treatment systems was carried out to extract the following data;

- Land usage or size
- Design capacity

Using this set of data, a regression analysis was performed to produce a regression model with land requirement (land usage or size) being the dependent variable and designed capacity or flow being the independent variable. With the population size (p.e.) or design flow of the study communities and the derived statistically significant regression model, the land requirements of the treatment alternatives were estimated (See Table 1 in Appendix B for data on treatment plants surveyed).

3.5.1.3 Construction cost

Analysis of the economics of MWWTPs shows that the cost of construction is an aggregate of certain cost components namely; land, civil engineering, electromechanical equipment, electricity and control costs (the last 3 components highly prominent in the case of conventional treatment systems). It also indicates that the costs of these components are ultimately determined by the following parameters;

- Size of the treatment system (determined by design capacity or served population size)
- Treatment level required
- Quality of raw sewage to be treated
- Type of treatment system or process

But likewise the land size requirement indicator, there is a strong correlation between the construction cost and size of the treatment system or design capacity. Assessment of the nature of the relationship between construction cost and design capacity will provide a model

(predictive model) that can be applied to estimate the construction cost of the treatment options being considered to be feasible for the study area. . For this, a survey of municipal wastewater treatment systems was carried out to extract the average values of the following variables;

- Construction cost
- Design capacity

Since the surveyed municipal wastewater treatment systems were constructed at different times and at different geographic locations with different economies, the construction costs needed to be normalized to the same basis by calculating their Present Values (PVs) in the year 2013 from their Historical Costs (HC). This was achieved by converting the HCs to PVs using changes in inflation rates (Consumer Price Index (CPI)) from their respective construction year's to 2013 in the different geographic locations according to the equation;

$$PV_{2013} = HC * (1+f_t)^{t-1}$$

Where f_t is average inflation over the time period t . (See Table 2 in Appendix B for annual average CPI for the different countries).

The PVs in the various currencies were then converted into US\$. Using this set of data (PV construction cost and design capacity), a regression analysis was performed to produce a regression model with PV construction cost being the dependent variable and designed capacity or flow being the independent variable. With the population size (p.e.) or design flow of the study area and the derived statistically significant regression model, the construction costs of the treatment system alternatives were estimated.

It must be emphasized that some of the alternative treatment systems are non-existent in the study area. Also, of those that exist, their design capacity, land size and construction cost data are not readily available. Consequently, the above named data categories of similar treatment systems from other countries (namely; Burkina Faso, Kenya, Germany, UK, and USA) where they were readily available were sourced by a treatment plant survey, and applied. See Table 1 in Appendix B for the names of the treatment plants and their surveyed parameters.

3.5.2 Quantification of qualitative indicators

Performance assessment survey was conducted to assess the performance of municipal wastewater treatment systems similar to the treatment options being considered to be feasible for the study area. Engineers, technicians, operators and managers of treatment plants were made to evaluate their respective treatment plants with the qualitative performance indicators developed for this study. A rating scale of 1 to 5, with 1 being 'low' and 5 being 'high' is presented to participants for the assessment. The average rating of an indicator against a treatment plant is computed to represent its measurement. See Appendix C for sample survey questionnaire.

3.6 Indicator classification

Conditional to the application of the 2 MADM methods selected for this work is the categorization of the identified decision making indicators into benefits (positives) and costs (negatives). In general indicators favourable to the decision making are termed benefits indicators and they represent the indicators that the decision maker wants to maximize. Contrary to this, indicators that the decision maker wants to minimize and are not favourable to the decision making are categorized as negative indicators. The partitioning of the assessment indicators into benefits and cost is largely context based. Therefore in the context of wastewater management of an urban community in a developing country with limited land space and financial constraints, partitioning was done to group indicators favouring the objective of selecting a treatment system of minimum land footprint, low construction, operating and maintenance cost and high treatment efficiency as benefit indicators. Indicators that do not favour this objective are grouped as cost indicators.

3.7 Application of MADM methods for the selection of an appropriate treatment technology

The central decision problem that this research is trying to resolve is described as follows; Given is a set of suitable municipal wastewater treatment systems (alternatives) that are being considered for construction at a certain community. The problem is to choose the most appropriate treatment system for the community or rank the alternatives according to how well they will perform. But in order to achieve this, the selection or ranking procedure must take into account not only the technical capacities of the treatment alternatives but also the

environmental, socio-cultural and economic concerns of the community. This makes it a multi-attribute decision making problem which can better be resolved by a Multi-Attribute Decision Making (MADM) method. A review of MADM methods and the nature of this decision problem (discrete decision making problem involving a finite set of alternatives) suggest that Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Simple Additive Weighting (SAW) are the most appropriate methods to apply.

3.7.1 Structure of the selected MADM methods

3.7.1.1 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is selected partly because of its logical approach to solving a MADM problem. Its step-by-step exposition as applied in selecting the most appropriate treatment systems for the 3 study communities are as follows;

Step 1: Involves the construction of the initial decision matrix as follows;

$$\begin{array}{c}
 I_1 \quad I_2 \quad \dots \quad I_n \\
 A_1 \left[\begin{array}{cccc} x_{11} & x_{12} & \dots & x_{1n} \\
 A_2 \left[\begin{array}{cccc} x_{21} & x_{22} & \dots & x_{2n} \\
 \vdots \left[\begin{array}{cccc} \vdots & \vdots & \vdots & \vdots \\
 A_m \left[\begin{array}{cccc} x_{m1} & x_{m2} & \dots & x_{mn} \end{array} \right.
 \end{array}
 \right.
 \end{array}$$

Where:

$A_i = (A_1, A_2, \dots, A_m)$ are the alternative treatment systems

$I_j = (I_1, I_2, \dots, I_n)$ are the assessment indicators

x_{ij} are the measures of performance of the alternative treatment systems as against the assessment indicators (quantification of indicators)

Step 2: Transformation of the decision matrix into a normalized decision matrix using equation (1) below.

$$r_{ij} = \frac{x_{ij}}{\sqrt{(\sum_{i=1}^M x_{ij}^2)}} \quad (1)$$

This is basically the standardization of the initial decision matrix due to the different units of measurements in which the various decision indicators are quantified.

The resulting normalized decision matrix is illustrated as:

$$\begin{matrix} & I_1 & I_2 & \dots & I_n \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} & \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \end{matrix}$$

Step 3: Determination of the weight of each indicator and subsequently deriving the weighted normalized decision matrix using equation (2). Because the various indicators are of different or equal significance to the decision-making, each indicator will be assigned a weight.

$$v_{ij} = w_j * r_{ij} \quad (2)$$

Where v_{ij} is an element of the weighted normalized decision matrix.

Step 4: Determination of the positive ideal solution (PIS) and negative ideal solution (NIS) by considering the weighted normalized decision matrix as follows;

$$A^+ = \{(\max_i v_{ij} | j \in J_1); (\min_i v_{ij} | j \in J_2) | i = 1, 2, \dots, N\} = \{v_1^+, v_2^+, \dots, v_j^+, \dots, v_M^+\} \quad (3)$$

$$A^- = \{(\min_i v_{ij} | j \in J_1); (\max_i v_{ij} | j \in J_2) | i = 1, 2, \dots, N\} = \{v_1^-, v_2^-, \dots, v_j^-, \dots, v_M^-\} \quad (4)$$

Where J_1 and J_2 are associated with a benefit and cost indicators respectively.

Step 5: Calculation of the distances of each alternative from the PIS and NIS as follows;

For distances from PIS, equation 5 applies

$$S_i^+ = \sqrt{\left[\sum_{j=1}^n (v_{ij} - v_j^+)^2\right]} \quad \text{for } i = 1, 2, \dots, N \quad (5)$$

For distances from NIS, equation 6 applies

$$S_i^- = \sqrt{\left[\sum_{j=1}^n (v_{ij} - v_j^-)^2\right]} \quad \text{for } i = 1, 2, \dots, N \quad (6)$$

Step 6: Calculation of the closeness coefficient of each alternative according to equation (7). The alternative with the highest C_i^+ is selected as the most appropriate.

$$C_i^+ = \frac{S_i^-}{(S_i^+ + S_i^-)} \quad \text{for } i = 1, 2, \dots, N \quad (7)$$

Where S_i^+ and S_i^- are the calculated distances of the i^{th} alternative from the PIS and NIS respectively.

3.7.1.2 Simple Additive Weighting

This MADM method is relatively simple for rank determination. It is often used as a benchmark to compare the ranking results obtained from other methods when applied to the same multi-criteria decision making problem. It derives the overall score of an alternative treatment system as the weighted sum of the indicator scores or utilities. For n number of indicators and m number of treatment alternatives, its analytical structure can be summarized as follows;

$$S_i = \sum_{j=1}^M W_j r_{ij} \quad \text{for } i = 1, 2, 3, \dots, N \quad (8)$$

Where

S_i is the overall score of the i^{th} treatment system

W_j is the weight of importance of the j^{th} indicator

r_{ij} is the normalized value of the i^{th} treatment technology for the j^{th} indicator.

r_{ij} for the benefit and cost indicators are further computed as

$$r_{ij} = \frac{x_{ij}}{\max_i x_{ij}} \quad \text{for the benefit indicator} \quad (9)$$

$$r_{ij} = \frac{(1/x_{ij})}{\max_i (1/x_{ij})} \quad \text{for the cost indicator} \quad (10)$$

Where x_{ij} is an element of the decision matrix representing the value of the j^{th} indicator and i^{th} alternative.

It must be emphasized that, because of the simple algorithms of the steps involve in both TOPSIS and SAW, their official softwares were not used but rather they were programmed into a spreadsheet and applied. This was to demonstrate their simplicity of application (critical in a decision support system) and the potential to be used by end users such as municipal engineers, developmental authorities, policy makers and planning officials.

3.7.2 Determination of the weights of importance of the indicators

Mostly, the selection of a wastewater treatment system for a community or city is done from several competing alternatives under various indicators. For the purposes of application of SAW and TOPSIS for the ranking of the treatment alternatives, the weight of importance of each indicator must be known. The weights of the assessment indicators are determined by the decision maker and therefore subjective. The weights can be made equal or apportioned to be unequal to reflect the general environmental requirements or specific wastewater treatment objectives of the host community.

Under simulation, uniform weight distribution is applied to represent the preference of an uninformed decision maker in this study. This represents the scenario (A) of the decision making. Under this scenario, the weight of importance of an indicator is given by the equation;

$$W_j = \frac{1}{n}$$

Where

W_j is the weight of the j^{th} indicator

n is the total number of indicators

In some instances, the weights of importance of the indicators for determining the most appropriate treatment system for a community are unequal and they are apportioned by the decision makers to reflect the treatment priorities of the community. To represent such an instance, the entropy coefficient method is adopted to determine the weights of indicators in scenario (B). The entropy coefficient concept's application in the context of this study is based on the fact that, the decision matrix possesses a certain amount of information that can be assessed to elicit the weights of importance of indicators. For a given decision matrix, if for example the alternatives being evaluated have a similar or the same value for a particular indicator, the entropy of that indicator is high and the weight assigned to it will be low. Such an evaluation indicator plays an insignificant role in the assessment process and can be eliminated. On the contrary, when the values of a particular indicator vary widely for the alternatives being assessed, the entropy will be small and the weight assigned to it will be high. Such an indicator is considered as highly relevant to the decision making.

The entropy coefficient method of weight determination and its algorithm steps are presented below.

- There is the normalization of the decision matrix representing the relative performance of the alternatives as follows;

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^m X_{ij}}$$

- The entropy of each indicator (e_j) is calculated as follows;

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^m p_{ij} \ln(p_{ij})$$

- The degree of diversity (d_j) of the information contained by each indicator is calculated as;

$$d_j = 1 - e_j$$

- Finally, the weight for each indicator (w_j) is given by

$$W_j = \frac{d_j}{\sum_{j=1}^n d_j}$$

- Satisfying the relation

$$W_j = 1$$

See appendix E for the step by step calculation of indicator weights given by the entropy method.

It must be emphasized that the derived indicator weights in scenarios (A) and (B) is for the purposes of this study only. For the practical application of this concept of appropriate treatment system identification, city authorities responsible for wastewater management in the community can assign indicator weights based on their treatment objectives. And these weights can be totally different from those obtained in scenarios (A) and (B).

Lastly, it must also be noted that indicator weights have the capacity of changing the ranking of the alternatives significantly. That is, for a particular selection problem with the same treatment alternatives, the same assessment indicators but different weights, different rankings can be achieved with different treatment systems being selected as the most appropriate.

3.8 Sensitivity analysis

Usually, the input data (weights and quantified values or performance measures) of some indicators in MADM problems are not constant. They can vary with change in conditions such as time, demography and geographic properties of the location of application. This can have an impact on the resulting ranking of the treatment system alternatives such that it may be considered to be unreliable. Therefore, after establishing the ranking of the alternative treatment systems by the application of MADM methods, sensitivity analysis was performed on the input data to ascertain the range of indicator weights and performance measures for

which the ranking will not be affected or otherwise. This is to verify reliability and improve decision making as to which treatment system is appropriate for a particular community.

The approach to sensitivity analysis employed in this study is to change the weights of some selected indicators and subsequently determine the changes in the ranking of the alternative treatment systems. This is in line with the practical application of this model of selection where most indicators will hardly be of equal weights.

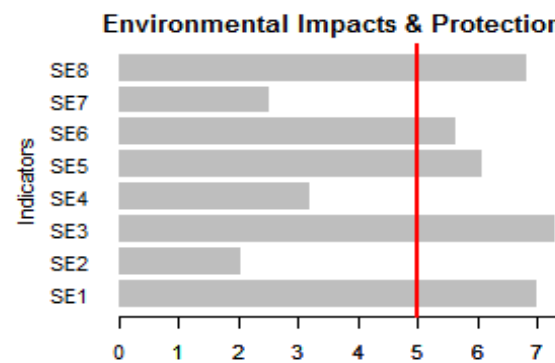
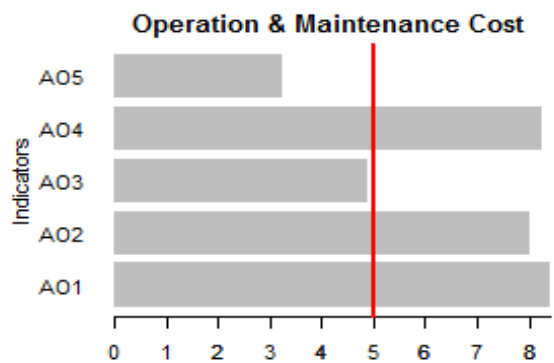
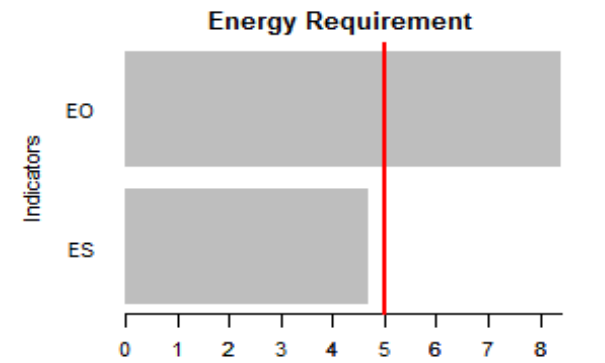
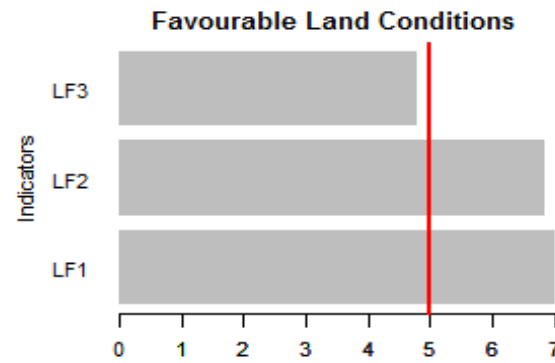
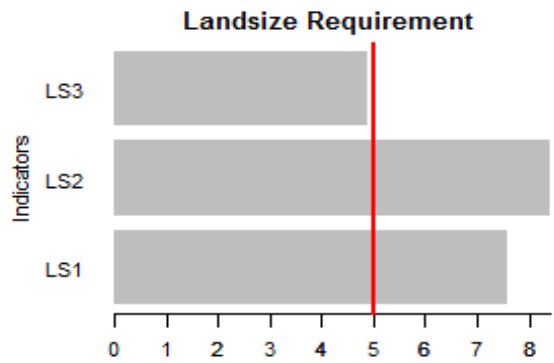
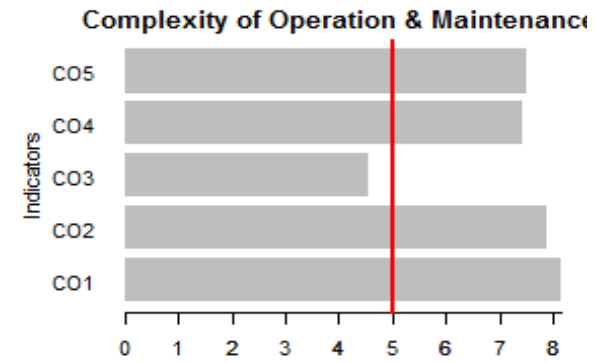
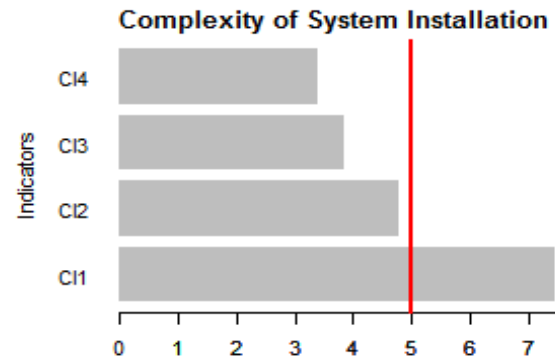
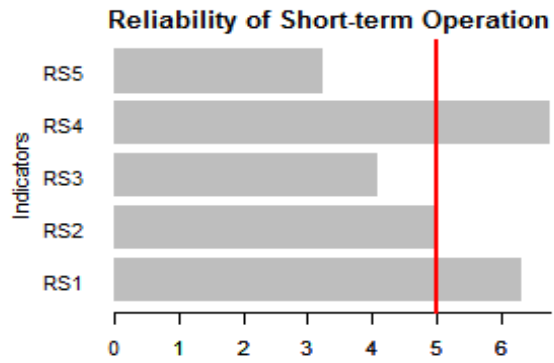
4 Results and discussions

4.1 Indicator assessment

As shown on Table 1 in appendix A, the proposed or initial set of criteria and indicators comprises of 8 criteria, 16 sub-criteria and 62 indicators. They are to assess the technical properties of treatment systems, economic, environmental and socio-cultural properties of host communities. A ranking method representing a quantitative scale of measurement was used by respondents to screen the proposed indicators according to their relevance in selecting appropriate wastewater treatment systems for communities in developing countries. The measurement method is a 9-point scale having the following definitions; 1 = unimportant; 3 = less important; 5 = moderately important; 7 = Important; 9 = extremely important. In the ranking process, respondents were asked to assign values from the above scale to the indicators according to how they consider them to be important. The rankings are aggregated and average rank of each indicator is calculated (See Table 2 in appendix A).

With number 5 (moderately important) on the ranking scale being the lower limit of importance, the average ranks of the following set of indicators; AO3, AO5, CA1, CA2, CI2, CI3, CI4, CO3, ES, LF3, LS3, PA4, RS2, RS3, RS5, SE2, SE4, SE7, SR3 and SR5 falls below it as shown in Figure 7 below.

Indicators CA1 (competence of municipal authority to supervise and monitor regular system operations) and CA2 (availability of institutions to research into unforeseen system problems and their capacity to resolve such problems) under the sub-criteria “institutional capacity and competence availability” have low average ranks. This reflects the opinion among most of the academicians and consultants who are of the view that, research institutions in Ghana are well equipped to resolve plant operation problems. Also the municipal authority can always depend on private sector support to monitor plant operations if they do not possess the expertise.



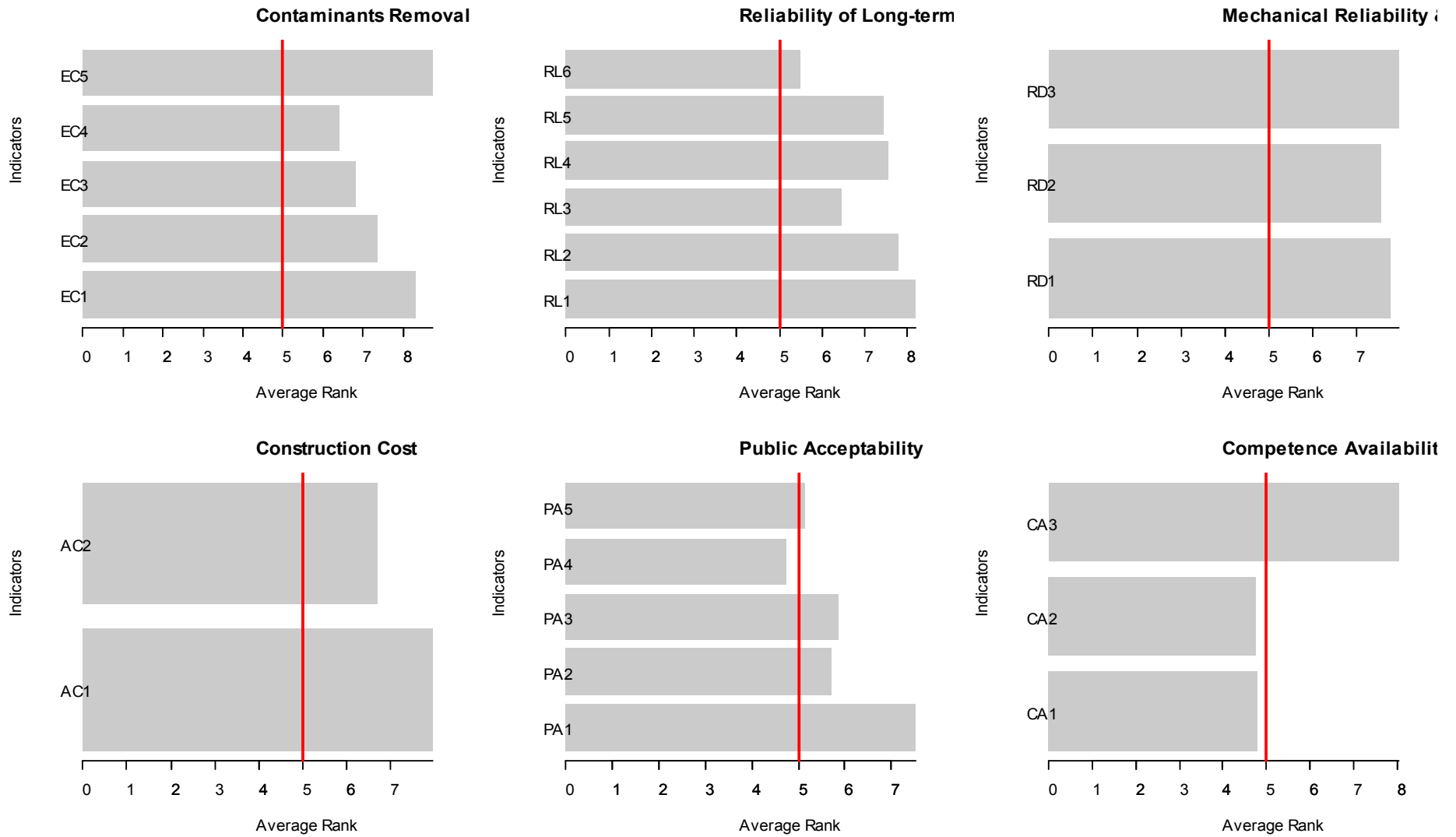


Figure 7: Results of indicators assessment by expert and community survey

On the technical criterion of “complexity” and sub-criterion of “system installation and start-up”, indicators CI2, CI3 and CI4 representing system start-up difficulty, time needed for system construction and time needed for system start-up respectively, were also ranked lower than 5 on the scale and considered not important factors to consider in choosing an appropriate wastewater treatment system for the communities. Reason being that, most communities in the city of Kumasi are not connected to any functioning treatment plant and therefore the waiting period for construction and startup is not an issue.

However in the same criterion and sub-criterion, indicator CII (overall complexity of system installation and construction) is considered to be an important indicator to help choose simple systems and subsequently to prevent expensive maintenance. In the same criterion but a different sub-criterion of “operation and maintenance”, indicator CO3 (time requirement for personnel training) ranked low in a developing country context since treatment plants are simple and training of personnel to monitor its operations is not expected to take long.

Under the economic criterion “affordability” and sub-criterion “operation and maintenance cost”, the indicators AO3 and AO5 representing annual personnel and administrative cost respectively incurred in the operation of a municipal treatment plant in Ghana were ranked low by local experts. They consider these cost components to be relatively low in most developing countries. This is due to the fact that most systems implemented in developing countries are simple or close-to-nature that do not require extensive administration. Therefore the indicators if not considered, will not negatively impact on the selection and operation of an appropriate treatment system.

Indicators SE2 (noise impact), SE4 (global warming potential) and SE7 (landscape / visual impact) under the sub-criteria “environmental impacts and protection” and criteria “sustainability” obtained low rankings from the household survey in the 3 communities sampled. Residents do not consider these indicators as important environmental impacts that need to be taken into account in selection of a treatment system for their communities. They are more concern about potential impacts such as odour and breeding of insects. As such, those indicators were ranked higher. Also under the same criterion of sustainability but a different sub-criterion of resource recovery, indicators SR3 and SR5 representing the possibility of effluent reuse for groundwater recharge and the general promotion of sustainable behaviour respectively received low ranks.

Under the technical criterion “reliability” and sub-criterion “reliability of short-term operation”, indicator RS2 representing “periodic shock BOD loads” was ranked low and considered to be an unimportant factor to consider. Perhaps it reflects the view that domestic wastewater have relatively low BOD and shock BOD loading of municipal treatment systems rarely occurs. Even if it occurs, most of the close-to-nature treatment systems that are usually implemented in developing countries are flexible and can support hydraulic and organic shock loads. Also under the same group, indicator RS3 (extremely low BOD loads) was considered to be unimportant.

Finally, indicator RS5 representing weather variations impact on technology performance was determined not to be an important indicator to apply. Reasons being that, weather conditions in the tropics especially ambient temperature range are supportive of the biological processes in the simple and natural treatment systems by enhancing the removal of BOD in short retention times. Therefore it is an advantage and will not impact negatively on treatment processes.

Using the average rankings of indicators obtained through the expert and community surveys as an assessment tool for the initial criteria and indicators, those with lower rankings below 5 are eliminated because based on the 9-point ranking scale of measurement they are considered to be irrelevant, less important or unimportant for the study communities. Further screening of the remaining indicators was performed to select the final set of indicators according to the following 3 principles;

- A selected indicator must be applicable to all the feasible treatment alternatives that will be considered in this study.
- A selected indicator must be practical to be quantified or to obtain quantitative data.
- A selected indicator must be simple to be understood by experts and as well as non-experts (municipal authorities) in charge of wastewater treatment.

Based on the first principle, the following indicators; operational energy requirement per population equivalent (EO), energy cost (AO4), life expectancy of mechanical components

(RD1), frequency of mechanical failures (RD2), mechanical failures impact on effluent quality (RD3) are also eliminated. This study limits itself to natural treatment technologies or conventional treatment technologies that are entirely biological. Therefore indicators relevant to mechanical technologies such as those listed above are not relevant to be applied.

Also based on the second principle, indicator AO1-AO2 representing annual operation and maintenance cost (O&M), although highly important for the comparison of different treatment systems was eliminated during data analysis section due to insufficient data on actual flow to which it is correlated (Unlike construction cost indicator that is dependent on design flow, annual O&M cost depends on actual flow).

Lastly, in spite of indicator RL6 above average ranking of 5.5, many experts adjudged it to be similar to RL5 and therefore had to be excluded from the list of important indicators.

The final number of criteria remains unchanged but the assessment indicators remaining after the survey was 34.

4.2 Feasible treatment options for the city of Kumasi

Treatment of municipal wastewater in developing countries is mostly achieved by the application of low cost and simple technologies which mostly constitute the natural or nature related treatment systems. This is as a result of the following factors;

Unlike the industrialized countries where high coverage of water and sanitation exist, developing countries are characterized by water crisis – both the provision of potable water and the treatment of municipal wastewater. With this situation and other developmental problems to contend with, municipal authorities rightly consider the provision of safe drinking water in the water management sector as more important than wastewater treatment. The less priority assigned to wastewater treatment means that highly mechanical treatment technologies mostly employed in developed countries are less applied in developing countries. Instead, low cost but effective wastewater treatment technologies are mostly implemented.

Also the type of treatment systems usually used in developing countries is a function of the cost components. That is operation and maintenance cost components play a decisive role in the choice of wastewater treatment technologies in developing countries. Conventional and mechanized wastewater treatment systems cost more to construct and operate. Usually capital cost needed to construct treatment systems can easily be obtained but it is much more difficult to get funds to cover operating and maintenance costs once the system is established. If funds cannot be generated internally to cover the high operating and maintenance cost of conventional or mechanized treatment systems, it will not be successful. Unlike industrialized countries, there is a limited capacity in most developing countries to mobilize funds required to maintain and operate conventional treatment plants. Therefore experience shows that highly mechanized treatment systems that are a common feature in wastewater management systems in developed countries are not sustainable in developing countries. A case in point is the wastewater treatment sector of Morocco where 60 percent of activated sludge treatment plants are out of service due to high operation and maintenance cost which cannot be covered by most communities (Choukr-Allah, 2005).

Most of the low cost and simple treatment systems are not mechanized but they are natural or nature-related that have biodegradation as their core contaminants removal mechanism.

These biological processes are temperature dependent. That is, in some of the treatment processes, temperature enhances conversion processes and positively impact removal efficiencies. For instance, mesophilic bacteria mostly responsible for the removal of BOD prominent in municipal wastewater perform optimally at a temperature range of 26 °C – 35 °C. Also for nutrient removal, the optimum temperature range for nitrifying bacteria falls within 29 °C – 33 °C. These temperature ranges fall within the ambient temperatures of most developing countries that are located in the tropics. As a result, the above favourable water temperatures are easily attained in developing countries all year round. Therefore there is a satisfactory performance of natural treatment systems in the tropics, hence their predominant application for the treatment of municipal wastewater.

Also the first step in the implementation of discharge standards is the adoption of the general guidelines set by international bodies such as WHO, and others. The next is the conversion of the general guidelines into country specific standards, taking into account the following characteristics which are peculiar to each country or geographic region;

- The wastewater source – domestic or industrial (determines the contaminants of concern and their level of removal to protect public health and environment).
- Technological development – The removal efficiencies of the accessible treatment systems in the country.
- The nature of the recipient environment – freshwaters, sea, farmland, etc. This is due the different level of sensitivity of the various ecosystems.

Other lesser determinants of discharge standards include;

- The population equivalent or the size of the treatment system.
- Economic, social and cultural aspects
- Prevailing diseases
- Acceptable risks

Low technological development of the study area makes mechanized treatment technologies capable of producing high quality effluent inappropriate. Therefore discharge standards in developing countries such as Ghana are set relatively lower than developed countries. And

these standards can be achieved by simple nature-related treatment systems such as WSP and CW as presented in Table 8 below.

Table 8: Comparison of Ghana's effluent discharge standards and the treatment capacities of WSP and CW in tropical climates

Parameter	Discharge standards (Ghana EPA)	Efficiency of treatment technologies in tropical climate			
		WSP		CW	
		Oxidation	facultative	CWfs**	CWrb**
COD (mg/l)	<250		150 – 200	46.93	64.75
BOD ₅ (mg/l)	<50	20 – 40	30 – 40	12.72	20.28
TSS (mg/l)	<50	80 – 140	40 – 100	32.7	19.96
TP (mg/l)	2.0	-	-	1.32	2.72
NH ₄ -N (mg/l)	1.0	-	-	2.68	10.25
Total coliforms (MPN/100ml)	400	-	-	-	-

Compiled from several sources: EPA Ghana, (2000); Isosaari et al., (2010); Zhang et al., (2014)

** represents average concentration

CWfs - Constructed Wetlands - free water surface

CWrb - Constructed wetlands reed bed

Again with relatively low industrial activity in Ghana, the management and treatment of domestic wastewater is the primary concern. These usually contain conventional pollutants which are highly amenable to treatment by the relatively low performing nature-related treatment systems.

Also to a lesser extent, low technical capacity of municipal authorities in developing countries to operate and maintain highly mechanized conventional treatment systems prevents their application for wastewater treatment. It is for this reason that natural or nature-related treatment technologies will be the focus of assessment in this study. These treatment systems are as follows;

- Waste Stabilization Ponds (WSP)
- Constructed Wetlands (CW) – free water surface (CWfs) and reed bed (CWrb)

- Trickling Filter (TF)

The list of treatment systems included in this research is by no means exhaustive but they represent the natural systems frequently employed for the treatment of municipal wastewater in developing countries. It must also be emphasized that the treatment systems included in this research are those mostly applied for at least the secondary treatment of municipal wastewater in developing countries under tropical or sub-tropical conditions.

Trickling filter is a conventional treatment system and therefore using the above defined criteria should not be part of the treatment alternatives being assessed for the study area. Its inclusion is due to the fact that it is one of the few conventional treatment systems capable of being constructed with minimal mechanization and operated without energy.

4.3 Overview of feasible treatment options

4.3.1 Waste stabilization pond (WSP)

4.3.1.1 Description

In contrast to complex high-maintenance conventional treatment systems, waste stabilization pond (WSP) is a simple low energy consuming ecosystem that use natural processes for the degradation of organic materials found in wastewaters. In many developing countries where it is not possible to provide the energy and maintenance requirement of conventional wastewater treatment systems, WSP have been an effective alternative for sewage treatment. This is because of the overriding objective of wastewater treatment in developing countries being more of the removal of pathogens and less of BOD and nutrients removal, and the proven capacity of WSPs in removing pathogenic microorganisms. Also its popularity in developing countries stems from the fact that sunlight is its main source of energy, and the all year round temperature and sunlight in tropical countries present an excellent opportunity for high pollutant removal efficiencies.

A stabilization pond is a shallow man-made excavation into which wastewater continuously flows, retained for a number of days to permit natural biological and physico-chemical reactions to take place to reduce the level of organic materials and pathogens in the wastewater before being discharged into the environment. There are diverse biochemical and

physical interactions in a pond ecosystem responsible for the reduction of BOD, nutrients and pathogens. But one that is well researched and understood is the relationship between phototrophic micro-algae and aerobic bacteria. In essence, with sunlight there is photosynthetic oxygen production by algae which is used by aerobic and facultative bacteria in the decomposition of organic matter. CO₂ being a product of bacteria decomposition of organic matter is utilized by algae to derive energy and fix carbon for growth through photosynthesis. Aside sedimentation, this algae enhanced bio-oxidation of organic material is one of the main pathways for BOD removal in stabilization ponds.

Faecal bacteria removal mechanisms have now been established to be die-off through time and exposure to high temperature, pH (>9) and light intensity.

Compared to BOD and faecal bacteria, nutrient removal by WSP is relatively low. The minimal nitrogen that is removed is achieved by the incorporation of ammonia into algal biomass for growth and volatilization at high pH values. There is little evidence of nitrification and consequently denitrification due to the low population of nitrifying bacteria in stabilization ponds (Mara, 1997). Phosphorus removal is also associated with algal biomass uptake and to a lesser extent by precipitation and sedimentation.

In a complete WSP system, a number of ponds are usually arranged in series such that successive ponds receive their flow from preceding ponds. Ponds in the treatment system are slightly different from each other and serve different purposes. They are distinguished by their design depths which consequently defines the dissolved oxygen layers within the pond and applicable organic loading rate. By this, the different pond types in WSP systems are anaerobic, facultative and maturation. The usual arrangement is to have an anaerobic pond, followed by a facultative and a number of maturation ponds all in series. The features and functions of the ponds are described in Table 9 below.

Table 9: Comparative features of pond types

Pond type	Depth (m)	HRT (d)	OLR (kg BOD5/ha/d)	Major function
Anaerobic	2 – 5	3 – 5	High, >300	BOD removal, sedimentation, removal of helminthes,
Facultative	1 – 2	4 – 6	Medium, 100-300	BOD removal
Maturation	1 – 2	12 – 18	Low, <100	Pathogen removal, nutrient removal

Source: Horan, 1993

WSPs are mostly used for the treatment of domestic wastewaters and also for treating industrial wastewater, particularly the agro-industrial wastewaters. Treatment is slow due to the reliance on sunshine as its sole energy source. This makes stabilization ponds require long detention times which consequently make it require large land areas. This represents a disadvantage in its potential application in areas of high land costs and where large tracts of land are unavailable. Its low nutrient removal efficiency is not of a major drawback for developing countries since the removal of pathogens for the protection of public health is of the utmost priority.

The presence of favourable temperature for operation in Kumasi coupled with the low skill needed for operation, low operation and maintenance cost of WSPs, make it the predominant treatment process for the treatment of municipal wastewater in the study area. Figure 8 and 9 show the layout of the Asafo Pilot Waste Stabilization Pond and photograph respectively.

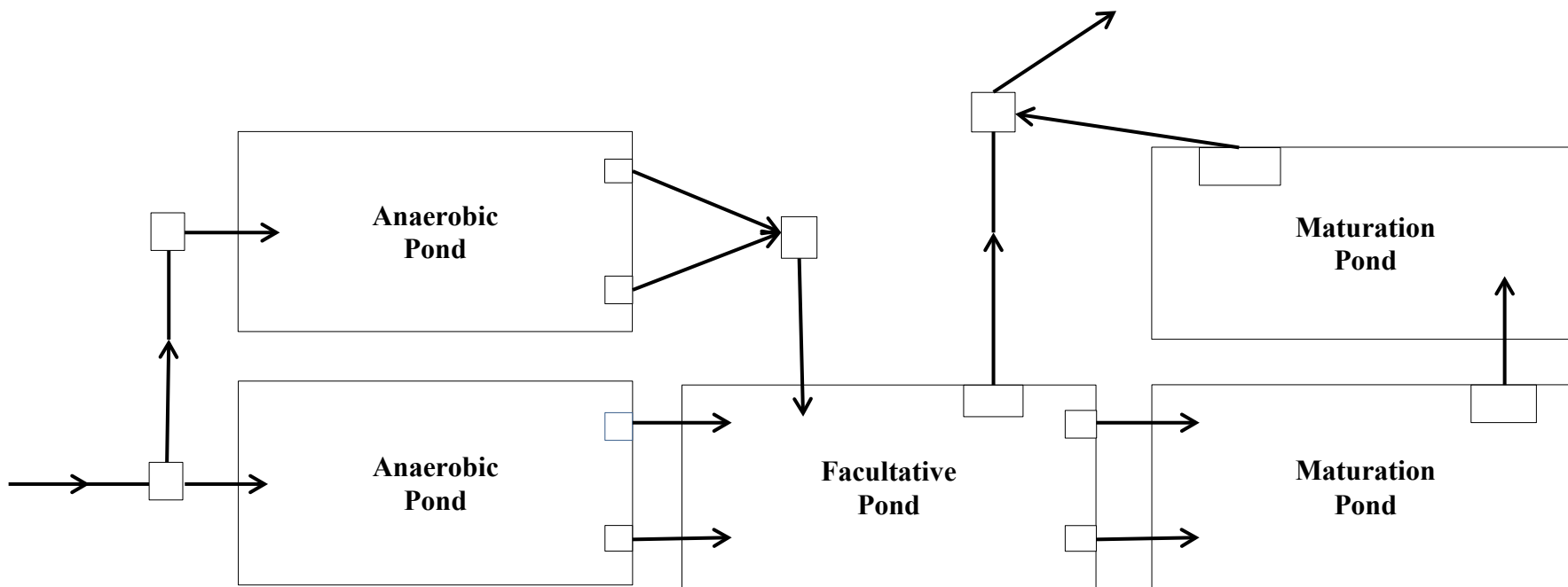


Figure 8: Layout of the Asafo Waste Stabilization Pond (KMA)



Figure 9: Views of the Asafo Waste Stabilization Pond (Field Photographs, 2014)

4.3.2 Constructed wetlands (CWs)

4.3.2.1 Description

Compared to wastewater stabilization ponds, constructed wetlands have higher hydraulic efficiency and lower effluent suspended solids. Although considered as matured in the treatment of municipal wastewater it is relatively young and at an evolutionary stage because the internal biotic and abiotic processes occurring in wetlands have not been adequately quantified. In its structural form, constructed wetland is an artificial treatment system designed and constructed to replicate the biological processes found in natural wetland ecosystems. It simulates the ecosystem's biochemical functions such as filtration and cleansing.

In general, constructed wetlands are considered to be suitable for secondary and tertiary treatment of municipal wastewater but only for tertiary treatment of industrial wastewater (Isosaari et al., 2010). It has been found to be effective in the removal of BOD, SS, N and P as well as reducing pathogens and organic pollutants. Microbial degradation and plant uptake as well as physicochemical processes such as sedimentation, adsorption, and precipitation at the water-sediment, root-sediment and plant-water interfaces constitute the main pollutant removal mechanism in constructed wetlands.

Constructed wetlands are among the nature-related treatment systems that can be constructed at lower costs with low-technology methods where no complex technological tools are needed. When properly designed, constructed wetlands do not require chemical additions and other procedures required in the operation of conventional treatment systems. In the absence of reliable source of energy to incorporate aeration mechanism into it, constructed wetland can depend on atmospheric re-aeration and aeration of the lower levels of the water column by the plant roots.

In terms of site requirements, it can be situated on a wide array of land types with varying geological conditions as compared to land application systems (Crites et al., 2006). Constructed wetlands are particularly suitable for areas with high water table or low permeable soil and also on former natural wetland sites. Tropical conditions where temperatures are usually in the range of 20 °C and above present suitable weather conditions for optimum performance. Cold temperatures impair its treatment efficiency. Since most

developing countries have warm tropical and subtropical climates, it is generally acknowledged that CWs are more suitable for wastewater treatment in such geographical areas (Denny, 1997; Haberl, 1999; Kivaisi, 2001). Despite having warm climates in most developing countries which is conducive to year round plant growth and microbial activity which in turn leads to high performance efficiencies of CWs, its adoption in these countries is still limited (Bojcevska and Tonderski, 2007).

It is the simple construction, low requirements for operation and maintenance of CWs, the favourable climatic conditions at the study area and the under-utilization or under application of CWs for municipal wastewater treatment in developing countries that makes this treatment process a suitable alternative to be considered in this study.

4.3.2.2 Applications and performance

Increasingly, CWs are becoming a popular treatment alternative to conventional treatment systems due to its high removal efficiency, low cost, simple operation and the potential for nutrient reuse (Kadlec, 2009; Vymazal, 2011). It has been applied to mitigate environmental pollution by the removal of a wide array of pollutants from wastewater such as organic compounds, suspended solids, pathogens, metals and nutrients (Kadlec and Wallace, 2008; Ranieri et al., 2013). The performance of CWs in terms of removal efficiencies depends on a number of variables such as pollutant loading, hydrologic regime, vegetation type and temperature (Trang et al., 2010). Unlike other treatment systems which take less time to achieve optimum performance, constructed wetlands take one or two years to establish feasible biological functioning and as a result not recommended for short duration time critical cleanups (Isosaari et al., 2010).

CWs are classified based on their flow regime and type of vegetation employed for the treatment. Based on these 2 classification methods, CWs generally fall into 3 categories: Free Water Surface (CWfs), Subsurface Flow (SSF) and Hybrid CWs. The SSF is further classified into horizontal subsurface flow (also known as Vegetative Submerged Bed or Reed Bed (CWrb)) and vertical subsurface flow (CWv) according to flow direction (Cooper et al., 1996; Kadlec and Knight, 1996). CWfs and CWrb are two types under the flow regime that are being considered as suitable alternatives in this study for the study area. This is due to their extensive application for the treatment of municipal wastewater to meet 30 mg/L BOD

and 30 mg/L TSS secondary discharge standards. It has also been reported that for CWfs, these standards are usually met with monthly influent flows of 60 kg BOD/ha/d and 50 kg TSS/ha/d with a retention time of at least 2 days (ITRC, 2003). On the other hand TSS removals by CWrb are good at loading rates not exceeding 200 kg/ha/d and to meet the 30 mg/L BOD secondary standards, BOD loading rates should be less than 60 kg/ha/d (USEPA, 2000).

Nitrification is highly limited in fully vegetated CWfs unless sufficient open water spaces for aeration are present. Also microbial nitrification requires about one or two growing seasons to be well established. Nitrogen removal efficiency is in the range of 33 – 45 % (Seabloom and Hansson, 2005). Removal of phosphorus is small due to adsorption to solids and plant detritus. It can be improved by harvesting vegetation since plant uptake is as high as terrestrial plants. A summary of the reported operational parameters and treatment efficiencies of CWfs and CWrb applications for the treatment of municipal wastewater in developing countries is presented in Tables 10 and 11 respectively.

Table 10: Summary of the operational parameters and removal efficiencies of CWfs applications in developing countries

	Removal performance							Dimensions (L * W * D)/ m ³	Plant species	References
	TSS	BOD ₅	COD	NH ₄ -N	NO ₃ -N	TN	TP			
Peradeniya, Sri Lanka										
Effluent concentration (mg L ⁻¹)	45.8	19.2	-	3.4	0.9	-	1.36	25.0 * 1.0 * 0.6	<i>Scirpus grossus</i>	Jinadasa et al. (2006)
Removal efficiencies (%)	71.9	68.2	-	74.4	50.0	-	19.0		<i>Typha angustifolia</i>	
Shanghai, China										
Effluent concentration (mg L ⁻¹)	30	7.7	32	-	-	6.15	0.32	800m ² * 0.75m	<i>Phragmites australis</i>	X. Li et al. (2009); M. Li et al. (2009)
Removal efficiencies (%)	70	15.4	17.9	-	-	83.4	96			
El Salvador										
Effluent concentration (mg L ⁻¹)	-	20.08	72.80	0.54	-	6.08	1.86	48.9 * 15.0 * 0.6	<i>Typha augustifolia</i>	Katsenovich et al. (2009)
Removal efficiencies (%)	-	80.78	65.18	95.75	-	58.59	66.5			
Petchaburi, Thailand										
Effluent concentration (mg L ⁻¹)	40.4	12.7	-	5.18	0.35	-	2.2	4.0 * 1.0 * 1.5	<i>Typha augustifolia</i>	Klomjek and Nitorisavut (2005)
Removal efficiencies (%)	46.5	74.3	-	75.4	-	-	44.9			

Table 11: Summary of the operational parameters and removal efficiencies of CWrb applications in developing countries

	Removal performance							Dimensions (L * W * D)/ m ³	Plant species	References
	TSS	BOD ₅	COD	NH ₄ -N	NO ₃ -N	TN	TP			
Juja, Nairobi city, Kenya										
Effluent concentration (mg L ⁻¹)	25.5	28.9	91.0	19.0	1.1	-	0.8	7.5 * 3.0 * 0.6	<i>Cyperus papyrus</i>	Mburu et al., (2013)
Removal efficiencies (%)	75.27	60.73	42.76	26.36	-	-	42.86			
Rongcheng, Shandong, China										
Effluent concentration (mg L ⁻¹)	27.8	23.8	91	11.3	-	-	2	150 * 30 * 0.5	<i>Phragmites australis</i>	Song et al., (2009)
Removal efficiencies (%)	71.8	70.4	62.2	40.6	-	-	29.6			
Dar es Salaam, Tanzania										
Effluent concentration (mg L ⁻¹)	-	-	41.80	15.86	0.83	-	-	4.2 * 1.4 * 0.6	<i>Typha latifolia</i>	Kaseva (2004)
Removal efficiencies (%)	-	-	60.70	23.01	44.30	-	-			
Mother Dairy Pilot Plant, India										
Effluent concentration (mg L ⁻¹)	12.0	4.0	55.0	-	-	7.5	1.5	69 * 46 * 0.3	<i>Phragmites australis</i>	Ahmed et al., (2008)
Removal efficiencies (%)	81	90	72	-	-	67	75			
Ocotlán, Jalisco Mexico										
Effluent concentration (mg L ⁻¹)	10.4	25.4	59.40	-	-	13.5	5.0	3.6 * 0.9 * 0.3	<i>Strelitzia reginae</i>	Zurita et al. (2011)
Removal efficiencies (%)	81.66	77.94	76.32	-	-	52.78	40.24			
Peradeniya, Sri Lanka										
Effluent concentration (mg L ⁻¹)	47.33	18.6	105.9	4.08	0.71	-	8.03	1 * 25 * 0.6	<i>Scirpus grossus</i>	Tanaka et al. (2013)
Removal efficiencies (%)	65.8	65.7	40.8	74.8	38.8	-	61.2		<i>Hydrilla verticillata</i>	

4.3.3 Trickling filter (TF)

4.3.3.1 Description

Trickling filter is a fixed film process whose development originated from the land application effluent treatment processes. Among the conventional treatment processes, it represents a simple and reliable form of effluent treatment and as a result it has been applied extensively worldwide for the treatment of domestic and industrial wastewater.

In its structural layout, trickling filter (also known as bio-filter, bacteria bed or percolating filter) is a reactor of rectangular or circular plan which consist of a bed of coarse contact media such as crushed rocks, corrugated plastic sections, hard coal, etc. (Figure 10). A distribution system just above the bed distributes sewage periodically over the filter media and in the process a microbial film develops over the surface of the media. Filtration by way of the separation of suspended solids from liquids is not performed by the microbial film but by a different and preceding screening unit in a primary treatment manner. Instead, the microbial film is responsible for the degradation of organic matter in the wastewater during its passage through the filter media before being collected by an underdrain system at its base. The oxidation of organic substances is aided by the distribution of air through the void spaces of the filter media by atmospheric circulation.

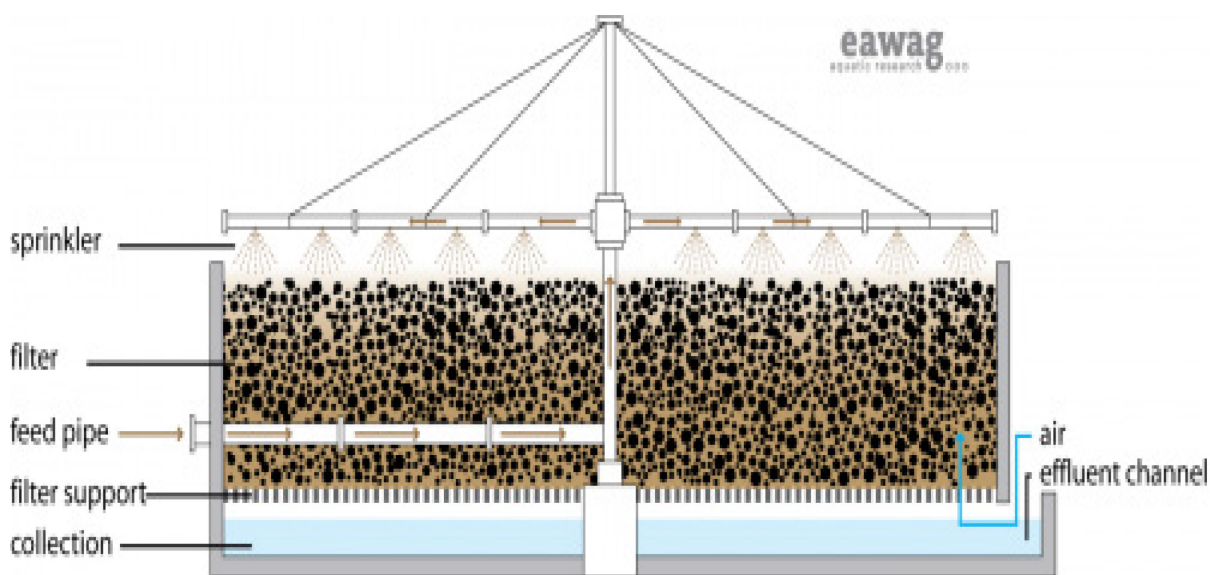


Figure 10: Schematic diagram of a trickling filter reactor (adapted from Eawag - SSWM)

The degradation of the organic material present in wastewater results in the growth and thickness of the microbial film attached to the filter media. Periodically, a section of the microbial film is sloughed off the filter media as humus sludge with the effluent. The cycle of microbial film growth, death and detachment from the filter media is a feature of well operated trickling filters. In a poorly managed system where design hydraulic and organic loads of influent to the filter are frequently exceeded, excessive growth of microbial film occurs blocking voids between the media and consequently leading to poor effluent quality. This being a common operational problem of trickling filters is resolved by recirculation where a fraction of the secondary clarifier effluent is recycled to dilute the influent to the filter. This has the effect of diluting the organic loads of the influent.

4.3.3.2 Design criteria and Applications

Aside being classified as low, intermediate and high rate trickling filters based on the organic and hydraulic loads of influent, the mode of recirculation are also used to classify trickling filters into single and multi-stage filtration.

Low-rate has a filter depth range of 1.5 – 3.0 m and recommended organic loading of 0.08 – 0.32 kg BOD/m³/d. They are mostly applied for the treatment of domestic and industrial wastewaters amenable to aerobic biological treatment and are capable of producing fully nitrified effluent in warm climates. On the other hand, high rate trickling filters have a filter depth of 1.0 – 2.0 m and loading rate of 0.32 – 1.0 kg BOD/m³/d. Limited nitrification is achieved and for the treatment of high strength industrial wastewaters, it employs recirculation to meet effluent standards (Horan, 1993).

4.3.3.3 Performance

With minimal degree of variability in hydraulic and organic loads and in climates where wastewater temperatures do not fall below 13 °C for long periods such as the tropics, trickling filters are highly reliable (Wang et.al, 2009). The low rate trickling filters are capable of nitrification as part of the pollutant removal mechanisms due to the presence of *Nitrosomonas* and *Nitrobacter* as part of the microbial population making up the biofilm. Generally, in its application for the treatment of domestic wastewater, the removal efficiencies of the conventional pollutants are high (Table 12).

Table 12: Performance efficiencies of various trickling filters treating domestic wastewater

Pollutant	Removal efficiencies of various trickling filters (%)		
	Low rate	High rate	High rate
	rock media	rock media	plastic media
BOD ₅	75-90	60-80	80-90
Suspended solids	75-90	60-80	80-90
Phosphorus	10-30	10-30	10-30
Ammonia nitrogen	20-40	20-30	20-30

Source: Wang et al., (2009)

One major operational advantage of trickling filters is their ability to tolerate shock and toxic loads due to the short contact times between the wastewater and the microbial film. Also among the conventional treatment systems, they are relatively easy to operate and have low operating cost due to the capability of making use of gravity to convey influent to the filter media and eliminating energy cost associated with using pumps. This makes it suitable for application in developing countries for the treatment of municipal wastewater in spite of its well-known limitations such as odour and fly problems.

4.4 Results and discussions of indicators quantification

4.4.1 Technical aspects

4.4.1.1 Removal efficiencies

For the identification of an appropriate wastewater treatment technology for the study area, this study takes into consideration the core purpose of a treatment plant, that is the removal of water quality contaminants. Contaminants in water are numerous but since the focus is on municipal wastewater treatment, the conventional water quality constituents associated with wastewater treatment namely: BOD, TSS, phosphorus, nitrogen and faecal coliforms are of much concern (Table 13). Synthetic organic compounds, volatile organic compounds and heavy metals usually associated with industrial wastewater are not taken into account. Of particular importance to the study area among the set of contaminants being considered is pathogen (faecal coliform) removal. This is due to the frequency of water borne diseases and the urgency of its reduction to safeguard public health. The removal of nutrients and BOD is also important for the protection of environmental health particularly the ecosystem of receiving water bodies. In general, the indicators selected for evaluating the efficiency of treatment systems in this study takes into account, prevailing water-borne diseases, acceptable risks and technological development of the study area.

Each treatment system has its characteristic range of removal efficiencies for the various contaminants. Also, different configurations of a particular type of system have their peculiar range of removal efficiencies. In this study, the observed ranges of removal efficiencies of the treatment systems being considered are adopted from technical literature (Table 14). The average values of these ranges are taken as the quantification for the treatment systems.

Table 13: List of indicators to evaluate system efficiency

Indicator	Unit of quantification	Significance
Removal efficiency of:		
EC1. BOD		The efficiency of the various treatment systems in removing the conventional water quality contaminants.
EC2. Total Nitrogen		
EC3. Total Phosphorus	Percent Removal	
EC4. Total Suspended Solids		
EC5. Pathogens (Faecal coliform)		

Table 14: Removal efficiencies of treatment systems

System	Removal efficiencies (%)				
	Average (Range)				
	BOD	TSS	TN	TP	FC
WSP	85 (75 – 95)	93 (90 – 95)	35 (10 – 60)	30 (10 – 50)	95 (90 – 99)
CWrb	77 (65 – 88)	91	42	41	82 (65 – 99)
CWfs	71 (54 – 88)	58 (23 – 93)	41	49	97 (95 – 99)
TF	83 (75 – 90)	83 (75 – 90)	30 (20 – 40)	20 (10 – 30)	55 (20 – 90)

Compiled from several sources: Horan (1993); Mara (2003); Metcalf & Eddy (2003); Vymazal (2005); Bitton (2005); Crites et al. (2006); Weber & Legge (2008); Wang et al. (2009); Oliveira and Sperling (2011).

Pond efficiencies adopted represent the standard pond system which comprises of an anaerobic pond, a number of secondary facultative and maturation ponds in series being operated in temperatures in excess of 20 °C (Horan, 1993). Stabilization ponds when properly designed have efficiencies comparable to conventional treatment systems. Possibilities to improve pond treatment efficiency include floating objects to alter hydraulic characteristics and algal attachment, solids recycling to improve ammonium removal.

Removal efficiencies of trickling filter represents those from the standard (low) rate which had been mostly applied for the secondary biological treatment of domestic wastewater before activated sludge became popular. It is capable of producing fully nitrified effluents in warm climates (Wang et. al., 2009).

It must be emphasized that the above removal efficiencies are not definitive of these treatment systems but indicative. Because other factors such as temperature, operation and age of the treatment system, season of the year, etc. can greatly impact on their efficiencies.

4.4.1.2 Reliability

The reliability of a wastewater treatment plant is a critical issue when the effluent is reused or discharged to water bodies. For the purposes of this study, reliability is understood to be the percentage of time at which the expected effluent concentrations comply with specified discharge standards (Oliveira and Sperling, 2011). As a result of numerous uncertainties underlying the design and operation of treatment systems, there is always the risk of occasional failure in performance. The objective of assessing reliability is not to identify and select a treatment system of zero failure in process performance since no system of such efficiency practically exist due to the variability of influent quality and quantity. But it is to identify a system with a characteristic minimum effluent discharge requirement violation. This indicates the close relationship between reliability of performance and effluent quality. Therefore reliability in this study is assessed based on the variability of treatment effectiveness under normal and unexpected operating conditions and the impact of failures upon effluent quality.

It is against this background that the following indicators have been selected to evaluate the reliability of the treatment alternatives being considered in this study (Table 15). Ideally, mechanical reliability should also be assessed but since this study restricts itself to nature-related treatment systems and limited mechanized treatment systems, indicators evaluating mechanical reliability have to be eliminated. Quantified values of the selected indicators obtained from the treatment plant survey are presented in Tables 16 and 17, and Figures 11 and 12 below.

Financial constraints are major barriers that undermine environmental restoration and public health maintenance in developing countries. With this in mind, the search for technologies for environmental projects should focus on durability. That is the selection of a wastewater treatment system capable of maintaining normal operation for the production of required effluent standards for longer periods (RL1 & RL2) is an important criteria that needs to be considered. Survey results (Figure 11) indicate constructed wetlands (reed bed and free water surface) and trickling filter systems to be more consistent in normal operations over the long-term than stabilization ponds.

Table 15: List of selected indicators to evaluate system reliability

Indicator	Unit of quantification	Significance
Long-term system operation		
RL1. Consistency of system normal operation over life time.	1=not very likely, 5=very likely	Assessment of system long-term normal performance.
RL2. Frequency of effluent meeting discharge standards.	1=very rarely, 5=very often	Consistency of effluent quality in compliance to discharge standards non-compliance.
RL3. Frequency of operational interruption due to process problems.	1=very rarely, 5=very often	Susceptibility of the system to shut downs due to inherent system defects.
RL4. Adverse impacts of operational interruption on effluent quality.	1=very low extent, 5=very high extent	Extent of negative impacts on effluent quality due to operational interruptions.
RL5. Capacity for expansion to absorb population growth.	1=very low capacity, 5=very high capacity	Evaluating the flexibility of system to long-term future expansion.
Short-term system operation		
Tolerance of the system to common influent characteristics:		
RS1. Extreme variations in flow rate.	1=very poor, 5=very good	Capacity of the process to withstand variations in flow rate and toxic pollutants sometimes found associated with domestic wastewater
RS4. Toxic pollutants.		

Table 16: Quantified values of indicators measuring long-term treatment plant reliability

System	Average score of indicators (standard deviation)					
	Long-term system operation					
	RL1	RL2	RL3	RL4	RL5	N
WSP	2.29 (1.11)	2.71 (0.76)	1.86 (0.90)	2.71 (1.11)	3.71 (0.49)	7
CWrb	4.00 (1.00)	4.20 (0.45)	1.40 (0.55)	1.60 (0.89)	3.60 (1.14)	5
CWfs	3.57 (0.98)	3.43 (1.13)	2.00 (0.82)	2.29 (0.95)	3.00 (1.00)	7
TF	3.43 (0.98)	4.00 (0.82)	2.71 (1.38)	2.86 (1.07)	2.71 (1.25)	7

Table 17: Quantified values of indicators measuring short-term treatment plant reliability

System	Average score of indicators (standard deviation)		
	Short-term system operation		
	RS1	RS4	N
WSP	4.00 (0.82)	3.71 (1.11)	7
CWrb	4.20 (0.84)	3.60 (0.55)	5
CWfs	3.00 (1.15)	2.29 (1.25)	7
TF	2.86 (0.90)	2.43 (0.79)	7

In most developed countries, usually compliance to discharge standards occurs. Therefore current effort is concentrated on micro-pollutants control, impacts of pollutants on sensitive areas and eliminating the occasional non-compliance. But for a developing country context, assessing the effluent qualities of suitable treatment systems in meeting discharge requirements is crucial due to the wide gap between effluent quality and discharge requirements. Therefore the inclusion of indicators to assess potential effluent qualities of the 4 feasible treatment systems is an exercise directed towards the development of a treatment system selection framework with the capacity of choosing a treatment system for the study area capable of achieving discharge compliance. Again survey results indicate constructed wetlands (reed bed and free water surface) and trickling filter systems as relatively better in terms of producing discharge compliance effluents.

Also due to population growth, it is often necessary to upgrade a treatment plant to accommodate the consequent increase in hydraulic and organic loads. Is the treatment system flexible enough to undergo an upgrade or expansion with minimal changes to the infrastructure of the plant? This is the import of indicator RL5 (Capacity for expansion to absorb population growth). Results of the treatment plant survey for this indicator presented as part of Figure 11 indicates that all treatment systems generally have the capacity for expansion but stabilization ponds are readily expanded on condition of land availability.

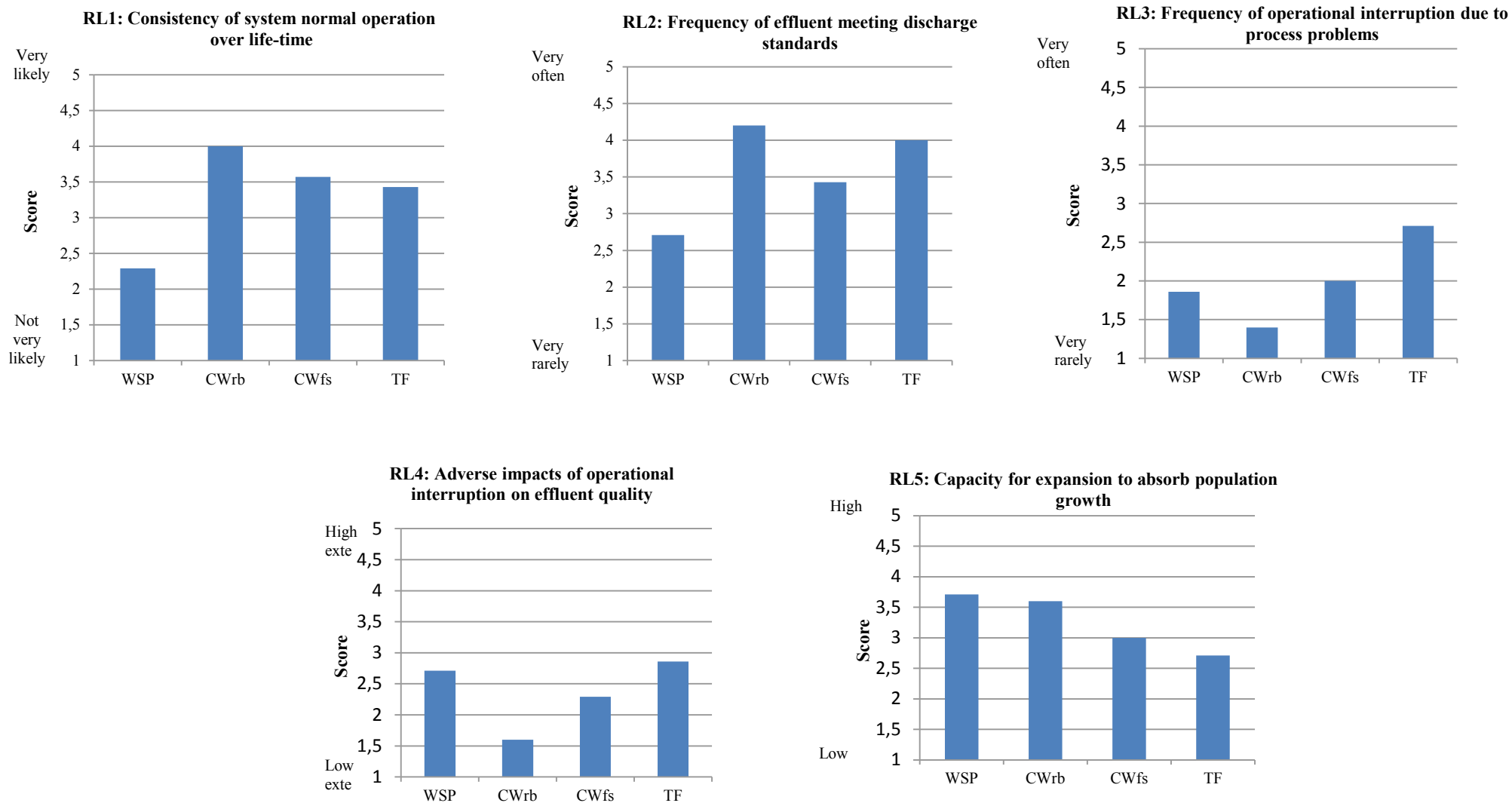


Figure 11: Quantified values of indicators measuring long-term treatment plant reliability

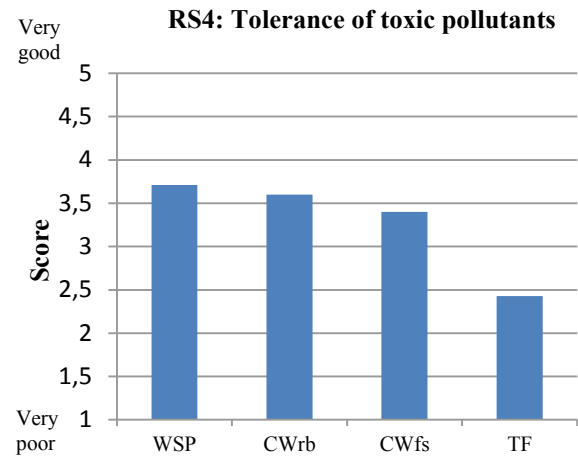
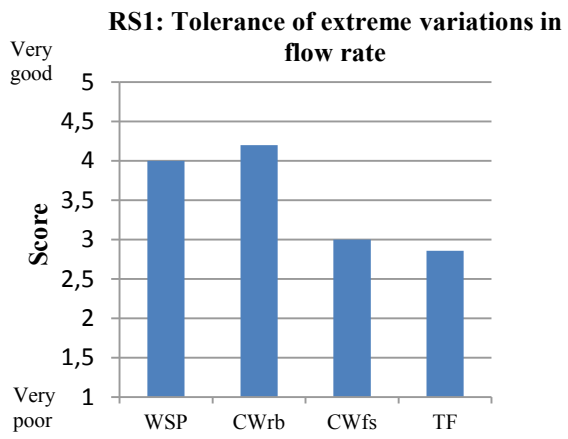


Figure 12: Quantified values of indicators measuring short-term treatment plant reliability

4.4.1.3 Complexity

Complexity assessment is being done to factor in the level of technological development in terms of treatment systems construction, operation and maintenance in developing countries in general and study area in particular. In the construction of new treatment plants or expansion of old plants, the tendency around the world is to adopt cutting-edge technologies. Sometimes in developing countries, investment financing for such complex treatment plants can be mobilized in the form of grants and soft loans. The problem then becomes availability of expertise for the construction, operation and maintenance of such treatment systems. Also, financial resources required to fund the high cost of operating these complex treatment systems over the long term becomes a problem. Reason being that, often, municipalities or water and sanitation utilities in developing countries do not have the capacity (expertise and finance) to operate and maintain complex treatment plants.

Experience shows that, many municipal wastewater treatment systems based on complex processes in developing countries have not been successful. For sustainability, this points to the need to implement treatment systems based on simple processes devoid of complex equipment. In some cases these treatment systems do not include equipment at all or the equipment components are highly limited and produced from local construction materials using local expertise. This facilitates their construction in developing countries and ensures that technical difficulties encountered during the operational stage are easily overcome. The longevity and operational sustainability of treatment systems based on simple processes with the capacity of integrating local materials and expertise in developing countries is therefore better than complex systems adopted from developed countries without considering local expertise. For this reason assessing complexity is crucial to the selection of appropriate treatment systems.

This study evaluates complexity of the treatment systems start-up or installation and complexity of their operation and maintenance. A wide range of indicators were initially developed for the assessment but those considered to be relevant to the context of the study area by the expert survey are presented in Table 18 below.

Table 18: List of indicators to evaluate complexity

Indicator	Unit of quantification	Significance
Ease of system installation and startup		
CI1. Overall complexity of system installation or construction.	1=very simple, 5=highly complex	Capacity of system implementation by local expertise.
Operation and maintenance requirement		
CO1. Complexity of system operation.	1=very simple, 5=highly complex	Assessing the requisite experience for the operation of treatment alternatives.
CO2. Skill level or personnel requirement.	1=low skilled, 5=high skilled	
CO4. Requirement of special maintenance.	1=very rarely, 5=very often	Capacity for system operation and maintenance by locally manufactured materials and expertise.
CO5. Requirement of special manufactured or imported spare parts.	1=very rarely, 5=very often	

The results of the treatment plant survey of indicators assessing system complexity are presented in Table 19 and Figure 13 below. Plant operators were given a scale of 1 - 5 with 1 being the least complex or low skilled and 5 representing highly complex or highly skilled.

Table 19: Quantified values of indicators assessing ease of system installation, operation & maintenance
Average score of indicators (standard deviation)

System	Ease of system startup	Operation & Maintenance				
	CI1	CO1	CO2	CO4	CO5	N
WSP	2.14 (1.07)	1.57 (0.79)	1.71 (0.76)	1.86 (0.90)	1.14 (0.38)	7
CWrb	2.86 (1.14)	1.40 (0.55)	2.20 (0.84)	2.00 (1.00)	1.20 (0.45)	5
CWfs	2.40 (1.29)	2.29 (0.76)	2.29 (0.76)	2.29 (0.95)	1.57 (0.79)	7
TF	3.00 (1.21)	3.14 (0.69)	3.57 (0.79)	3.29 (0.49)	2.57 (0.79)	7

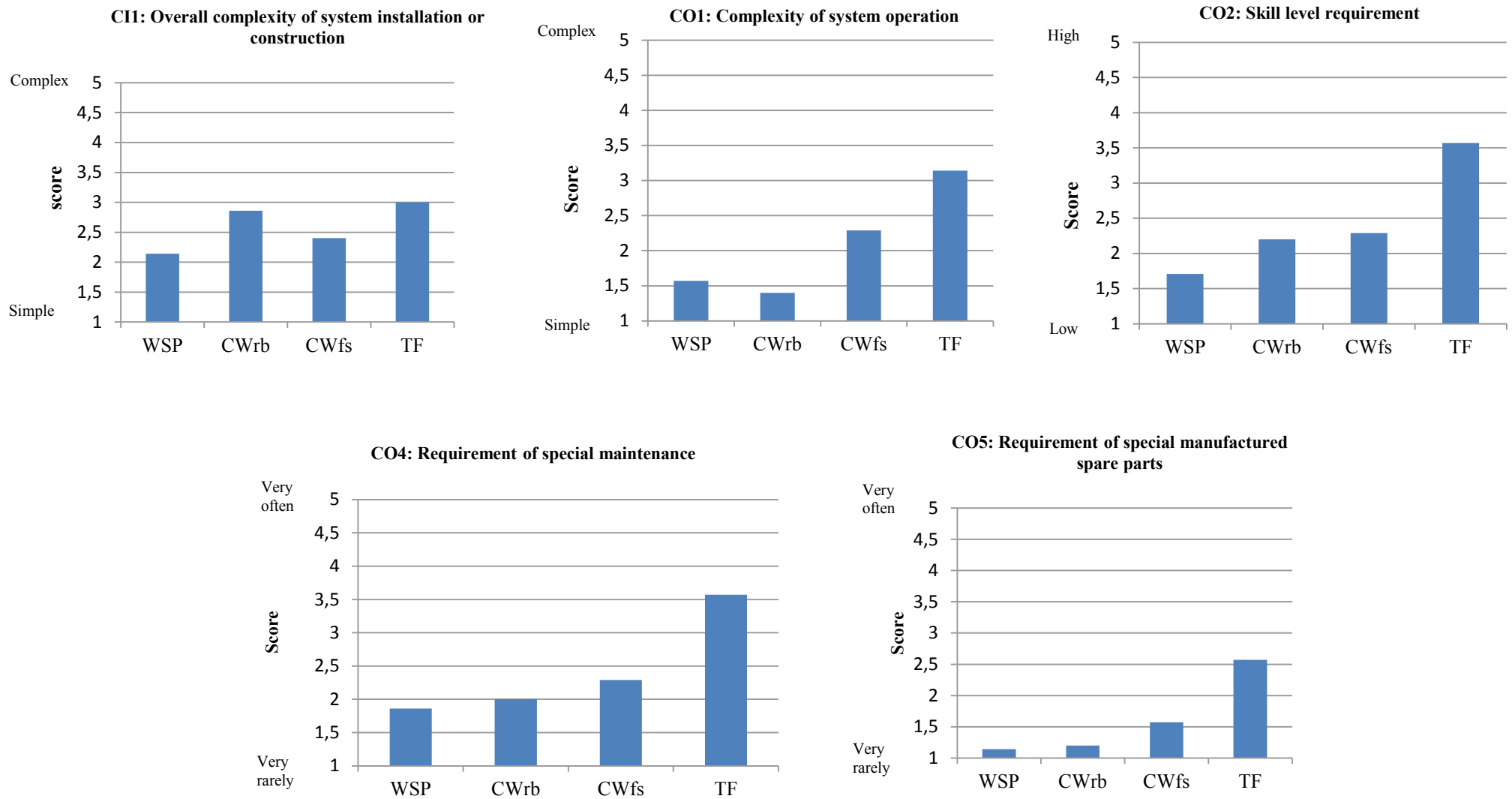


Figure 13: Quantified values of indicators assessing ease of system installation, operation & maintenance

The optimum performance of a treatment system will not be achieved without informed operation and responsible administration. Poor operator capacity in understanding and application of process control is mostly responsible for limiting treatment plant performance. The implication is that, an operator highly skilled in treatment processes can reduce the risk of process failure, protect worker safety and solve performance problems better than one with low expertise. With the lower skill level of municipal authorities in charge of treatment systems in the study area, the skill level required (CO2) to operate the treatment system alternatives needs to be assessed.

Complexity of system operation (CO1) in developing countries is valued as an indicator of sustainability and also dictates skill level or personnel requirement. The more complex and highly mechanized treatment systems such as activated sludge, trickling filter, etc. require highly skilled personnel than the less mechanized processes such as stabilization ponds and land treatment systems. Also, assessing special maintenance (CO4) and imported spare parts (CO5) is important in determining the degree of local materials and expertise application in operation and maintenance.

In response to the complexity of construction, operation and maintenance, the survey results presented in Figure 13 above indicated trickling filter as the most complex and also the system that usually requires relatively highly skilled personnel, special maintenance and spare parts.

4.4.1.4 Land requirement

Generally, close-to-nature treatment systems have high hydraulic retention times, which translate into large land requirements compared to conventional treatment systems such as the activated sludge that have low retention times and consequently, small land requirements (Table 20). Coupled with the situation of Kumasi, a fast growing city with high rate of urbanization where land availability is constrained, the land size requirements and suitable land conditions required for the establishment of the treatment system alternatives being considered in this study need to be assessed. In the context of this study, minimum land requirement is seen as a benefit; by the reduction of capital cost and also the availability of public space for other economic and environmental purposes.

Table 20: Land requirement of different treatment technologies treating 1 MGD

Treatment technology	Land size requirement (Acre/MGD)
Conventional treatment (Mechanical)	
Activated sludge	0.4
Lagoon treatment	
Facultative pond	49-161
Aerated ponds	5-16.3
Land treatment	
Slow rate	60-700
Rapid infiltration	3-60

Sources: Crites and Tchobanoglous, (1998); Metcalf and Eddy, (2003).

Indicators used for the evaluation of treatment systems land requirements are presented in Table 21 below.

Table 21: List of indicators to evaluate land requirement

Indicator	Unit of quantification	Significance
Land size requirement		
LS2. Total footprint of the system		Total potential area to be occupied by the treatment system
- Design capacity	$m^2 / \text{design capacity } (m^3/d)$	
- Land size/ p.e.		
Favourable land conditions		
LF1. Flooding risk	1=not vulnerable, 5=highly vulnerable	Vulnerability of the treatment system to;
LF2. Risk of groundwater		Flooding High groundwater table

Land size requirement

Analysis of the data on land size and design capacity was carried out to ascertain the land size structure associated with the design capacities of the treatment plants sampled. The results (Figure 14) indicate that the specific land requirement on all four treatment processes decline with design capacity. That is, land sizes per design capacity for small treatment plants are higher than those of plants with high design capacities representing an economy of scale. In general WSPs have the higher land requirement with those in the less than 5000 m³/day capacity category having the highest land sizes in the range of 20-25 m² per design capacity. It is followed by the free water surface constructed wetland (CW_{fs}) which also have high land size per design capacity in the lower category of design capacity.

Although not enough data have been obtained to present the land size per design capacity for trickling filters in various design capacities, their land size requirements are relatively lower than WSPs and CWs owing to the high surface areas of bacteria growth that populates the filter beds. The land size per design capacity economy of scale is still evident when all the treatment systems are put together (though not as evident as individually) indicating this as a general trend in at least the four different treatment systems being considered for the study area.

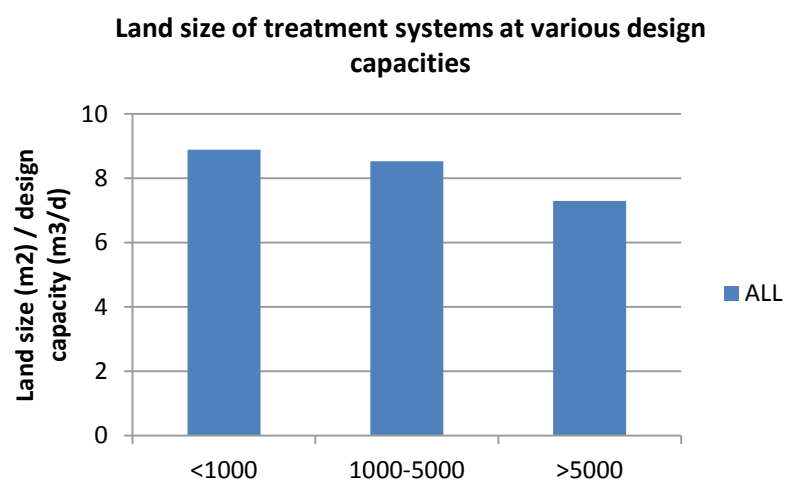
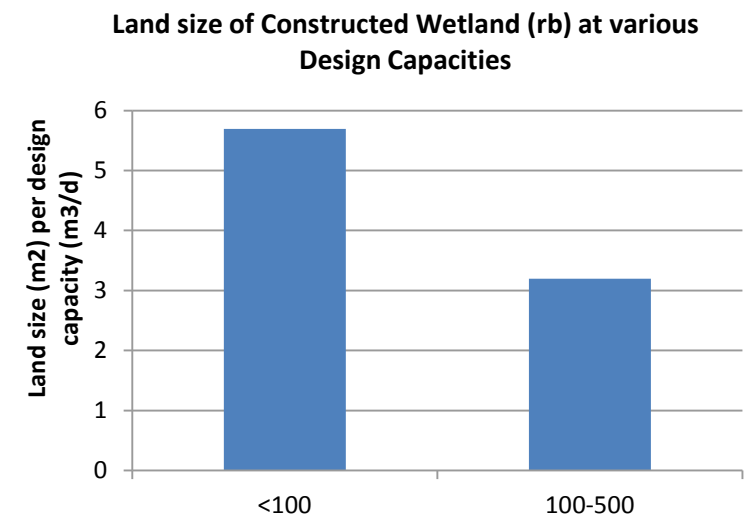
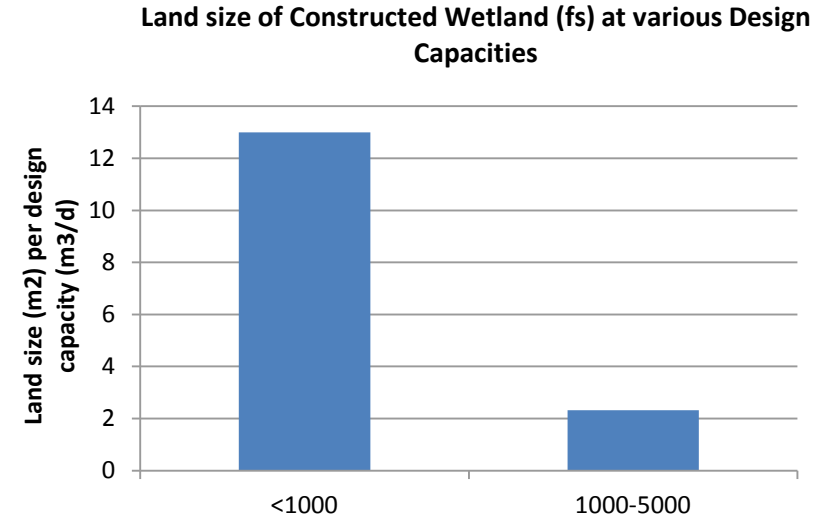
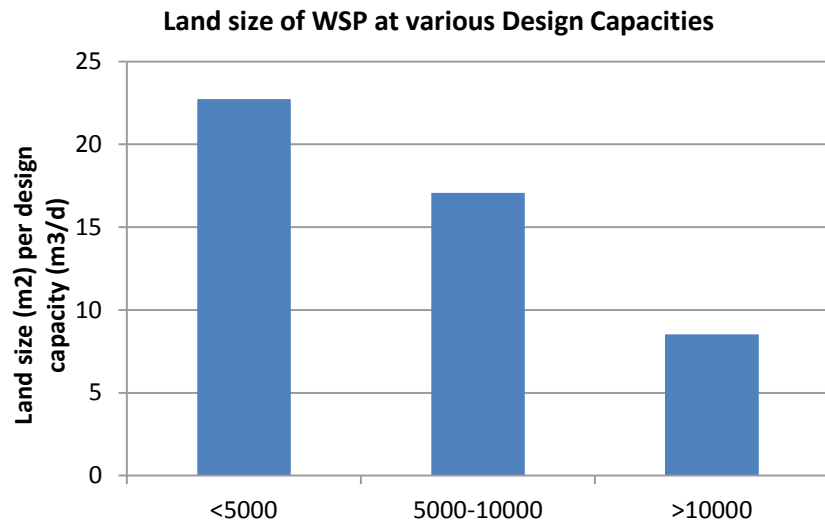


Figure 14: Land size requirements per design capacities of the different treatment systems

Once the land structure in relation to design capacity is obtained, least squares regression methods were used to relate land size to design capacity in an attempt to produce models capable of interpreting the relationship between the two variables and can be applied to estimate the land size requirement of the treatment plants for the study area. Figure 15 illustrates the relationship between land size and design capacity for each of the four treatment process. Their specific models are also presented in Table 22 below. The regression models are represented in the general form;

$$L = k * Q^b$$

Where L = Land size, k = Regression constant, Q = Design capacity, b = Power coefficient

With coefficients of determination R^2 being more than 0.5 ($R^2 \geq 0.5$), it can be said that half or more than half of the variance in the dependent variable (L) is being explained by the independent variable (Q) for all the treatment alternatives. Coupled with their high statistical significance ($p < 0.05$), the land size requirement models (with the exception of that of trickling filter of limited data) can be said to be of good fit or have a high predictive capability that can be depended on to estimate the land size requirements. The economy of scale component of land size requirement in all the four treatment alternatives is being indicated by the less than one power coefficient in all the estimation models.

Table 22: Land size estimation models for the treatment system options

System	N	Land Size Requirement Model	R^2	NHST
		($L = k * Q^b$)		(p)
WSP	8	$L = 450.75 * Q^{0.6146}$	0.63	$P < 0.05$ (0.001)
CW_{rb}	5	$L = 128.34 * Q^{0.2443}$	0.71	0.05
CW_{fs}	7	$L = 28.56 * Q^{0.6004}$	0.73	$P < 0.05$ (0.04)
TF	3	$L = 90.27 * Q^{0.324}$	0.98	$P < 0.05$ (0.02)

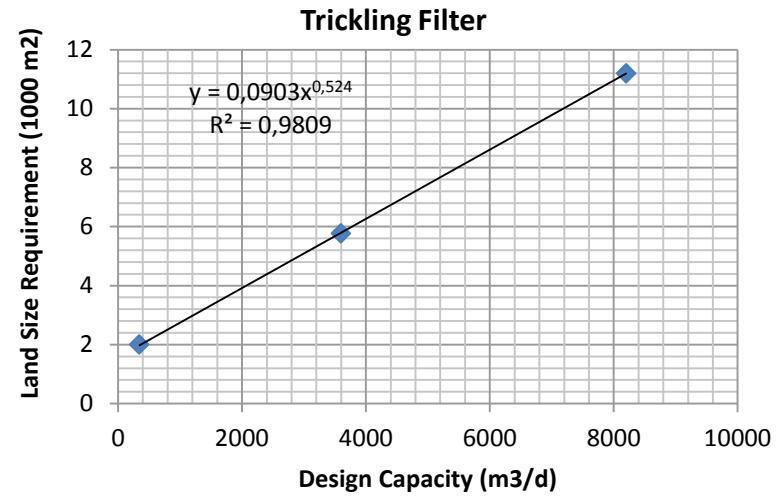
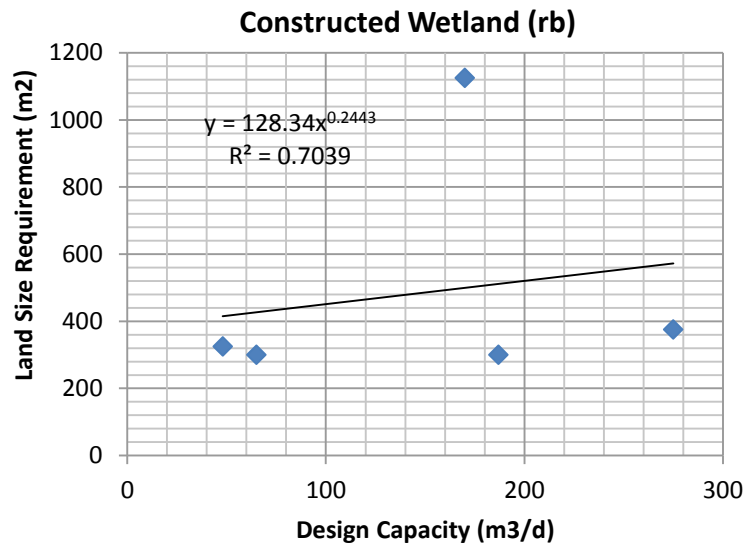
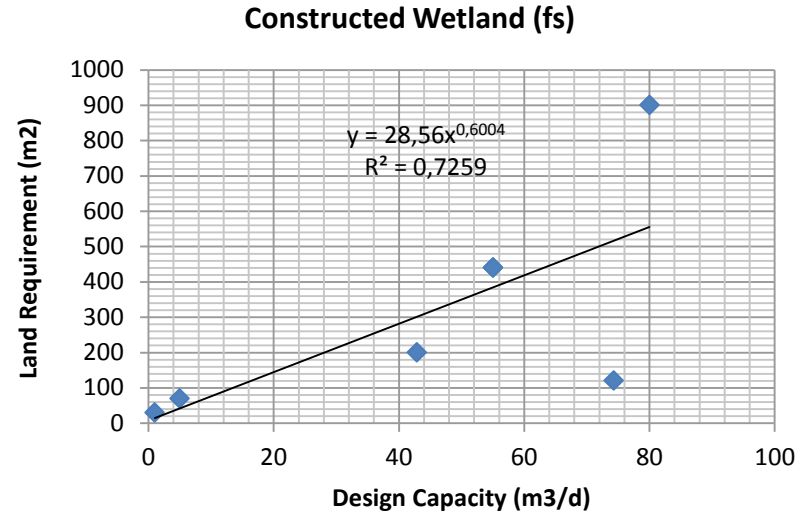
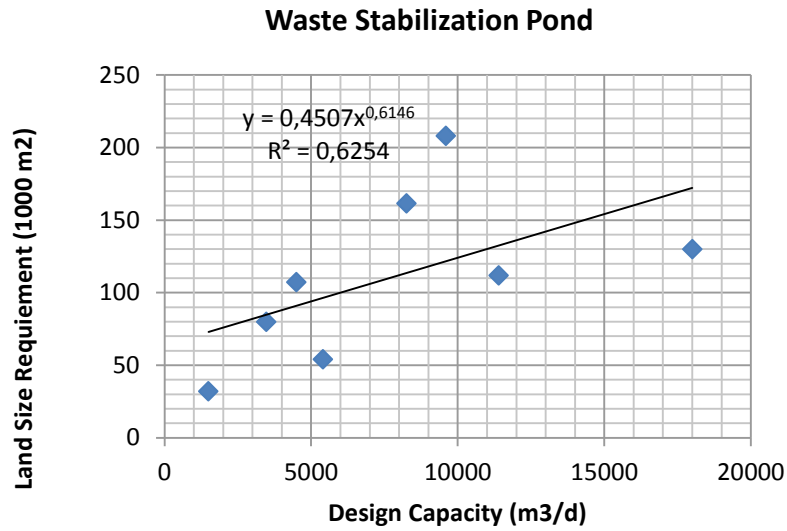


Figure 15: Regression models for estimating land size requirements of treatment options

Favourable land conditions

Every geographical location has its peculiar geological properties, soil conditions, flood hazards and other factors that can affect the feasibility and implementation of treatment systems. Among these land conditions, flooding risk (LF1) and risk of high groundwater table (LF2) on treatment plant operations have been selected as relevant for the study area. These two indicators were therefore used to assess the treatment system alternatives in order to determine how vulnerable they are. Plant managers and operators assessed their treatment systems vulnerability to these conditions on a scale of 1-5 with 1 being not vulnerable and 5 being highly vulnerable. Table 23 and Figure 16 present the results of the survey.

Table 23: Quantified values of indicators assessing favourable land conditions

System	Average score of indicators (standard deviation)		
	Favourable land conditions		
	LF1	LF2	N
WSP	2.14 (1.21)	2.43 (0.79)	7
CWrb	1.60 (0.89)	1.20 (0.45)	5
CWfs	1.34 (0.82)	1.86 (1.07)	7
TF	1.20 (0.79)	1.29 (0.49)	7

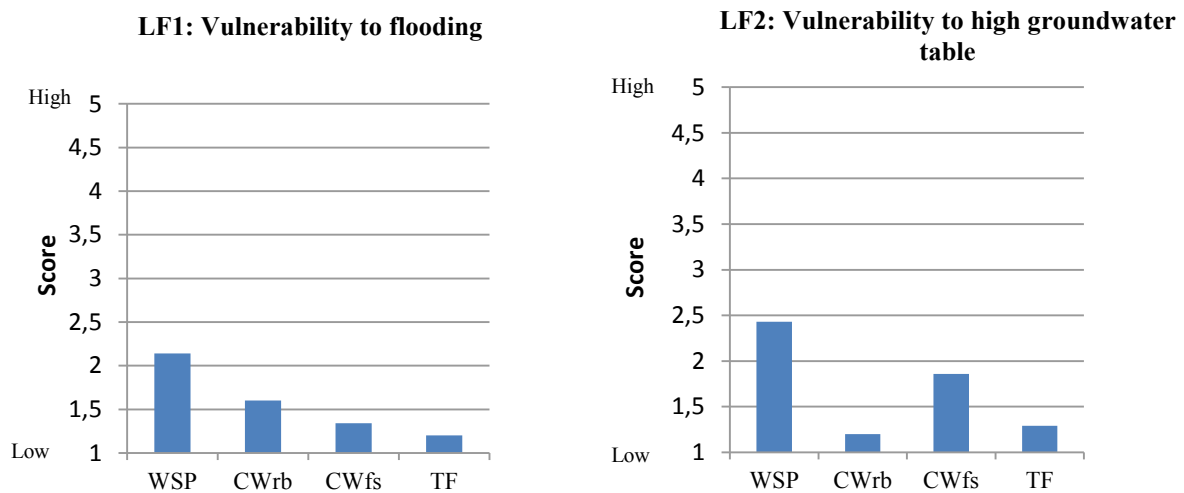


Figure 16: Quantified values of indicators assessing favourable land conditions

Results indicate no significant impacts of flooding and high groundwater table on all the four treatment system alternatives. The marginal vulnerability of stabilization ponds and constructed wetland (free water surface) to high groundwater table can easily be reduced by

well design and constructed systems that make use of geo-synthetic liners and impervious native clays that isolate the treatment system from groundwater.

4.4.2 Economic aspects

4.4.2.1 Affordability

Economic aspect of wastewater treatment systems is an important issue in both the developed and developing world but it is critical in the latter. Usually, the pollution of rivers, streams, etc. caused by the discharge of untreated and partially treated city and industrial effluents into these water bodies is as a result of the absence of treatment systems or the presence of inefficient treatment facilities in communities of developing countries. This invariably is as a result of the high cost of construction, operation and maintenance of conventional and advanced treatment technologies. Economic criteria especially affordability is therefore one of the key factors acting as a constraint to the application of wastewater treatment technologies and practices in developing countries. Affordability addresses the potential financial obligation in terms of the capital, operation and maintenance cost to be borne by the community for which the treatment plant is to be constructed. Affordability problems for mechanized systems are more pronounced in developing countries. This is partly the reason for this study in considering nature-related and highly limited mechanized treatment alternatives. It is also for this reason that indicators (Table 24) pertaining to capital, operation and maintenance costs are being used to assess the treatment alternatives.

Table 24: List of indicators assessing affordability

Indicator	Unit of quantification	Significance
Initial construction cost		
AC1. Construction cost (including land cost)	US\$/design capacity (m ³ /d)	Assessing the current cost of a treatment system alternative
Annual operation & maintenance cost		
AO1. Operation cost		
AO2. Maintenance	US\$/design capacity (m ³ /d)	Assessing the current operation and maintenance cost
AO3. Personnel cost	Current flow rate	
AO5. Administration cost		

Construction cost

Analysis of the PV construction costs and their corresponding design flows was carried out to determine how they are related. As illustrated in Figure 17, the construction cost per design capacity for all 4 treatment systems decline with design capacity. That is, construction cost per design capacity for small treatment plants are higher than those of plants with high design capacities representing an economy of scale. In general constructed wetlands have the lowest construction cost per design capacity (\$5000) in the less than 1000 m³/d design capacity category. Trickling filter on the other hand is the most costly to build among the treatment process in this study in the design capacity range 1000 – 5000 m³/d. But it must be emphasized that, the data used for this analysis is from highly mechanized trickling filters that are relatively expensive to construct. Among the well-known conventional treatment systems, it can be constructed with minimal mechanization (utilization of gravity to eliminate pumps and motors required to drive the distribution arms making it suitable for low income countries) and as a result considerable reduction in construction and operation cost. The dramatic fall in construction cost exhibited by CWs and trickling filter in their high design capacity ranges is due to the fact that limited data was used in their calculation. However, there is a gradual decline in cost per design capacity when all treatment systems are put together illustrating economy of scale in construction cost against design capacity as a common feature in treatment systems.

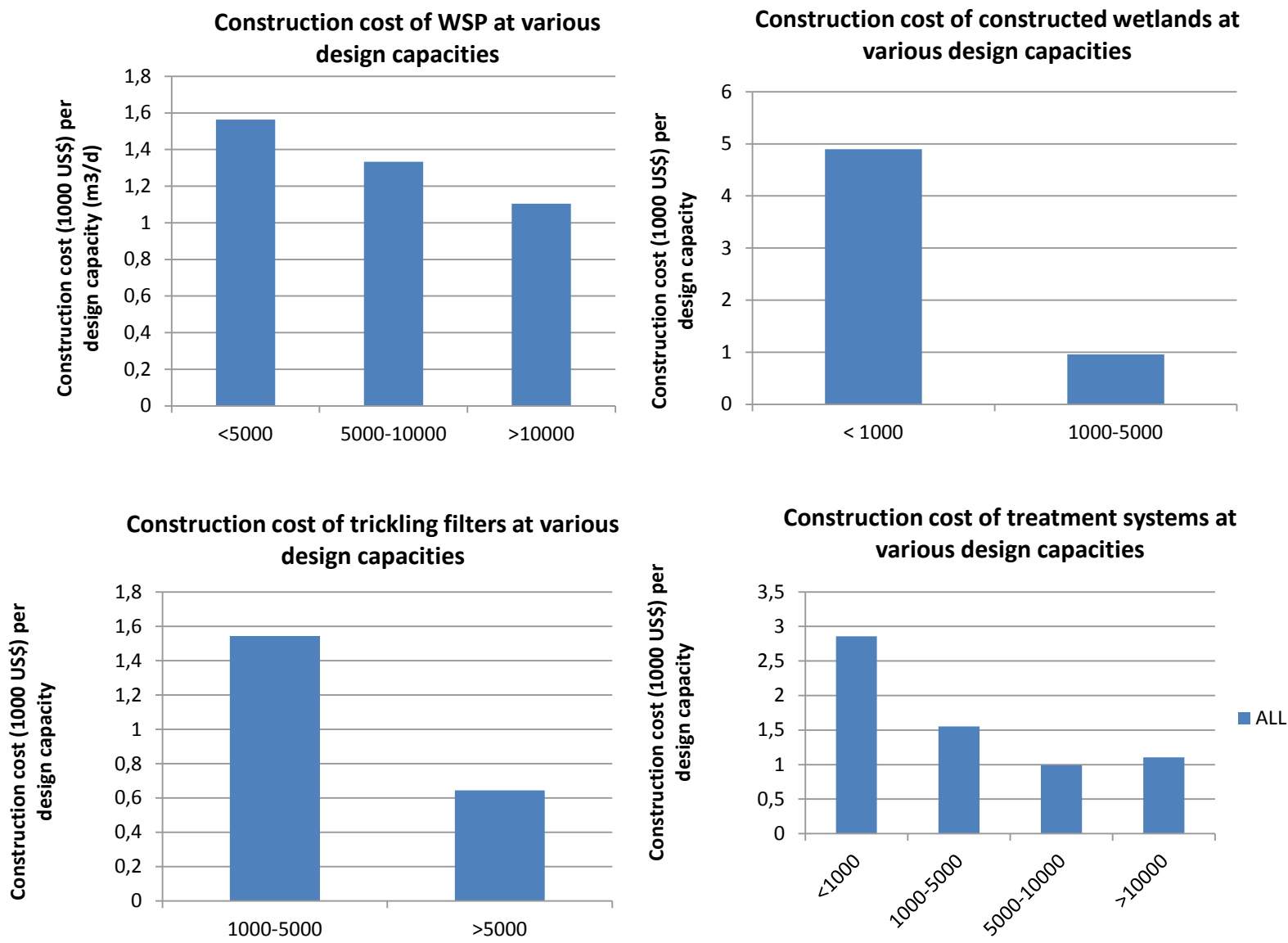


Figure 17: Construction cost per design capacities of the different treatment systems

Having obtained the impact of design capacity on construction cost, regression analysis was employed to derive cost functions expressing the effects of design capacity on construction cost (Figure 18). With the regression coefficients of the model obtained and the potential design capacity capable of being estimated from the population equivalence, the models can be applied to estimate the potential construction costs for treatment system alternatives for the study area. The models are presented in Table 25 and in the general form below because the power function gives the best fit;

$$C = k * Q^b$$

Where C = Construction cost, k = Regression constant, Q = Design capacity, b = Power coefficient.

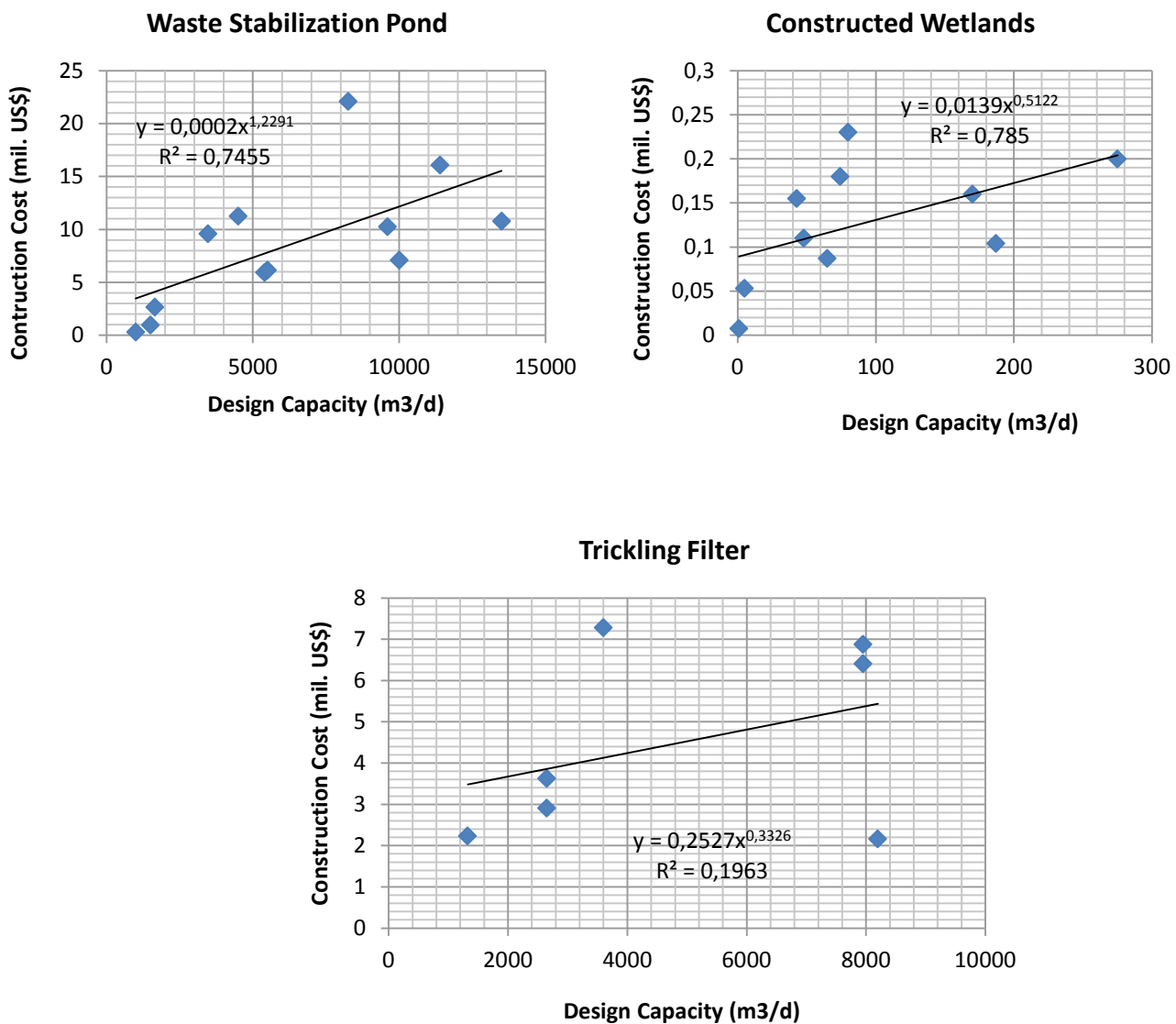


Figure 18: Models for estimating the construction costs of the treatment plant options

Table 25: Construction cost estimation models for the treatment system options

System	N	Construction Cost Estimation Model		NHST
		(C = k*Q ^b)	R ²	(p)
WSP	12	$C = 0.0002 * Q^{1.291}$	0.75	P<0.05 (0.0003)
CW	10	$C = 0.0139 * Q^{0.5122}$	0.76	P<0.05 (0.008)
TF	7	$C = 0.253 * Q^{0.3326}$	0.20	P<0.05 (0.005)

With coefficients of determination R^2 being more than 0.5 ($R^2 \geq 0.5$), for stabilization ponds and constructed wetlands and their high statistical significance ($p < 0.05$), the models have a high predictive capability and as such can be employed to estimate costs of construction of both treatment processes in the study area. Although the relationship between construction cost and design capacity for the trickling filter is statistically significant ($p < 0.05$), its predictive capacity is low due to very low R^2 (0.196). This indicates that, the construction cost is not greatly determined by the design capacity.

It should be emphasized that due to the absence of functional municipal wastewater treatment plants and the non-availability of construction costs data of the existing stabilization ponds in the study area, construction costs data of the treatment alternatives from other countries which were readily available were used to estimate the construction costs for the treatment plant options being considered. For the design capacity, the population size of the study area will be used as the served population size (p.e. – population equivalent) to calculate the potential sizes of the treatment options. It is also worth noting that, construction cost of developed countries applied for cost estimation in the study area (a developing country) might be higher than the real costs that would have been obtained from the study area if such data had been available. This is as a result of high standard of living and high minimum wages of the developed countries that increase cost components.

4.4.3 Estimation of the quantitative indicators for the 3 study communities

In this study, the potential design capacities are being equated to the maximum domestic wastewater that can be generated from each of the 3 communities under study in the study area. These represent the maximum flows that are to be treated and as such the treatment system alternatives must be design to accommodate such flows. The domestic wastewater flow of a particular community is usually estimated from the domestic water consumption in the relation below;

$$Q_{ww} = 10^{-3}kqP$$

Where Q_{ww} is the wastewater flow (m^3/day); k is the return factor (fraction of water consumed that becomes wastewater) and is usually in the range of 0.8 – 0.9; q is the average daily domestic water consumption of an inhabitant ($l/person/day$); P is the population size. This represents the Dry Weather Flow (DWF) and for design purposes and flow variations, it is usually increased 1.3 times more than the estimated flow (Q_{ww}).

An alternative approach to estimate potential design capacities will be to multiply population sizes by the average domestic water consumption of inhabitants in the study area. This approach will be under the assumption that all water consumed is returned as wastewater. This will result in higher design capacities and it is not considered to be realistic since not all water consumed is returned as wastewater.

By integrating current existing local conditions of the 3 study communities into the above equation to estimate the design flow and subsequently integrating the design flow into the derived land requirement and construction cost models, the construction costs and land requirements of the treatment alternatives for the 3 study communities are estimated and presented in Table 26.

Table 26: Estimation of land size requirement and construction cost for the 3 study communities

Community	Population* size	Flow** (m³/d)	Treatment system	Land Usage (m²)	Construction Cost (Mill. US\$)
Asafo	5,549	549.35	WSP	21,769	0.69
			CWrb	599	0.35
			CWfs	1,261	0.35
			TF	697	2.06
Ahinsan	3,954	391.45	WSP	17,676	0.44
			CWrb	552	0.29
			CWfs	1,028	0.29
			TF	625	1.84
Chirapatre	3,763	372.50	WSP	17,145	0.42
			CWrb	545	0.29
			CWfs	998	0.29
			TF	614	1.81

*Population sizes (Data source: Estimated from the summary report of the 2000 population & housing census)

- Average household size in the metropolis = 5.1 persons
- Average number of households per house = 3.4
- Total number of houses covered by treatment plants in the communities are
 - Asafo = 320
 - Ahinsan = 228
 - Chirapatre = 217

**Average water consumption in Ghana = 110 L/cap/day (Data source: PURC, 2002. Water Accessibility and Supply in Ghana).

4.4.4 Socio-cultural aspects

4.4.4.1 Social acceptability and capacity

Public acceptance of construction, operation and maintenance is a non-technical factor with no direct impact on decision making regarding the choice of treatment system. But it influences its sustainability. Communities in developing countries have come to associate wastewater treatment works as a health and environmental concern instead of a measure to forestall and remedy water pollution problems. This is due to the periodic emissions such as odours, dust, noise, and other unsightly conditions that emanates from their operations. Such public doubts and uneasiness about nearby treatment facilities can have adverse impacts on their long-term operation. The creation of public awareness about the problem at hand (the need for wastewater treatment), provision of information on available solution options and their consequences (treatment system options and operational requirements) and the provision of opportunity to assist in decision making will generate public support. Therefore the assessment of public acceptability and participation in the construction, operation and maintenance phases of the treatment alternatives in similar geographic locations is critical for the identification of the appropriate treatment system for the study area. Indicators used for this assessment are listed in Table 27 below.

Table 27: Indicators for the evaluation of social acceptability and capacity

Indicator	Unit of quantification	Significance
Public acceptability		
PA1. Public acceptability of system planning and construction	1=very low, 5=very high	Measuring public support for a certain treatment system. An indirect determination of sustainability
PA2. Public participation in system planning and construction		
PA3. Public acceptability of system operation		
PA5. Public support for wastewater fee collection		Willingness of inhabitants to foot the operation and maintenance cost generated by the treatment system.
Institutional capacity and competence availability		
CA3. Availability of competent personnel for system operation	1=not very important, 5=very important	Assessing the need of skilled personnel for daily system operation.

Public acceptability of system planning, construction (PA1) and operation (PA3) are important in evaluating acceptance of the technology while public participation in system planning and construction (PA2) to some extent indicates the level of reduction in construction cost that can be achieved by community provision of unskilled labor. Availability of competent personnel for system operation (CA3) serves as a guide on the level of sophistication that the system should possess. Table 28 and Figure 19 below present the results of the public acceptability and institutional capacity indicator assessment.

Table 28: Quantified values of indicators assessing public acceptability & institutional capacity

System	Average score of indicators (standard deviation)					
	Public acceptability				Inst. capacity	
	PA1	PA2	PA3	PA5	CA3	N
WSP	3.43 (0.79)	1.29 (0.49)	3.00 (1.73)	1.43 (0.53)	2.43 (0.98)	7
CWrb	4.20 (0.45)	1.20 (0.45)	3.40 (0.55)	1.20 (1.10)	2.40 (0.89)	5
CWfs	3.67 (0.82)	1.83 (1.17)	3.33 (0.82)	1.00 (0.89)	2.50 (1.05)	6
TF	3.86 (0.69)	1.14 (0.69)	4.00 (0.58)	2.29 (1.25)	3.86 (1.07)	7

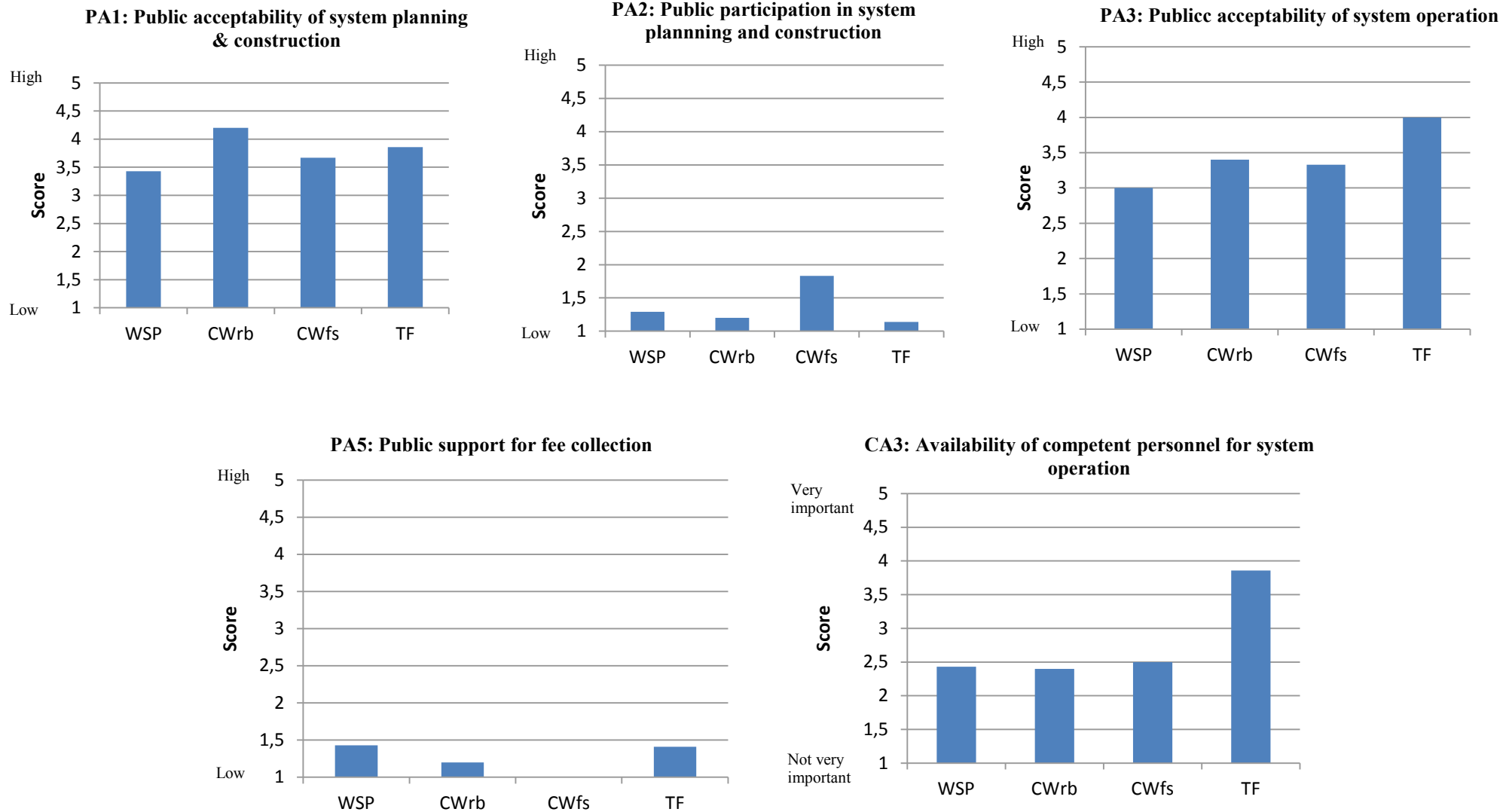


Figure 19: Quantified values of indicators assessing public acceptability & institutional capacity

The low levels of public participation in system planning and construction (PA2) in all treatment alternatives can be attributed to the fact that, the construction of a wastewater treatment plant is a complex process that requires the skills of experts specialized in civil engineering. The general public does not possess such expertise and can therefore not be expected to be of much help in the construction. Also, most of the treatment plants surveyed were constructed in the distant past and with no records to show whether the communities they serve participated in their construction, most current plant managers and operators being respondents of the survey could not assess their plants as far as this indicator is concern.

The survey results show that there is a high acceptability of treatment system operation (PA3) for all the treatment alternatives. The relatively lower value for stabilization pond is due to the presence of nuisance odour and insects that sometimes come about due to their poor management and operation.

The availability of competent personnel for system operation (CA3) is not highly required for stabilization ponds and constructed wetlands but it is a priority for trickling filter due to their relatively high degree of mechanization and inherent problems with their filter beds that requires troubleshooting to ensure smooth operation.

4.4.5 Environmental aspects

4.4.5.1 Sustainability

In the context of this study, sustainability assessment is about the measurement of self-sufficiency of a treatment system and the absence of major environmental impacts resulting from its operation. The study therefore analyses two aspects of environmental sustainability; environmental impacts or protection and possibility of resource recovery.

Environmental impacts and protection

The capacity of the system to minimize the transfer of pollutants to the environment; atmosphere, surface and groundwater resources, soil ecosystem and consequently bio-accumulate in food chains is being assessed by indicators under this category. The objective is to select a treatment system with low environmental footprint with the transfer of emissions to the different media within environmentally acceptable limits. Indicators for this assessment are listed in Table 29 below.

All treatment systems have the potential of generating odorous emissions that presents an aesthetic problem to communities in close proximity to such facilities. Assessment of the treatment alternatives to identify one with least emission of odours (SE1) will enhance public and regulatory agencies acceptance of its operations. Also, with malaria being endemic in tropical countries and other infectious disease causing agents carried and transmitted by insects in developing countries, it is worthwhile to subject the treatment alternatives to an indicator that assesses the extent to which they promote insect breeding (SE3).

Effluent qualities from the treatment alternatives in terms of their nutrient contents are also assessed by an appropriate indicator to ascertain their potential for eutrophication (SE5) and its adverse impacts on receiving water bodies' ecosystems. Groundwater pollution or quality impact (SE6) indicator is about the assessment of treatment alternatives with regard to their adverse impacts on groundwater resources. This is necessary to avoid the creation of health hazards and other undesirable conditions. Finally, any adverse impact on nearby settlements (SE8) as far as the siting of the treatment system is concern is also assessed.

For this section of the assessment, an operator of a treatment system score it high if a certain treatment system alternative has a higher possibility of causing any of the outlined environmental impacts.

Possibility of resource recovery

In sustainability terms, wastewater is now being acknowledged as a renewable resource from which water, materials (e.g., organic manure, fertilizers), bioplastics and energy can be recovered (Kleerebezem and Loosdrecht, 2007; Daigger, 2008; Larsen et al., 2009). This, as stated by Guest et al., (2009) has shifted the old paradigm of treatment from what must be removed to a new paradigm of what can be recovered turning sanitation systems into resource recovery systems. In line with this, assessment of the alternative treatment systems is being made to ascertain if the following can be achieved;

- possibility of direct recovery of energy and value added products
- possibility of high quality effluent that meet water reclamation and reuse requirements

A treatment system with a characteristic high capacity for pathogen and pollutants removal will render effluents safe for reuse activities such as irrigation and groundwater recharge. Anaerobic systems such as UASB have the capacity for methane production that can be captured as biogas. The sale of these recovered resources can be used to offset operation and maintenance cost to enhance operational sustainability. Indicators SR1, SR2 and SR4 in Table 29 below is for the evaluation of the treatment system alternatives to determine their capacities regarding the above mentioned useful by-products. Systems with high capacities of producing these by-products are given high ratings. Results of the survey are presented in Table 30 and illustrated in Figures 20 and 21 below.

Table 29: List of indicators to evaluate sustainability

Indicator	Unit of quantification	Significance
Environmental impacts or protection		
SE1. Odour production potential		
SE3. Breeding of insects and other parasites		
SE5. Eutrophication potential	1=very low, 5=very high	The extent to which the operation of a treatment system alternative causes any of the outlined impacts on nearby settlements and discharge waterbodies.
SE6. Groundwater quality impact		
SE8. General impacts on nearby settlements		
Possibility of resource recovery		
SR1. Biogas production potential		Possibility of any of the following useful by-products of wastewater treatment being generated by a treatment system alternative; <ul style="list-style-type: none"> • Methane for biogas • Organic matter for fertilizer • Effluent suitable for irrigation
SR2. Possibility of effluent reuse for irrigation	1=very low, 5=very high	
SR4. Recycling of organic matter for use as fertilizer		

Table 30: Quantified values of indicators assessing environmental sustainability

System	Average score of indicators (standard deviation)								
	Environmental impacts & protection					Resource recovery			
	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4	N
WSP	3.43 (0.98)	3.29 (0.76)	2.43 (0.98)	1.57 (0.53)	2.14 (0.38)	1.14 (0.38)	3.29 (0.76)	2.43 (0.79)	7
CWrb	1.80 (0.84)	2.00 (1.00)	1.2 (0.45)	1.00 (0.00)	1.20 (0.45)	1.00 (0.00)	3.80 (0.84)	1.20 (0.45)	5
CWfs	2.57 (1.13)	1.67* (0.52)	1.57 (0.79)	1** (0)	1.71 (0.76)	1.33* (0.82)	3.00 (0.58)	2.5* (1.05)	7
TF	2.71 (1.11)	3.14 (0.90)	2.00 (1.15)	1.29 (0.49)	1.57 (0.79)	1.14 (0.90)	2.43 (1.51)	2.71 (1.60)	7

** 5 respondents,

* 6 respondent

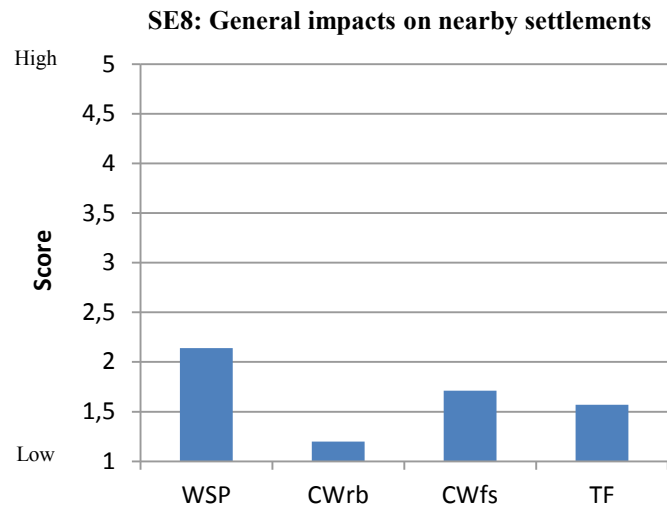
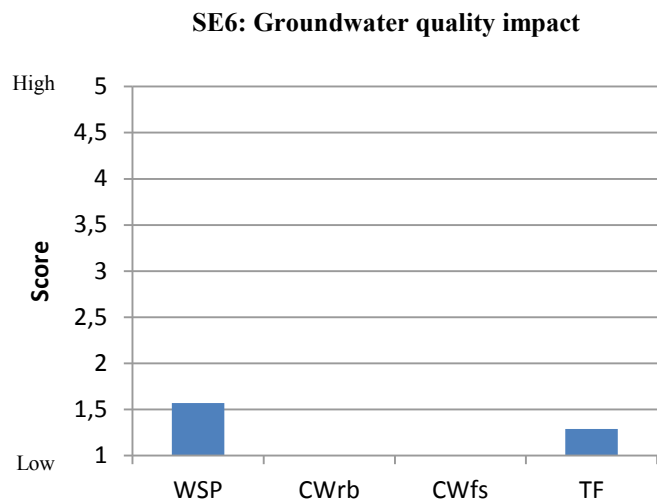
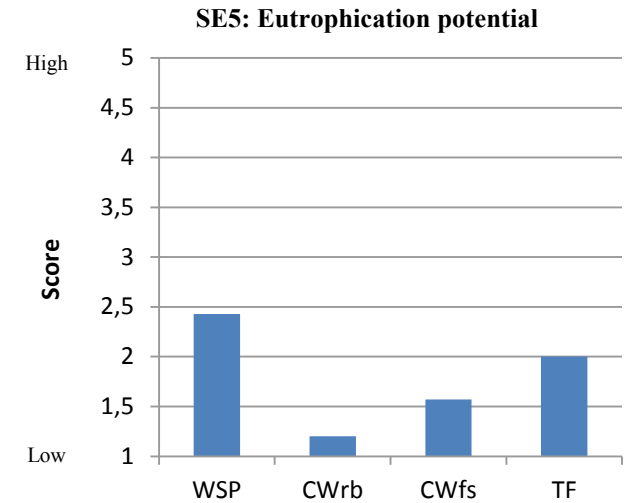
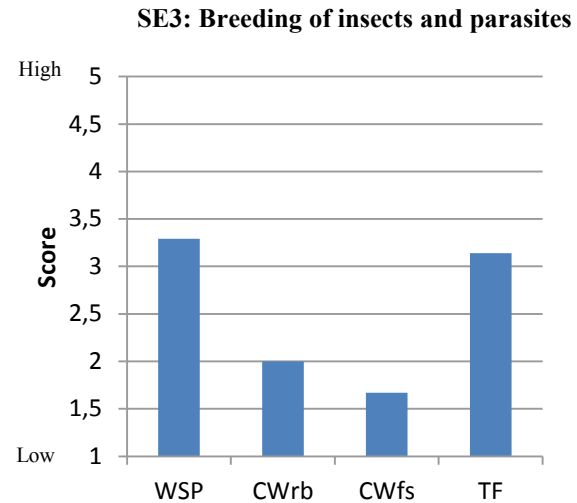
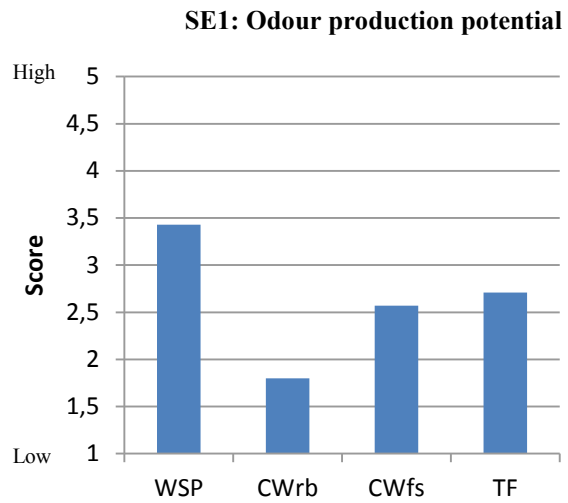


Figure 20: Quantified values of indicators assessing environmental impacts

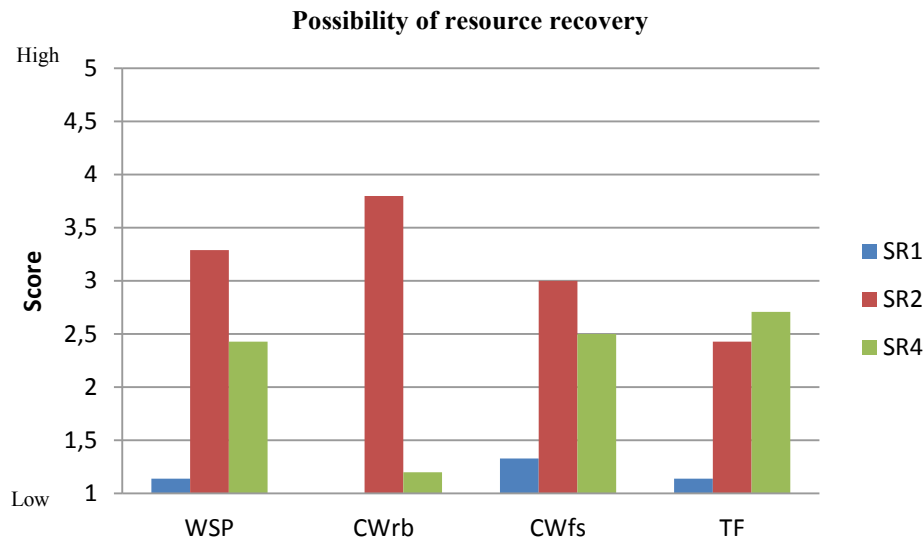


Figure 21: Quantified values of indicators assessing possibility of resource recovery

4.5 Results and discussions of indicator classification

It must be noted that the partitioning of the established indicators into benefits and cost is largely context based. An indicator can be of the benefit type at a particular geographic location due to its prevailing physical and or socio-economic conditions but can be a cost indicator in a different setting as a result of the presence of different physical and or socio-economic conditions. For instance, the indicator land requirement in this study is classified as a cost indicator for the context of the study area. This is due to the unavailability of land resulting from high population density and ongoing developmental projects competing for land with sanitation infrastructures. And usually sanitation projects are not a priority. But for another city in a developing country with current land availability and a projected future population growth, land requirement will be seen as an investment due to projected future demand and rise in the cost of land and as a result, a benefit indicator.

Also the objective of treatment can be a basis for the categorization of the assessment indicators. The specific purpose of treatment, whether to produce effluent suitable for reuse in agriculture or aquaculture or to produce effluent for safe discharge into freshwaters or coastal waters can inform the choice of benefit and cost indicators due to the different effluent quality standards required for each purpose. In the case of effluent to be reused for irrigation, more emphasis will be on the microbiological quality than the removal of nutrients such as N and P. Therefore indicators representing the removal of N and P can be classified

as cost due to the beneficial effect of these nutrients on plant growth. On the other hand, pathogen removal indicators can be classified as benefits due to the potential risk to farmers and consumers. Therefore, for a developing country context, the indicators have been partitioned as follows (Table 31).

Table 31: Classification of assessment indicators

Benefit indicators		Cost indicators	
Code	Indicator	Code	Indicator
EC1	Removal efficiency of BOD	RL3	Operational interruption frequency
EC2	Removal efficiency of Total Nitrogen	RL4	System failures generating effluent of low quality
EC3	Removal efficiency of Total phosphorus	CI1	Overall complexity of system installation or construction
EC4	Removal efficiency of Total Suspended Solids	CO1	Complexity of operation
EC5	Removal efficiency of pathogens	CO2	Skill and personnel requirement
RL1	Consistency of treatment system normal operation	CO4	System requirement of special maintenance
		CO5	System requirement of special manufactured or imported spare parts
RL2	Consistency of effluent meeting discharge standards	LS2	Total footprint of treatment system
RL5	Capacity of the system for expansion to accommodate future population growth	LF1	Flooding risk
RS1	Tolerance of extreme variations in flow rate	LF2	Risk on groundwater
RS4	Tolerance of toxic pollutants	AC1	Construction cost
PA1	Public acceptability of system planning and construction	SE1	Odour production
PA2	Public participation in system planning and construction	SE3	Breeding of insects and other parasites
PA3	Public acceptability of system operation	SE5	Eutrophication potential
PA5	Public support for wastewater fee collection	SE6	Groundwater quality impact
CA3	Availability of competent personnel to man the system	SE8	General impacts on nearby settlements
SR1	Biogas production potential		
SR2	Possibility of effluent reuse for irrigation		
SR4	Recycling of organic matter for use as fertilizer		

4.6 Application of the MADM methods

The application of MADM methods for the selection of an appropriate wastewater treatment system for the city of Kumasi in this study is carried out against the background that, wastewater treatment in the city is highly limited as a result of limited treatment plants in communities within the city and the inefficient treatment capacities of existing treatment plants.

Evidently, such a municipal wastewater management system necessitates a search for appropriate treatment plants for communities within the city. The following 4 treatment systems have been preselected as suitable alternatives for the communities selected for this research;

- Waste Stabilization Pond (WSP)
- Constructed Wetlands – vertical flow / reed bed (CWrb)
- Constructed Wetlands – horizontal flow / free water surface (CWfs)
- Trickling Filter (TF)

These are considered to be generally suitable for the study communities due to their low construction, O&M costs, low skill required in their operation, etc. However, due to the differences in socio-economic conditions, infrastructural development and many other factors of different geographic regions that impact on implementation of wastewater management systems, the treatment alternatives cannot be said to be equally suitable for all communities. Therefore, a comparative assessment of these 4 treatment systems are carried out on the basis of the identified and quantified indicators (from the previous section) in order to identify the most appropriate treatment system.

As mentioned earlier (literature review and methodology), TOPSIS and SAW are used for this comparative assessment. TOPSIS is based on the concept that the appropriate alternative should have the shortest distance to the Positive Ideal Solution (PIS) and longest distance from the Negative Ideal Solution (NIS). As explained in the methodology and indicated in the indicator quantification process in the previous section, the developed indicators are classified into benefit and cost indicators. Thus for a cost indicator, the lowest score of an alternative treatment system is considered its PIS and highest score is considered NIS and

vice versa. A compensatory approach inherent in TOPSIS similar to the nature of human decision making uses the favourable score of an alternative on an indicator to offset an unfavourable score of the same alternative on another indicator. TOPSIS assumes that each indicator has a monotonically increasing or decreasing score and the overall score of each alternative is estimated based on the indicator scores and their weights of importance. SAW on the other hand is applied to calculate the overall score of each treatment system from the decision matrix and the indicator weights, and the alternative treatment system with the highest score is selected as the most preferred one.

With the application of these two decision making methods, the development of the selection model involves the following steps;

- Construction of the decision matrix
- Determination of the weights of importance of the indicators
- Ranking of wastewater treatment alternatives

4.6.1 Construction of decision matrix

The quantified assessment indicators as against the treatment systems established in the indicator quantification section above constitutes the resultant decision matrix. This is presented in Appendix D (Section 1) according to their respective criteria. In these matrices, the benefit and cost indicators are marked by '+' and '-' signs respectively.

4.6.2 Weights of importance of the indicators

As indicated in the methodology, under simulation, all weights are made equal to indicate equal importance for all indicators. Such a uniform distribution is being applied in this study to represent a scenario (A) where decision makers have no reason to make some indicators more important than the others. The weight of an indicator as calculated under this scenario equals 0.02942 as shown on Table 32 below.

Under scenario B, the entropy coefficient method for indicator weight generation was applied as stated in the methodology section. Results as shown in scenario B of Table 30 puts land size requirement (LS2) and capital cost (AC1) as the highest weighted indicators with values

of 0.44 and 0.17 respectively. This is due to the major differences in the land size requirements and construction costs of the treatment systems being considered in this study. For instance, the land size required for the treatment of 549 m³/d of wastewater by WSP (higher land footprint treatment system among the alternatives) is approximately 21,000 m² as compared to 697 m² required by trickling filter (low land requirement system) with a corresponding construction cost of approximately US\$ 690 thousand and US\$ 2 million respectively to treat the same volume of wastewater. And as indicated earlier, these wide diversities in the indicators scores is responsible for their high weights.

Other medium weighted indicators include removal efficiency of phosphorus (EC3) and pathogens (EC5), frequency of operational interruptions (RL3), complexity of system operation (CO1), skill labour requirement (CO2), etc. Indicators with very low weights of importance that can be considered as not important to the decision making include the removals of BOD (EC1) and suspended solids (EC2), because of the comparable removal efficiencies of the treatment system alternatives. Others include consistency of system operation (RL1), complexity of system installation (CI1), public acceptability of system planning and construction (PA1), biogas production potential (SR1) etc. A look at the scores of the four treatment systems on any one of these indicators reveals similar scores. Hence the low weights. This illustrates the point made earlier that, the entropy method of weight elicitation tends to assign high weights to indicators with major differences in their values.

Table 32: Weights of importance of assessment indicators

Weights of Indicators (W_{ij})												
Criteria	Efficiency					Reliability						
Indicator	EC1	EC2	EC3	EC4	EC5	RL1	RL2	RL3	RL4	RL5	RS1	RS4
Scenario A	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294
Scenario B	0.0015	0.0046	0.0251	0.0079	0.0111	0.0096	0.0068	0.0136	0.0112	0.0043	0.0072	0.0117
Criteria	Complexity					Social Acceptability & Capacity						
Indicator	CI1	CO1	CO2	CO4	CO5	PA1	PA2	PA3	PA5	CA3		
Scenario A	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	
Scenario B	0.0047	0.0255	0.0185	0.0132	0.0284	0.0017	0.0095	0.0030	0.0254	0.0112		
Criteria	Land size & Affordability				Sustainability							
Indicator	LS2	LF1	LF2	AC1	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
Scenario A	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294
Scenario B	0.4445	0.0125	0.0204	0.1698	0.0123	0.0194	0.0164	0.0093	0.0104	0.0028	0.0065	0.0199

4.6.3 Ranking of wastewater treatment alternatives

The resultant decision matrix and indicator weights are analyzed by TOPSIS in order to rank the wastewater treatment alternatives and identify the most appropriate one for each of the 3 communities. SAW is used as a benchmarking tool to verify the results of TOPSIS. The detail step by step analysis by TOPSIS and SAW are presented in Appendix D (Section 2 – Section 9).

4.7 Analyzing the results

The variants of constructed wetland are ranked as the most preferred treatment systems in all 3 study communities as can be seen from Figure 22 below. For the community of Asafo, when equal weights (scenario A) are applied, TOPSIS identifies vertical flow (CWrb) as the most appropriate treatment system (with a score of 0.73) while horizontal flow (CWfs) is ranked a close second with a score of 0.66. This result to some extent is confirmed by SAW which places CWrb as the most preferred treatment system with a score of 0.91 and CWfs as a second (with a score of 0.80). At the remaining two communities, the rank order of the treatment systems remains the same but with slightly different rank values.

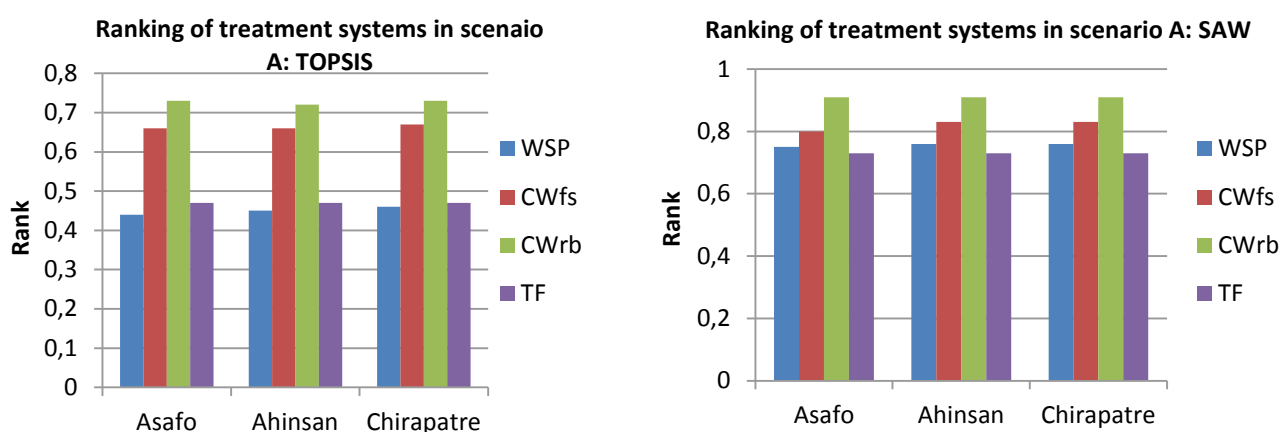


Figure 22: Ranking of treatment systems in the 3 communities according to scenario A

In scenario B under unequal weights, TOPSIS and SAW rank CWfs as the most preferred treatment system with CWrb occupying a close second in all the 3 communities as shown in Figure 23. It must be emphasized that the identical ranking of treatment systems in all communities is due to the identical assessment indicator weights applied for the 3 communities. This is due to the homogeneity of communities within the city of Kumasi and

also the absence of marked differences in the treatment objectives of the study communities. The identical ranking can also be attributed to the similar indicator scores of all indicators (with the exception of land requirement and construction cost) from one community to the other.

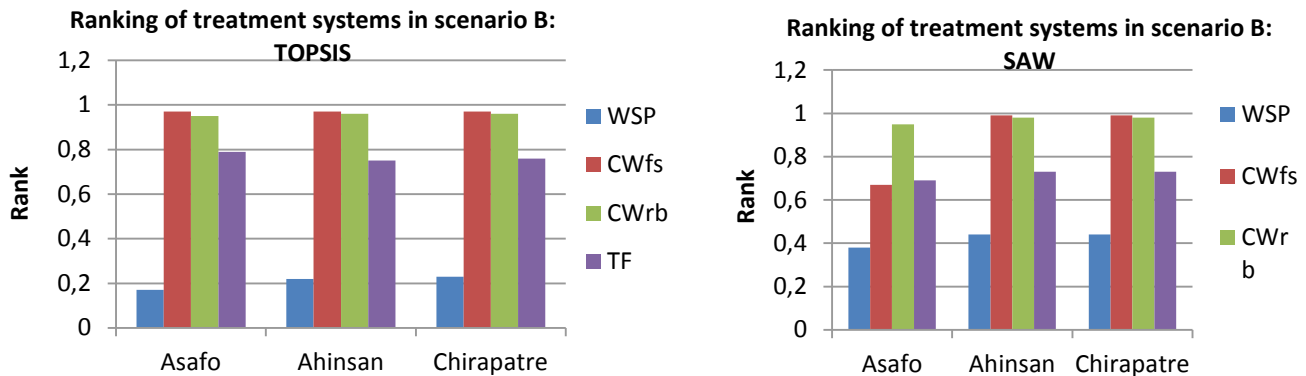


Figure 23: Ranking of treatment systems in the 3 communities according to scenario B

The choice of constructed wetlands as the most preferred for these communities is against the background of urban communities in a developing country where land space is becoming a constraint and capital funding is not readily available but effluent quality is supposed to be moderately high to minimize the pollution of water bodies and ultimately to prevent water borne diseases. This condition is expressed in the relative importance of the assessment indicators as land size (LS2) and construction cost (AC1) are at least 44 % and 14 % respectively important than the remaining indicators at all the 3 communities in scenario B. With this background it is expected that trickling filter would have been selected as the most appropriate since it has a characteristically low land footprint and high effluent quality. But trickling filter represents or is close to the negative ideal solution on most of the moderately weighted indicators such as construction cost (AC1), complexity of system installation or construction (CO1) requirement of special maintenance (CO4) and manufactured spare parts (CO5), frequency of operational interruption due to process problems (RL3) and the removal of phosphorus (EC3). And with the compensatory approach of the decision making methodologies applied where a low value of a treatment system on an indicator is compensated for by a high value on another indicator, trickling filter becomes one of the least preferred systems as a result of its many low values on many of the moderately weighted indicators.

WSP on the other hand has over the years been the treatment system of choice for developing countries due to its low construction, operation and maintenance costs and also the simplicity of its construction and operation. It is in fact the implemented treatment system at the 3 study communities. But it is being ranked as the least preferred system at all the 3 communities and in almost both scenarios (equal weights and entropy weights) by the two decision making methodologies. In the community of Ahinsan, the results of TOPSIS in scenario B indicate that not only is WSP the least preferred system, but it is lowly ranked with a score of 0.16 which represents a large step down from the third ranked trickling filter of score 0.79. This unexpected last position of WSP in the ranking is largely due to land size requirement (LS2) being a highly important indicator and also being a cost indicator in the decision making process. In all the 3 communities and when equal and unequal weights are applied, WSP is identified as the negative ideal solution (NIS). That is the least preferred alternative as far as minimum land requirement is concern due to its characteristic large land footprint.

The outcomes of CWrb and CWfs constructed wetlands for the study communities are reasonable in the sense that among the treatment alternatives, CW can be considered as a compromising solution. That is, it is at the mid-point as far as most of the high to medium weighted assessment indicators are concern. On the land size requirement (LS2) and construction cost (AC1) indicators, CWfs is the positive ideal solution (PIS) while CWrb lies in the middle of PIS and NIS (It conforms to observations that generally WSPs have large land footprint and low construction cost than CWs and trickling filters). Similarly on medium weighted indicators such as removal efficiency of phosphorus (EC3), complexity of system installation or construction (CO1), requirement of special maintenance (CO4) and manufactured spare parts (CO5), Eutrophication potential (SE5), etc. both types of CWs for the most part lies in the middle of PIS and NIS (see Appendix D, Section 3 - 4 for PIS and NIS of indicators).

Although CW technologies are relatively young, they are capable of producing high quality effluents meeting the standards of discharge into water bodies once feasible biological functioning of the artificial ecosystem is established. The absence of cold temperatures in the study area will also ensure optimum performance all year round. The choice of CWrb and CWfs is therefore consistent with the priorities of an urban area in a developing country where land is becoming scarce to select a high land footprint natural treatment system and

capital funding is not readily available to also establish a relatively expensive conventional treatment system.

4.8 Sensitivity analysis

In the practical application of this model of selection, indicator weights will be assigned based on the context of the priorities of each community. Hence a sensitivity analysis with unequal indicator weights can be seen as a test of the practical application of this model.

Indicators, land size requirement (LS2) and construction cost (AC1) have been selected for weight variation. The choice of LS2 and AC1 as subjects for sensitivity analysis is due to their potential variability from one community to the other. This is due to the differences in the availability of land spaces and financial capacities of different communities. For instance, in land constrained urban communities, decision makers may increase the weight of LS2 for the selection model to rank high treatment systems with low land foot prints. On the contrary, in sub-urban or rural communities with high availability of land space, the weight on LS2 may be made equal or less than other indicators. And the objective is to express land requirement as not crucial in the selection of a treatment system for such an environment. Similarly, in urban communities with relatively better financial capacities than sub-urban or rural communities, the weight placed on AC1 may be low to express the relatively non-importance of construction cost in the selection of a treatment system for such a community. This may not be done in sub-urban or rural communities with limited financial capacities. Instead, AC1 may be weighted high to rank high systems with low construction cost.

Again, from this model of treatment plant selection, the quantified values of LS2 and AC1 are subject to change from one community to the other since both indicators are highly dependent on population size and the consequent flows. These make LS2 and AC1 critical indicators because they are indicators whose weights and values are likely to vary from community to community. The other indicators are robust and their weights are less likely to change.

Although the sensitivity analysis can be conducted on any of the 3 communities, the ranking result of the Asafo community is selected as the subject of the sensitivity analysis. The initial weight of the land requirement indicator (LS2) which is 0.02942 was varied in the range of

0.01 to 4. Since the total weight of all indicators are supposed to be equal to 1, the weights of the remaining indicators are recalculated after the weight variations of LS2. With these new weights, the preference value of each treatment system is calculated and rank obtained. Similarly, if the variation is imposed on the initial weight of construction cost (AC1), the weights of the remaining indicators are recalculated and subsequently applied to the calculation of treatment systems preference values. Table 33 and Figure 24 present the results of the land requirement sensitivity analysis. Results from Table 33 indicates that constructed wetland remain the most appropriate treatment system with vertical flow system (CWrb) being the most highly preferred and horizontal flow (CWfs) occupying the second position at all levels of LS2 weight variation. It also shows that when the weight of LS2 is reduced below its original weight of 0.02942, waste stabilization pond (WSP) is ranked higher than trickling filter (TF). But when the weight is equal to or more than the original weight of LS2, WSP becomes the least appropriate among the four treatment systems.

Figure 24 also shows that the weight variations of LS2 have a similar positive impact on the constructed wetlands and TF. They increase in preference with the increase in weight of LS2. The graph also shows that at weights below the original weight of 0.02942, the preferences of the treatment systems are clearly defined with the CWrb being the most appropriate. Although it remains the highly preferred treatment system at the highest weight variation where the original weight of LS2 is increased four times, CWfs and TF also increase highly in preference close to the CWrb. WSP on the other hand decreases in preference with increase in weight and becomes the least appropriate treatment system at high weights. In effect all 4 treatment systems are sensitive to changes in weight of the land requirement indicator.

Table 33: Variation of the weight of land requirement and its impact on treatment system ranking

Variation Factor	Weights of Indicators		Ranking of treatment systems
	LS2	Others	
0.05	0.001471	0.03026	CWrb > CWfs > WSP > TF
0.1	0.002942	0.0303	CWrb > CWfs > WSP > TF
0.5	0.01471	0.0299	CWrb > CWfs > WSP > TF
1	0.02942	0.02942	CWrb > CWfs > TF > WSP
1.5	0.04413	0.02897	CWrb > CWfs > TF > WSP
2	0.05884	0.02853	CWrb > CWfs > TF > WSP
2.5	0.07355	0.02808	CWrb > CWfs > TF > WSP
3	0.08826	0.02764	CWrb > CWfs > TF > WSP
3.5	0.10297	0.02720	CWrb > CWfs > TF > WSP
4	0.11768	0.02674	CWrb > CWfs > TF > WSP

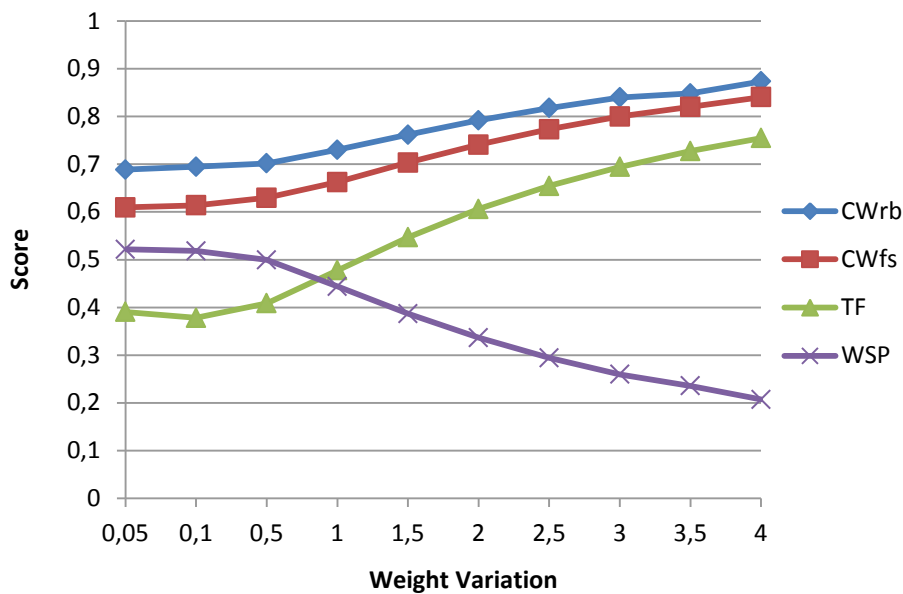


Figure 24: Impact of land requirement weight variation on treatment plant ranking

Results from Table 34 below shows that like the variation in weight of LS2, the variation in weight of AC1 presents constructed wetlands as the appropriate treatment system for the study community. The sensitivity analysis ranks CWrb as the most preferred and CWfs as the second most appropriate system maintaining the original ranking of the treatment systems.

Table 34: Variation of the weight of construction cost and its impact on treatment system ranking

Variation Factor	Weights of Indicators		Ranking of treatment systems
	AC1	Others	
0.05	0.001471	0.03026	CWrb > CWfs > TF > WSP
0.1	0.002942	0.0303	CWrb > CWfs > TF > WSP
0.5	0.01471	0.0299	CWrb > CWfs > TF > WSP
1	0.02942	0.02942	CWrb > CWfs > TF > WSP
1.5	0.04413	0.02897	CWrb > CWfs > WSP > TF
2	0.05884	0.02853	CWrb > CWfs > TF > WSP
2.5	0.07355	0.02808	CWrb > CWfs > WSP > TF
3	0.08826	0.02764	CWrb > CWfs > WSP > TF
3.5	0.10297	0.02720	CWrb > CWfs > WSP > TF
4	0.11768	0.02674	CWrb > CWfs > WSP > TF

Figure 25 reveals that CWrb remains the most appropriate treatment system at all levels of AC1 variation. But the difference in preference between CWrb, CWfs and WSP are marginal at the most highest level of AC1 variation. It also shows that the ranking of the treatment systems does not change when the original weight of AC1 (0.02942) is reduced. But at the lowest weight of AC1 (0.0014) there is a significant difference in ranking between all the treatment systems. The original ranking is disturbed slightly when AC1 is increased by about 0.5 of its original weight. That is WSP becomes highly ranked than TF. After that there is an overall increase and decrease in preference of WSP and TF respectively but their sustained increase and decrease begins when the original weight of AC1 is increased about 2.1 times. It can therefore be stated that although all the treatment systems are sensitive to variation of the weight of AC1, it did not impose much impact on the order of CWrb and CWfs but influenced a lot on WSP and TF.

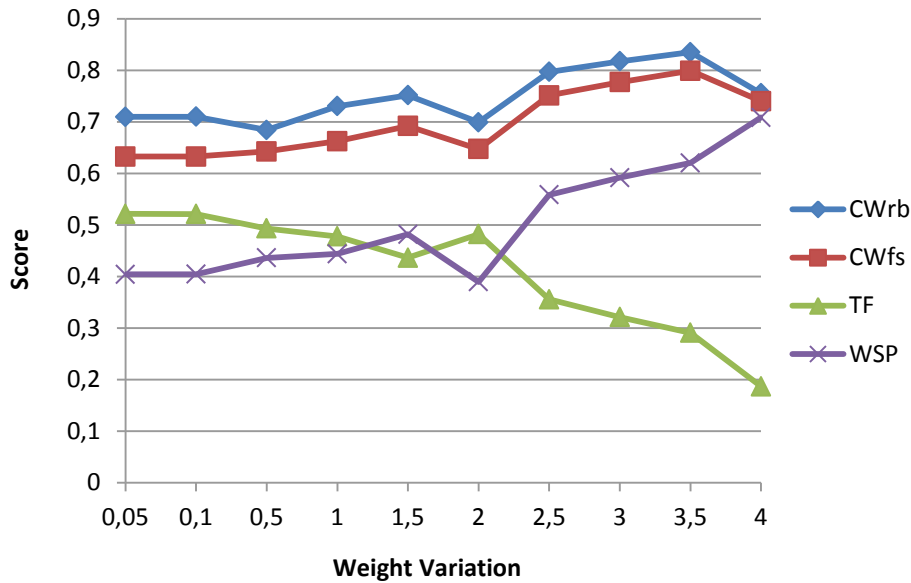


Figure 25: Impact of construction cost weight variation on treatment plant ranking

The conclusive results that can be drawn from this sensitivity analysis is that the appropriateness of CWrb for the community of Asafo is robust as it remains unchanged irrespective of the weight variation of the indicators, land requirement (LS2) and construction cost (AC1). Also for the construction cost, there is no change in ranking if the weight is decreased, meaning that there is no sensitivity to lower weights. But at lower weights for land requirements, the ranking is slightly altered. This analysis again shows that almost both assessment results begin to change when the original weights of both indicators are increased.

Finally the implication of these results is that, when availability of land is a concern in the selection of a treatment system for the community and the weight on the land requirement indicator is consequently increased to express this concern in the selection procedure, treatment systems with high land footprint such as WSP will be lowly ranked as it is seen in the land requirement sensitivity analysis where WSP is ranked as the least appropriate treatment among the alternatives. Similarly, when decision makers are more concern with the construction cost as it is in most developing countries, the selection model has the capacity of ranking low treatment systems with high construction cost as shown in the construction cost sensitivity analysis where TF was ranked as the least appropriate treatment system.

4.9 Decision support system

As shown in this study, the implementation of wastewater treatment systems in communities in developing countries is less of a technical design problem and more of a complex integrated decision task where many non-technical factors must be considered alongside technical factors. This makes the problem of choosing an appropriate treatment system for a community a multi-criteria decision making problem which requires an assembly of experts to be working together to arrive at a satisfactory solution. This complexity, coupled with the difficulty of assembling the required technical and non-technical treatment expertise in developing countries necessitates the use of decision support aids to assist in decision making regarding the selection and implementation of treatment systems. It is against this background that the various steps taken in this study to identify appropriate treatment systems for the study communities are being combined to form a decision support system (DSS) that can be applied to assist in treatment system selection decision making.

By integrating the steps taken so far to derive the appropriate treatment system, ranging from analysis of the wastewater treatment problem of Kumasi to the verification of the identified treatment system carried out through sensitivity analysis, a DSS can be constructed. Figure 26 below presents the data flow of how the DSS proceeds to identify the appropriate treatment system for a particular community. It must be emphasized that, the below described DSS is conceptual and the data flow is meant to be used as a guide in the DSS construction through suitable programming methods.

	Knowledge Acquisition			
Problem Analysis	Data Gathering & Analysis	Knowledge Base	Decision Support	Usability

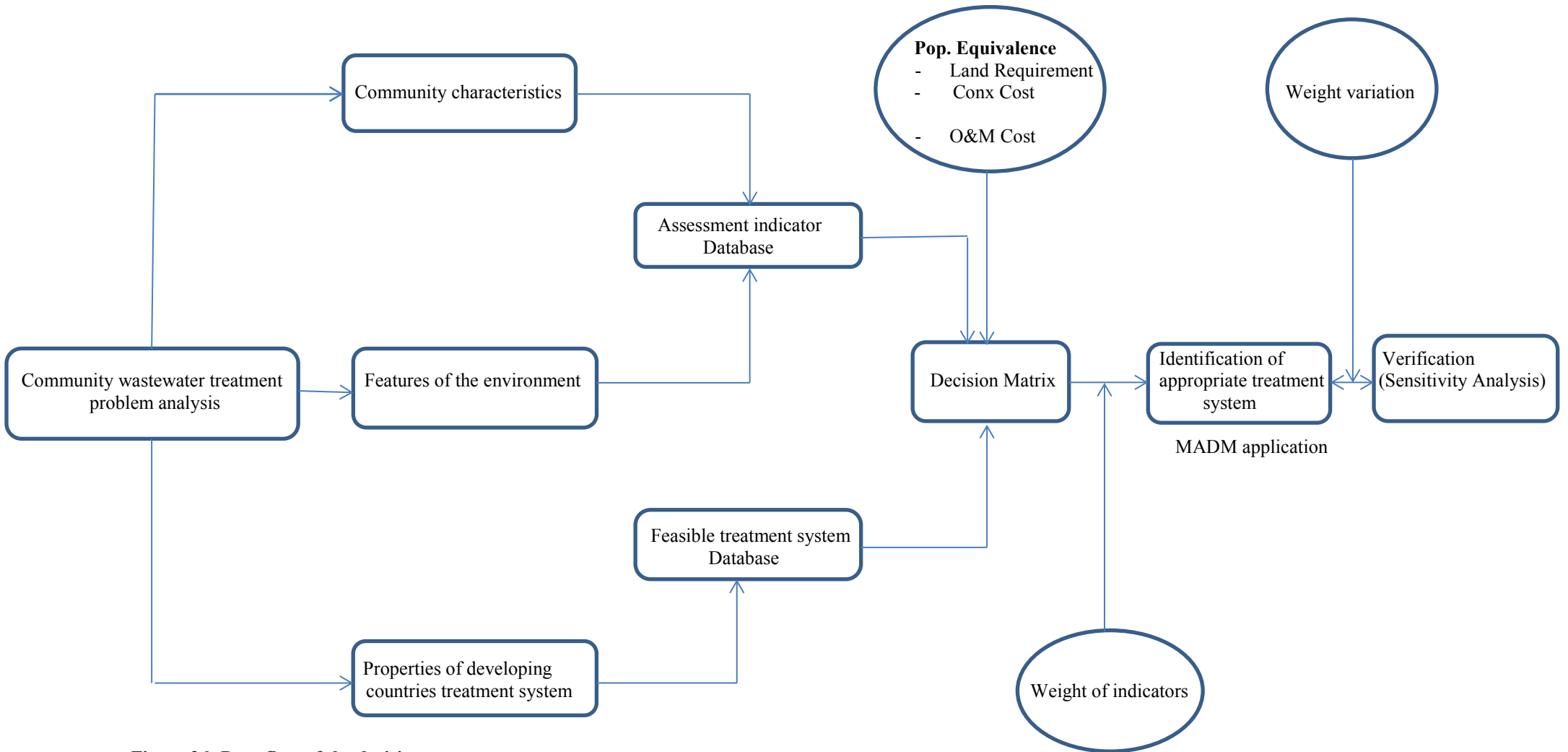


Figure 26: Data flow of the decision support systems

The description of the steps involve in the DSS construction are as follows;

The first step of the DSS is the analysis of the community in general in order to identify and characterize its wastewater treatment problem. For this reason, a baseline study was carried out in the study area, and this was for site characterization. This also allowed for the identification of existing treatment systems, their current condition, constraints and the identification of treatment objectives. The observations made as reported earlier in chapter 3 under the sub heading “The wastewater situation of Kumasi” indicates WSP as the predominant treatment technology and its implementation decision largely based on its relatively low construction, operation and maintenance cost. Their current poor state also indicates the deficiency of making treatment system selection decisions largely on economic considerations. This suggests the identification and implementation of appropriate treatment systems. And this can be realized by the application of new dimensions of analysis where characteristics of the community itself (environmental, economic and socio-cultural properties) and the technical aspects of wastewater treatment systems for developing countries are taken into account. Thus, in order to identify appropriate treatment systems from suitable ones, it is necessary to acquire and integrate knowledge from the receiving environment, treatment technologies and the interactivity between these two entities. The outcome of a DSS is more likely to be sustainable when it adopts a holistic approach to problem analysis.

Knowledge acquisition is the next step in the DSS. The development of a DSS to aid in the selection of wastewater treatment systems need to include a conceptual stage where the output of the problem analysis stage can be used to capture the objectives governing the selection procedure. This makes this stage a knowledge acquisition phase. First, an inventory of treatment systems that are usually implemented in developing countries is made and this represents the feasible treatment system database. Secondly, factors that are usually considered in the selection of treatment systems for developing countries and the properties of treatment systems usually implemented in developing countries were also analysed. Equipped with such information, a comprehensive set of assessment criteria and indicators representing factors that need to be considered in the selection of treatment systems in the study area were developed. They were evaluated through expert and community survey to identify the most relevant ones. The final assessment indicators were used to evaluate and elements of the treatment system database through a treatment plant survey. As a result, each indicator (except quantitative indicators) possesses a value for each element of the treatment

system database. And this represents the assessment indicator database. Together, these 2 databases form the knowledge base of the DSS.

The assessment of the treatment systems by the quantitative indicators is a function of the population equivalent of the community concern. Due to this, a user interphase is created at the onset of the decision support stage to enable users to enter the population size of the community concern in order to derive the values for the quantitative indicators. The decision matrix is the starting point of the decision support step and it represents the performance measures of the elements of the treatment system database as measured by elements of the assessment indicator database. The matrix therefore forms the core of the decision making problem and after being analyzed can result in the identification of the appropriate treatment system. As multiple assessment indicators of various relative importance are used to evaluate the treatment alternatives, the overall score of each alternative must be derived in order to identify the most appropriate. To proceed, a user interphase that permits the user to specify the weights of the selected indicators according to his/her preference is created. Next, multi-criteria analysis method (TOPSIS or SAW) is incorporated in the DSS to process the decision matrix to derive the overall score of each treatment system and the one with the highest score is presented as the most appropriate.

Lastly, a user interface that allows the variation of weights of importance of indicators in order to ascertain the change in rankings of treatment alternatives is incorporated as a way of checking the robustness of the selected treatment system and also the consistency and correctness of the outcome of the DSS (sensitivity analysis). That is, the last stage is intended as a verification step to test the trust worthiness of the DSS output.

The intended operation of this DSS is described as follows:

By way of an input user interphase, the user enters the name of the community for which a wastewater treatment system is required. The DSS program reads the assessment indicator database that stores the indicators for the various communities and retrieves the relevant assessment indicators for that particular community. Based on these indicators, alternative treatment systems are selected from the feasible treatment system database. Their corresponding performance measures with respect to the assessment indicators are used to construct a partial treatment system – indicator decision matrix. The user enters the population equivalence of the community and the DSS produces the performance measures of

the quantitative indicators to complete the decision matrix. On entering the weight of importance of the indicators according to the preference of the user, the MCDA method (TOPSIS or SAW) incorporated in the DSS ranks the alternative treatment systems and produce the most appropriate for the community. In addition, a report is produced containing the characteristics of the community and features of the environment used in the reasoning process of the DSS. The report also gives the technical justification for the identified treatment system. Lastly, the user can check the robustness of the identified treatment system by varying the weights of some indicators which the DSS can respond with new ranking order if such a change in weight will have an impact on the ranking.

Many DSS have been developed for the planning and implementation of small wastewater systems but few appear on the market as useful products. SANEX, a DSS employed by the United Nations Environmental Programme (UNEP) for water systems implementation is an example of one of the few highly circulated DSS. Reason for low the usability of most DSS is as a result of their complexity of application for non-experts (Denzer, 2005). But judging from the above data flow, the DSS that will be developed from this study will be simple in its application. Also the treatment system problem being resolved in this study is not specific to the study area but a common problem in communities in developing countries. Therefore the investment in a DSS guided by the above data flow that is not specific to the study communities will be justified since it will find application not only in the city of Kumasi but other communities as well.

5 Conclusions and recommendations

5.1 Conclusions

Treatment systems that satisfy not only the technical requirements but environmental, economic and socio-cultural concerns of communities in developing countries have been recognized as indispensable tools in the sustainability of wastewater treatment.

The search for such treatment systems is a complex task due to the large number of different factors that must be considered. This usually burdens city authorities and planners in charge of municipal wastewater management to the extent that they employ ineffective assessment models that result in the selection and implementation of treatment systems that are not sustainable.

As a result, this study focuses on resolving the problem of selecting appropriate wastewater treatment systems for communities in developing countries in general using the city of Kumasi as a case study. To achieve this goal, the following tasks were performed;

- Identification and analysis of factors that must be considered in the assessment of treatment systems in order to identify the most appropriate for a particular location.
- Performance assessment of a selected number of treatment systems with these factors.
- Establishing a procedure of processing the resultant performance assessment data in order to select the treatment system that performs best on all the assessment factors.

It was established that in addition to the technical factors such as discharge standards that treatment systems must achieve, for a successful implementation, they must also satisfy the environmental, economic and socio-cultural parameters of the host community. An initial set of assessment criteria and indicators were constructed from these four parameters. An expert and community surveys were conducted to evaluate the relevance of the indicators in being used to assess treatment systems to identify the most appropriate for the selected communities. A final set of indicators accounting for efficiency, reliability and simplicity of a treatment system were considered as important for assessment. Findings also show that indicators pertaining to public acceptability of the treatment system, resource constraints,

resource recovery and environmental protection of the study area are also relevant to be considered in selecting a treatment system for the study area. The final indicators derived from both surveys captures the wastewater management priorities of the city of Kumasi. Together, the indicators express an appropriate treatment system for communities within the city as a highly reliable system of low land footprint with limited mechanized parts capable of meeting discharge standards and being acceptable to users. The methodology applied in deriving the assessment indicators can be applied in municipal treatment system selection decision making situations encountered in developing countries. And this can subsequently help yield the appropriate treatment systems required for sustainable wastewater treatment.

The second task of evaluating and analyzing the four alternative treatment systems (waste stabilization pond, constructed wetlands-vertical flow, constructed wetland-horizontal flow and trickling filter) considered to be suitable for the study area was performed by way of measuring their performance against each of the derived assessment indicators in the first part of this study. Results provide comprehensive information not only to support the decision making process but also data on some qualitative properties of the treatment systems that have hitherto not been assessed. For instance, indicators under the criteria of complexity such as complexity of system construction, complexity of system operation, skill level of personnel required for system operation and maintenance etc. are not conventional properties of treatment systems that are usually assessed when making a decision on their suitability for a particular location. But they were derived through the methodology employed for this study. The resultant data offers a ready-made snapshot of the practical weaknesses and strengths of the treatment systems as far as complexity is concern. This makes it possible for the most appropriate treatment system to be identified based solely on these qualitative indicators should a decision maker decides to do so.

The resultant decision matrix from the treatment system assessment step becomes a decision problem that municipal authorities in charge of wastewater management needs to solve. TOPSIS verified by SAW is used to process the matrix and rank the treatment alternatives. In real-life, decision makers consider both the positive and negative aspects of the alternatives and select the alternative with major positives as the best solution. TOPSIS mimics this type of decision making nature whereby it uses the positive on an indicator to offset the negative on another indicator for the same alternative. It therefore in effect is a sound logic that represents the rational of human choice. The algorithm is a simple computation process that

can easily be programmed into a spreadsheet and made available as a decision support tool for end users as was done in this study.

The findings show that trickling filter being a conventional treatment system that is relatively complex and expensive to construct and operate and usually requires energy for operation cannot be appropriate for any of the three study communities. It also reveals that, the existing stabilization ponds in the study communities that constitute the most simplest and inexpensive treatment system to construct and operate among the alternatives is not appropriate, but constructed wetlands which are also a nature related treatment system are ranked as the most appropriate for the study communities. Among the alternatives, constructed wetlands can be described as moderate as far as many of the assessment indicators are concern. And as a result of the inherent trade-off nature of TOPSIS where a weakness in an indicator is offset by the strength of another indicator, constructed wetland is rightly ranked as the most suitable. For instance on the indicator, efficiency of pathogen removal, waste stabilization pond with maturation pond as part of the system is the most efficient but this comes with a large land footprint which is a major weakness with regard to an urban community. Constructed wetlands on the other hand are effective for the removal of pathogens but with relatively less land footprint. They have low capital and operating cost and are relatively simple to design and implement when compared to conventional systems such as trickling filter. It therefore represents a suitable alternative to be used to meet environmental constraints in the face of financial limitations of the communities.

It is also worth noting that application of the two different MADM methods produced almost the same results within the same scenario. That is, under conditions where the same procedure for assigning weights to the indicators was used. But when a particular MADM method applies weights derived from different procedures different treatment systems emerge as appropriate. The implication is that, the result is determined more by the weights of the indicators than the applied MADM method. It also implies that, it is the decision situation which decides the suitability of the treatment system and not the treatment system itself.

As a result of this inherent sensitivity of the MADM method, making final decisions based solely on its results may not be reliably. It is against this background that the robustness of the constructed wetlands as the most preferred systems was tested through a weight variation sensitivity analysis. Results of the sensitivity analysis prove reed bed variant of constructed

wetland as the most appropriate treatment system in situations of low to high land constraints and in communities where construction cost is of much concern. Therefore based solely on this selection model, constructed wetlands can be said to be highly appropriate for the study communities. But since selection model is meant to be decision aid tool and not to replace thinking, the two variants of constructed wetlands identified as appropriate for the three study communities may not be taken as the best possible treatment systems. The final decision regarding the optimum solution should be made by decision makers taking cognizance of local needs and conditions. That is, aspects of local factors with the potential of impacting on the operational sustainability of treatment systems in general and the highly ranked constructed wetlands in particular in the three communities that were not captured by the assessment indicators must be analyzed to identify the most suitable alternative and consolidate the final choice.

Another conclusion of this study is that, it identifies the framework that can be applied to develop a DSS to facilitate the selection of treatment systems for small communities in developing countries. It also advocates for the holistic approach in the treatment problem analysis in order to identify and address all constraints of treatment in the community concern.

5.2 Recommendations

Insufficient dataset on the performance assessment of the treatment system alternatives was a setback for this study. Larger dataset that can be obtained by surveying large number of treatment systems can provide a better performance measures and ultimately a more accurate ranking of the treatment systems. Such a survey can also provide sufficient actual flow data of treatment systems that can be used to estimate their operating and maintenance cost – a highly important indicator that was eliminated from this study as a result of lack of data.

Having found that weights of indicators impacts more on the ranking and the weights applied in this study being mostly theoretical, a study that employs actual weight elicitation through another round of expert and community survey will help improve the reliability of this study.

Having come to the understanding through this study that the decision situation determines the appropriateness of a treatment system and not the treatment system itself, future research can be directed towards;

- Applying the methodology in identifying a suitable treatment system for communities clearly distinct from those studied such as rural and sub-urban communities.
- Using different sets of alternative treatment systems with the same or different sets of assessment indicators.

As demonstrated in this study about the impact of population equivalence on the quantitative indicators such as land size requirement and construction cost, a study that uses population growth rates in the study area to ascertain the changes in the appropriateness of suitable treatment systems with the passage of time will provide an insight into the sustainability of implemented or identified treatment systems.

Lastly, a study that constructs a DSS from the data flow and proceed to check its validity by field testing it through an application to a real treatment system decision making problem or testing of its results against a treatment system selection problem whose result is already known will help to ascertain the usefulness of it.

Appendix A

Table 1: Summary of initial criteria, sub-criteria and indicators

Criteria	Sub-criteria (Dimension of interest)	Indicators (variables for measurement)
Technical aspects		
Efficiency	Efficiency of conventional contaminants removal	EC1. Removal efficiency of BOD
		EC2. Removal efficiency of Total Nitrogen
		EC3. Removal efficiency of Total phosphorus
		EC4. Removal efficiency of Total Suspended Solids
		EC5. Removal efficiency of pathogens
Reliability	Long-term operation	RL1. What is the possibility of the treatment technology being consistent in its normal operation over its life time?
		RL2. What is the possibility of the effluent consistently meeting discharge standards?
		RL3. What is the frequency of operational interruption due to hardware or process problems?
		RL4. What is the possibility of system failures generating effluent of low quality?
		RL5. Capacity of the system for expansion to accommodate future population growth
		RL6. Does the system have limiting factors for upgrade or extension?
	Short-term operation	How tolerant is the technology to the following influent characteristics?
		RS1. Extreme variations in flow rate?
		RS2. Periodic shock BOD loads?
		RS3. Extremely low BOD loads?
		RS4. Toxic pollutants (Pesticides, household cleaning agents, heavy metals, etc.)?
Mechanical reliability and durability	RS5. To what extent can weather variations affect the technology performance?	
	RD1. Life expectancy of the system	
	RD2. What is the frequency of shut downs due to mechanical failures?	

Continued

		RD3. What is the magnitude of mechanical failures impact on effluent quality?
		CI1. What is the overall complexity of system installation or construction?
	Ease of technology installation and startup	CI2. How difficult will it be to start the system?
		CI3. How much time is needed for system construction?
		CI4. How much time is needed for system start-up?
Complexity		CO1. What is the complexity of operation?
		CO2. Skill and personnel requirement?
	Operation and maintenance requirement	CO3. Time requirement for personnel training?
		CO4. Does the system require special maintenance?
		CO5. Does the system require special manufactured or imported spare parts?
		LS1. Land area per population equivalent?
	Size of land requirement	LS2. Total footprint of the system.
		LS3. Buffer zone requirements.
Land requirement		LF1. Flooding risk.
	Favourable land conditions	LF2. Risk on groundwater.
		LF3. Soil type required.
Energy requirement	Construction and startup energy requirement	ES. Energy expenditure in construction and startup.
	Operational energy requirement	EO. What is the energy requirement per population equivalent?
Economic aspects		
		What is the magnitude of the following components associated with initial construction cost?
	Initial construction cost	AC1. Construction cost
		AC2. Land cost
Affordability		What is the magnitude of the following components associated with annual operation and maintenance cost?
		AO1. Operational cost
	Annual operation and maintenance costs	AO2. Maintenance cost (material and equipment)
		AO3. Personnel cost
		AO4. Energy cost
		AO5. Administration cost

Continued

		AO6. What is or will be the source of revenue for operation and maintenance?	
Socio-cultural aspects			
Social acceptability and capacity	Public acceptability	PA1. Public acceptability of system planning and construction	
		PA2. Public participation in system planning and construction	
		PA3. Public acceptability of system operation	
		PA4. Public participation in system operation and maintenance	
		PA5. Public support for wastewater fee collection	
	Institutional capacity and competence availability	CA1. Competence of municipal authority to supervise and monitor regular system operations	
		CA2. Availability of institutions to research into unforeseen system problems and their capacity to resolve such problems	
		CA3. Availability of competent personnel to man the system	
	Environmental aspects		
	Environmental impacts and protection	SE1. Odour production	
SE2. Noise impact			
SE3. Breeding of insects and other parasites			
SE4. Global warming potential			
SE5. Eutrophication potential			
SE6. Groundwater quality impact			
SE7. Landscape / visual impact			
SE8. General impacts on nearby settlements			
Sustainability	Possibility of resource recovery	SR1. Biogas production potential	
		SR2. Possibility of effluent reuse for irrigation	
		SR3. Possibility of effluent for groundwater recharge	
		SR4. Recycling of organic matter for use as fertilizer	
		SR5. General promotion of sustainable behaviour	

Table: 2 Descriptive statistics of indicator rankings

Criteria	Sub-criteria	Indicators	Ranking	Mean	Standard	Variance
			Min – Max	ranking	deviation	
Efficiency (E)	Efficiency of contaminants removal (EC)	EC1	4 – 9	8.30	1.26	1.59
		EC2	5 – 9	7.35	1.35	1.82
		EC3	4 – 9	6.80	1.44	2.06
		EC4	1 – 9	6.40	1.93	3.73
		EC5	7 – 9	8.75	0.64	0.41
Reliability (R)	Long-term operation (RL)	RL1	7 – 9	8.20	0.89	0.80
		RL2	3 – 9	7.80	1.85	3.43
		RL3	3 – 9	6.45	2.06	4.26
		RL4	5 – 9	7.55	1.15	1.31
		RL5	3 – 9	7.45	1.73	3.00
		RL6	1 – 9	5.50	2.76	7.63
	Short-term operation (RS)	RS1	3 – 9	6.30	1.84	3.38
		RS2	2 – 9	4.95	2.21	4.89
		RS3	1 – 7	4.10	1.89	3.57
		RS4	1 – 9	6.75	2.53	6.41
		RS5	1 – 9	3.25	2.22	4.93
Durability (RD)	RD1	5 – 9	7.75	1.37	1.88	
	RD2	5 – 9	7.55	1.61	2.58	
	RD3	7 – 9	7.95	0.94	0.89	

Continued

Criteria	Sub-criteria	Indicators	Ranking Min – Max	Mean ranking	Standard deviation	Variance
Complexity (C)	System Installation (CI)	CI1	1 – 9	7.45	2.19	4.79
		CI2	1 – 9	4.80	2.33	5.43
		CI3	1 – 7	3.85	1.76	3.08
		CI4	1 – 9	3.40	2.28	5.20
	Operation & Maintenance (CO)	CO1	5 – 9	8.15	1.31	1.71
		CO2	5 – 9	7.90	1.17	1.36
		CO3	1 – 9	4.55	2.68	7.21
		CO4	3 – 9	7.45	1.50	2.26
		CO5	3 – 9	7.50	1.54	2.37
Land requirement (L)	Size of land (LS)	LS1	5 – 9	7.60	1.23	1.52
		LS2	5 – 9	8.40	1.10	1.20
		LS3	2 – 9	4.90	2.15	4.62
	Favourable land conditions (LF)	LF1	1 – 9	7.00	2.73	7.47
		LF2	1 – 9	6.85	2.50	6.24
		LF3	1 – 9	4.80	2.80	7.85
Energy requirement (E)	Construction and Start-up (ES)	ES	1 – 9	4.70	2.45	6.01
	Operational (EO)	EO	7 – 9	8.40	0.75	0.57

Continued

Criteria	Sub-criteria	Indicators	Ranking Min – Max	Mean ranking	Standard deviation	Variance	
Affordability (A)	Construction cost (AC)	AC1	5 – 9	7.95	1.15	1.31	
		AC2	1 – 9	6.70	2.08	4.33	
	Operation & maintenance cost (AO)	AO1	7 – 9	8.40	0.88	0.78	
		AO2	5 – 9	8.00	1.34	1.79	
		AO3	2 – 9	4.90	1.83	3.36	
		AO4	7 – 9	8.25	0.91	0.83	
		AO5	1 – 9	3.25	2.52	6.37	
	Social acceptability & capacity (A)	Public acceptability (PA)	PA1	1 – 9	7.53	2.22	4.92
			PA2	1 – 9	5.69	2.64	6.97
			PA3	1 – 9	5.87	2.46	6.04
PA4			1 – 9	4.73	2.83	7.98	
PA5			1 – 9	5.14	3.52	12.40	
Competence availability (CA)		CA1	1 – 9	4.80	2.24	5.01	
		CA2	1 – 9	4.75	2.65	7.04	
		CA3	6 – 9	8.05	1.00	1.00	
Sustainability (S)	Environmental impacts (SE)	SE1	1 – 9	6.98	2.32	5.37	
		SE2	1 – 9	2.05	1.91	3.66	
		SE3	1 – 9	7.29	1.89	3.57	
		SE4	1 – 9	3.20	2.38	5.67	
		SE5	1 – 9	6.08	2.32	5.39	
		SE6	1 – 9	5.63	2.42	5.85	
		SE7	1 – 9	2.51	2.11	4.46	
		SE8	1 – 9	6.81	2.71	7.37	
	Resource recovery (SR)	SR1	1 – 9	6.48	2.92	8.51	
		SR2	1 – 9	5.38	2.65	7.04	
		SR3	1 – 9	4.23	2.87	8.26	
		SR4	1 – 9	7.04	2.43	5.93	
SR5		1 – 9	2.95	2.52	6.37		

Appendix B

Table 1: Surveyed treatment plants for the estimation of quantitative indicators

System	Treatment plant's name	Country	Start year	Design Capacity (m ³ /d)	Actual flow (m ³ /d)	Population equivalent (p.e.)	Land size (m ²)	Construction cost (million country currency)	Present value at 2013 (million country currency)	Present value at 2013 (Million US\$)	O & M cost (2013) (US\$)
WSP	Kosodo Wastewater Treatment Plant	Burkina Faso	1987	180,000			130,000				
	2IE		1983								
	Dandora	Kenya	1980	9,600	32,000		208,000	16.32	855.80	10.26	360,000

Continued

System	Treatment plant's name	Country	Start year	Design Capacity (m ³ /d)	Actual flow (m ³ /d)	Population equivalent (p.e.)	Land size (m ²)	Construction cost (million country currency)	Present value at 2013 (million country currency)	Present value at 2013 (Million US\$)	O & M cost (2013) (US\$)
Constructed Wetlands	Wetlands for Water(H)	UK	1999	80			900	0.11	0.15	0.23	6,260
		Jordan	2013	1	0.75		30	\$7,500		0.0075	250
	Mine water treatment	UK	2011	4,320	3456		17,000	1.40	1.48	2.31	15,650
	Crynant Sewage Treatment Works(H)		2007	3,400		5,680	2,400				
	Llanfair PG, Cheshire County Council (H)		2009	55			440				
	Anglian Water, Earls Colne, Colchester (H)		2004		1,168		1,600				
	Lower Basildon, Thames Water (H)		2013			166	684				
	St Hughes School (H)		2013	42.86			200	0.099	0.099	0.155	
	Torver (H)		2012	4.97			70	0.333	0.339	0.053	
	Forest Hill (H)		2013	74.3			120	0.115	0.115	0.18	

Continued

System	Treatment plant's name	Country	Start year	Design Capacity (m ³ /d)	Actual flow (m ³ /d)	Population equivalent (p.e.)	Land size (m ²)	Construction cost (million country currency)	Present value at 2013 (million country currency)	Present value at 2013 (Million US\$)	O & M cost (2013) (US\$)
Constructed Wetlands	Berkhamstead, Thames Water (V)	UK	2008		11,000	24,000	16,000	1.40	1.63	2.55	
	Resolis, Cullicudden, Black Isle (V)		2007		10		400				
	Chilton (V)		2013	48			325	0.072	0.072	0.11	
	Dane End STW (V)		2013	170			1125	0.10	0.10	0.16	
	Chillerton (V)		2012	275			375	0.124	0.13	0.20	
	Leaden Roden (V)		2012	187			300	0.65	0.67	0.104	
	Bramfield (V)		2013	65			300	£56,000	0.056	0.087	
	Lidsey Wastewater Treatment Works (V)						3900	£490,000			
	Conway Center Reed Bed (V)						450	£475,000			
	Weston Wastewater Treatment Works (V)						500	£280,000			

Continued

System	Treatment plant's name	Country	Start year	Design Capacity (m ³ /d)	Actual flow (m ³ /d)	Population equivalent (p.e.)	Land size (m ²)	Construction cost (million country currency)	Present value at 2013 (million country currency)	Present value at 2013 (Million US\$)	O & M cost (2013) (US\$)
Constructed Wetlands	Brickendon Wastewater Treatment Works (V)	UK					200	£120,000			
Trickling Filter	Wayne County	US	1959	1325		5000		0.27	2.23	2.23	
	McHenry County		1957	2650		10,000		0.43	3.63	3.63	
	Jo Davies County		1962	7950		30,000		0.87	6.88	6.88	
	Rock Island		1960	2650		10,000		0.36	2.91	2.91	
	Littleton / Englewood		1957	7950		30,000		0.76	6.41	6.41	
	Ostfildern	Germany	1955		346		2000				53,120
	waldstetten		2004	8200	8208		11,200	1.4	1.63	2.16	
	Aichwald		1979	3600	3715		5765	2.56	5.48	7.28	146,080
Verbandskläranlage	1981		100,000	15,000		90,000	40				

Table 2: Average annual inflation rate (Consumer Price Index (CPI)) for various countries for the calculation of present value of treatment plant

Year	Average annual CPI per country			
	Germany	US	UK	Kenya
1957		3.3		
1958		2.7		
1959		1.0		
1960		1.5		
1961		1.1		
1962		1.2		
1963		1.2		
1964		1.3		
1965		1.6		
1966		3.0		
1967		2.8		
1968		4.3		
1969		5.5		
1970		5.8		
1971		4.3		
1972		3.3		
1973		6.1		
1974		11.0		
1975		9.2		
1976		5.8		
1977		6.5		
1978		7.6		
1979	4.0	11.2		
1980	5.4	13.6		13.9
1981	6.3	10.4		11.6
1982	5.3	6.2		20.7
1983	3.3	3.2		11.4
1984	2.4	4.3		10.3
1985	2.1	3.6		13.0
1986	-0.1	1.9		2.5
1987	0.3	3.7		8.6
1988	1.3	4.1		12.3
1989	2.8	4.8		13.8
1990	2.7	5.4		17.8
1991	4.0	4.3		20.1
1992	5.1	3.0		27.3
1993	4.4	3.0		46.0
1994	2.7	2.6		28.8
1995	1.7	2.8		1.6
1996	1.4	2.9		8.9
1997	1.9	2.3		11.4

Continued

Year	Average annual CPI per country			
	Germany	US	UK	Kenya
1998	0.9	1.6		6.7
1999	0.6	2.2	1.3	5.7
2000	1.5	3.4	0.8	10.0
2001	2.0	2.8	1.2	5.7
2002	1.4	1.6	1.2	2.0
2003	1.0	2.3	1.4	9.8
2004	1.7	2.7	1.3	11.6
2005	1.5	3.4	2.1	10.3
2006	1.6	3.2	2.3	14.5
2007	2.3	2.9	2.3	9.8
2008	2.6	3.9	3.6	26.2
2009	0.3	-0.3	2.2	9.2
2010	1.1	1.6	3.3	4.0
2011	2.1	3.2	4.5	14.0
2012	2.0	2.1	2.8	9.4
2013	1.5	1.5	2.6	5.7

Source: The World Bank – International Financial Statistics & Data Files

<http://data.worldbank.org/indicator/FP.CPI.TOTL.ZG/countries/1W?display=default>

Appendix C

Sample questionnaire for the assessment of treatment systems

Indicators Evaluating Treatment Plant Reliability

Code	Indicator	Value				
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Sub-criterion: Long-term system operation

RL1.	What is the probability of this treatment plant being consistent in its normal operations over its life time?	1-not very likely <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very likely <input type="checkbox"/>
RL2.	How often does the effluent meets discharge standards?	1-very rarely <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very often <input type="checkbox"/>
RL3.	What is the frequency of operational interruption due to hardware or process problems?	1-very rarely <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very often <input type="checkbox"/>
RL4.	To what extent do operational interruptions impact negatively on the effluent quality?	1-very low extent <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high extent <input type="checkbox"/>
RL5.	What is the capacity for expansion to accommodate population growth?	1-very low capacity <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high capacity <input type="checkbox"/>

Indicators Evaluating Treatment Plant Reliability

Code	Indicator	Value				
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Sub-criterion: Short-term system operation

	How tolerant is this treatment plant to the following influent characteristics?					
RS1.	Extreme variations in flow rate?	1-very poor <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very good <input type="checkbox"/>
RS4.	Toxic pollutants (Pesticides, household cleaning agents, heavy metals, etc.)?	1-very poor <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very good <input type="checkbox"/>

Indicators Evaluating Treatment Plant Reliability

Code	Indicator	Value				
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Sub-criterion: Mechanical reliability and durability

RD1.	How high is the life expectancy of this plant	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
RD2.	What is the frequency of shut downs due to mechanical failures?	1-very rarely <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very often <input type="checkbox"/>
RD3.	To what degree do mechanical failures impact on effluent quality?	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>

Indicators Evaluating Treatment Plant Complexity

Code	Indicator	Value				
Sub-criterion: Ease of plant installation, operation and maintenance						
C11.	What was the overall complexity of plant installation or construction?	1-very simple <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-highly complex <input type="checkbox"/>
CO1.	How complex is it to operate this treatment plant?	1-very simple <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-highly complex <input type="checkbox"/>
CO2.	What is the skill level of personnel required to operate this plant?	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
CO4.	How often does this plant require special maintenance?	1-very rarely <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very often <input type="checkbox"/>
CO5.	How often does the system require special manufactured or imported spare parts?	1-very rarely <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very often <input type="checkbox"/>

Indicators Evaluating Land Requirement

Code	Indicator	Value				
Sub-criterion: Favourable land conditions						
LF1.	How vulnerable is this treatment plant to flooding?	1-not vulnerable <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-highly vulnerable <input type="checkbox"/>
LF2.	How vulnerable is this treatment plant to high groundwater table?	1-not vulnerable <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-highly vulnerable <input type="checkbox"/>

Indicators Evaluating Social Acceptability and Capacity

Code	Indicator	Value				
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Sub-criterion: Public acceptability

What is or was the level of public acceptance or participation in the following?						
PA1.	Acceptability of the treatment plant planning and construction	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
PA2.	Participation in treatment plant construction	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
PA3.	Acceptability of the treatment plant operation	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
PA5.	Support for wastewater treatment fees collection	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>

Sub-criterion: Institutional capacity and competence availability

CA3	How important is the availability of competent personnel to the operation of the plant?	1-not very important <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very important <input type="checkbox"/>
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Indicators Evaluating Environmental Sustainability

Code	Indicator	Value				
Sub-criterion: Environmental impacts and protection						
	To what extent does the operation of this treatment plant causes the following environmental impacts?					
SE1	Odour	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
SE3	Breeding of insects and parasites	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
SE5	Eutrophication	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
SE6	Groundwater pollution	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
SE8	General impacts on nearby settlements	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
Sub-criterion: Possibility of resource recovery						
	What is the capacity of the treatment plant in producing the following by-products?					
SR1	Biogas	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
SR2	Effluent suitable for irrigation	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>
SR4	Organic matter suitable for manure or fertilizer	1-very low <input type="checkbox"/>	2 <input type="checkbox"/>	3 <input type="checkbox"/>	4 <input type="checkbox"/>	5-very high <input type="checkbox"/>

SECTION B

Please provide estimates of the following data concerning this treatment plant.

Year of Commissioning	Cost of Construction	Operation & Maintenance Cost (2013)	Population Size of Community	Design Capacity	Actual Flow	Land size

Appendix D

Section 1: Decision Matrix

Decision Matrix for Efficiency (Xij)					
IND.	EC1	EC2	EC3	EC4	EC5
Type	+	+	+	+	+
WSP	85	35	30	93	95
CW-h	71	41	49	58	97
CW-v	77	42	41	91	82
TF	83	30	20	83	55

Decision Matrix for Reliability (Xij)							
IND.	RL1	RL2	RL3	RL4	RL5	RS1	RS4
Type	+	+	-	-	+	+	+
WSP	2.29	2.71	1.86	2.71	3.71	4	3.71
CW-h	3.57	3.43	2	2.29	3	3	2.29
CW-v	4	4.2	1.4	1.6	3.6	4.2	3.6
TF	3.43	4	2.71	2.86	2.71	2.86	2.43

Decision Matrix for Complexity (Xij)					
IND.	C11	CO1	CO2	CO4	CO5
Type	-	-	-	-	-
WSP	2.14	1.57	1.71	1.86	1.14
CW-h	3	2.29	2.29	2.29	1.57
CW-v	2.4	1.4	2.2	2	1.2
TF	2.86	3.14	3.57	3.29	2.57

Decision Matrix for Land size requirement & Affordability (Xij)				
IND.	LS2	LF1	LF2	AC1
Type	-	-	-	-
WSP	21769	2.14	2.43	0.69
CW-h	599	1.34	1.86	0.35
CW-v	1261	1.6	1.2	0.35
TF	697	1.2	1.29	2.06

Decision Matrix for Social Acceptability & Capacity (Xij)					
IND.	PA1	PA2	PA3	PA5	CA3
Type	+	+	+	+	+
WSP	3.43	1.29	3	1.43	2.43
CW-h	3.67	1.83	3.33	1	2.5
CW-v	4.2	1.2	3.4	1.2	2.4
TF	3.86	1.14	4	2.29	3.86

Decision Matrix for Sustainability (Xij)								
IND.	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
Type	-	-	-	-	-	+	+	+
WSP	3.43	3.29	2.43	1.57	2.14	1.14	3.29	2.43
CW-h	2.57	1.67	1.57	1	1.71	1.33	3	2.5
CW-v	1.8	2	1.2	1	1.2	1	3.8	1.2
TF	2.71	3.14	2	1.29	1.57	1.14	2.43	2.71

Section 2: Normalized Decision Matrix (Topsis)

Normalized Decision Matrix for Efficiency (rij)					
IND.	EC1	EC2	EC3	EC4	EC5
Type	+	+	+	+	+
WSP	0.536686	0.468965	0.40893	0.564072	0.565887
CW-h	0.448291	0.549359	0.66792	0.351787	0.577801
CW-v	0.486175	0.562758	0.558872	0.551941	0.48845
TF	0.524058	0.40197	0.27262	0.503419	0.327619

Normalized Decision Matrix for Reliability (rij)							
IND.	RL1	RL2	RL3	RL4	RL5	RS1	RS4
Type	+	+	-	-	+	+	+
WSP	0.338549	0.373132	0.454285	0.56109	0.565322	0.561105	0.602849
CW-h	0.527781	0.472266	0.488478	0.474131	0.457133	0.420829	0.372109
CW-v	0.591352	0.578285	0.341935	0.331271	0.54856	0.589161	0.584975
TF	0.507084	0.550748	0.661888	0.592146	0.412944	0.40119	0.394858

Normalized Decision Matrix for Complexity (rij)					
IND.	CI1	CO1	CO2	CO4	CO5
Type	-	-	-	-	-
WSP	0.40794	0.355275	0.336962	0.383462	0.331735
CW-h	0.571878	0.518203	0.451254	0.472112	0.456863
CW-v	0.457502	0.316805	0.433519	0.412325	0.349194
TF	0.54519	0.710549	0.703483	0.678274	0.747858

Nor Decision Matrix for Land size requirement & Affordability (rij)				
IND.	LS2	LF1	LF2	AC1
Type	-	-	-	-
WSP	0.997441	0.664378	0.688173	0.309672
CW-h	0.027446	0.416013	0.526749	0.15708
CW-v	0.057778	0.496732	0.339838	0.15708
TF	0.031936	0.372549	0.365326	0.924529

Nor. Decision Matrix for Social Acceptability & Capacity (rij)					
IND.	PA1	PA2	PA3	PA5	CA3
Type	-	-	-	-	-
WSP	0.451263	0.463304	0.434605	0.458461	0.424203
CW-h	0.482839	0.657245	0.482412	0.320602	0.436422
CW-v	0.552567	0.43098	0.492552	0.384722	0.418966
TF	0.507836	0.409431	0.579473	0.734178	0.673836

Normalized Decision Matrix for Sustainability (rij)								
IND.	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
Type	-	-	-	-	-	+	+	+
WSP	0.637442	0.627691	0.653902	0.634169	0.633574	0.492033	0.519099	0.531041
CW-h	0.477617	0.318615	0.42248	0.403929	0.506267	0.574039	0.473343	0.546339
CW-v	0.334518	0.381575	0.322915	0.403929	0.355275	0.431608	0.599568	0.262243
TF	0.503635	0.599073	0.538191	0.521069	0.464819	0.492033	0.383408	0.592231

Section 3: Weighted Normalized Decision Matrix & Identification of PIS & NIS (Scenario A)

*PIS & NIS of each indicator in bold print

Wt. Norm. Decision Matrix for Efficiency (Vij)					
IND.	EC1	EC2	EC3	EC4	EC5
Type	+	+	+	+	+
WSP	0.015778578	0.013788	0.012023	0.016584	0.016637
CW-h	0.013179753	0.016151	0.019637	0.010343	0.016987
CW-v	0.014293535	0.016545	0.016431	0.016227	0.01436
TF	0.015407317	0.011818	0.008015	0.014801	0.009632

Wt. Norm. Decision Matrix for Reliability (Vij)							
IND.	RL1	RL2	RL3	RL4	RL5	RS1	RS4
Type	+	+	-	-	+	+	+
WSP	0.009953	0.01097	0.013356	0.016496	0.01662	0.016496	0.017724
CW-h	0.015517	0.013885	0.014361	0.013939	0.01344	0.012372	0.01094
CW-v	0.017386	0.017002	0.010053	0.009739	0.016128	0.017321	0.017198
TF	0.014908	0.016192	0.01946	0.017409	0.012141	0.011795	0.011609

Wt. Norm. Decision Matrix for Complexity (Vij)					
IND.	CI1	CO1	CO2	CO4	CO5
Type	-	-	-	-	-
WSP	0.011993	0.010445	0.009907	0.011274	0.009753
CW-h	0.016813	0.015235	0.013267	0.01388	0.013432
CW-v	0.013451	0.009314	0.012745	0.012122	0.010266
TF	0.016029	0.02089	0.020682	0.019941	0.021987

Wt. Norm. Matrix for Land size requirement & Affordability (Vij)				
IND.	LS2	LF1	LF2	AC1
Type	-	-	-	-
WSP	0.029324765	0.019533	0.020232	0.009104
CW-h	0.000806906	0.012231	0.015486	0.004618
CW-v	0.001698678	0.014604	0.009991	0.004618
TF	0.000938921	0.010953	0.010741	0.027181

Wt. Norm Decision Matrix for Social Acceptability & Capacity (Vij)					
IND.	PA1	PA2	PA3	PA5	CA3
Type	+	+	+	+	+
WSP	0.013267	0.013621	0.012777	0.013479	0.012472
CW-h	0.014195	0.019323	0.014183	0.009426	0.012831
CW-v	0.016245	0.012671	0.014481	0.011311	0.012318
TF	0.01493	0.012037	0.017037	0.021585	0.019811

Wt. Norm. Decision Matrix for Sustainability (Vij)								
IND.	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
Type	-	-	-	-	-	+	+	+
WSP	0.018741	0.018454	0.019225	0.018645	0.018627	0.014466	0.015262	0.015613
CW-h	0.014042	0.009367	0.012421	0.011876	0.014884	0.016877	0.013916	0.016062
CW-v	0.009835	0.011218	0.009494	0.011876	0.010445	0.012689	0.017627	0.00771
TF	0.014807	0.017613	0.015823	0.015319	0.013666	0.014466	0.011272	0.017412

Section 4: Weighted Normalized Decision Matrix & Identification of PIS & NIS (Scenario B)

*PIS & NIS of each indicator in bold print

Wt. Norm. Decision Matrix for Efficiency (Vij)					
IND.	EC1	EC2	EC3	EC4	EC5
Type	+	+	+	+	+
WSP	0.000829684	0.002207	0.010579	0.004602	0.006467
CW-h	0.00069303	0.002586	0.017279	0.00287	0.006603
CW-v	0.000751596	0.002649	0.014458	0.004503	0.005582
TF	0.000810162	0.001892	0.007053	0.004108	0.003744

Wt. Norm. Decision Matrix for Reliability (Vij)							
IND.	RL1	RL2	RL3	RL4	RL5	RS1	RS4
Type	+	+	-	-	+	+	+
WSP	0.003367	0.002636	0.006384	0.006513	0.002504	0.004169	0.007307
CW-h	0.005249	0.003336	0.006865	0.005503	0.002025	0.003127	0.004511
CW-v	0.005882	0.004085	0.004805	0.003845	0.00243	0.004377	0.007091
TF	0.005044	0.003891	0.009302	0.006873	0.001829	0.002981	0.004786

Wt. Norm. Decision Matrix for Complexity (Vij)					
IND.	CI1	CO1	CO2	CO4	CO5
Type	-	-	-	-	-
WSP	0.001961	0.009355	0.006446	0.005205	0.009727
CW-h	0.002748	0.013645	0.008632	0.006408	0.013396
CW-v	0.002199	0.008342	0.008293	0.005596	0.010239
TF	0.00262	0.01871	0.013456	0.009206	0.021928

Wt. Norm Matrix for land size requirement & Affordability (Vij)				
IND.	LS2	LF1	LF2	AC1
Type	-	-	-	-
WSP	0.480305362	0.008589	0.014498	0.037308
CW-h	0.013216175	0.005378	0.011097	0.018925
CW-v	0.027822365	0.006421	0.007159	0.018925
TF	0.015378421	0.004816	0.007696	0.111384

Wt. Norm Decision Matrix for Social Acceptability & Capacity (Vij)					
IND.	PA1	PA2	PA3	PA5	CA3
Type	+	+	+	+	+
WSP	0.00077	0.004547	0.001326	0.012019	0.004905
CW-h	0.000824	0.006451	0.001472	0.008405	0.005046
CW-v	0.000943	0.00423	0.001503	0.010086	0.004844
TF	0.000866	0.004019	0.001768	0.019247	0.007791

Wt. Norm. Decision Matrix for Sustainability (Vij)								
IND.	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
Type	-	-	-	-	-	+	+	+
WSP	0.008097	0.012581	0.01105	0.006092	0.006777	0.001429	0.00346	0.010942
CW-h	0.006067	0.006386	0.007139	0.00388	0.005415	0.001667	0.003155	0.011257
CW-v	0.004249	0.007648	0.005457	0.00388	0.0038	0.001253	0.003996	0.005403
TF	0.006397	0.012008	0.009095	0.005005	0.004972	0.001429	0.002555	0.012203

Section 5: Calculation of Each Treatment System to the Ideal Solution (Ranking)

Scenario A (Equal weights)

D+ Decision Matrix for Efficiency (Xij)					
	D+	D-	(D+) + (D-)	R	Rank
WSP	0.042318	0.033786	0.076104	0.443944	4
CW-h	0.023852	0.046837	0.070689	0.662578	2
CW-v	0.01929	0.052245	0.071535	0.730342	1
TF	0.041398	0.037852	0.07925	0.477627	3

Scenario B (Unequal weights)

D+ Decision Matrix for Efficiency (Xij)					
	D+	D-	(D+) + (D-)	R	Rank
WSP	0.450385	0.090775	0.541161	0.167742	4
CW-h	0.014635	0.463285	0.477919	0.969378	1
CW-v	0.01882	0.449806	0.468626	0.95984	2
TF	0.113027	0.447705	0.560732	0.798429	3

Section 6: Normalized Decision Matrix (SAW)

Normalized Decision Matrix for Efficiency (rij)					
IND.	EC1	EC2	EC3	EC4	EC5
Type	+	+	+	+	+
WSP	1	0.833333	0.612245	1	0.979381
CW-h	0.835294	0.97619	1	0.623656	1
CW-v	0.905882	1	0.836735	0.978495	0.845361
TF	0.976471	0.714286	0.408163	0.892473	0.56701

Normalized Decision Matrix for Reliability (rij)							
IND.	RL1	RL2	RL3	RL4	RL5	RS1	RS4
Type	+	+	-	-	+	+	+
WSP	0.5725	0.645238	0.752684	0.590406	1	0.952381	1
CW-h	0.8925	0.816667	0.699996	0.69869	0.808625	0.714286	0.617251
CW-v	1	1	1	1	0.97035	1	0.97035
TF	0.8575	0.952381	0.516602	0.559441	0.730458	0.680952	0.654987

Normalized Decision Matrix for Complexity (rij)					
IND.	CI1	CO1	CO2	CO4	CO5
Type	-	-	-	-	-
WSP	0.999999	0.891714	1	1	1.000003
CW-h	0.713333	0.61135	0.746719	0.812234	0.726117
CW-v	0.891666	1	0.777267	0.930008	0.950003
TF	0.748251	0.445857	0.478988	0.565354	0.443581

Nor Decision Matrix for Land size requirement & Affordability (rij)				
IND.	LS2	LF1	LF2	AC1
Type	-	-	-	-
WSP	0.034926	0.56075	0.493829	0.833334
CW-h	1.09872	0.895526	0.645164	1.206898
CW-v	1	0.750003	1.000004	1.206898
TF	0.975248	1.000004	0.930236	0.19337

Nor. Decision Matrix for Social Acceptability & Capacity (rij)					
IND.	PA1	PA2	PA3	PA5	CA3
Type	+	+	+	+	+
WSP	0.888601	0.704918	0.75	0.624454	0.629534
CW-h	0.950777	1	0.8325	0.436681	0.647668
CW-v	1.088083	0.655738	0.85	0.524017	0.621762
TF	1	0.622951	1	1	1

Normalized Decision Matrix for Sustainability (rij)								
IND.	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
Type	-	-	-	-	-	+	+	+
WSP	0.524777	0.507601	0.493829	0.82166	0.56075	0.857143	0.865789	0.896679
CW-h	0.700384	1.000004	0.764334	1.290006	0.701757	1	0.789474	0.922509
CW-v	0.999992	0.835003	1.000004	1.290006	1.000004	0.75188	1	0.442804
TF	0.664201	0.531849	0.600002	1.000005	0.764334	0.857143	0.639474	1

Section 7: Weighted Normalized Decision Matrix (Scenario A)

Wt. Norm. Decision Matrix for Efficiency (Vij)						
IND.	EC1	EC2	EC3	EC4	EC5	Total
Type	+	+	+	+	+	
WSP	0.02584	0.021533	0.01582	0.02584	0.025307	0.114341
CW-h	0.021584	0.025225	0.02584	0.016115	0.02584	0.114604
CW-v	0.023408	0.02584	0.021621	0.025284	0.021844	0.117998
TF	0.025232	0.018457	0.010547	0.023062	0.014652	0.091949

Wt. Norm. Decision Matrix for Reliability (Vij)								
IND.	RL1	RL2	RL3	RL4	RL5	RS1	RS4	Total
Type	+	+	-	-	+	+	+	
WSP	0.014793	0.016673	0.019449	0.015256	0.02584	0.02461	0.02584	0.142461
CW-h	0.023062	0.021103	0.018088	0.018054	0.020895	0.018457	0.01595	0.135609
CW-v	0.02584	0.02584	0.02584	0.02584	0.025074	0.02584	0.025074	0.179348
TF	0.022158	0.02461	0.013349	0.014456	0.018875	0.017596	0.016925	0.127968

Wt. Norm. Decision Matrix for Complexity (Vij)						
IND.	CI1	CO1	CO2	CO4	CO5	Total
Type	-	-	-	-	-	
WSP	0.02584	0.023042	0.02584	0.02584	0.02584	0.126402
CW-h	0.018433	0.015797	0.019295	0.020988	0.018763	0.093276
CW-v	0.023041	0.02584	0.020085	0.024031	0.024548	0.117545
TF	0.019335	0.011521	0.012377	0.014609	0.011462	0.069304

Wt. Norm Decision Matrix for Land size requirement & Affordability (Vij)					
IND.	LS2	LF1	LF2	AC1	Total
Type	-	-	-	-	
WSP	0.000902482	0.01449	0.012761	0.122833	0.150986
CW-h	0.028390925	0.02314	0.016671	0.035483	0.103685
CW-v	0.02584	0.01938	0.02584	0.035483	0.106543
TF	0.025200414	0.02584	0.024037	0.005685	0.080763

Wt. Norm Decision Matrix for Social Acceptability & Capacity (Vij)						
IND.	PA1	PA2	PA3	PA5	CA3	Total
Type	+	+	+	+	+	
WSP	0.022961	0.018215	0.01938	0.016136	0.016267	0.09296
CW-h	0.024568	0.02584	0.021512	0.011284	0.016736	0.099939
CW-v	0.028116	0.016944	0.021964	0.013541	0.016066	0.096631
TF	0.02584	0.016097	0.02584	0.02584	0.02584	0.119457

Wt. Norm. Decision Matrix for Sustainability (Vij)									
IND.	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4	Total
Type	-	-	-	-	-	+	+	+	
WSP	0.01356	0.013116	0.012761	0.021232	0.01449	0.022149	0.022372	0.02317	0.142849
CW-h	0.018098	0.02584	0.01975	0.033334	0.018133	0.02584	0.0204	0.023838	0.185233
CW-v	0.02584	0.021576	0.02584	0.033334	0.02584	0.019429	0.02584	0.011442	0.189141
TF	0.017163	0.013743	0.015504	0.02584	0.01975	0.022149	0.016524	0.02584	0.156513

Section 8: Weighted Normalized Decision Matrix (Scenario B)

Wt. Norm. Decision Matrix for Efficiency (Vij)						
IND.	EC1	EC2	EC3	EC4	EC5	Total
Type	+	+	+	+	+	
WSP	0.001280182	0.003248	0.013116	0.006757	0.009268	0.033669
CW-h	0.001069329	0.003805	0.021423	0.004214	0.009463	0.039974
CW-v	0.001159694	0.003898	0.017925	0.006611	0.008	0.037594
TF	0.00125006	0.002784	0.008744	0.00603	0.005366	0.024174

Wt. Norm. Decision Matrix for Reliability (Vij)								
IND.	RL1	RL2	RL3	RL4	RL5	RS1	RS4	Total
Type	+	+	-	-	+	+	+	
WSP	0.004715	0.003775	0.008759	0.005675	0.003668	0.005859	0.010038	0.042489
CW-h	0.007351	0.004777	0.008146	0.006716	0.002966	0.004395	0.006196	0.040547
CW-v	0.008236	0.00585	0.011638	0.009612	0.003559	0.006152	0.00974	0.054787
TF	0.007063	0.005571	0.006012	0.005377	0.002679	0.00419	0.006575	0.037466

Wt. Norm. Decision Matrix for Complexity (Vij)						
IND.	CI1	CO1	CO2	CO4	CO5	Total
Type	-	-	-	-	-	
WSP	0.00398	0.019444	0.01584	0.011239	0.024281	0.074784
CW-h	0.002839	0.013331	0.011828	0.009129	0.017631	0.054757
CW-v	0.003549	0.021805	0.012312	0.010453	0.023067	0.071185
TF	0.002978	0.009722	0.007587	0.006354	0.01077	0.037412

Wt. Norm. Decision Matrix for Land size requirement & Affordability (Vij)					
IND.	LS2	LF1	LF2	AC1	Total
Type	-	-	-	-	
WSP	0.01359599	0.006003	0.008615	0.236209	0.264422
CW-h	0.427712396	0.009587	0.011255	0.342095	0.790649
CW-v	0.389282437	0.008029	0.017446	0.342095	0.756852
TF	0.379646996	0.010705	0.016228	0.054811	0.461391

Wt. Norm Decision Matrix for Social Acceptability & Capacity (Vij)						
IND.	PA1	PA2	PA3	PA5	CA3	Total
Type	+	+	+	+	+	
WSP	0.001255	0.005729	0.001895	0.013556	0.006028	0.028463
CW-h	0.001343	0.008128	0.002103	0.00948	0.006201	0.027255
CW-v	0.001537	0.00533	0.002148	0.011376	0.005953	0.026343
TF	0.001413	0.005063	0.002527	0.021709	0.009575	0.040286

Wt. Norm. Decision Matrix for Sustainability (Vij)									
IND.	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4	Total
Type	-	-	-	-	-	+	+	+	
WSP	0.00552	0.008425	0.00691	0.006536	0.004967	0.002061	0.004779	0.0153	0.054498
CW-h	0.007367	0.016598	0.010696	0.010262	0.006216	0.002404	0.004357	0.015741	0.073641
CW-v	0.010519	0.01386	0.013994	0.010262	0.008857	0.001808	0.005519	0.007556	0.072374
TF	0.006987	0.008828	0.008396	0.007955	0.00677	0.002061	0.00353	0.017063	0.061589

Section 9: Calculation of the Overall Score each Treatment System (Ranking)

Scenario A (Equal weights)

	Score (Si)	Rank
Alt		
WSP	0.751022	3
CW-h	0.80393	2
CW-v	0.907443	1
TF	0.73006	4

Scenario B (Unequal weights)

	Score (Si)	Rank
Alt		
WSP	0.381764	4
CW-h	0.670262	3
CW-v	0.950224	1
TF	0.693907	2

Appendix E

Elicitation of Indicator weights of importance

Table 1: Decision matrices

Efficiency					Reliability							Complexity					
IND.	EC1	EC2	EC3	EC4	EC5	RL1	RL2	RL3	RL4	RL5	RS1	RS4	CI1	CO1	CO2	CO4	CO5
WSP	85	35	30	93	95	2.29	2.71	1.86	2.71	3.71	4	3.71	2.14	1.57	1.71	1.86	1.14
CW-h	71	41	49	58	97	3.57	3.43	2	2.29	3	3	2.29	3	2.29	2.29	2.29	1.57
CW-v	77	42	41	91	82	4	4.2	1.4	1.6	3.6	4.2	3.6	2.4	1.4	2.2	2	1.2
TF	83	30	20	83	55	3.43	4	2.71	2.86	2.71	2.86	2.43	2.86	3.14	3.57	3.29	2.57
Total	316	148	140	325	329	13.29	14.34	7.97	9.46	13.02	14.06	12.03	10.4	8.4	9.77	9.44	6.48

Land Req. & Affordability				Social Acceptability & Capacity					Sustainability								
IND.	LS2	LF1	LF2	AC1	PA1	PA2	PA3	PA5	CA3	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
WSP	21,769	2.14	2.43	0.69	3.43	1.29	3	1.43	2.43	3.43	3.29	2.43	1.57	2.14	1.14	3.29	2.43
CW-h	599	1.34	1.86	0.35	3.67	1.83	3.33	1	2.5	2.57	1.67	1.57	1	1.71	1.33	3	2.5
CW-v	1,261	1.6	1.2	0.35	4.2	1.2	3.4	1.2	2.4	1.8	2	1.2	1	1.2	1	3.8	1.2
TF	697	1.2	1.29	2.06	3.86	1.14	4	2.29	3.86	2.71	3.14	2	1.29	1.57	1.14	2.43	2.71
Total	24326	6.28	6.78	3.45	15.16	5.46	13.73	5.92	11.19	10.51	10.1	7.2	4.86	6.62	4.61	12.52	8.84

Table 2: Normalized decision matrices

Decision Matrix for Efficiency					Reliability							Complexity					
IND.	EC1	EC2	EC3	EC4	EC5	RL1	RL2	RL3	RL4	RL5	RS1	RS4	CI1	CO1	CO2	CO4	CO5
WSP	0.2689	0.2364	0.2142	0.2861	0.2887	0.1723	0.1889	0.2333	0.2864	0.284	0.2844	0.3083	0.2057	0.1869	0.1750	0.1970	0.1759
CW-h	0.2246	0.2770	0.35	0.1784	0.2948	0.2686	0.2391	0.2509	0.2420	0.2304	0.2133	0.1903	0.2884	0.2726	0.2343	0.2425	0.2422
CW-v	0.2436	0.2837	0.2928	0.28	0.2492	0.3009	0.2928	0.1756	0.1691	0.2764	0.2987	0.2992	0.2307	0.1666	0.2251	0.2118	0.1851
TF	0.2626	0.2027	0.1428	0.2553	0.1671	0.2580	0.2789	0.3400	0.3023	0.2081	0.2034	0.2019	0.275	0.373	0.3654	0.3485	0.3966

Land Req. & Affordability				Social Acceptability & Capacity					Sustainability								
IND.	LS2	LF1	LF2	AC1	PA1	PA2	PA3	PA5	CA3	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
WSP	0.894	0.340	0.358	0.2	0.2262	0.2362	0.2185	0.2415	0.2171	0.3263	0.3257	0.3375	0.3230	0.3232	0.2472	0.2627	0.2748
CW-h	0.024	0.2133	0.27	0.1014	0.2420	0.3351	0.2425	0.1689	0.2234	0.2445	0.1653	0.2180	0.2057	0.2583	0.2885	0.2396	0.2828
CW-v	0.051	0.2547	0.176	0.1014	0.2770	0.2197	0.2476	0.2027	0.2144	0.1712	0.1980	0.1666	0.2057	0.1812	0.2169	0.3035	0.1357
TF	0.028	0.191	0.190	0.5971	0.2546	0.2087	0.2913	0.3868	0.3449	0.2578	0.3108	0.2777	0.2654	0.2371	0.2472	0.1940	0.3065

Table 3: Natural logarithm of normalized decision matrix

Efficiency					Reliability								Complexity				
IND.	EC1	EC2	EC3	EC4	EC5	RL1	RL2	RL3	RL4	RL5	RS1	RS4	CI1	CO1	CO2	CO4	CO5
WSP	-1.313	-1.441	-1.540	-1.251	-1.242	-1.758	-1.666	-1.455	-1.250	-1.255	-1.257	-1.176	-1.581	-1.677	-1.742	-1.624	-1.737
CW-h	-1.493	-1.283	-1.049	-1.723	-1.221	-1.314	-1.430	-1.382	-1.418	-1.467	-1.544	-1.658	-1.243	-1.299	-1.450	-1.416	-1.417
CW-v	-1.411	-1.259	-1.228	-1.272	-1.389	-1.200	-1.227	-1.739	-1.777	-1.285	-1.208	-1.206	-1.466	-1.791	-1.490	-1.551	-1.686
TF	-1.336	-1.596	-1.945	-1.364	-1.788	-1.354	-1.276	-1.078	-1.196	-1.569	-1.592	-1.599	-1.290	-0.984	-1.00	-1.054	-0.924

Land Req. & Affordability				Social Acceptability & Capacity						Sustainability							
IND.	LS2	LF1	LF2	AC1	PA1	PA2	PA3	PA5	CA3	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
WSP	-0.111	-1.076	-1.026	-1.609	-1.486	-1.442	-1.520	-1.420	-1.527	-1.119	-1.121	-1.086	-1.129	-1.129	-1.397	-1.336	-1.291
CW-h	-3.704	-1.544	-1.293	-2.288	-1.418	-1.093	-1.416	-1.778	-1.498	-1.408	-1.799	-1.523	-1.581	-1.353	-1.243	-1.428	-1.263
CW-v	-2.959	-1.367	-1.731	-2.288	-1.283	-1.515	-1.395	-1.596	-1.539	-1.764	-1.619	-1.791	-1.581	-1.707	-1.528	-1.192	-1.996
TF	-3.552	-1.655	-1.659	-0.515	-1.367	-1.566	-1.233	-0.949	-1.064	-1.355	-1.168	-1.280	-1.326	-1.439	-1.397	-1.639	-1.182

Table 4: Determination of the entropy (e), degree of diversity (d) and weight of each indicator (W)

Efficiency					Reliability							Complexity					
IND.	EC1	EC2	EC3	EC4	EC5	RL1	RL2	RL3	RL4	RL5	RS1	RS4	CI1	CO1	CO2	CO4	CO5
WSP	0.2546	0.2458	0.2379	0.2581	0.2586	0.2184	0.2270	0.2448	0.2582	0.2579	0.2578	0.2615	0.2345	0.2260	0.2199	0.2307	0.2204
CW-h	0.2418	0.256	0.2649	0.2217	0.2596	0.2545	0.2466	0.250	0.2475	0.2438	0.2376	0.2276	0.2585	0.2554	0.2451	0.2477	0.2476
CW-v	0.2480	0.2577	0.2593	0.2569	0.2496	0.2605	0.2593	0.220	0.2167	0.2562	0.2602	0.2603	0.2439	0.2153	0.2420	0.2370	0.2251
TF	0.2531	0.2332	0.2004	0.2513	0.2155	0.2520	0.2567	0.2644	0.2607	0.2355	0.2335	0.2329	0.2559	0.2652	0.2652	0.2648	0.2644
e	0.9977	0.9932	0.9626	0.9882	0.9835	0.9856	0.9898	0.9797	0.9832	0.9936	0.9892	0.9825	0.9930	0.9619	0.9723	0.9804	0.9576
d	0.0022	0.0067	0.0373	0.0117	0.0164	0.0143	0.0101	0.0202	0.0167	0.0063	0.0107	0.0174	0.0069	0.0380	0.0276	0.0195	0.0423
W	0.0015	0.0046	0.0255	0.0080	0.0112	0.0098	0.0069	0.0138	0.0114	0.0043	0.0073	0.0119	0.0047	0.0259	0.0188	0.0133	0.0289

Land Req. & Affordability				Social Acceptability & Capacity					Sustainability								
IND.	LS2	LF1	LF2	AC1	PA1	PA2	PA3	PA5	CA3	SE1	SE3	SE5	SE6	SE8	SR1	SR2	SR4
WSP	0.0716	0.2645	0.2651	0.2320	0.2424	0.2457	0.2396	0.2474	0.2391	0.2634	0.2634	0.2643	0.2631	0.2632	0.2491	0.2532	0.2559
CW-h	0.0657	0.2376	0.2558	0.1673	0.2475	0.2641	0.2477	0.2165	0.2414	0.2483	0.2145	0.2394	0.2345	0.2520	0.2585	0.2468	0.2575
CW-v	0.1106	0.2511	0.2209	0.1673	0.2563	0.2400	0.2492	0.2332	0.2380	0.217	0.2312	0.2153	0.2345	0.2231	0.2390	0.2609	0.1954
TF	0.0733	0.2280	0.2276	0.222	0.2511	0.2358	0.2590	0.2648	0.2647	0.2519	0.2618	0.2565	0.2538	0.2460	0.2491	0.2294	0.2613
e	0.3214	0.9813	0.9695	0.7888	0.9975	0.9858	0.9955	0.9621	0.9833	0.9816	0.9710	0.9756	0.9861	0.9845	0.9958	0.9903	0.9702
d	0.6785	0.0186	0.0304	0.2111	0.0024	0.0141	0.0044	0.0378	0.0166	0.0183	0.0289	0.0243	0.0138	0.0154	0.0041	0.0096	0.0297
W	0.4634	0.0127	0.0207	0.1442	0.0016	0.0096	0.0030	0.0258	0.0113	0.0125	0.0197	0.0166	0.0094	0.0105	0.0028	0.0065	0.02031

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