Impact of Wastewater Effluents from a Sugar Industry and a Molasses Based Distillery on Water Quality of River Musamya in Lugazi, Uganda

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IMPACT OF WASTEWATER EFFLUENTS FROM A SUGAR INDUSTRY AND A MOLASSES BASED DISTILLERY ON WATER QUALITY OF RIVER MUSAMYA IN LUGAZI, UGANDA

BY

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A dissertation submitted to the Directorate of Research and Graduate Training in partial fulfillment of the requirements for the award of Master of Science in Environment and Natural Resources of Makerere University

May 2013

DECLARATION

I Turinayo Yonah Karibwije do declare that this research is my own and all the contents presented are original and have not been submitted to any other University or institution of higher learning for any degree award.

Signed……Date……..

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DEDICATION

To my parents Mr. & Mrs. George Karibwije, relatives and friends; who believed in me and gave me courage in all difficult times.

ACKNOWLEDGEMENT

I wish to express my sincere deepest and heartfelt appreciation to my supervisors; Dr. Joseph Kyambadde and Mr. Robinson Odong for their dedication and patience when helping me to accomplish this dissertation. May God bless you.

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ACRONYMS

AMAS: Annual Meeting of Agricultural Scientists
ANOVA: Analysis of variance
APHA: American Public Health Association
BOD: Biochemical Oxygen Demand
COD: Chemical Oxygen Demand
DO: Dissolved Oxygen
EC: Electrical Conductivity
EHS: Environmental, Health, and Safety
EPA: Environment Protection Agency
NEMA: National Environment Management Authority
NTUs: Nephelometric Turbidity Units
SCOUL: Sugar Corporation of Uganda limited
SDPI: Sustainable Development Policy Institute
SOPAC: South Pacific Applied Geoscience Commission
TDS: Total Dissolved Solids
TFe: Total Iron
TKjN: Total Kjeldhal Nitrogen
TN: Total Nitrogen
TP: Total Phosphorus
TSS: Total Suspended Solids
UMCES: University of Maryland Center for Environmental Science
UNEP: United Nations Environment Programme
UNESCO: United Nations Educational, Scientific and Cultural Organization
UN-HABITAT: United Nations Human Settlements Programme
USCTA: Uganda Sugar Cane Technologists' Association
USEPA: United States Environmental Protection Agency
USh: Uganda shillings
WRMD: Water Resources Management Department

ABSTRACT

The sugar industry in Uganda and East Africa is of economic importance in terms of employment opportunities, government revenue, and sugar production for export and domestic consumption. However, there is a problem of environmental pollution due to its wastewater disposal without proper treatment. Sugar Corporation of Uganda Ltd (SCOUL) is one of the major sugar industries in Uganda milling over 1,583 tons of sugar cane per day and generating over 1000m^3 of wastewater per day. Wastewater disposed by SCOUL is in septic conditions and causes serious pollution to the nearby river water source. However, there is little information regarding ecological studies to examine water quality of river Musamya after receiving effluents from SCOUL. This study therefore assessed the impact of wastewater effluents from SCOUL on the water quality of River Musamya so that environmental pollution mitigation measures can be put in place. Physico-chemical characteristics of wastewater from SCOUL and water from River Musamya at the point of discharge, upstream and downstream of the river were determined using standard methods for the examination of water and wastewater. Impact of wastewater from SCOUL on River Musamya was evaluated and results showed that pollutant concentration in effluent from SCOUL were above permissible discharge limits by NEMA. River Musamya received 2,523±728 m^3/day of wastewater with a high organic matter and nutrient load of 20,346 ± 4,449 kg COD/day, 5,692±1,666 kg BOD/day, 121±29 kg TN/day and 40±14 kg TP/day. The pH, TDS, EC, T-Fe, Na^+, Ca^{2+}, TN, TP, Turbidity, Temperature, BOD, COD, DO of the upstream and downstream river after wastewater discharge varied from 7.1 to 5.6, 88 to 1007mg/l, 108 to 1524µs/cm, 3.2 to 10.5mg/l, 5.5 to 8.0mg/l, 8.5 to 25mg/l, 1.4 to 6.8mg/l, 0.8 to 2.7mg/l, 49 to 616NTU, 24.8 to 25.7˚C, 3.8 to 184mg/l, 13 to 675mg/l, 6.5 to 2.83mg/l, respectively, and the difference was significant ($P < 0.05$). Therefore, despite the sugar processing industry (SCOUL) being economically important, the impact of its effluent wastewaters on the environment is significant. Hence there is urgent need for intervention by employing technologies that reduce the quantity of wastewater effluents generated and also by installing a wastewater treatment system that impacts less on the environment.

TABLE OF CONTENS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

1. INTRODUCTION

1.1. Background

The sugar industry in Uganda and the East African Community plays an important role in terms of economic development and eradication of extreme poverty and hunger (Millennium Development Goal number one). It has demonstrated a high potential of employment opportunities and production of sugar – one of the foods with the highest energy content. Uganda has five sugar factories. Three of which include; Kakira Sugar Works, Kinyara Sugar Ltd and Sugar Corporation of Uganda Ltd (SCOUL) operate on large scale while other two sugar factories (GM Sugar and Mayuge Sugar Plant) operate on a small scale. Currently, Uganda's population is growing at a high rate of about 3.2% while the sugar consumption rate is about 2% implying that the per capita consumption of sugar is 10 kg, per annum (UBOS 2010). However, Uganda still lags behind in terms of sugar production compared to other countries. For example, the recoverable sugar content in sugar cane is around 9% in Uganda while in countries, such as Swaziland, it is as high as 14% (USCTA, 2010).

Sugar Corporation of Uganda Limited (the study area) is located in Lugazi town council (1195m above sea level, 00^{o} 24' N Latitude and 32^{o} 56' E Longitude), Buikwe district, Uganda. The factory lies on the fringes of River Musamya where effluents from sugar processing and distillery are discharged after forming a single channel (Figure 1.1). SCOUL comprises of agricultural land of about 11,000ha including 486ha under forest cover, a sugar plant and a distillery – the only one in Uganda producing about 30 million liters of alcohol per annum. In addition to the sugar cane produced in its estate, SCOUL also buys sugarcane from out growers (about 1,300 out growers supply approx. 90,000 tons of cane per annum amounting to about 3.4 billion USh) (USCTA, 2010).

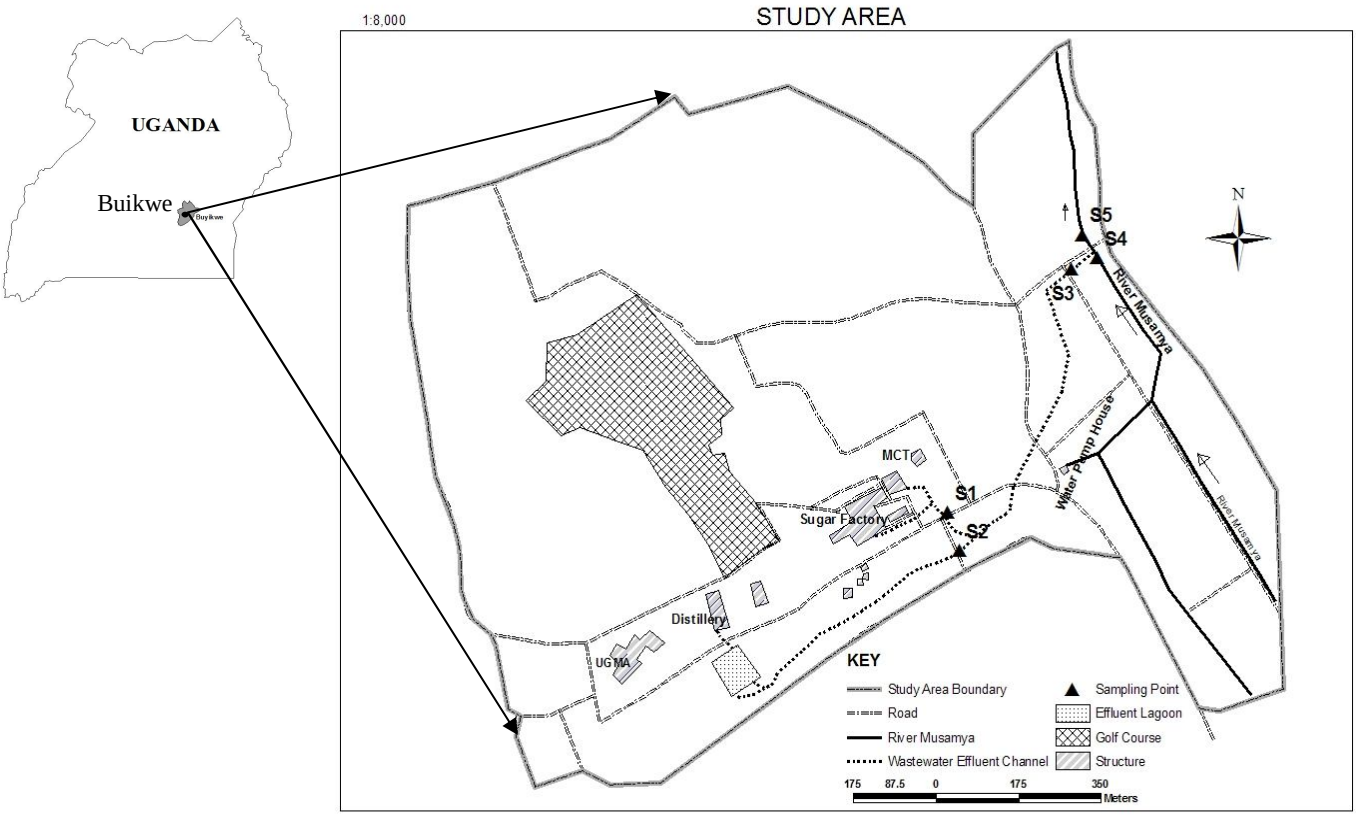

Figure 1. 1: Location map of SCOUL and sampling points used in this study. Source: Google maps world gazetteer: http://www.maplandia.com/uganda/.

Despite the socio-economic importance of sugar industry in Uganda, there is a high degree of organic pollution load in both aquatic and terrestrial ecosystems as a result of wastewater effluent discharge. Sugar is made in plants and is extracted in a factory. Extraction of sugar begins by processing sugar canes to produce sugar and molasses (by-product). Molasses are further processed in the distillery to produce alcohol. However, during sugar processing and distillation of alcohol, large quantities of organic-rich wastewaters are discharged with Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) concentrations of about 40,000 and 100,000 mg/l, respectively (Nadia and Muhmood, 2006). This waste also contains high concentrations of nitrogen and phosphorus (World Bank, 2007), higher amount of suspended solids, dissolved solids, and calcium and magnesium (Baskaran *et al.,* 2009). If discharged untreated into the environment, it causes pollution of underground and surface waters, consequently reducing oxygen concentration in waters, and possible deaths to the aquatic life (Günter *et al.,* 2009).

In a number of developing countries, most of the water bodies near urban areas are the recipients of industrial waste discharges (Suthar *et al*., 2009). It is estimated that 90 per cent of all wastewater discharged directly into water bodies such as rivers, lakes or the oceans (Corcoran *et al*., 2010) is untreated. Most of the sugar cane industries in developing countries are not connected to the municipal sewage network (Emru, 1991). Nalukowe (2006) found that River Musamya at Lugazi is one of the water bodies receiving effluents from SCOUL and these effluents did not meet the required discharge standards of NEMA. River Musamya is the main source of water for SCOUL and according to Mwesigye *et al*., (2006), the river forms ecologically important riverine corridor habitats as well as drinking water sources for forest animals.

Climate is being impacted as a result of wastewater generating green house gases (GHGs) such as methane and nitrous oxide (Corcoran *et al*., 2010). 17% of man-made GHGs come from agriculture and agribusiness (World Bank, 2010), including sugar industry. Corcoran *et al*. (2010) reported that the rise in methane and nitrous oxide gas is estimated to be 50 percent and 25 percent, respectively between 1990 and 2020. However, various waste management technologies can reduce GHG emissions and have positive effects on the environment, but they may cause water pollution in case of improperly designed or managed facilities (Bates *et al.,* 2008). Therefore, ensuring environmental sustainability (MDG7) through proper wastewater treatment technologies can lead to a substantial reduction in GHGs hence combating climate change and improving on the livelihoods of communities.

Some of the wastewater treatment technologies include, among others; the use of activated sludge processes, stabilization ponds and constructed wetlands (Mashauri *et al*., 2000 and Kyambadde *et al.,* 2004). In developing countries however, such treatment may not be fully achieved owing to high costs, either lack of or insufficient infrastructure and poor maintenance of the available systems (Mbabazi *et al.,* 2010). As a result, industries opt to discharge untreated wastewaters into the environment. The commonest technology used in such treatment in Uganda is by stabilization ponds. The main difficulties with this are long retention times and limited aerobic nitrification zones (Mbabazi *et al.,* 2010). SCOUL uses stabilization ponds for wastewater treatment but due to lack of direct monetary benefits, these ponds are either often neglected or poorly maintained.

1.2. Problem statement

Sugar Corporation of Uganda Ltd (SCOUL) is one of the major sugar producing companies in Uganda processing over 1,583 tons of sugar cane per day, and generating about 1000m^3 of highly polluted wastewater per day. This wastewater emanates from both sugar processing plant and the distillery. Though the industry operates stabilization ponds for wastewater treatment, the effluents discharged into River Musamya are in septic conditions, brownish and with a foul-smell of hydrogen sulfide.

Studies on characteristics of waste water effluents from selected sugar mills have been carried out (Nalukowe, 2006 and Nadia *et al.*, 2006) and their impact on the growth and biochemical characteristics of terrestrial and aquatic plants (Ayyasamy *et al.,* 2008). However, there is little information regarding ecological studies to examine water quality of bodies receiving sugar mill effluents by assessing factors such as occurrence of natural biodiversity, availability of dissolved oxygen (DO), BOD and COD (Nadia *et al*., 2006).

For over decades, River Musamya water has been of economic and ecological importance in terms of irrigation, industrial and domestic use, and support of aquatic life. However, up to now this river receives untreated wastewater from sugar processing and distillery from SCOUL, which impacts negatively on water quality as well as aquatic and terrestrial life. Apparently, no studies have been carried out to assess the impact of wastewater from SCOUL on water quality of River Musamya. This therefore justifies the need to assess the impact of sugar processing and distillery operations of SCOUL on the water quality of River Musamya.

1.3. General objective

The purpose of the study is to assess the impact of sugar processing and distillery operations of SCOUL on the water quality of River Musamya at Lugazi.

1.4. Specific objectives

i. To determine the physico-chemical characteristics of wastewater effluent discharged into River Musamya by SCOUL
ii. To evaluate the impact of the wastewater effluent from SCOUL on water quality of River Musamya

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Sugar and alcohol production processes

Sugarcane is one of the most common raw materials used in sugar industry and ethanol production (Selladurai *et al.,* 2010). Sugar cane is processed to produce sugar as the major product and molasses as a minor product (World Bank, 2007). Other products are bagasse used as fuel in boilers to produce steam for electricity generation, boiling and heating of juices. Typical cane processing facilities may process between 500 to 10,000 tons of cane per day (World Bank, 2007). A distillery with a daily ethanol production of 100 m^3 has a vinasse discharge of 1,300 m^3 (Navarro *et al.*, 2000). Filter cake/mud is given as a waste but taken to sugarcane plantation as a fertilizer, while molasses is sent to the distillery for ethanol production. During production of sugar, a number of activities and stages are involved before consumable sugar comes out. On arrival at the factory, sugar cane is weighed, washed and then passed into a series of mills. Mills extract juice out of prepared cane and give out bagasse as a waste. The juice is clarified using lime, phosphoric acid and organic flocculants, and thereafter evaporated to prepare the syrup (Hugot, 1986). The syrup is then bleached using sulphur dioxide obtained from burning sulphur in a furnace and crystallized under vacuum to separate out the liquor (Hugot, 1986). During crystallization, sodium hydrosulphite is added to reduce the viscosity before the material is centrifuged to separate molasses from the sugar crystals. Final molasses are sent to the distillery for ethanol production.

Molasses, also known as mother liquor (Hugot, 1986), are the raw materials for distillery and contain about 50 % sugar (World Bank, 2007), comprising: disaccharide (sucrose, 30.8%), monosaccharide (glucose, 4.39% and fructose, 6.67%), and Lactose, 8.14% (Dionex, 2003). The disaccharide present in molasses is first converted into monosaccharides and then converted into alcohol. Molasses are pumped into a fermenter, where they are diluted with water, supplemented with nutrients and then inoculated with yeast culture. The fermentation period normally takes about 24 to 30 hours for yeast to convert sugars to 7.5 – 9.5 % alcohol. This mixture of alcohol and fermentation broth is called the fermented wash. After completion of fermentation, distillation of fermented wash is done to recover aqueous alcohol as distillate. The next step is the rectification of

aqueous alcohol to concentrate the alcohol. A typical distillery adopts multi pressure distillation (pressure and vacuum) technique to first of all produce rectified spirit / extra neutral alcohol from the fermented wash, and thereafter, ethanol is produced from rectified spirit after removing the moisture to achieve 99.8% alcohol content using a molecular sieve (Suksri *et al*., 2007).

2.2. Characteristics of wastewater generated from the sugar industry

There are two major wastewater sources associated with the sugar factories: one is the waste process water from the sugar mills and the other is the effluent from the cane molasses distilleries (Wei and Xu, 2004). Sugar mills generate two types of waste waters; spray pond/cooling tower over-flows and factory wastes (Vawda, 2009). The cooling water is generated by condensing vapours in the barometric condensers and the organic content varies depending on the extent of evaporator entrainment and blow down practice. Sugar mills wastewater has many sources: Cane yard, mill house and boiling house washings containing bagacillo, juice and molasses tank over flows, floor washings, heat exchanger chemical cleaning, boiler ash sluicing water, grease and oil spillage. Storm water run-off from cane yards exacerbates water pollution. Whereas distilleries generate huge volumes of wastewater known as vinasse or spent wash from the distillation of fermented molasses, which is organic rich with BOD and COD concentrations ranging from 45,000mg/l to 70,000mg/l and 100,000 to 150,000mg/l respectively (Ryznar-Luty *et al.* 2008; World Bank 2007; Wei and Xu, 2004). The production and characteristics of spentwash are highly variable and dependent on feedstocks and various aspects of the ethanol production process (Pant and Adholeya, 2007). Wash water used to clean the fermenters, cooling water blow down, and boiler water blow down further contribute to its variability (Duarte *et al.*, 1997). Because of pollution problems, the treatment of the distillery wastewater is one of the most significant and challenging issue in the industrial production of ethanol (Navarro *et al.*, 2000).

According to Sanjay (2005), sugar processing plants consume on average about 2000 liters of water and generate about 1000 liters of wastewater per ton of cane crushed. World Bank (1998) reported that sugar manufacturing effluents typically have 1,700–6,600 mg/l BOD and 2,300–8,000 mg/l COD. However, the amount and quality of waste generated depends on the quality of the raw materials themselves and on the way cane is handled in the field during harvesting (World Bank, 2007). Fertilizers comprising of nitrogen and phosphorus are used to boost sugar production in the

field (Ovidio and Melgar 1998) and during harvesting, cane comes with soil containing these nutrients. These nutrients find their way in wastewater during sugar processing.

The sugar mill wastewater is characterized by its brown color, burnt-sugar like odor, high temperature, low pH, high ash or solid residues and contains high percentage of dissolved organic and inorganic matter of which 50% may be present as reducing sugars (Memon *et al.,* 2006). In addition, sugar mill effluents carry the constituents such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and oil and greases in the range, which more often exceed the stipulated National Environmental Quality Standards (Memon, *et al.,* 2006).

Molasses-based distilleries are also considered to be one of the most polluting agro-based industries due to generation of large amount of anaerobically digested, foul-smelling, coloured wastewater called post-methanated distillery effluent (Jain *et. al*, 2004 and Pant Adholeya, 2007;). Rajeshwari *et al.* (2000) reported that the distillation process effluent is characterized by high COD and BOD which is unsafe for disposal in water sources.

2.3. Impact of wastewater effluents on water quality

The change of the water chemistry is the main environmental impact associated with discharging sugar industry's effluent into an open water body (Salequzzaman *et al.,* 2008). Sugar mills play a major role in polluting the water bodies and land by discharging a large amount of wastewater as effluent. These effluents contain higher amount of suspended solids, dissolved solids, BOD, COD, chlorides, sulphates, nitrates, calcium and magnesium (Baskaran *et al.,* 2009), and cause odor nuisance during decomposition (Prasad *et al.,* 2007). Sugar and distillery wastewater with high COD and BOD add to oxygen demand in streams or lakes and can cause dissolved oxygen (DO) depletion leading to fish mortality (Günter *et al,* 2009). If vinasse is discharged on land, the alkalinity of the soil is reduced (Kumar and Viswanathan, 1991) and may lead to crop destruction due to toxicity of excessive manganese (Schulte and Kelling, 1999). Manganese availability increases as soil pH decreases and its toxicity is common in acid soils below pH 5.5 (Schulte and Kelling, 1999). This may also inhibit seed germination (Kannabiran and Pragasam, 1993).

2.3.1. Effect of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Dissolved Oxygen (DO) on water quality

Wastewater from sugar factory with its high BOD and COD rapidly deplete DO when discharged into water bodies endangering fish and other aquatic life (Salequzzaman *et al.*, 2008). Rayment (2003) reports that prior to the 1990s, fish kills due to hypoxic or anoxic conditions in water in cane areas were mostly believed to be associated with releases of sugar cane juices and vapours from sugar mills and distilleries with high levels of BOD and COD. BOD is a measure of the tendency of microorganisms in effluent to consume dissolved oxygen while degrading it during 5-day incubation period at 20 $^{\circ}$C. Whereas COD test measures the combined oxygen demands of biochemically reducible contaminants and non-biochemically degradable reduced contaminants. Fats, greases, and lignins are biochemically degradable. However, the rate of oxidation is very slow and they have little effect on the 5-day BOD test but are measured by the COD test (Memon *et al.*, 2006). Wastewater with high BOD contains high levels of organic matter, which serves as food for bacteria. Bacterial overgrowth causes oxygen depletion by heterotrophic biodegradation when entering surface waters (Günter *et al*, 2009). On complete exhaustion of the oxygen the bacteria begin to breakdown sulfates in the water stream to get their oxygen. This leaves a foul smelling (hydrogen sulfide) gas, which in turn can precipitate iron, turning the water black and highly toxic for aquatic life (Chicas, 2008).

According to Chapman (1996), the oxygen content of natural waters varies with temperature, salinity, turbulence, the photosynthetic activity of algae and plants, and atmospheric pressure. The solubility of oxygen decreases as temperature and salinity increase and in fresh-waters, DO at sea level ranges from 8 mg l^{-1} (at 25° C) to 15mg l^{-1} (at 0° C). Pandey *et al.*, (2008) found that wastewater from distillery reduced DO to 0.34 mgl^{-1}, compared to 9.3 mgl^{-1} DO in tap water, whereas sugar factory wastewater, DO is in a range of 0 to 2.0 mgl^{-1} (Kolhe, Sarode and Ingale, 2002). Mosley *et al*. (2004) found that DO concentrations below 5 mg/l is stressful to many freshwater species and therefore DO below 5 mg/l could be detrimental. Low DO promotes reducing conditions that facilitate the release from sediments of nutrients such as phosphorus and metal toxicants to the water column (Rayment, 2003).

2.3.2. Effects of Nutrients on water quality

Phosphorus (P) and nitrogen (N) are essential elements affecting the trophic status of water bodies. At elevated concentrations, these nutrients generally lead to increased biological productivity and a tendency towards Lake eutrophication (Daniel *et al.,* 1998). Fried *et al.* (2003) found out that both Nitrogen and Phosphorus have a positive effect on algal growth in lakes and streams. This usually reduces levels of dissolved oxygen in water below what fish and other aquatic species need to survive. It is therefore important to remove excess phosphorus and nitrogen from industrial wastes. Besides adding to nutrient-content of the water, addition of nitrogen and phosphorus will increase BOD and COD (Mahdieh and Amirhossein, 2009). The forms of nitrogen found in surface water are nitrate, nitrite, and ammonia (USEPA, 2002). Ammonia (unstable compound) is usually rapidly converted to nitrate (a stable form of nitrogen) in aerobic waters, as is true in soils (Zeng *et al.*, 2006). The stressing effects of ammonia on aquatic organisms increase at low dissolved oxygen levels and at increased pH and it was observed by Capkin *et al,* (2010) that the toxicity of ammonia is based primarily on unionized ammonia (NH_3) and the proportion of NH_3 species to NH_4^+ species is dependent on pH, ionic strength and temperature.

2.3.3. Effect of pH on water quality

The pH is a measure of the acid balance of a solution and is defined as the negative of the logarithm to the base 10 of the hydrogen ion concentration (Chapman, 1996). As reported by Salequzzaman *et al.* (2008), pH changes of sugar industry wastewater can tip the ecological balance of the aquatic system if discharged in water bodies, and excessive acidity can result in the release of hydrogen sulfide. In waters with high algal concentrations, pH varies diurnally, reaching values as high as 10 during the day when algae are using carbon dioxide in photosynthesis (Chapman, 1996). pH drops during the night when the algae respire and produce carbon dioxide. Variation in pH can affect algal growth in a number of ways (Chen and Durbin, 1994; Zeng *et al.*, 2006). It can change the distribution of carbon dioxide species and carbon availability, and alter the availability of trace metals and essential nutrients (Chen and Durbin, 1994). The relative concentrations of CO_2, HCO_3^-, and CO_3^{2-} and the pH of seawater are closely linked. As pH increases, carbonate increases and bicarbonate and molecular CO_2 decrease. At the average pH of seawater (pH 8.2), only about 1 % of total CO_2 is found as molecular CO_2, 90 % as HCO_3^-, and the rest as CO_3^{2-} (Steeman, 1975). At

any given pH, the concentrations of these species are set by any one of the following: partial pressure of CO_2 or total alkalinity. The removal of CO_2 by photosynthetic uptake leads to an increase in pH and a decrease in CO_2 partial pressure when CO_2 replacement processes occur more slowly than the utilization. These replacement processes include atmospheric CO_2 influx via diffusion, respiration, fermentation, and the slow hydration and dehydration reactions of dissolved CO_2 (Goldman *et al.* 1974; Owens and Essias 1976).

Driven by rapid utilization rates of inorganic carbon for photosynthesis during dense algal blooms (Hansen, 2002; Hinga, 2002), persistent high pH in shallow water can influence benthic dynamics with progressive pH penetration from the overlying water into sediments (Bailey *et al.,* 2006). When pH is above a critical threshold (9 – 9.2), inorganic phosphorus desorbs from iron oxides at mineral surfaces (Andersen, 1975; Eckert *et al.*, 1997). Elevation of pore water pH (approximately 9.8 in tidal-fresh regions, Eckert *et al.,* 1997) can promote sediment release of soluble reactive phosphorus (SRP), and simultaneously support phosphorus demand during cyanobacterial blooms in lakes (Xie et al., 2003) and tidal fresh and oligohaline estuaries (Seitzinger, 1991; Andersen, 1975).

The pH of water affects the solubility of toxic and nutritive chemicals such as cyanides, sulfides and ammonia. Therefore, the availability of these substances to aquatic organisms is affected. Most metals become more water soluble and more toxic with increase in acidity. Toxicity of cyanides and sulfides increase with a decrease in pH (Tuorinsky *et al.,* 2008) and according to Mosley *et al*. (2004), water with a pH > 8.5 indicates that the water is hard.

2.3.4. Effect of Electrical Conductivity (EC), Total Dissolved Solids (TDS) and Turbidity on water quality

Electrical conductivity (EC) is a function of total dissolved solids (TDS) known as ion concentration including the cations of calcium, magnesium, sodium, iron and potassium; and the anions of carbonate, bicarbonate, nitrate, phosphate, chloride and sulfate, among others, which determines the quality of water (Tariq *et al*., 2006). Electrical conductivity or total dissolved solids is a measure of how much total salt is present in the water (Mosley *et al*., 2004), the more ions the higher the conductivity. Conductivity itself is not a human or aquatic health concern, but because it

is easily measured, it can serve as an indicator of other water quality problems. If the conductivity of a stream suddenly increases, it indicates that there is a source of dissolved ions in the vicinity (Silver and Schulz, 2007). Therefore, conductivity measurements can be used as a quick way to locate potential water quality problems. Natural water contains dissolved solids due to the dissolution and weathering of rock and soil (Moldan *et al.*, 1994). In accordance with the National Environment (Standards for Discharge of Effluent into Water or on Land) Regulations (NEMA, 1999), 1200mg/l TDS is the permissible limit of discharge into the environment. Therefore discharge of wastewaters with TDS values higher than 1200mg/l is unhealthy to the environment (Barnes *et al.*, 1998), causing the receiving water to be deemed unfit for drinking and domestic purposes, reducing crop yield if used for irrigation, and exacerbating corrosion in water networks (Nadia and Muhmood, 2006).

Turbidity means an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through a water sample (Smith and Davies-Calley, 2001). In water, turbidity is caused by the presence of suspended matter such as clay, silt, finely divided organic and inorganic matter, plankton, and other microscopic organisms (Kerr, 1995). Photoelectric turbidimeters measure turbidity in nephelometric turbidity units, NTUs (Smith and Davies-Calley, 2001). Turbidity units are supposed to correspond to TSS concentrations, but this correlation is only approximate. Waters with turbidity in excess of 50 NTU are quite cloudy, and waters with turbidities exceeding 500 NTU are downright muddy (Brown and Caldwell, 2001). Suspended sediment is a ubiquitous water pollutant, with a multitude of environmental impacts on water bodies, including transport of other pollutants such as sorbed nutrients and toxic materials. Effects on aquatic organisms include benthic smothering once sediment settles out of the water column (Smith and Davies-Calley, 2001). However, the most visually and ecologically significant, impact of suspended sediment is optical - increased light attenuation through water (Kerr, 1995), decreasing algal growth, and low algal productivity can reduce the productivity of aquatic invertebrates, a food source of many fish (Nicholls *et al.*, 2009). A report by Lloyd (1985) on a review of published and unpublished literature relevant to the use of turbidity as a water quality standard, revealed that an increase in turbidity of 25 NTU in shallow, clear-water systems may significantly reduce stream productivity by 13-50% or more and be associated with an increase in suspended sediment concentration of approximately 25-100 mg/l. According to Birtwell *et al.*,

2008, it was found out that turbidity levels of approximately 25 NTU and 100 NTU are predicted to reduce the productivity of the biota after hours and days of exposure, respectively. Rosetta (2005) reviewed the results of field studies by Davies-Colley *et al.*, (1992) and determined that periphyton productivity was correlated with turbidity, and that the 50% and 25% response level was 2.6 NTU and 1.6 NTU respectively, an indication of a chronic exposure.

2.4. Industrial wastewater treatment options

Wastewater treatment options may be classified into groups of processes according to the function they perform and their complexity (Schölzel and Bower, 1999). Figure 2.1 categorizes wastewater treatment technologies as primary, secondary, tertiary and advanced. However in the sugar processing industry, advanced wastewater treatment technology is not a common practice since tertiary is adequate to treat and discharge wastewater within environmental regulations standards (Vawda, 2009).

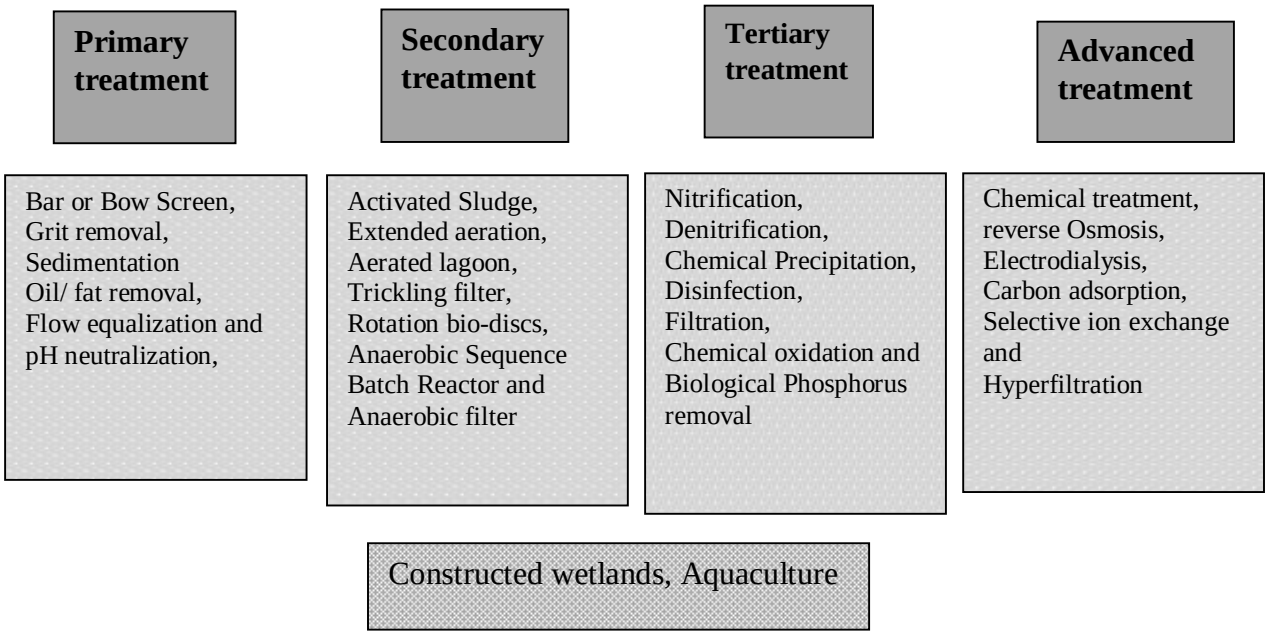

Figure 2. 1: Wastewater treatment categorization and technologies, Source: Schölzel and Bower, (1999)

In the **primary treatment**, physical processes consisting of unit operations to remove suspended solids, oils and major debris are involved. Their removal is important in order to increase the effectiveness of the later treatment processes and prevent damages to the pipes, pumps and fittings.

Secondary (Biological) Treatment involves biological reduction of a large proportion of organic material that remains in the wastewater after primary treatment. The treatment processes can be divided into two groups depending on oxygen presence (aerobic) or absence (anaerobic). Aerobic treatment uses bacteria which use oxygen to live and grow, whereas anaerobic bacteria can use alternatives such as nitrate or sulphate. Aerobic and anaerobic processes can be further divided into attached or suspended growth. In an attached growth process the bacteria are attached to an inert media or structure, whereas the bacteria within suspended growth processes form hoes of matter which are suspended by entrained gas introduced by injection or agitation.

The vast majority of secondary treatment is undertaken using trickling filter and activated sludge based processes. Some examples of secondary treatment systems (Figure 2.1) consist of Activated sludge process ASP (Sludge return facility), Waste stabilization Ponds (Oxidation ponds), Oxidation lagoons (Aerated Lagoons), Oxidation ditches (Extended Aeration Systems), Rotating Biological Contactor (RBC), Up-flow anaerobic Filter (UAF) and Up-flow anaerobic Sludge Blanket (USAB).

Tertiary treatment is the polishing process whereby treated effluent is further purified to acceptable levels for discharge. It is usually for the removal of specific pollutants e.g. nitrogen or phosphorus or specific industrial pollutants. Tertiary treatment processes are generally specialised processes which involve: granular-media filtration; i.e. sand filters to remove suspended solids, nitrification/de-nitrification to remove nitrogen; chlorine and dissolved gases, biological and chemical processes to remove nitrogen and phosphorous, chemical precipitation, adsorption; to dissolve inorganic and organic compounds.

Natural and artificial wetland systems are mainly for secondary and tertiary wastewater treatment (Vymazal, 2008). They have been used as a cost-effective alternative to conventional wastewater treatment methods for improving final effluent quality. Metcalf and Eddy (1991) defined wetlands as inundated land areas with water depths typically less than 0.6m that support growth of emergent plants such as cattail, bulrush, reeds, and sedges. And according to Leverenz *et al.* (2002), a wetland refers to land in which the water table is at, or above, the ground surface to maintain

saturated soil conditions and growth of related vegetation. Over the last century, wetlands have been widely regarded as biological filters, providing protection for water resources such as streams, lakes, estuaries, and groundwater (Kyambadde, 2005). However, theses wetlands have gained increasing acceptance for many types of bioremediation, including domestic sewage, mining and agribusiness wastewater (Nelson *et al.*, 2003).

Mbuligwe *et al.* (2011) categorized wetlands as either natural or artificial (engineered). Under the artificial type of wetlands fall constructed wetlands (Vymazal, 2010) and restored wetlands which are basically natural wetlands recreated after having been disrupted by anthropogenic activities (Mitsch and Gosselink, 2000). Since many natural wetlands that have long acted as wastewater disposal sites are rapidly being modified for agriculture and infrastructure development (Muwanga and Barifaijo, 2006), upstream treatment of wastewaters using constructed wetlands is one option that can be exploited to optimize pollutant removal in degrading natural treatment wetlands to ensure a sustainable supply of safe and clean water (Kyambadde, 2005).

Due to the nature of wastewater from sugar industry and molasses based distillery, characterized by high levels of BOD and COD, biological treatment options have been the most promising technologies (Rajeshwari *et al.*, 2000). Some of these biological treatment options consist use of up-flow anaerobic sludge blanket (UASB) (Stewart, 2004), expanded granular sludge bed (EGSB) (Driessen and Vereijken, 2003), rotating biological contactor (RBC) (Hammer and Harmer 1996), anaerobic baffled reactor (ABR) (Foxon *et al.*, 2004) and constructed wetlands (CWs) (Vymazal, 2010), as described in the following sections.

2.4.1. Use of Up-Flow Anaerobic Sludge Blanket (UASB) reactor for treatment of wastewater from distilleries and sugar industries

Biological anaerobic technologies are widely used for the treatment of high strength industrial effluents. Since it's development in the 1970s, the UASB reactor is considered as a breakthrough allowing high organic loading rates of up to 10 - 15 kg COD/m^3/day (Mutombo, 2004). UASB technology is suitable for effluents such as distilleries and food processing units including sugar industry (Rajeshwari *et al.*, 2000; Wolmarans *et al.*, 2002; Stewart 2004 and Lowna-Marie, 2007).

Up-Flow Anaerobic Sludge Blanket (UASB) reactor (Figure 2.2) is one of the biological wastewater treatment options which work under anaerobic conditions. The process involves converting the organic matter (in absence of oxygen) into biogas (mainly methane and carbon dioxide) through a series of reactions, involving a consortium of facultative and obligate anaerobic microorganisms. A UASB essentially consists of gas-solids separator (to retain the anaerobic sludge within the reactor), an influent distribution system and effluent draw off facilities.

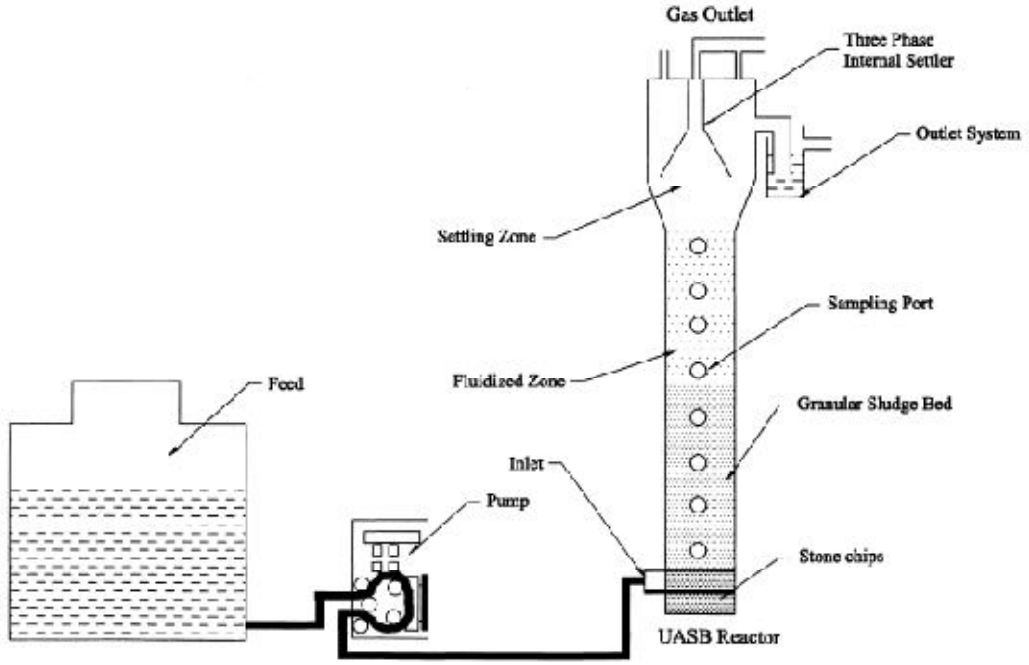

Figure 2. 2: Upflow anaerobic sludge blanket reactor (UASB) reactor (source: Rajeshwari et al., 2000).

In the study of the treatment of sugar factory wastewater using a pilot upflow anaerobic sludge blanket (UASB) reactor, Ragen *et al.* (2001) observed a sharp drop in the COD removal efficiency at a hydraulic retention time (HRT) of two hours and at an average organic load rate (OLR) above 11.5 kg COD/ m^3/day. The optimum HRT was between four and six hours. After a successful start-up of the reactor, results showed that with a HRT at or above four hours and with an average OLR below 6.7 kg COD/ m^3/day, the COD removal efficiency of the system was over 76%.

Hampannavar and Shivayogimath (2010) treated sugar industry wastewater using UASB reactor (at ambient temperature of 29 – 37 ^{0}C), and found that at a HRT of 6 hours, a maximum COD removal

efficiency of 89.4% was achieved with OLR of 16 g COD/L per day. Maximum volumetric biogas production was 4.66 L/day at OLR of 16 g COD/L per day. The methane content in the biogas was found to be between 73 and 82% at steady state conditions.

A laboratory scale study conducted by Kumar et al., (2007) to investigate the performance of anaerobic hybrid (combining sludge blanket and filter) and UASB (upflow anaerobic sludge blanket) reactors for the treatment of distillery-spent wash, revealed that hybrid reactor is capable of resisting organic shock load up to 2 times as compared to the UASB reactor capable of resisting the shock loading up to 1.5 times of normal organic load.

Study by Philippine Bio-Sciences (PhilBIO), as requested by a major sugar central milling company, Central Azucarera de Tarlac ("CAT"), concluded that distillery slops from sugar cane derived materials with very high concentrations of COD (60,000 – 160,000 mg/L), which contain ethanol, are readily available to convert into biogas via advanced anaerobic digestion systems (Stewart, 2004) and UASB process has proved to be successful despite expected toxicity problems arising from the high concentration of COD, sulfide and salts.

The UASB has an important role in removing total suspended solids, biological oxygen demand and intestinal nematode eggs but is deficient in removing pathogenic bacteria and nutrients (Abdel-Aziz, 2004). A major advantage is that the technology has comparatively less investment requirements when compared to an anaerobic filter or a fluidized bed system (Rajeshwari *et al.*, 2000). A major disadvantage of UASB is that it has a long start-up period (Wolmarans *et al.*, 2002), requires sufficient amount of granular seed sludge for faster startup, needs skilled operation and also there is need for wash-out of sludge during the initial phase of the process (Medhat *et al.*, 2004 and Abdel-Aziz, 2004).

2.4.2. Expanded Granular Sludge Bed (EGSB)

Expanded Granular Sludge Bed (EGSB) reactors are defined as vertically stretched versions of UASB reactors. UASB reactors are commonly built of 4.5 to 6.5 m while EGSB are 12-16meters tall (Driessen and Vereijken, 2003). Dinsdale et al. (2000) define the EGSB reactor (Figure 2.3) as a modification of the UASB reactor in which the granules are partially fluidized by effluent recycle at

a liquid upflow velocity of 5 to 6 $m.hr^{-1}$. EGSB reactors can be operated as ultra-high-loaded anaerobic reactors (up to 30 kg chemical oxygen demand (COD) m^{-3} d^{-1}) to treat effluents from the chemical, biochemical and biotechnological industries (Zoutberg and de Been, 1997) and EGSB systems have been shown to be suited to low temperatures ($10^{o}C$) and low strengths ($<1gCOD.l^{-1}$), and for the treatment of recalcitrant toxic substrates (Lettinga, 1996).

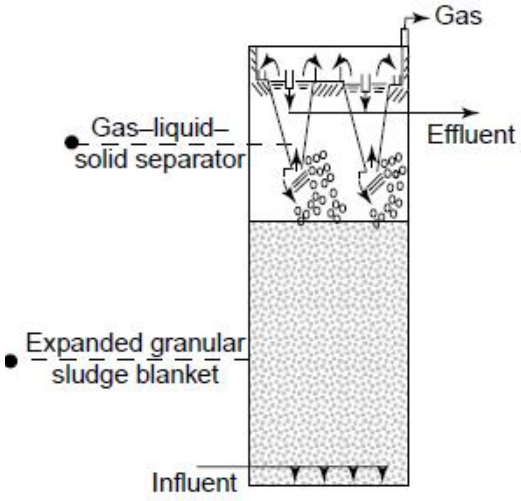

Figure 2. 3: Expanded granular sludge blanket (source: Nicolella et al., 2000)

The EGSB reactor shows improved mass transfer characteristics over the UASB reactor. It is generally applied in situations where the volumetric gas production rate is low and mixing in a USAB reactor by up flow velocity alone (0.5 to 2 m/hr) is insufficient (Dinsdale et al., 2000). Other researchers have compared the overall performance of an EGSB to the UASB reactor and the EGSB performed better than the UASB (Frankin and Zoutberg, 1996). To summarize them the EGSB reactor offers a smaller footprint, higher mixing due to the higher up flow velocity and consequently an improved mass transfer and biomass activity than the UASB reactor. As a derivative of the UASB, it responds to the need of small and medium sized industries (Kato *et al.*, 1997).

Microbial community structure of EGSB bioreactors is the key parameter for efficient removal of organic matter from sugar industry and distillery wastewater. Microbial diversity of anaerobic reactors treating alcoholic beverage effluents is mainly comprised of hydrolytic *Firmicutes*, acidogenic syntrophic *proteobacteria*, methanogenic *Methanosaeta* spp. and *Methanobacteriales*

group (Ince *et al.,* 2010). Combined use of molecular tools provided a deeper insight to microbial ecology of bioreactors.

The advantages of EGSB are found in its small footprint and higher loading rates compared with conventional UASB systems (Mutombo, 2004). The loading rates may reach values up to 20-40 kg COD/m3/day, depending on the type of system and wastewater to be treated (Van Lier *et al*., 2001). One of the most serious problems associated with expanded-bed digesters is the instability of the granular conglomerates during continuous operation (Parawira, 2004). This also applies, though to a much lesser extent, to UASB reactors and loss of biomass might occur due to: (i) granule disintegration, (ii) wash-out of hollow granules, (iii) occurrence of fluffy granules, and (iv) scaling due to inorganic precipitates (Parawira, 2004).

2.4.3. Rotating Biological Contactor (RBC)

A schematic diagram of a rotating biological contactor (RBC) reactor is shown in Figure 2.4. RBC can work both under anaerobic or aerobic conditions. The system configuration of anaerobic RBC is similar to that of the aerobic RBC, except that the tank is covered to avoid contact with air (Sperling and Chernicharo, 2005). In a RBC system, microorganisms attach to an inert support medium and form a biological film. The rotating biological contactors (RBC) are described as fixed-film systems, consisting of partly submerged rotating discs on which biofilms form (Hammer and Harmer 1996). RBC reactors are mechanical secondary treatment systems which are robust and capable of withstanding surges in organic loads. First implemented in the 1960s, they since developed into reliable operating systems based on simple construction (Vawda, 2009).

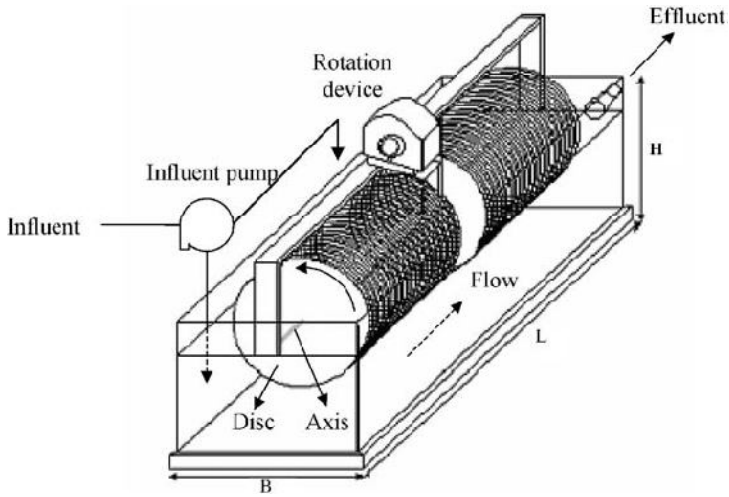

Figure 2. 4: Schematic representation of the RBC reactor (source: Windey et al., 2005).

The rotating biological contactor is a proven technology for large-scale wastewater treatment applications, offering several advantages: operation at a high biomass concentration without using settlers or recirculation, rapid start-up with no order or fly problems, low-shear environment, easy scale-up, high surface area per unit volume, low maintenance costs, low energy requirements, simple construction and operation (Malandra *et al.,* 2003; Guimarães, 2005 and Lowna-Marie, 2007;). Disadvantages include: high hydraulic loads that negatively affect BOD reduction; relatively high capital cost; little or no denitrification and the need for housing to protect against damage by weather (Henry and Heinke, 1996).

On the study of decolourization of a sugar refinery wastewater in a modified RBC, with *Phanerochaete chrysosporium* immobilized on polyurethane foam disks, Guimarães (2005) found out that there was a reduction in the colour, total phenols and chemical oxygen demand by 55, 63 and 48%, respectively during the course of operation.

Other studies done by Malandra *et al.* (2003) on winery wastewater with high organic content (over 12,000mg/l COD) using RBC, found out that one of the yeast isolates, *Candida krusei* was able to reduce the COD of synthetic wastewater by 95% and 46% within 24h under aerated and non-aerated conditions, respectively. It was concluded that the yeast isolate could therefore play an important role in degradation of organic compound under aerobic conditions, such as those associated with RBC.

2.4.4. Anaerobic Baffled Reactor (ABR)

An anaerobic baffled reactor (ABR), Figure 2.5, consist of a tank and standing baffles that compartmentalize the reactors and force liquid to flow up and down from one compartment to the next, enabling an enhanced contact between the fresh wastewater entering the reactor and the residual sludge, containing the microorganisms responsible for anaerobic digestion of the organic pollutants. The compartmentalized design separates the solids retention time from the hydraulic retention time, making it possible to anaerobically treat wastewater at short retention times (EPA 2006). The baffled design of the ABR ensures a high solids retention resulting in high treatment rates, while the overall sludge production is characteristically low (Foxon et al., 2004). They are simple to build and simple to operate, as well as very robust to hydraulic and organic shock loading (Sasse 1998). Yet, both sludge and effluent still need further treatment.

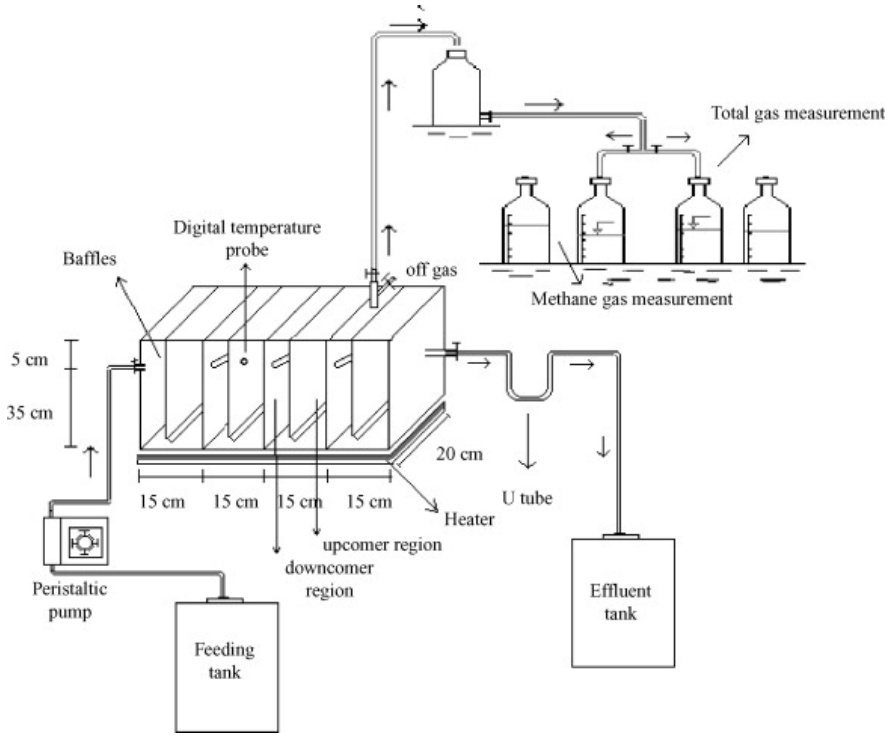

Figure 2. 5: Schematic diagram of the anaerobic baffled reactor (ABR) (source: Kuşçu and Sponza, 2005)

Using slaughter house wastewater, experiments conducted on ABR by Polprasert *et al.* (1992) to investigate its efficiency on organic carbon removal, was achieved up to 90% on a total COD basis

within 8 days of operation. This was evaluated under OLR of 0.67 g COD/ L/ day, HRT of 26 hr and at ambient temperature (30 to 35°C in day time and 25 to 30°C in night time). With OLR up to 4.73 g COD/ L/ day at HRT of 2.5 hr, treatment efficiency up to 75% was reached on a total COD basis and to 84% on a filtered COD basis. According to Stewart (2004), ABR reduces BOD by over 95% and COD by over 60%.

The biological advantages of the ABR are well documented by Barber and Stuckey, (1999). These include higher resilience to hydraulic and organic shock loads, longer biomass retention times and lower sludge yields than many other high rate anaerobic treatment systems. It has been proposed that the ABR is an appropriate means of providing short or medium term sanitation solutions to low-income communities (Foxon *et al.*, 2004) since; flow within the reactor is directed by baffles under the force of the pressure head at the influent. No mechanical mixing is required (and may even be undesirable) since flow is brought into intimate contact with the biomass as it is forced through the sludge bed. Therefore, there are no power requirements during normal operation; The ABR has been shown to function effectively under a wide range of flow and load conditions (Barber and Stuckey, 1999). It is also more resistant to shock loads than most conventional anaerobic treatment processes; little or no maintenance is required for an ABR. The end compartments promote endogenous respiration and are designed for low sludge carry-over rates.

Rajeshwari *et al.* (*2000*), in their review on State-of-the-art of anaerobic digestion technology for industrial wastewater treatment, rated the various reactor types basing on their performance and ease of operations in the order that follows: Fixed Film < UASB < RBC < Fluidized bed; regarding energy consumption the ratings followed the order UASB < Fixed Film < EGSB < Fluidized bed < RBC; Capital cost, land requirement, O&M: RBC < Fixed Film < UASB < EGSB < Fluidized bed. It was concluded that UASB and Fixed Film configurations appear to be the most suitable reactors for industrial wastewater with high COD under anaerobic condition.

2.4.5. Constructed Wetlands (CWs) for industrial wastewater treatment

Constructed wetlands (CW) popularly known as engineered wetland systems (EWS) are those wetland systems conceived, planned, designed, implemented (constructed), and operated as well as maintained for their specific objective such as wastewater treatment. Constructed wetlands (CWs)

have a great potential for the treatment of wastewater (Mbuligwe *et al.,* 2011). These systems consist of beds or channels which have been planted with macrophytes, which rely upon physical, chemical and biological processes (Table 2.1) to remove contaminants from wastewater (Ashutosh, Kumar, and Chhaya, 2011). CWs are capable of reducing contaminants including inorganic matter, organic matter, toxic compounds, metals and pathogens from different wastewaters (Ashutosh et al., 2011). Reduction or removal of contaminants is accomplished by diverse treatment mechanisms including sedimentation, filtration, chemical precipitation, adsorption, microbial interactions and uptake or transformation by macrophytes (Watson *et al.,* 1989). All these processes take place simultaneously. Incoming nutrients support the growth of macrophytes, which convert the inorganic chemicals into organic materials and form the basis of CW food chain (Brix, 1993). Microorganisms also play a main role in biochemical transformation of contaminants (Hoppe *et al.,* 1988; Madigan *et al.,* 1997).

Table 2. 1: Contaminant removal mechanisms in constructed wetlands (source: Ashutosh *et al.,* 2011)

Parameters	**Physical**	**Chemical**	**Biological**
Suspended solids	Sedimentation Filtration		Biodegradation
Biochemical oxygen demand	Sedimentation	Oxidation Reduction	Biodegradation
Chemical oxygen demand	Sedimentation	Oxidation Reduction	Biodegradation Phytodegradation Phytovolatilization Plant uptake
Nitrogenous Compounds	Sedimentation Volatilization	Adsorption	Bio-denitrification- nitrification Plant uptake
Phosphoric Compounds	Sedimentation	Adsorption Precipitation	Microbial uptake Plant uptake
Metals	Sedimentation Filtration	Adsorption Precipitation	Plant uptake
Pathogens	Filtration UV ray action	Adsorption Oxidation	Natural death Exposure to natural toxins Bacteriophage attack

The broadest classification of engineered wetland systems groups them into horizontal flow (HF) and vertical flow (VF) wetland systems (Cooper *et al.,* 1996; Kadlec *et al.,* 2000) as shown in Figure 4.

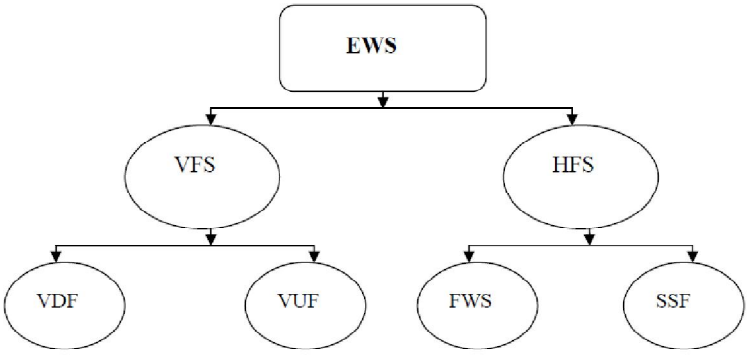

Figure 2. 6: Schematic classification of engineered/constructed wetland systems (source: Mbuligwe *et al.,* 2011). EWS = engineered wetland systems; VFS = vertical flow wetland systems; HFS = horizontal flow wetland systems; VDF = Vertical downward flow wetland systems; VUF = vertical upward flow wetland systems; FWS = free water surface wetland system; SSF = sub-surface flow wetland system.

Most of the available literature (Metcalf and Eddy, 1991; Reed *et al.,* 1995; Kadlec and Knight, 1996; Crites and Tchobanoglous, 1998; Mitsch and Gosselink, 2000) focus on horizontal flow (HF) wetland systems compared to vertical flow (VF) wetland systems. Suthersan (1999) mentions about VF wetland systems but still states that the main types of engineered wetland systems are sub-surface flow wetland system (SSF) and free water surface wetland system (FWS), which are in common use. FWS exposes the water surface in the system to the atmosphere whereas SSF maintains the water level below the surface of gravel or other media placed in the wetland bed (EPA, 1993 and Nelson *et al.,* 2003).

2.4.5.1. Subsurface Flow (SSF) constructed wetlands

The subsurface flow (SSF) constructed wetland system (Figure 2.7) is composed of a bed of gravel or other aggregate packing materials contained in a lined bed. Subsurface flow systems are often used for the treatment of wastewater that have high concentrations of biodegradable organic material because the treatment process is primarily anaerobic (Leverenz *et al.,* 2002). In a

subsurface flow constructed wetland system, the water to be treated flows through a porous packing material. The packing material has sufficient depth so that the water is not seen from the surface. The vegetation of the wetland provides some oxygen to the root zone and provides surface area for biological growth. The vegetation also stabilizes the bed surface, and improves the wetland aesthetics. Mixed cultures of wetland vegetation typically provide a more stable and effective wastewater treatment process. An outlet device is used to control the depth of water in the wetland.

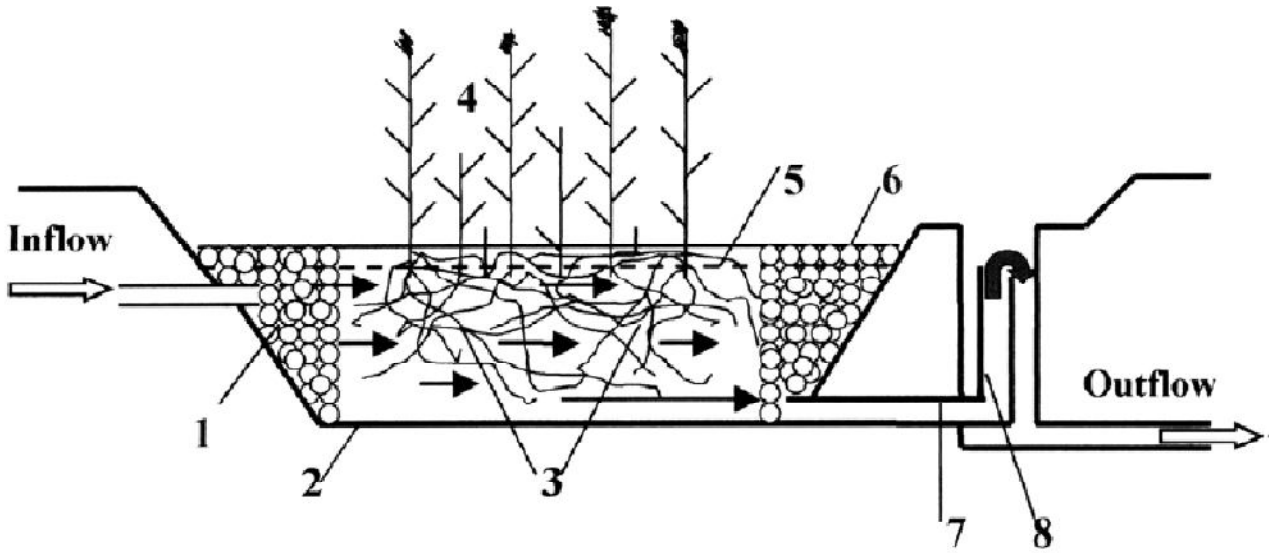

Figure 2. 7: Schematic layout of a constructed wetland with horizontal subsurface flow (source: Vymazal, 2010). **1** inflow distribution zone filled with large stones; **2** impermeable layer; **3** filtration material; **4** vegetation; **5** water level in the bed; **6** outflow collection zone; **7** drainage pipe; **8** outflow structure with water level adjustment.

Subsurface flow wetlands offer several advantages over other surface flow wetlands; however, the need to import packing material significantly increases the cost of subsurface flow constructed wetlands. According to EAP (1993), Nelson *et al.* (2003) and Vipat *et al*. (2008), subsurface flow (SSF) wetlands have a number of advantages. These include: lack of mosquitoes and other insect vectors, and minimal risk of public exposure and contact with the water in the system; the process can remove BOD_5 and suspended solids to very low concentrations and produce the equivalent of tertiary effluent; and nitrogen removal to very low levels is possible if sufficient detention time and oxygen to support the necessary nitrification reactions are present (EAP, 1993). Because the technology requires little machinery and no chemicals, and relies more on natural ecological

mechanisms (microbial and plant metabolism), maintenance requirements are minimized, and systems can be expected to have long operating lifetimes (Nelson *et al.*, 2003). SSF systems can be used to improve water quality and provide wildlife habitat. The system also requires a relatively low technology that utilize a long hydraulic residence time (HRT) and passive solar energy to achieve treatment. The SSF wetlands have received high popularity when compared to the free water surface (FWS) systems due to decreased nuisance from flies, odour and great efficiency in terms of usage and pollutant removal per unit area. However, the system is still on pilot scale in developing countries (Vipat *et al*., 2008).

2.4.5.2. Free water surface (FWS) constructed wetlands

A typical free water surface (FWS) constructed wetland (Figure 2.8) with emergent macrophytes is a shallow sealed basin or sequence of basins, containing 20-30cm of rooting soils, with a water depth of 20-40cm. Dense emergent vegetation covers a significant fraction of the surface, usually more than 50%. Besides planted macrophytes, naturally occurring species may be present (Vymazal, 2008).

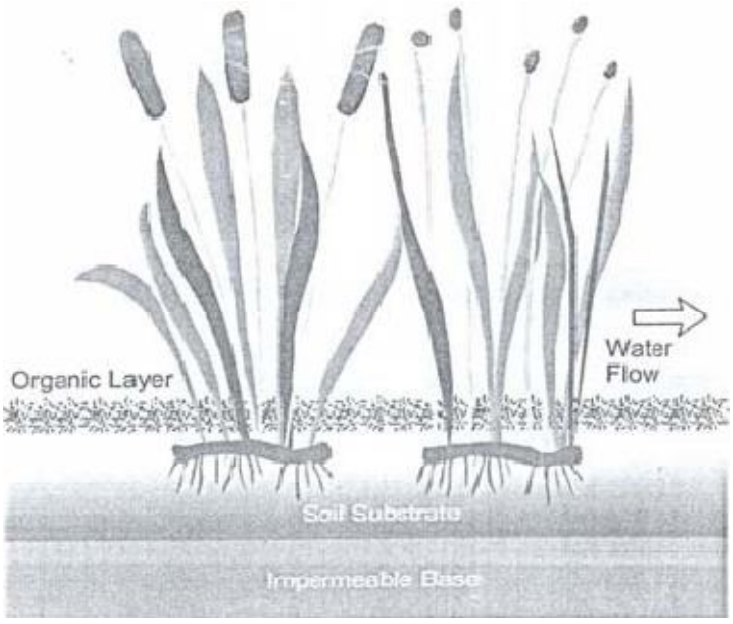

Figure 2. 8: Free Water Surface Constructed Wetland (source: Oketch, 2006)

Free water surface (FWS) constructed wetlands with emerging vegetation are used across the world for various types of wastewaters. The primary use is for secondary and tertiary treatment of

municipal sewage but treatment of wastewater from industrial and agricultural facilities is becoming more important (Vymazal, 2008). Nitrogen is most effectively removed in FWS constructed wetlands by nitrification/denitrification. FWS treatment wetlands typically have aerated zones, especially near the water surface because of the atmospheric diffusion, and anoxic and anaerobic in and near the sediments. Biomass decay provides a carbon source for denitrification, but the same decay components with nitrification for oxygen supply (Kadlec and Knight, 1996).

Free water surface constructed wetlands provide sustainable removal of phosphorus but at relatively slow rates. Phosphorus removal in FWS occurs from adsorption, absorption, complexation and precipitation. However, precipitation with Al, Fe and Ca ions – is limited by little contact between water column and the soil (Kadlec and Knight, 1996; Vymazal *et al.*, 1998). If improperly designed or maintained, nuisance conditions may result (Leverenz *et al.*, 2002). FWS constructed wetlands are a potential vector for mosquito propagation. In summer months, algae in the effluent can result in high TSS concentrations (Leverenz *et al.*, 2002).

Several studies on wastewater treatment using constructed wetlands have been carried out. The results show that use of constructed wetlands is one of the best options in optimization of pollutant removal in order to; ensure environmental conservation and sustainable supply of safe and clean water. Experimental research in the last 10 decades have shown that CWs may reduce concentrations of suspended solids, BOD_5, Nitrogen, phosphorus and coliform bacteria by up to 98% (Mimis and Gaganis, 2007).

Kyambadde (2005), in his study to optimize nutrient removal using substrate-free constructed wetlands (CWs), planted with *Cyperus papyrus* and *Miscanthidium violaceum* found out that there were highly promising treatment efficiencies, notably in papyrus-based treatments. Plant biomass productivity, nutrient storage, and overall system treatment performance were higher in papyrus-based constructed wetlands, and resulted in effluent that met national discharge limits. It is generally accepted that constructed wetlands may enable the effective, economical and ecological treatment of industrial and municipal wastewater (Kuschk *et al.*, 2005).

2.5. Wastewater treatment in Uganda

In Uganda, wastewater treatment technologies involve use of conventional biological wastewater treatment systems including anaerobic digestion by use of stabilization ponds, anaerobic sequencing batch reactor (SBR) systems – on a pilot scale, natural and constructed wetlands (Kyambadde, 2005). Use of stabilization pond systems is the most common technology for industrial wastewater treatment in Uganda (Mbabazi *et al.,* 2010). However, such treatment may not be fully achieved owing to high costs, lack of or insufficient infrastructure and poor maintenance of the available systems (Kyambadde, 2005 and Mbabazi *et al.,* 2010). Activated sludge processes are only applied in Kampala City and Masaka town (Kyambadde, 2005). This is due to the high energy inputs, use of chemicals, deployment of skilled man-power and large capital investments to build and operate, all of which make the technology expensive and unattractive to developing countries like Uganda.

Natural wetlands have also been used in Uganda to dispose of wastewater. But due to the high rate of population growth, natural wetlands have been degraded by turning them into settlement areas and agricultural land for food crops. This has led to the need for development of constructed wetlands which, to supplement the degrading natural wetlands receiving wastewater discharges.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Site selection and sampling frequency

Sampling regime was designed on the basis of geographical accessibility, location of distillery and sugar processing factory discharges as both join and drain into River Musamya (Figure 3.1).

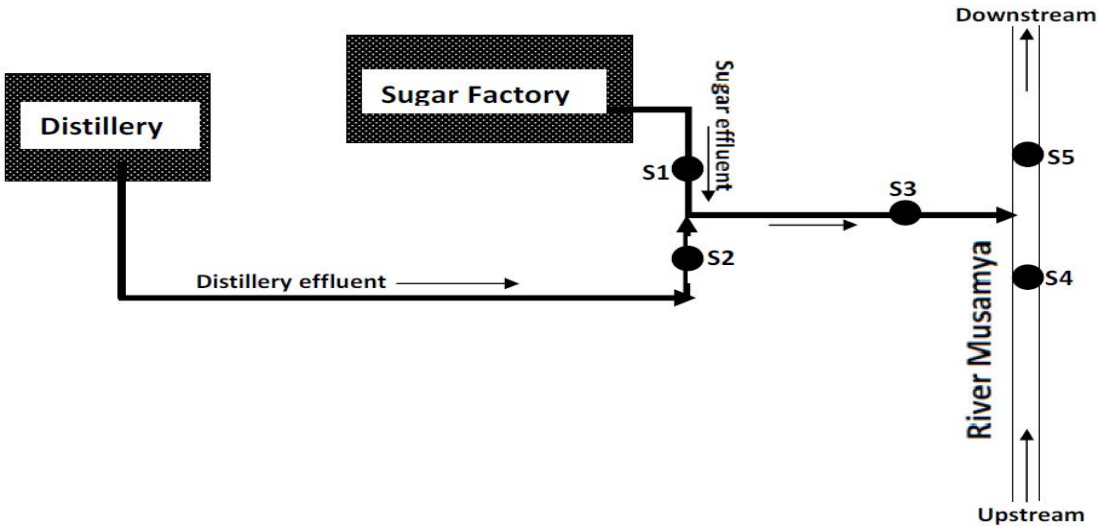

Figure 3. 1: Sampling points along sugar effluent, distillery effluent and River Musamya.

The chosen sampling points were from Sugar Processing Factory and distillery drainage channel (S_1 & S_2, respectively), the channel after distillery and factory wastewater effluents have mixed (50m before discharge into the river, S_3) and two other sampling points along the river upstream (100m before effluent discharge, S_4) and downstream (100m after effluent discharge, S_5). Sample collection was done when the factory and distillery were in operation (between 7:00am and 6:00pm) and one sample was picked per point for analysis. Sampling was done twelve times between February and April, 2010. Water samples for laboratory analysis were collected in clean 500ml plastic bottles, filled to the brim, tightly sealed and kept in a cool box prior to transportation to Water Resource Management Department (WRMD) – Entebbe for analysis of BOD, COD, Turbidity, Total Iron, Na^+, Ca^{2+}, Total Phosphorus, and Total Nitrogen.

3.2. Water analyses

3.2.1. Analysis of temperature, pH, Electrical conductivity (EC), total dissolved solids(TDS) and dissolved oxygen (DO)

Water quality parameters (Temperature, pH, electric conductivity, TDS and DO) were measured *in situ* using Hach Portable Multiparameter Meter (Figure 3.2) according to manufacturer's instructions.

Figure 3. 2: Hach sensION156 portable multiparameter probe

Temperature and pH were measured by placing the electrode in the sample after rinsing the electrode in distilled water. During measurement, **READ** key was pressed. Temperature and pH values were recorded after the system was stable.

To measure conductivity and total dissolved solids (TDS) with the sension156 meter, the probe was placed into the sample and the slot on the end of the probe was totally immersed. The sample was agitated with the probe for 5–10 seconds to remove bubbles that may have been trapped in the slot. CON/TDS/SAL key was pressed until the conductivity icon appeared in the lower left corner of the screen. The appropriate range and units were automatically selected by the instrument and the conductivity value for the sample being measured was displayed. To measure TDS, the CON/TDS/SAL key was pressed until the TDS icon appeared in the lower left corner of the screen. The instrument displayed the TDS value for the currently displayed conductivity measurement.

For dissolved oxygen (DO) measurement, the probe was inserted into the sample to the desired depth, agitated to dislodge air bubbles from the sensing area of the probe tip. The sample was

vigorously stirred with the probe until the displayed value no longer increased with the stirring rate. When the reading on the meter stabilized, the value on the meter was recorded.

3.2.2. Analysis of total nitrogen (TN) and total phosphorus (TP)

Total nitrogen (TN) and total phosphorus (TP) were determined by cadmium reduction and ascorbic acid methods, respectively (APHA, 1998). Both total nitrogen (TN) and total phosphorus (TP) samples were digested with potassium persulphate and autoclaved for 30 minutes at about 121°C. For digestion of TN samples, potassium persulphate and sodium hydroxide were used simultaneously. Colorimetric determination for TN and TP was by HACH DR 3800 visible spectrophotometer at a wave length of 410nm and 660nm, respectively.

3.2.3. Analysis of turbidity

Turbidity was measured using HACH electronic turbidity meter in nephelometric turbidity units (NTU) according to manufacturer's instructions. The method is based upon a comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension; the higher the intensity of scattered light, the higher the turbidity. Readings, in NTUs, are made in a nephelometer.

3.2.4. Analysis of Chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5)

Chemical oxygen demand (COD_5) was determined by the dichromate acid (sulphuric acid) digestion method using DR 3800 spectrophotometer, manufactured by HACH LANGE while 5 – day biochemical oxygen demand (BOD) was determined by incubation method (APHA, 1998).

During BOD measurement, the dissolved oxygen content was determined before and after incubation. Sample incubation was for 5 days at 20°C in BOD bottle and BOD was calculated after the incubation period. The concentration of dissolved oxygen (DO) present in the water samples was estimated by Winkler method for measuring dissolved oxygen, involving titrating a sample with sodium thiosulfate.

During the experiment, a sample is treated with manganous sulfate, potassium hydroxide, and potassium iodide (the latter two reagents combined in one solution) and finally sulphuric acid. The initial precipitate of manganous hydroxide, $Mn(OH)_2$ combines with the dissolved oxygen (DO) in the sample to form a brown precipitate, manganic hydroxide, $MnO(OH)_2$. Upon acidification, the manganic hydroxide forms manganic sulfate which acts as an oxidizing agent to release free iodine from the potassium iodide. The iodine, which is stoichiometrically equivalent to the dissolved oxygen in the sample, is then titrated with sodium thiosulfate.

BOD at 5-day, $20^oC = (D_0 - D_5)$* Dilution factor – $(C_0 - C_5)$ mg/l. Where; D_0 is the initial DO of the diluted sample before incubation, D_5 is the DO after 5 days of incubation, C_0 is the Initial DO of distilled water and C_5 is the DO after 5 days (blank).

3.2.5. Determination of sodium, calcium and iron

Sodium was determined by flame photometer (Model Systronic 128) while calcium and iron were analyzed directly by atomic absorption spectrophotometer (model AA3100, manufactured by Perkin Elmer).

3.3. Determination of pollution load

Pollution load (kg/day) was determined by multiplying mean pollutant concentration (kg/m^3) with the mean effluent discharge (m^3/day). Mean pollutant concentrations in mg/l for TDS, T-Fe, Na^+, Ca^{2+}, TN, TP, BOD, and COD at the point of discharge into River Musamya (sampling point S_3) were divided by 1000 to convert to kg/m^3.

Effluent discharge (m^3/s) was determined using Francis formulas (Perry *et al*, 2007) given below for a rectangular sharp-edged weir (Figure 3.3).

$$q = 0.415(L - 0.2h_o)\, h_o^{1.5} \sqrt{(2g)}$$

Where q = volumetric flow rate (m^3/s), L = crest length, h_o = weir head (measured on site), and g = local acceleration due to gravity (9.81 m/s^2). A factor of 86400 was multiplied by the determined values of volumetric flow rate (m^3/s) to convert into m^3/day

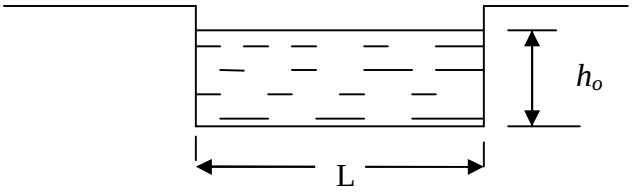

Figure 3. 3: Rectangular snarp-edged weir (source: Perry *et al.*, 1997) for determining wastewater discharge

3.4. Data analysis

Data analysis (mean & standard deviation) was performed using Minitab 16. Differences in each water quality variable between sampling sites were tested using analysis of variance (ANOVA), processed by the Minitab 16 statistics software. Results were considered significant if calculated P-values were < 0.05.

CHAPTER FOUR

4. RESULTS

4.1. Physico-chemical characteristics of wastewater effluent discharged into River Musamya by SCOUL

The changes in values of physico-chemical parameters for the five sampling points (S_1, S_2, S_3, S_4 and S_5) are presented in Table 4.1. The difference in water quality variables of the upstream and downstream river after wastewater discharge was highly significant ($P < 0.05$). The pH for wastewater from SCOUL discharged into River Musamya was very low and not within permissible limits by NEMA (Table 4.1). The lowest values of pH (3.8 ± 0.2; Table 4.1) were detected from distillery effluents. There was a significant decrease ($P = 0.000$) in pH of River Musamya water downstream after effluent discharge.

Total dissolved solids (TDS) and Electrical conductivity (EC) values (9104 ± 2833mg/l and 10089 ±3722µs/cm, respectively) of wastewater discharged into River Musamya at point S_3 were very high and deviated from NEMA standards (1200mg/l and 1500µs/cm, respectively) for wastewater discharge into the environment (Table 4.1). After discharge into the river, there was a significant increase ($p = 0.002$) in TDS values of downstream water from 88 ±15 to 1007 ± 262 (Table 4.1). The TDS values in distillery wastewater were significantly higher ($p = 0.032$) than those in sugar processing wastewater.

Electrical Conductivity and Total Dissolved Solids values depicted a linear relationship (Pearson correlation coefficient = 0.965) and after effluent discharge into River Musamya, EC of downstream river water significantly increased ($p = 0.007$).

Turbidity of river water downstream (after effluent discharge) was significantly higher than upstream river water (before effluent discharge; $p = 0.014$). There was no significant difference between turbidity of distillery wastewater and sugar processing wastewater ($p = 0.242$). However, mean turbidity values (4774 ± 1851NTU) of effluent discharge from SCOUL into River Musamya did not conform to the NEMA standard (300NTU) for wastewater discharge (Table 4.1).

The mean wastewater temperature values (27.3 ± 0.3˚C) for all sampling points were within NEMA permissible limits (20 – 30˚C) for wastewater discharge into the environment (Table 4.1). However, there was a significant increase (p = 0.004) in river water temperature after effluent discharge. It was discovered that sugar processing generated wastewater with temperature significantly higher (p = 0.005) than that of distillery wastewater (30.7 ± 0.6 and 25.8 ± 0.4˚C, respectively).

Table 4. 1: Mean ± standard deviation of chemical and physico-chemical variables determined at selected sampling points (n = 12)

Variable	S_1	S_2	S_3	S_4	S_5	Level of Signifiance between S_4 and S_5	permissible limits. NEMA (1999)
pH	4.2 ± 0.2	3.8 ± 0.2	4.3 ± 0.1	7.07 ± 0.01	5.6 ± 0.2	a	6.0 – 8.0
TDS (mg/l)	3142 ± 1149	15104± 5098	9104 ± 2833	88 ± 15	1007 ± 262	a	1200
EC (µs/cm)	4697 ± 1564	19361 ± 7046	10089 ±3722	108± 32	1524 ± 472	a	1500
T Fe (mg/l)	44.8 ± 8.8	65.6 ± 19.8	61.9 ± 12.3	3.2 ± 0.4	10.5 ± 1.4	a	10
Na^+ (mg/l)	40.7 ± 7.8	42.8 ± 12.0	31.3 ± 8.5	5.5 ± 0.7	8.0 ± 1.0	a	*
Ca^{2+} (mg/l)	79 ± 15	175 ± 30	126 ± 18	8.5 ± 0.8	25 ± 4	a	100
TN (mg/l)	41 ± 10	71 ± 14	48 ± 10	1.4 ± 0.3	6.8 ± 1.5	a	10
TP(mg/l)	20 ± 8	18 ± 4	16 ± 4	0.8 ± 0.2	2.7 ± 0.7	a	10
Turbidity(NTU)	2940± 1492	6531 ± 2584	4774 ± 1851	49 ± 8	616 ± 212	a	300
Temp (˚C)	30.7 ± 0.6	25.8 ± 0.4	27.3 ± 0.3	24.8 ± 0.2	25.7 ± 0.2	a	20 – 30
BOD (mg/l)	1295 ± 569	4723 ± 1242	2256 ± 820	3.8 ± 1.1	184 ± 43	a	50
COD (mg/l)	3821 ± 1229	16152 ± 4109	8064± 2250	13± 4	675 ± 70	a	100
DO (mg/l)	0.19 ± 0.02	0.14 ± 0.03	0.25 ± 0.03	6.50 ± 0.30	2.83 ± 0.29	a	*

S_1 = sugar processing wastewater; S_2 = distillery wastewater; S_3 = mixed distillery and sugar processing wastewater; S_4 = upstream river water; S_5 = downstream river water. *missing values. significant = a, insignificant = b
Results are considered significant if P-values are ≤ 0.05, otherwise insignificant

SCOUL generated wastewater with high values of BOD (2256 ± 820mg/l) and COD (8064± 2250mg/l), and low DO (0.25 ± 0.03mg/l) concentrations, which were outside NEMA permissible limits for wastewater discharge (50mg/l BOD and 100mg/l COD; Table 4.1). After discharge into River Musamya, there was a significant difference between BOD and COD concentrations in upstream and downstream river water (p < 0.001), while the average DO concentration significantly decreased from 6.50 ± 0.30mg/l to 2.83 ± 0.29mg/l (p = 0.000). Results further showed that the distillery generated wastewater of higher BOD (p = 0.02) and COD (p = 0.009) levels than the sugar processing.

4.2. Nutrients

Mean values of Total Nitrogen (TN) and Total Phosphorus (TP) concentrations (48 ± 10mg/l and 16 ± 4mg/l, respectively) of effluent discharged into River Musamya were determined (Table 4.1 and Figure 4.1). It was observed that there was a significant increase in concentrations of TN ($p = 0.002$) and TP ($p = 0.010$) in the river water, from 1.4 ± 0.3mg/l to 6.8 ± 1.5mg/l and 0.8 ± 0.2mg/l to 2.7 ± 0.7mg/l, respectively, after the discharge of wastewater from SCOUL. Total phosphorus and TN concentrations in effluent from SCOUL were outside NEMA permissible limits (10mg/l) for discharge into the environment. Results (Table 4.1 and Figure 4.1) show that concentrations of TN were higher than TP at all sampling points. However, there were no significant differences detected between concentrations of TP ($p = 0.878$) and TN ($p = 0.105$) in sugar processing and in distillery wastewater.

Concentrations of total iron (T-Fe, 61.9 ± 12.3mg/l), Na^+ (31.3 ± 8.5mg/l) and Ca^{2+} (126 ± 18mg/l) detected in wastewater from SCOUL were also outside discharge NEMA standards (10mg/l Na^+ and 100mg/l Ca^{2+}) (Table 4.1). It was observed in Figure 4.1 and Table 4.1 that concentrations of Ca^{2+}, T-Fe and Na^+ followed a trend of Ca^{2+} > T-Fe > Na^+ in the mixed distillery and sugar processing wastewater and river water downstream after effluent discharge.

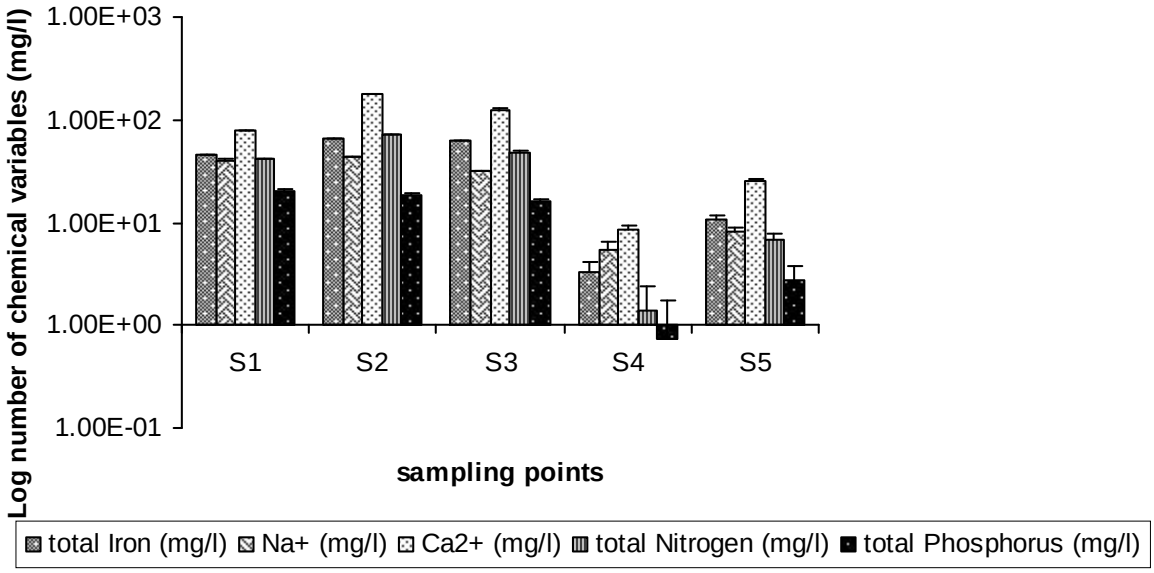

Figure 4. 1: Mean concentrations of chemical parameters of sugar processing effluent, distillery effluent and R. Musamya water

There was a significant increase in concentrations of Ca^{2+} ($p = 0.001$), total iron ($p < 0.001$) and Na^{+} ($p = 0.043$) from about 8.5mg/l to 25mg/l, 3.2mg/l to10.5mg/l and 5.5mg/l to 8.0mg/l, respectively in the river water downstream after discharge of wastewater effluent. Ca^{2+} concentrations in sugar processing wastewater (175 ± 30mg/l) was significantly higher ($p = 0.008$) than in distillery wastewater (79 ± 15mg/l), as detected by one-way ANOVA. In contrast, there was no significant difference between total iron ($p = 0.348$) and Na^{+} ($p = 0.819$) in sugar processing wastewater (65.6 ± 19.8mg/l and 42.8 ± 12.0mg/l, respectively) and in distillery wastewater (44.8 ± 8.8mg/l and 40.7 ± 7.8mg/l, respectively).

4.3. Pollution load

Results of pollution load from SCOUL into River Musamya are depicted in Table 4.2. It was observed that there was high pollution load (kg/day) of TDS, COD and BOD (22970 ± 8453, 20346 ± 4449 and 5692 ± 1666, respectively) into the river compared to T-Fe, Na^{+}, Ca^{2+}, TN and TP (156 ± 35, 68 ± 19, 319 ± 49, 121 ± 29 and 40 ± 14, respectively).

Table 4. 2: Mean pollution load (kg/day) discharged in River Musamya (n = 12)

Variable	**S_3**
TDS (kg/day)	22970 ± 8453
T-Fe (kg/day)	156 ± 35
Na^{+} (kg/day)	68 ± 19
Ca^{2+} (kg/day)	319 ± 49
TN (kg/day)	121 ± 29
TP (kg/day)	40 ± 14
BOD (kg/day)	5692± 1666
COD (kg/day)	20346 ± 4449
Discharge (m^3/day)	2523± 728

S_3 = Sampling point were distillery and sugar processing wastewater is mixed before discharge into River Musamya

CHAPTER FIVE

5. DISCUSSIONS

The observations from the quantified water quality parameters suggest a high vulnerability of River Musamya to pollution when compared with NEMA permissible limits of wastewater discharge into the environment (Table 4.1). In the present study, the pH of effluent from distillery and sugar processing was found to be highly acidic with values of 3.8 ± 0.2 and 4.2 ± 0.2, respectively (Table 4.1). Kumar and Gurdeep (2007) found the pH of spent wash collected from distillery to be 3.3 – 3.9 which was close to that of the present study. However, Jiranuntipona *et al.* (2009) found the pH in distillery effluents to be 3.8 – 4.5 which was relatively less acidic than in the present report. The low pH of the distillery effluent is due to the presence of higher concentration of organic acids such as CH_3COOH formed during biochemical conversion of highly biodegradable organic matter (Ale *et al.,* 2008; Theron and Lues, 2009) resulting from high BOD and COD loading (Table 4.2). Doke *et al.* (2011) found the pH in sugar process effluent to be 4.35 which was close to that of the present study (Table 4.1). On the other hand, the acidity of sugar processing wastewater was possibly due to the use of phosphoric acid and sulfur dioxide during clarification of sugar cane juice (Doke *et al.*, 2011). The acidic nature of the downstream river water was attributed to the discharge of large volumes of acidic wastewater (2523±728m^3/day; pH 4.3 ± 0.1) from SCOUL.

The high values of electrical conductivity and total dissolved solids recorded from both distillery and sugar processing wastewater could be attributed to high levels of total iron, Ca^{2+}, Na^+ TN and TP (Hagler, 1999) as shown in Tables 4.1 and 4.2. Whereas high turbidity values were probably due to mud and molasses from sugar processing and large volumes of spent wash from distillery (World Bank, 1998), high values of TN and TP in effluent could be due to nitrogenous (nitrogen, Asparagine, Glutamine, Aspartic) and phosphate (P_2O_5, phosphoric acid) (Walford, 1996) matter found in sugar cane juice (Hagler, 1999). These compounds come along with sugar cane from plantation and find their way into molasses and mud after sugar process, then later in wastewater. On the other hand, nitrogen and phosphate are introduced in sugar cane plantations as fertilizers to boost its growth. High concentration of Ca^{2+} are due to lime spill during sugarcane processing (about 2.25 tones of lime is used per day in SCOUL for juice clarification and raising the pH of condenser water). High concentration of total iron could probably be due to hydrated iron III oxide,

as a result of corrosion of metallic equipments both in distillery and sugar processing, since most of the liquid materials handled are acidic. However, run-off of nutrients (in form of fertilizers) from the plantation field and sediments due to soil erosion could have also contributed to high load of TN, TP, Total Iron, Ca^{2+}, Na^{+} and TDS into River Musamya (Nalukowe, 2006). When wastewater from SCOUL with high total iron, Ca^{2+}, Na^{+} TN, TP, EC and TDS values was discharged into River Musamya, it altered the quality of the river water downstream significantly ($p < 0.05$).

The high values of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) could have been due to distillery spent wash from fermented molasses, spillages of molasses and juice from sugar processing which are organic in nature (Rajeshwari *et al*, 2000; Pant and Adholeya, 2007 and Ryznar-Luty *et al*. 2008). The average DO concentration downstream along River Musamya dropped from 6.5 ± 0.3 to 2.8 ± 0.3 mg/l, due to high load of oxygen-consuming organic pollutants discharged into the river and a significant rise ($p = 0.004$) in temperature of polluted river water (Tables 4.2). This is in conformity with the study by Salequzzaman *et al* (2008) and Chapman (1996) who found out that solubility of oxygen decreases with an increase in temperature, and effluent with high BOD and COD accelerates bacterial growth in the river; hence reduce the dissolved oxygen levels.

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

1. Despite the sugar industry (SCOUL) being economically important, the impact of its effluent wastewaters on the environment is significant. Results showed that pollutant concentration in effluent from SCOUL were above permissible discharge limits by NEMA.
2. River Musamya received 2,523±728m^3 wastewater /day from SCOUL, with a high organic matter and nutrient load of 20,346 ± 4449 kg/day COD, 5,692±1666 kg/day BOD, 121±29 kg/day TN and 40±14 kg/day TP. The difference in water quality variables of the upstream and downstream river after wastewater discharge was highly significant ($P < 0.05$).
3. The distillery is more polluting than the sugar processing by generating high strength organic waste (4723 ± 1242mg/l BOD and 16152 ± 4109mg/l COD), compared to sugar processing which generated 1295 ± 569mg/l BOD and 3821 ± 1229mg/l COD.

6.2. RECOMMENDATIONS

1. SCOUL should employ technologies that reduce the quantity of waste effluents generated.
2. SCOUL should install a wastewater treatment system that impacts less on the environment.
3. Further studies should be conducted on the impact of SCOUL's operations on the general ecology of River Musamya.

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Appendices

Appendix 1: SensIONTM 156 Portable Multiparameter meter specifications

Parameter	Specifications
pH Mode	Range:-2.00–19.99 Resolution (selectable): 0.001/0.01/0.1 Slope (meter allowable): 48–65 mV/decade Instrument Drift: <40 µV/°C Input Bias Current: -1 pico amp ≤ input bias ≤ 1 pico amp at 25 °C; ±4 picoamp over full range
Millivolt Mode	Range: -2000–2000 mV Resolution: 0.1 mV Accuracy (meter only): ±0.2 mV or ±0.15% of the reading, whichever is greater
Temperature	Range: -10.0–110 °C Resolution: 0.1 °C Accuracy: ±0.3 °C from 0–70 °C; ±1.0 °C from 70–110 °C
Conductivity Mode	Range: 0–19.99 µS; 20–199.9 µS/cm; 200–1999 µS/cm; 2–19.99 mS/cm; 20–199.9 mS/cm TDS: 0–50,000 mg/L as NaCl Salinity: 0–42 ppt (‰) Temperature: -10–105 °C
Dissolved Oxygen Mode	Range: 0–20 mg/L (ppm), 0–200% sat. Accuracy: ±1% full scale Temperature: 0–50 °C

Appendix 2: Raw data of physical chemical characteristics of SCOUL's wastewater (at sites 1, 2, & 3) and river Musamya water before (site 4) and after (site 5) effluent discharge

Exp_No-	1	2	3	4	5	6	7	8	9	10	11	12	Mean
Sites_(S)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	
pH	3.68	4.13	4.41	3.82	4.20	5.01	4.72	4.52	3.78	5.10	3.12	4.19	**4.22**
TDS (mg/l)	663	1146	478	1201	1782	2345	321	998	13098	1908	9088	4678	**3142**
EC (µs/cm)	613	3246	812	1589	1326	1529	708	1209	16700	9096	12556	6981	**4697**
TFe (mg/l)	23.20	32.12	102.65	33.41	30.34	18.78	17.32	102.65	25.43	56.55	66.12	29.09	**44.80**
Na (mg/l)	36.19	50.00	95.19	43.97	35.70	89.54	11.34	23.90	8.97	27.79	32.11	33.20	**40.66**
Ca (mg/l)	67.13	37.07	95.19	150.35	182.56	110.37	34.79	11.78	56.80	108.73	46.38	41.57	**78.56**
TN (mg/l)	43.06	2.36	0.03	57.21	62.31	63.97	51.44	0.85	52.34	0.67	40.66	120.25	**41.26**
TP (mg/l)	3.23	1.08	0.04	12.24	79.23	8.78	0.06	14.45	79.23	2.43	18.95	18.96	**19.89**
Tbdty (NTU)	358	576	926	872	1799	1210	453	1050	17987	1090	7985	970	**2940**
Temp (°C)	27	31	32	31	30	29	32	29	34	30	33	30	**31**
BOD (mg/l)	160	7345	215	458	793	287	1468	687	1891	579	780	878	**1295**
COD (mg/l)	1070	14097	1650	1370	1857	875	3579	1790	10781	998	4974	2810	**3821**
DO (mg/l)	0.23	0.21	0.21	0.20	0.24	0.18	0.10	0.32	0.00	0.20	0.17	0.08	**0.18**
Sites_(S)	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**Mean**
pH	4.03	4.42	4.52	2.78	5.03	3.77	3.15	3.81	3.19	3.21	3.45	4.30	**3.81**
TDS (mg/l)	1700	14675	782	834	2034	3130	1390	54280	35766	32098	23567	10987	**15104**
EC (µs/cm)	1065	14987	823	1003	1708	1935	2034	73780	52090	37890	32677	12344	**19361**
TFe (mg/l)	37.14	9.44	13.06	42.10	38.33	40.06	11.24	13.06	230.32	87.90	154.23	110.34	**65.60**
Na (mg/l)	21.80	34.31	87.17	20.63	23.57	156.87	26.37	15.23	19.90	11.57	55.19	40.79	**42.78**
Ca (mg/l)	105.21	74.15	87.17	83.84	107.94	256.60	201.54	201.12	89.53	345.97	367.77	181.35	**175.18**
TN (mg/l)	51.17	8.93	0.03	98.50	101.23	87.39	54.33	124.00	146.45	1.76	102.29	72.11	**70.68**
TP (mg/l)	26.25	3.10	3.14	18.12	15.12	46.22	22.00	1.34	15.12	5.37	43.99	21.49	**18.44**
Tbdty (NTU)	436	447	745	367	693	789	2340	17540	28190	4590	13877	8356	**6531**
Temp (°C)	24	27	26	27	26	23	26	25	25	27	27	27	**26**
BOD (mg/l)	275	9332	355	523	678	7345	2994	3976	10786	1089	9967	9360	**4723**
COD (mg/l)	40982	17798	705	1203	1567	15057	6754	24086	43510	10367	15898	15899	**16152**
DO (mg/l)	0.31	0.23	0.24	0.25	0.22	0.11	0.05	0.04	0.09	0.07	0.06	0.04	**0.14**
Sites_(S)	3	3	3	3	3	3	3	3	3	3	3	3	**Mean**
pH	3.95	4.45	4.60	3.67	4.82	4.83	4.02	4.21	4.07	4.53	3.87	4.21	**4.27**
TDS (mg/l)	1418	9860	521	1032	1520	2502	921	26983	25368	18578	13087	7456	**9104**
EC (µs/cm)	987	10987	717	1298	1411	1739	1697	36876	27655	717	25888	11093	**10089**
TFe (mg/l)	34.38	10.03	83.98	37.22	32.59	25.83	13.21	83.98	147.24	74.76	103.33	96.72	**61.94**
Na (mg/l)	2.14	20.00	60.12	24.24	19.78	109.20	12.98	11.68	12.87	20.76	42.45	39.01	**31.27**
Ca (mg/l)	98.20	59.12	60.12	129.90	152.30	189.21	105.86	101.23	67.88	236.21	233.47	83.21	**126.39**
TN (mg/l)	44.17	2.16	0.03	55.30	70.27	58.73	50.44	34.66	97.32	0.86	81.52	82.39	**48.15**

TP (mg/l)	8.28	1.25	1.07	13.77	37.98	25.89	8.67	5.89	37.98	3.92	31.57	15.55	**15.98**
Tbdty (NTU)	460	501	692	521	1092	998	1357	8907	20821	3521	12788	5624	**4774**
Temp (˚C)	26	28	28	28	27	26	28	26	28	27	28	27	**27**
BOD (mg/l)	270	320	345	351	708	3783	2006	2690	708	345	6781	8764	**2256**
COD (mg/l)	23890	15001	905	876	1639	8532	2386	15754	1639	905	12450	12790	**8064**
DO (mg/l)	0.42	0.34	0.25	0.37	0.23	0.21	0.21	0.22	0.10	0.23	0.26	0.11	**0.25**
ho (m)	0.04	0.05	0.05	0.06	0.07	0.05	0.07	0.06	0.06	0.06	0.04	0.05	**0.06**
L (m)	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	**1.23**
q (m3/day) *	1553	2166	2038	2843	3885	2430	3203	2914	2843	2565	1670	2166	**2523**
Sites_(S)	4	4	4	4	4	4	4	4	4	4	4	4	**Mean**
pH	7.17	6.72	6.53	7.18	7.07	6.97	7.09	7.24	7.54	6.53	7.54	7.31	**7.07**
TDS (mg/l)	81	57	28	69	72	78	57	87	109	123	231	67	**88**
EC (µs/cm)	62	109	47	62	70	59	105	122	70	47	267	91	**93**
TFe (mg/l)	4.73	0.03	1.94	4.26	4.04	3.78	3.53	1.94	4.03	3.34	2.91	4.11	**3.22**
Na (mg/l)	7.41	2.00	6.01	7.41	7.08	5.82	6.59	2.50	7.08	0.76	7.71	5.03	**5.45**
Ca (mg/l)	12.02	5.01	6.01	12.68	10.36	9.43	10.91	3.80	9.12	4.90	8.89	8.31	**8.45**
TN (mg/l)	2.63	0.00	0.00	2.63	2.23	1.58	1.68	0.43	1.97	0.00	2.39	0.94	**1.37**
TP (mg/l)	0.32	0.10	0.00	1.24	1.89	0.09	0.45	0.08	1.89	0.08	1.38	1.23	**0.73**
Tbdty (NTU)	40	26	56	23	35	43	59	12	87	37	69	71	**46**
Temp (˚C)	25	26	25	25	25	24	24	24	25	24	25	25	**25**
BOD (mg/l)	2	2	3	3	2	3	3	2	2	3	5	8	**3**
COD (mg/l)	7	17	13	6	4	5	8	11	4	13	11	16	**10**
DO (mg/l)	5.69	5.44	5.57	6.80	6.66	6.23	5.29	7.22	6.92	8.71	6.01	7.23	**6.48**
Sites_(S)	5	5	5	5	5	5	5	5	5	5	5	5	**Mean**
pH	6.00	4.41	4.81	6.18	6.47	6.12	5.74	5.10	5.38	5.23	5.89	6.24	**5.63**
TDS (mg/l)	234	587	111	342	502	521	257	756	1020	986	756	562	**553**
EC (µs/cm)	179	852	159	331	489	358	612	1002	865	104	769	675	**533**
TFe (mg/l)	9.93	2.47	8.18	11.92	9.88	8.45	7.24	8.18	20.33	17.48	11.95	10.23	**10.52**
Na (mg/l)	7.41	3.00	12.02	8.35	8.13	13.24	7.12	4.01	8.13	3.87	12.33	8.28	**7.99**
Ca (mg/l)	16.03	8.02	12.02	41.23	45.21	35.12	17.55	30.91	14.76	12.01	50.44	16.55	**24.99**
TN (mg/l)	3.23	0.32	0.00	8.20	9.97	8.48	5.35	7.76	13.35	0.10	8.56	16.35	**6.81**
TP (mg/l)	0.49	0.23	0.00	2.56	7.15	4.32	2.54	1.39	4.98	0.12	4.11	4.62	**2.71**
Tbdty (NTU)	67	102	267	127	365	222	258	698	1005	520	689	347	**389**
Temp (˚C)	25	26	27	26	26	25	27	25	25	25	26	25	**26**
BOD (mg/l)	56	70	45	68	105	187	151	168	105	45	256	282	**128**
COD (mg/l)	723	672	275	476	622	679	710	756	622	106	781	598	**585**
DO (mg/l)	2.64	0.96	3.95	4.10	3.86	2.10	2.17	3.03	2.89	4.11	2.03	2.09	**2.83**

*

Francis formulas for estimation of effluent discharge, q, at location S_3

$$q = 0.415(L - 0.2h_o)\, h_o^{1.5} \sqrt{(2g)}$$

Appendix 3: Estimation of pollution load discharged by SCOUL into river Musamya at location S3

Mean pollutant concentration (mg/l)		pollution load (kg/day)
TDS	9104	22970
Total Iron	61.94	156
Na+	27.09	68
Ca2+	126	319
Total Nitrogen	48.15	121
Total Phosphorus	15.98	40
BOD	2256	5692
COD	8064	20346
ho (m)	0.06	
L (m)	1.23	
q (m^3/day)	2523	

Appendix 4: Pairwise comparison using p – values of water quality variables between sampling sites by one-way ANOVA and Tukey's multiple tests.

pH					TDS				
	S_1	**S_2**	**S_3**	**S_4**		**S_1**	**S_2**	**S_3**	**S_4**
S_2	0.117				**S_2**	0.032			
S_3	0.819	0.050			**S_3**	0.064	0.315		
S_4	0.000	0.000	0.000		**S_4**	0.014	0.007	0.004	
S_5	0.000	0.000	0.000	0.000	**S_5**	0.084	0.011	0.009	0.002

EC					**T Fe**				
	S_1	**S_2**	**S_3**	**S_4**		**S_1**	**S_2**	**S_3**	**S_4**
S_2	0.054				**S_2**	0.348			
S_3	0.195	0.257			**S_3**	0.270	0.877		
S_4	0.008	0.012	0.014		**S_4**	0.000	0.005	0.000	
S_5	0.065	0.019	0.032	0.007	**S_5**	0.001	0.011	0.000	0.000

Na^+					**Ca^{2+}**				
	S_1	**S_2**	**S_3**	**S_4**		**S_1**	**S_2**	**S_3**	**S_4**
S_2	0.883				**S_2**	0.008			
S_3	0.422	0.441			**S_3**	0.055	0.177		
S_4	0.000	0.005	0.006		**S_4**	0.000	0.000	0.000	
S_5	0.000	0.009	0.012	0.043	**S_5**	0.002	0.000	0.000	0.001

TN					**TP**				
	S_1	**S_2**	**S_3**	**S_4**		**S_1**	**S_2**	**S_3**	**S_4**
S_2	0.105				**S_2**	0.878			

S_3	0.631	0.198			**S_3**	0.674	0.681		
S_4	0.001	0.000	0.000		**S_4**	0.030	0.000	0.001	
S_5	0.003	0.000	0.000	0.002	**S_5**	0.050	0.002	0.003	0.010

Turbidity

	S_1	**S_2**	**S_3**	**S_4**
S_2	0.242			
S_3	0.449	0.586		
S_4	0.066	0.020	0.018	
S_5	0.137	0.033	0.036	0.014

Temperature

	S_1	**S_2**	**S_3**	**S_4**
S_2	0.000			
S_3	0.000	0.005		
S_4	0.000	0.018	0.000	
S_5	0.000	0.713	0.000	0.004

BOD

	S_1	**S_2**	**S_3**	**S_4**
S_2	0.020			
S_3	0.346	0.112		
S_4	0.033	0.001	0.012	
S_5	0.064	0.001	0.019	0.000

COD

	S_1	**S_2**	**S_3**	**S_4**
S_2	0.009			
S_3	0.112	0.098		
S_4	0.005	0.001	0.002	
S_5	0.018	0.001	0.003	0.000

DO

	S_1	**S_2**	**S_3**	**S_4**
S_2	0.171			
S_3	0.160	0.016		
S_4	0.000	0.000	0.000	
S_5	0.000	0.000	0.000	0.000

Results are considered significant if P-values are ≤ 0.05