

SUSTAINABLE DRAINAGE SYSTEMS AND GROUNDWATER QUALITY IN FREETOWN, SIERRA LEONE

*A dissertation submitted in partial fulfilment of the requirements for the degree of
MSc in Water Engineering with Management*

by

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DECLARATION

I certify that all material in this dissertation **which is not my own work** has been identified and appropriate acknowledgement and referencing has been provided. I also certify that no material is included for which a degree has previously been conferred upon me.

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ABSTRACT

The aim of the study is to examine qualitative relationship between stormwater and groundwater in terms of sustainable drainage systems by taking into account the infiltration ponds as the key point of the design in the Maeba Town, Freetown, Sierra Leone urban catchment. In the first part of the project the quality of infiltrated water from infiltration ponds, which are located in the downstream of the catchment, to soil in terms of Total Suspended Solids, Total Phosphorus and Total Nitrogen analysed for different sustainable drainage systems design scenarios and different physical and geological properties of infiltration ponds. In the second part of the project, three heavy metal pollutants (Iron, Copper and Manganese) are attached the chosen relatively worse design scenario and groundwater quality models are built for the beginning of the rainy season (15.04.2010-15.05.2010) and for yearly (01.01.2010-21.12.2010). The infiltrated water from ponds and their transportation processes in the three-dimensional modelled aquifer are examined and their possible effect on boreholes, which are the main drinking water sources, in the region observed. As a consequence, a general framework is formed about how sustainable drainage systems influence the groundwater quality in the tropical monsoon climate.

Key words: Sustainable drainage systems, stormwater quality, groundwater quality, infiltration systems

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LIST OF ABBREVIATIONS AND UNITS

CIRIA	Construction Industry Research and Information Association
Cu	Copper
EPA	Environmental Protection Agency
Fe	Iron
HMSO	Her or His Majesty's Stationery Office
Mn	Manganese
L	Meter
L ²	Square meter
L ³	Cubic meter
M	Kilogram
NSTC	National Science and Technology Council
ONS	Office for National Statistics
SuDS	Sustainable Drainage Systems
T	Time
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UK	United Kingdom
US	United States
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

Chapter 1 - Introduction

1.1 Background information and justification

Water is the main source of life for all living creatures on the Earth. Similarly, humanity needs water from the first moment they appear on the stage of history to survive. However, the main difference in the interaction of human beings and other living organisms with water is that human beings use water not only to survive, but also to maintain his/her complex social structure, to develop, and to preserve the comfort of his/her life. In other words, in the 21st century, a quality human life is dependent on enough quality and quantity fresh water in areas such as sanitation, drinking, manufacturing, leisure, and agriculture (Fry, 2008). On the other hand, because of the combination of population growth, socio-economic development and changing consumption patterns directly affects water usage which has been increasing by about 1% per year since the 1980s. Global water demand is anticipated to stay in similar trends until 2050. This brings to an increase of approximately 25% above the actual water usage rates. Moreover, more than 2 billion people live in countries with high water stress, and about 4 billion people suffer from severe water scarcity for at least a month of the year (UNESCO, UN-Water, 2019). According to UN (2011), for today, 55% of the population in the world lives in urban areas, a percentage that is expected to increase to approximately 68% by 2050. Simulations demonstrate that combination of urbanization, rural-urban migration and the overall growth of the world's population creates possible risks to add extra 2.5 billion people to urban areas by 2050. Additionally, nearly 90% of this increase arise from developing world in Asia and Africa. Moreover, While the predictability of climate change remains uncertain, its effects continue to be felt every day. July-2019 was the world's hottest month on record according to World Meteorological Organization (WMO, 2019). When this is taken into consideration, it is clear that multi-directional and sustainable water management strategies are necessary to protect water quality at the macro and micro levels. Urbanization and the water crisis make surface water a valuable resource and require more precise management strategies. The philosophy of sustainable drainage systems has emerged exactly at this point and aims to protect the highest level of surface water quality while minimizing its the negative effects. The SuDS approach (or Water Sensitive Cities in Australia, The Sponge Cities in China) includes decelerating and reducing the quantity of surface water runoff in urban catchment area to minimise flood risk, and reducing the contamination risk of that runoff. This is obtained by storing, infiltrating, slowing down and treating stormwater runoff directly on site (CIRIA,2015). The impact of sustainable drainage systems on different natural or artificial systems is still an important research topic under investigation.

1.2 Aim and objectives

The aim of this study is to investigate the influence of different sustainable drainage system designs on stormwater quality and groundwater quality by taking into consideration the constructed ponds as key point of design. Moreover, examine the interactions between stormwater quality and groundwater quality while the ponds' physical, hydrological and geological patterns are changing. The objectives are as follows:

1. Model the semi-hypothetical urban catchment of Maeba Town, Freetown, Sierra Leone.

2. Model the sustainable drainage systems on existing urban catchment model and examine how they influence groundwater quality by taking into consideration infiltration ponds as key point of design.
3. Examine and compare the concentration of different water quality parameters of water that infiltrates from infiltration ponds to soil in different sustainable drainage system design scenarios
4. Examine and compare the concentration of different water quality parameters from infiltration ponds to soil in different hydrological, physical and geological conditions of ponds.
5. Model the semi-hypothetical groundwater system of the catchment
6. Define ponds as areal contamination sources on groundwater model
7. Define safe zones around ponds for hypothetical wells specifically for related water quality parameters

1.3 Outline of the thesis

This thesis comprise of five chapters, including this one. The following list indicates the chapters, which are:

- (1) Chapter 2 – Literature Review This chapter provides a compendious insight into urbanization on drinking water catchments, stormwater and groundwater quality, sustainable drainage systems. A short historic overview of water resources, geology, climate, the regulatory authorities and their responsibilities about urban policies, water management in developing countries.

- (2) Chapter 3 – Methodology This chapter provides a description of the models and analyses being solved in the semi-hypothetical case study section. It also comprises the formulation, methods and assumptions being applied.
- (3) Chapter 4 – Case Study This chapter features an urban catchment of Maeba Town, Freetown, Sierra Leone as a semi-hypothetical case study. The methodology defined in Chapter 3 has been applied in this section to achieve the objectives justified in Chapter 1.
- (4) Chapter 5 – Conclusion This chapter provides a summary of the work carried out in previous chapter. It also presents the key findings of the study, and gives recommendations for further work.

Chapter 2. Literature review

2.1 Introduction

The aim of the literature review is to provide a general outline and highlight the significant concepts of hydrology, urban water management and water quality from different approaches as well as in this project. This chapter consists of five different sections, which are:

- (1) Section 2.2 - A brief historical background of hydrology as a science and basic terminology about water management.
- (2) Section 2.3 - Summary of the importance of water management in developing countries.
- (3) Section 2.4 - Basic concepts and importance of drinking water quality, stormwater quality, groundwater quality as well as explanation of related water quality parameters.
- (4) Section 2.5 - Sustainable Drainage Systems concept and similar approaches from all over the world

2.2 Definitions of key terminology in water management

2.2.1 Hydrology

Hydrology is an interdisciplinary science that examines the distribution of waters on earth and their mechanical, physical, chemical and biological properties (Marshall, 2013). Since living things on earth need to use and control water in order to continue their lives, people have been interested in water since the beginning of history, they have tried to recognize all the features of water, to identify the theories governing its movement, to identify the dangers it may create, to prevent and to make the best use of water. The science that examines the movement of water is called hydromechanics and the application of this science in the technique is called hydraulics. Hydrology or water science examines the distribution and properties of water in the world. The broadest definition of hydrology was proposed by the Scientific Council of Science and Technology of the Federal Council of Hydrology, and their definition is: "Hydrology is a fundamental and applied science that examines the circulation, distribution, physical and chemical properties of water in the earth (ie, on earth, underground and in the atmosphere), and their interrelationship with the environment and living things." (Smith, 1984). The history of hydrology dates back to 5000 BC. The oldest known hydrological management systems are located in the north-west of Azerbaijan and Georgia (Ollivier et al., 2018). In addition, ancient Anatolian, Asian and Mesopotamian civilizations built earth walls to protect the cities from floods and developed

water management systems to increase agricultural productivity. The history of modern hydrology goes back 400 years. For the first time in the 17th century, Perrault demonstrated the relationship between the total rainfall in the basin and the flow of the rivers in the Siene River, Paris (Nace,1974). In the 18th and 19th centuries, the methodology of modern science began to be applied to hydrology and the foundations of modern water engineering were laid. In his book *Hydrodynamica* (Latin for Hydrodynamics) , published in 1738, Bernoulli introduced the Bernoulli's principle, one of the fundamental principles of fluid mechanics. Chezy, Darcy and Manning published their important researches on hydrology and water engineering during the same period. Since the beginning of the 20th century, hydrology has become an area where empirical methods have been replaced by theoretical methods. Sherman's unit hydrograph concept (1932) and Horton's flow and infiltration ideas (1940) were published during this period (Bras,1999). Today, hydrology uses many advanced technologies such as geographic information systems, artificial intelligence applications, radar measurements and it has more than ten branches.

2.2.2 Meteorology and Hydrometeorology

Meteorology is a sub-branch of atmospheric sciences. In addition to dealing with the physical and chemical properties of the Earth's atmosphere, it focuses on precipitation measurement, weather forecasting and prediction, statistical models of precipitation. On the other hand, activities on the earth for drinking water, agriculture, electricity production and supply of industrial utility water should be linked to precipitation in the atmosphere. These activities need a lot of information, from reaching the earth in the form of precipitation to the flow of water and even evaporation into the atmosphere. It is the subject of hydrometeorology to collect, process, develop calculations and methods necessary for systematic, rational and economic activities of these activities (Bruce and Clark, 2013).

2.2.3 Water cycle management

Water cycle management regard to all strategy, planning, decision-making and operating stages to use the water cycle in the most effective way to meet all environmental objectives.

2.2.4 Water resources management

Water resources management refers to the general management of freshwater resources in certain areas. These sources can be lakes, rivers, groundwater or freshwater aquifers on the ocean floor (Gustafson, Key and Evans, 2019).

2.2.5 Integrated urban water management

Integrated urban water management is subject to the perspective of total water cycle management by considering all parts of water which have interaction with urban areas such as stormwater runoff, drinking water, wastewater, groundwater or water re-use (Goldenfum, Tucci and Parkinson, 2010). Urban and rural settlements, commercial and industrial areas and their existing and planned infrastructures related to these areas are in direct interaction with water resources (Government of Western Australia, 2017).

2.3 Water management in developing countries

Water management in developing countries is a serious challenge especially for the countries in the Middle-East, Africa and Central Asia due to rapid population growth, unplanned urbanization and inadequate and contaminated water resources (Tuncok, Mays and Briscoe, 1999). In developing world, over 1.1 billion people do not have adequate access to water and nearly 2.6 billion people do not have basic sanitation. Moreover, approximately 2 million people die every year (340,000 of them are under five) as a result of diarrhea and 440 school days are lost yearly because of water-related diseases (UN, 2006). Moreover, more than 80% of waste water is returned to the ecosystem without any treatment (UNESCO, 2017). Water quality problems in developing countries is a kind of trigger to affect all water-related problems therefore water quality should be taken into consideration more seriously and sustainable solutions should be produced (Kumar et al., 2014). Therefore, international organizations have been trying to find sustainable solutions for water-related crisis for decades. The United Nations Water Conference (1977), the International Drinking Water Supply and Sanitation Decade (1981-1990), the International Conference on Water and the Environment (1992) and the Earth Summit (1992) are general comprehensive conferences and meetings to discuss this issue. The 'Water for Life' International Decade for Action 2005-2015 helped around 1.3 billion people in developing countries gain access to safe drinking water and drove progress on sanitation as part of the effort to meet the Millennium Development Goals. Recent milestone agreements include the 2030 Agenda for Sustainable Development, the 2015-2030 Sendai Framework for Disaster Risk Reduction, the 2015 Addis Ababa Action Agenda on Financing for Development, and the 2015 Paris Agreement within the UN Convention Framework on Climate Change.

The urban water management is relatively new concept for developing world with the difference of developed world. Quantity control of urban water nearly solved in developed world and the quality of water is now more likely to remain on the agenda. In developing world, both quantity and quality of water is still a serious challenge. Likewise, urban drainage systems are inadequate and there is usually no control on quality of urban water quality (Tucci, 2001).

2.4 Water Quality

Water quality refers to physical, chemical, biological and radiological aspects of water. Likewise, water quality is defined as the all components of water which includes both dissolved materials and any other materials carried by water. It is a measurement of the actual water pollution to meet the requirements for living creatures in the water or usage of humanity for different intends (Johnson et al., 1997).

The measurement of the amounts of contaminants in the water is defined as concentration. In other words, the rate of contaminant mass in the water to total water volume is contaminant's concentration in the water. The expressions of concentrations are usually mg/l or g/m³. This expression is numerically equals to parts per million (ppm) according to assumption of density of the mixture is equals to the density of water (1000kg/m³) (Butler et al., 2018).

The complexity of the factors defining water quality and the variety of variables used for quantitative measurements in aquatic systems make it difficult to define water quality in a simple way. Since the quality of water required for different purposes may vary, water quality standards are published and regulated by many institutions around the world.

It is very important to distinguish between water quality criteria and water quality standards. The criteria are qualitative and quantitative limitations on different substances that ensure safe use of water and impair water quality. Standards, along with these criteria, are the necessary treatment and inspection ways that are planned to preserve the specific purposes and quality of use. Criteria are scientific decisions, standards are applicable explanations covering the rules to be followed in water use. Criteria may change only as new scientific data are available. The criteria also takes into account changes under certain conditions and the interaction of certain factors with each other. On the other hand, standards are more static and often show the normal results or factors without explanation for the amount of statistical variation (US EPA,2016), (Allen,1993), (Van Der Kooij et al., 1991).

2.4.1 Drinking water quality

Drinking water quality defines the quality of the water to be used as drinking water. Although clean drinking water is the most basic right for all people, there is no internationally accepted general drinking water standards (Shmueli, 1999). UK – Drinking Water Inspectorate, Australian Government National Health and Medical Research Council (NHMRC), European Drinking Water Directive, US Environmental Protection Agency – Safe Drinking Water Act, World Health Organization, Environmental Protection Law and Water Pollution Prevention and Control of People of Republic of China, Ministry of Environment – Republic of Korea are main institutes about drinking water quality and standards. Drinking water standards are not only standard lists that show limits for certain parameters, but also guides describing sampling methods and frequency, statistical and analytical methods to be used when calculating parameters, and acceptable testing and laboratory conditions. The main drinking water quality parameters are turbidity, colour, taste and odour, hardness, total dissolved solids, total suspended solids, hardness, heavy metals, nitrogen containing substances, microorganisms and radiological substances (WHO, 2017).

2.4.2 Stormwater Quality

Stormwater is the flow that occurs on the land surface during rainfall events or due to melting of snow or ice. Urban stormwater include a mixture of organic and inorganic materials. It also includes a small amount of human-related contaminants as a result of transportation and industrial development (Butler et al., 2018). In recent times, stormwater in urban areas and related non-point pollution sources have been taken into consideration as one of the primary sources of water pollution (Estèbe et al., 1997), (Fisher et al., 1999). Normally, traditional point sources of water pollution are easy to identify and measure. However, non-point sources are relatively difficult to classify and quantify because they include a high variety (Gromaire et al., 2001). Contamination is not only derived from land-use but also from atmospheric deposition. The influence of stormwater pollution to natural or constructed water bodies depends on several elements such as concentration of pollutants, mixture of pollutants or total load of pollutants. Although the urban

stormwater includes many types of pollutants, the major groups are total suspended solids (TSS), heavy metals, hydrocarbons and nutrients (nitrogen and phosphorus). Pollutants from these categories often get through physical and chemical processes before they influence the natural or constructed water bodies.

Excessive increase in urbanization increases the imperviousness of earth's surface and this directly increases the peak flows and runoff volumes. Similarly, urban pollutants in the first flush and their peak load increases. On the other hand, increase in imperviousness reduce the groundwater recharge and this may affect the decrease in dry weather base flow in urban catchments and significant changes in catchment hydrology (Aryal et al., 2010).

Westerlund and Viklander's study (2006) about comparison of stormwater quality during the snowmelt period and the rainfall period in northern Sweden demonstrated that pollutant concentration during snowmelt period is eight times higher than the pollutant concentrations during rainfall period. The reason is explained as the relatively slow flow during snowmelt period. On the other hand, stormwater quality comparison between dry and wet period in tropical climate is a controversial issue. Although the heavy rain is more likely to generate more pollutants especially in developing world's condition, the concentrations of pollutants in total stormwater are unlikely to follow same trend due to very high total stormwater volume. For instance, the study about river Damador, India demonstrates that pollutant concentrations during pre-monsoon period is significantly higher in river for 8 different heavy metal parameters than post-monsoon period (Pal and Maiti, 2018). The other important factor is about urban stormwater quality in tropic climates is the evaporation. Sharma (2012) suggested for evapotranspiration rates in tropic African countries as 50-60% of rainfall. That means annual evaporation could approach 1.5 m/year and definitely may be a main factor for stormwater quality.

2.4.3 Groundwater Quality

Although the pollution and degree of groundwater can vary considerably from region to region and locally, it is possible to group the main causes of pollution under major headings. The most obvious reason for the contamination of groundwater is the transfer of urban and industrial wastes to the groundwater depending on the climatic conditions, soil structure and time. Another important reason of groundwater pollution is the unconscious use of pesticides and fertilizers and the direct disposal of household waste to the soil (Bastani and Haarter, 2019), (Yu and Michael, 2019). Likewise, degradation-resistant compounds such as detergents can reach groundwater and cause problems for drinking water especially in urban areas. Another potential pollution source for groundwater is landfill areas and seawater intrusion. Recent studies demonstrated that leachate pollution from unlined landfill areas can have detrimental effects on groundwater quality (Stefania et al., 2019).

Groundwater is the focal point of improved drinking water and water supply in many areas in the world especially United States and Sub-saharan Africa. Moreover, most of Sub-saharan urban areas directly dependent to groundwater (Showers, 2002). Nitrogen-containing compounds easily contaminate the groundwater sources due to fertilizers, decaying plants, manure and rainwater recharge. Therefore, shallow aquifers include more risk than deeper aquifers especially for Sub-saharan cities.

2.4.4 Sediment and Suspended Solids

Sediments and suspended solids in stormwater mainly originate from soil erosions, asphalt/building erosion, human/animal waste, vehicles, particules transported by wind. Sedimentation in stormwater is usually measured as TSS or turbidity. TSS is the measurement of the total suspended sediments in water. TSS include different type of organic and inorganic pollutants which may play crucial role in transportation of chemical materials in water sources. Most of stormwater pollutants exist in stormwater as particules that attached to other finer sediments or organic materials. Therefore, stormwater pollutants have a direct relationship with total suspended solids concentration in the water. While the transportation is happening, pollutants have possibility to be reduced or transform to different forms. TSS is an important index for stormwater quality due to their carrying capacity. Rapid urbanization is one of the main reason of high concentration TSS in stormwater. According to Robert and Pierce (1976), after the increase in urban and residential area from 10% to 23% in the Patuxent River Basin, USA, total suspended solids in Patuxent River increased nearly three times. On the other hand, particule size of TSS in the water is also significantly important for stormwater quality. The particule size distribution of TSS in the runoff depends on hydraulic condition of urban catchment and dry-weather conditions of the region (USGS, 2001).

2.4.5 Heavy Metals

Heavy metals in stormwater are mainly arisen from brakes, tyres, frames and body of vehicles and road asphalt. Furthermore, the roads which have high traffic density, generates high concentration of heavy metals in stormwater. Main heavy metals in urban stormwater are Fe, Mn, Cu, Pb, Ni, Cr, and Zn and their concentrations may change between different locations (Reddy, Xie, and Dastgheibi, 2014). Normally, these toxic elements are essential for human and living organisms in particular levels. However, when the critical level excesses, they become mortally dangerous for human health and environment.

High proportion of heavy metals are in correlation with finer particules (Zanders, 2005). Moreover, the seasonal variations have a direct effect on heavy metal concentration in stormwater. Total concentrations of Cd, Cu, Ni, Pb, Zn is higher during snowmelt period or during rainfall events which occur slow flows. Likewise, correlation between TSS and heavy metals is very high for snow melt period but not very significant during rainfall events (Westerlund and Viklander, 2006).

2.4.6 Hydrocarbons

Hydrocarbons generally defined as a wide range of organic compounds. However, according to International Union of Pure and Applied Chemistry (IUPAC, 2003) hydrocarbons are organic compounds which only include carbon and hydrogen. Hydrocarbons are classified as two groups which are aliphatic hydrocarbons and aromatic hydrocarbons. Benzene, Phenols, aldehydes are the main hydrocarbons that considered as pollutants dangerous for human health. Materials of road surface, losses from lubrication systems, vehicle tires are the main source of hydrocarbons in stormwater (Pengchai, Nakajima and Furumai, 2005). Moreover, airborne particules, industrial

and vegetation waste may be transported by wind and surface water and become a stormwater pollutant for any other catchment (Vardar, Odabasi, Holsen, 2002). Hydrocarbons in stormwater may affect the water sources aesthetically such as sheens, occur de-oxygenation in the confined water ways and soils and reduce the aquaculture population or bio-diversity (Kennedy et al., 2016). Because of their relatively low octanol-watercoefficient, hydrocarbons easily infiltrates from soil and create hazardous toxic impacts on shallow groundwater aquifers (Logeshwaran et al., 2018)

2.4.7 Nutrients

Nutrients in stormwater generally defined as total nitrogen and total phosphorus. Nitrogen and phosphorus naturally take place nearly all water related ecosystems and they are critically essential for growth and health of plants. Fertilizers are widely used for effective agricultural production to increase nitrogen and phosphorus level in particular level in farms or gardens. However, if the level of total nitrogen and phosphorus level become too high, they may have hazardous impacts on water quality. High concentration of nutrients in stormwater may cause the eutrophication in surface water sources such as lakes, rivers or reservoirs (Yang and Lusk, 2018). The eutrophication of both freshwater and coastal marine systems causes a wide range of undesirable symptoms directly or indirectly related to the detrimental increase of aquatic plants. Primary symptoms include high levels of chlorophyll-a, increased epiphytic algae, and macroalgae burst; For secondary symptoms, low dissolved oxygen, loss of submerged aquatic vegetation and algae burst may be indicated. These symptoms of eutrophication have a large impact on the use of coastal ecosystems. Extreme and unsightly algae bursts adversely affect boating, swimming and tourism. Loss of submerged aquatic vegetation and low dissolved oxygen significantly reduces habitat for fish, other commercial and ecologically important organisms. Other less obvious effects include changes in phytoplankton community structure as a result of changes in the proportions of essential plant nutrients (such as nitrogen, phosphorus, and silicon) (NSTC,2003).

Source of compounds which include nitrogen and phosphorus may be agricultural areas, house gardens, some sport fields such as golf and horse-race courses, landscape areas and they may occur in stormwater in different forms. Phosphorus occurs in urban runoff as phosphate, orthophosphates, poly-phosphates. Main specific measurement of phosphorus in stormwater is total phosphorus. Nitrogen occurs in urban runoff as ammonia (NH_3), nitrite (NO_2) and nitrate (NO_3). Nitrate is relatively more important between other nitrogen compounds because of its anionic chemical nature. Nitrate accumulation in the soil contribute it's contamination of groundwater (Lee et al, 2003). Urban stormwater is the main reason of nutrient-based contaminated groundwater (Wakida and Lerner, 2005).

Drinking water containing high doses of nitrate causes the hemoglobin in the blood to convert to methemoglobin. This causes serious reductions in oxygen levels in the blood. Similarly, in areas where excessive nitrate-containing water is used as drinking water, thyroid gland discomfort has been observed to increase significantly in 15 different types of cancer (especially gastric cancer) (Forman, Al-Dabbagh and Doll, 1985).

2.5 Sustainable Drainage Systems

Traditional drainage systems have existed as a main infrastructure in urban areas to collect and convey the urban runoff from urban areas for a long time. The handicap of traditional drainage systems is that they designed to focus on only quantity of water. However, today's drainage perspective covers other significant sides of urban water such as stormwater quality, amenity, economic contribution such as recreational activities and water re-uses for different purposes (Chocat et al., 2007), (Larsen and Gujer, 1997). Sustainable Drainage Systems basically, contributes the rainfall to penetrate more underground while at the same time allowing the stormwater to circulate through the permeable surfaces, preventing contamination and slowing the surface flow rate with the help of coating materials such as vegetation and purifying water (Quigley, Strecker and Urbonas, 2003).

Although the terminology changes among regions, sustainable drainage systems approach have been applied and recommended in different urban areas all over the world with nearly similar design philosophy. In Europe, SuDS is applied by taking into consideration to sustaining better public health, minimizing pollutants in water resources, protect biological diversity and create sustainable water management for future demand (Butler and Parkinson, 1997) (Hellström, Jeppsson and Kärrman, 2000). Water Sensitive Urban Design (WSUD) is the catchment-based approach in Australia and SuDS is the main component of it. In that case, SuDS is defined as all engineering and planning process of sustainable integration of urban water management and urban landscape for the purpose of minimum negative environmental impact and obtain a satisfied harmonization between urban areas and water (Roy et al., 2008), (Sharma et al., 2008). Low impact development (LID) and Best management practices (BMP) are the application of SuDS in the United States and Canada. These concepts focus on protecting valuable water resources and meeting water demand by combining microscale hydrological control to minimize detrimental outcome of urbanization. Very similar approach is low impact urban design and development (LIUDD) in New Zealand. In Denmark, nationwide multidisciplinary programs about urban water have studied the transition and transformation of traditional infrastructure to sustainable version (Vandibyer.dk, 2019). In the United Kingdom, Construction Industry Research and Information Association (CIRIA) encourages the application of SuDS and also published lots of documents and guides about planning, constructing and maintenance processes. China's 'Sponge Cities' concept have arisen from similar perspective. Sponge City is a city designed for passive absorber, cleaner and friendly use of rainfall on an ecological scale where rain water is managed properly and the flow of dangerous and polluted water is reduced. Cities are created by designing green areas such as permeable roads, roof gardens, rain water collection systems, rain gardens, ponds and lakes. Associated strategies such as green space can be developed to improve quality of life, air quality and reduce urban warming islands.

The main sustainable drainage system techniques are filter trenches, permeable surfaces, stormwater storage tanks, wet or dry swales, rainwater harvesting systems, infiltration and detention ponds and wetlands (Elliott and Tworsdale, 2007) (Butler et al., 2018). SuDS devices can be structural by ensuring suitable hydrological and geological urban aspects such as infiltration systems, ponds and swales. On the other hand, non-structural components can be microscale such as vegetative areas. Regulations, urban policies, educational programs and promoting stakeholders

to contribute sustainable urban water management can be counted as soft devices of sustainable urban drainage systems (Charlesworth, 2010) (Dawson et al., 2011). All the SuDS components may be used separately or mixed in series. However, these techniques are usually used as combination of several types to maximise their function and provide more effective temporal and spatial urban water management.

As mentioned above, the main difference of SuDS from traditional drainage systems, in other words the trademark of the SuDS, is that SuDS have potential to improve quality of water in significant level. Many studies from all over the world demonstrated that logically applied catchment-based sustainable drainage systems protect the stormwater quality or support the process of urban water cycles's convergence to natural water cycle (Arora and Reddy, 2013), (Hatt et al., 2004), (Wang et al., 2008). Main methodology of the water quality improvement of the SuDS are;

- Reduce runoff and storm flow
- Reduce CSO spills & pollutants into water bodies
- Improve water quality
- Improve public health and other benefits

2.6 Summary

The literature review which has been achieved in this project demonstrates that water, which is an indispensable element for the continuation of life, should be managed with the by the agency of the best possible effective integrated methods. Moreover, the quality of water is just as important as the quantity of water. How new-generation sustainable perspectives ensure the qualitative relationship between different water sources should be considered in all aspects especially for urban catchments in developing countries.

Chapter 3. Methodology

3.1 Introduction

This chapter provides the methodology applied to examine the groundwater quality effect of different sustainable drainage system design scenarios in the case study. It consists of two main sections:

- (1) Section 3.2 – Description of the urban catchment model in the case study area;
Definition and formulation of qualitative and quantitative models.
- (2) Section 3.3 – Description of groundwater quality model.
- (3) Section 3.4 – Summary of methodology

3.2 Qualitative Relationship Between the Stormwater and the Groundwater

In this study, the qualitative relationship between the stormwater and the groundwater is identified as a possible problem in the case study. In the first part of the project, the Maeba Town, Freetown urban catchment is modelled and five different sustainable urban drainage system scenarios are implemented. Afterwards, two infiltration ponds in the downstream of the catchment which are fixed for all design scenarios are examined in detail by changing their physical properties. Similarly, compounds of the stormwater quality models are changed hypothetically to examine the relatively worse condition of the urban catchment in the case study area in terms of water quality. For the first part of the project, the annual concentration of total suspended solids, total phosphorus and total nitrogen are taken into consideration in the infiltrated water from ponds to groundwater. In the second part of the project, iron, manganese and copper are added to the relatively more serious stormwater quality models. In the second part, two groundwater quality models are achieved. The first one covers the 30 days of the transition period between dry and wet periods (15/04/2010-15/05/2010) in the case study area and the second one covers the all model period for 365 days (01/01/2010-31/12/2010). The qualitative effects of related stormwater quality parameters in the modelled aquifer are examined by defining water quality goals.

3.2.1 Rainfall and Evapotranspiration Data

The rainfall data (from 01/01/2010 to 31/12/2010) of Lungi-International Airport of Freetown, Sierra Leone was obtained from the National Centers for Environmental Information, the National Oceanic and Atmospheric Administration and U.S. Department of Commerce (Figure 3.1). The annual time period was chosen as 2010 because it was the wettest year since 1991 across the country (World Bank, 2019). The evapotranspiration (ET) data was calculated as the recommended rates from Sharma (2012), which is between 50%-60% of rainfall. In this project, ET is adopted as 55% of the rainfall (Figure 3-1).

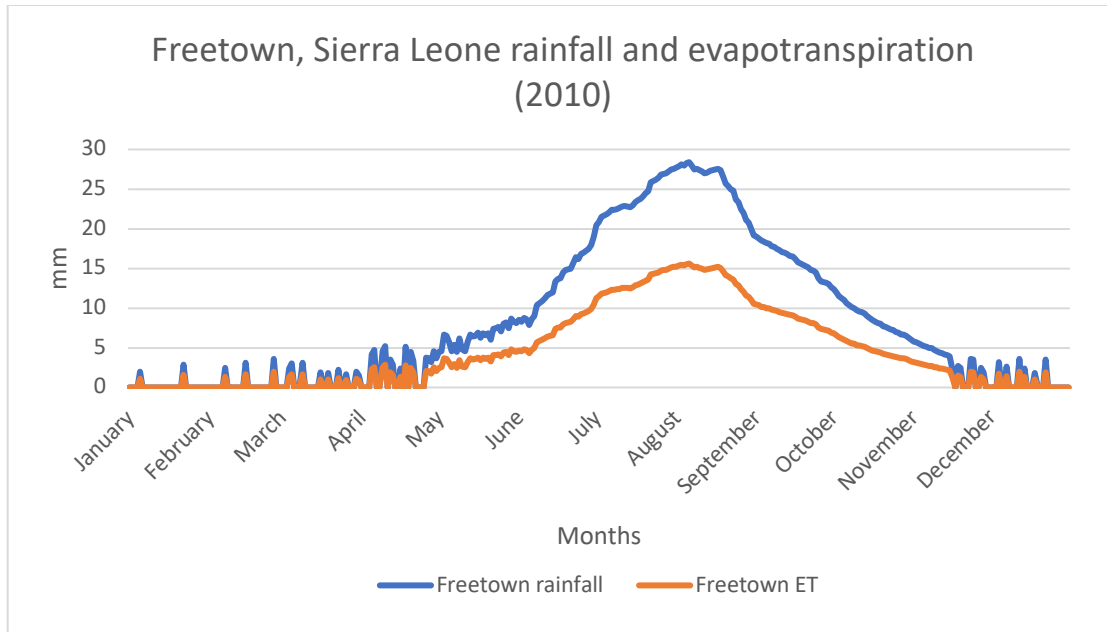


Figure 3.1: Rainfall and evapotranspiration data, Lungi-International Airport, Freetown, Sierra Leone, 2010

Table 3.1: Statistics of annual rainfall Lungi-International Airport, Freetown, Sierra Leone, 2010

Statistics	Rainfall	Evapotranspiration
	(mm/Day)	(mm/Day)
Mean	8.469	4.658
median	5.2	2.86
maximum	28.4	15.62
minimum	0	0
10 percentile	0	0
90 percentile	23.8	13.09
Mean Annual (mm/yr)	3091	1700

3.2.2 Catchment Modelling

The urban catchment is first divided into two main sub-catchments and then 30 areas and 44 paths by superposing the topographic and contour maps of the region. These two sub-catchments are modelled as main stormwater ways from upstream of the catchment to downstream and considered as merging at the downstream of the catchment by taking into consideration of the hydrological condition of the catchment during wet season (Figure 3-2), (Figure3-3), (Figure3-4) and (Table 3-2). The time-step for the catchment modelling and related sustainable drainage scenarios is from 01/01/2010 to 31/12/2010.

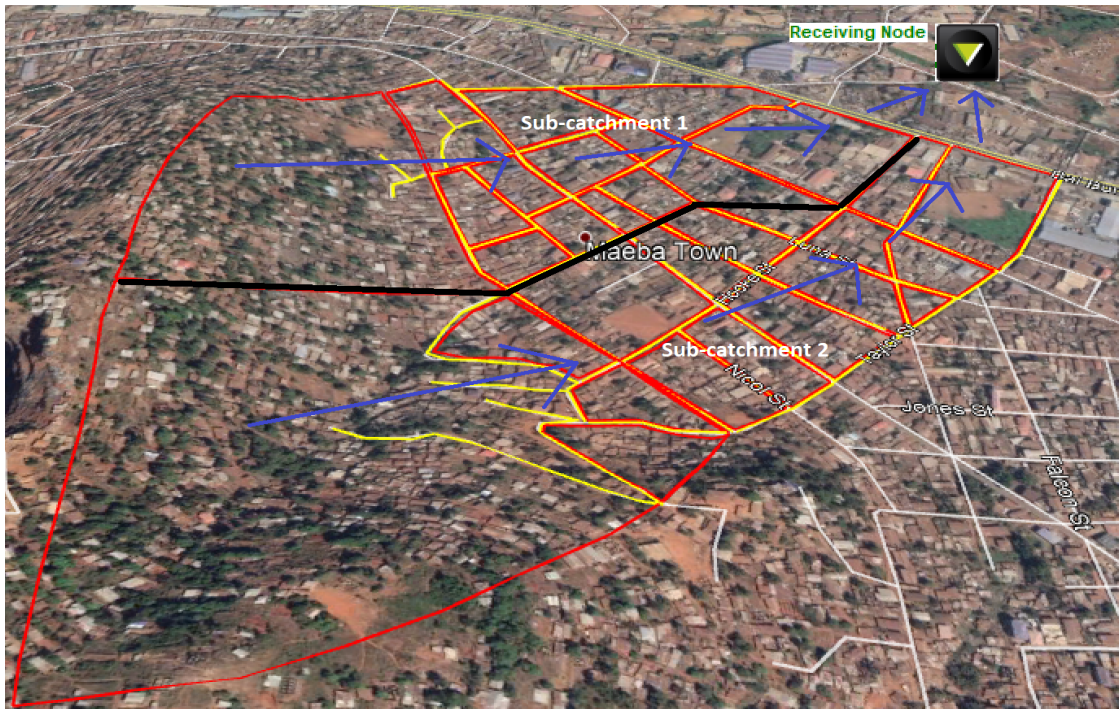


Figure 3.2: Sub-catchments of Maeba Town



Figure 3.3: Division of Areas, Urban Catchment – Maeba Town

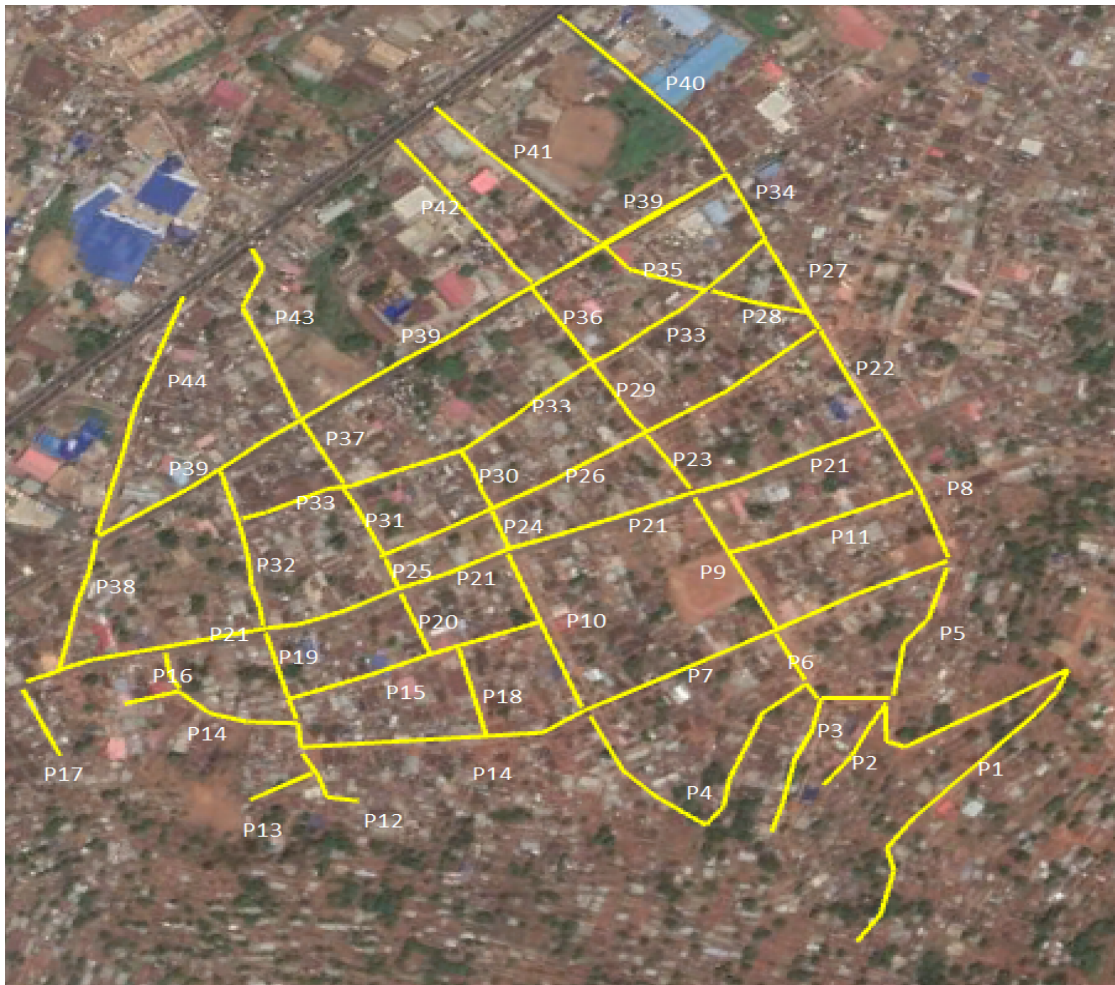


Figure 3.3: Division of Paths, Urban Catchment – Maeba Town

Sub-catchment one includes Area 2-3, Area 7, Area 8-16, two-thirds of Area 20, Area 21 and Path 12-20, half of Path 21, Path 25, Path 31-33, Path 37-38, half of Path 39, Path 43-44. Sub-catchment two includes Area 1, Area 4-6, Area 17-19, one-third of Area 20, Area 22-30 and Path 1-11, half of Path 21, Path 22-24, Path 26-30, Path 33-36, half of Path 39, Path 40-42. All paths are unsealed roads except Path 21 and Path 39, which are sealed roads and all areas are residential areas.

Table 3.2: Sizes of Residential Areas and Roads of Urban Catchment – Maeba Town

Areas	Size (Ha)	Paths	Size (Ha)	Areas	Size (Ha)	Paths	Size (Ha)
Area 1	20.90	Path 1	0.31	Area 24	1.36	Path 24	0.02
Area 2	11.67	Path 2	0.06	Area 25	1.22	Path 25	0.02
Area 3	1.96	Path 3	0.11	Area 26	0.20	Path 26	0.26
Area 4	1.34	Path 4	0.20	Area 27	0.74	Path 27	0.06
Area 5	0.84	Path 5	0.08	Area 28	0.79	Path 28	0.05
Area 6	1.12	Path 6	0.03	Area 29	1.08	Path 29	0.05
Area 7	1.78	Path 7	0.20	Area 30	2.85	Path 30	0.04
Area 8	2.08	Path 8	0.08	Total Area	67.39	Path 31	0.05
Area 9	0.46	Path 9	0.09	Urban Catchment		Path 32	0.10
Area 10	1.07	Path 10	0.10			Path 33	0.32
Area 11	0.70	Path 11	0.10			Path 34	0.05
Area 12	0.90	Path 12	0.04	Total Area		Path 35	0.06
Area 13	0.66	Path 13	0.03			Path 36	0.06
Area 14	0.61	Path 14	0.25			Path 37	0.04
Area 15	0.34	Path 15	0.15	72.46 ha		Path 38	0.10
Area 16	0.64	Path 16	0.02			Path 39	0.58
Area 17	2.51	Path 17	0.04			Path 40	0.14
Area 18	0.76	Path 18	0.05	Residential	67.39 ha	Path 41	0.12
Area 19	0.93	Path 19	0.04	Unsealed	4.05 ha	Path 42	0.12
Area 20	2.11	Path 20	0.04	Road		Path 43	0.12
Area 21	3.70	Path 21	0.44	Sealed	1.02 ha	Path 44	0.15
Area 22	1.13	Path 22	0.07	Road		Total Area	5.07
Area 23	0.99	Path 23	0.04	Urban Catchment - Maeba Town			

3.2.3 Model for Urban Stormwater Improvement Conceptualisation

The urban catchment and sustainable drainage systems design scenario models were built in Model for Urban Stormwater Improvement Conceptualisation (MUSIC), which was initially the MUSIC development team for the Cooperative Research Centre for Catchment Hydrology and now the improvements and upgrades belong to eWater Cooperative Research Centre. MUSIC is designed to model stormwater systems in urban catchments and is suitable for catchments ranging from 0.01 km² to 100 km².

3.2.3.1 Modelling Catchment Hydrology

In urban catchments, the majority of stormwater is generated from impervious surfaces. Baseflow, which has a direct relationship with urban geology and groundwater characteristics, is less dominant in urban catchments. MUSIC generates urban runoff according to the algorithm adapted from Chiew and McMahon (1997). The algorithm is subject to a simplified model of rainfall-runoff processes in urban catchments, including two soil moisture storages which are a pervious store and source of baseflow in the sub-surface (Figure 3-4).

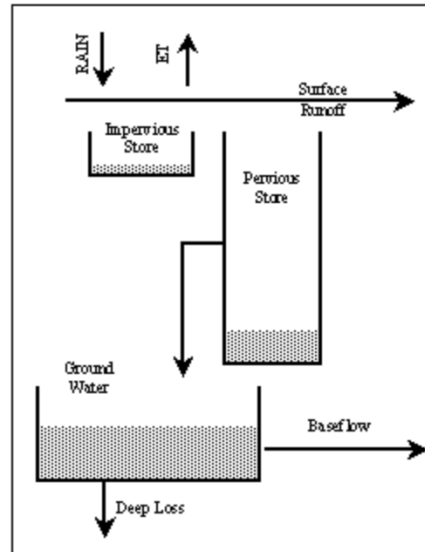


Figure 3.4: Rainfall-Runoff Model adopted for MUSIC (Chiew and McMahon, 1997)

The Muskingum-Cunge flood routing method is used by MUSIC for runoff-routing through the urban-catchment. The Muskingum method, first developed by the US Army Corps of Engineers and McCarthy for controlling floods in the Muskingum river basin in Ohio in the mid-1930s, is a well-known and widely used coefficient model. Later, the method was improved by Cunge (1969) and named the Muskingum-Cunge method (Barry and Bajracharya, 1995).

3.2.3.2 Water Quality Parameters Generation and Treatment

Water quality parameter concentrations, total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP) and Fe, Mn, Cu for the second part of project, are generated from residential areas, sealed and unsealed roads. The pollutant generation rates were adapted from a comprehensive statistical overview for urban stormwater quality by Duncan (1999) (Table 3-3). Duncan's report summarises the stormwater concentrations of more than 20 water quality parameters from over 500 overseas studies and examines the relationship between pollutant types and catchment characteristics.

Table 3-3: Pollutant concentrations generated from sources (adapted from Duncan, 1999)

Pollutant	Urban		Sealed Roads		Unsealed Roads	
	Log Transformed Data					
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
TSS	2.19	0.48	2.41	0.46	1.84	0.66
TP	-0.4	0.34	-0.59	0.44	-0.59	0.44
TN	0.42	0.28	0.33	0.3	0.33	0.3

The simulation of the stormwater treatment measures was achieved by MUSIC using the Universal Stormwater Treatment Model (USTM), which was a two-stage process. The hydrodynamic model of treatment facilities was undertaken as a series of well-mixed water bodies set in the physical form of the stormwater treatment system. Afterwards, the reduction of contaminants in these water bodies was calculated using the first-order decay equation.

Stormwater has the tendency to spread as it moves throughout the treatment system as a result of turbulence and hydrodynamic effects. Therefore, the most effective scenarios occur in the treatment system when the surface area is completely engaged and stagnant zones do not come into existence through flow paths. In other words, as the flow characteristic converges into the ideal pug-flow condition, more effective treatment occurs in the system due to all sections of inflow depends on the equal detention time. This behaviour of stormwater is modelled as Continuously Stirred Tank Reactors (CSTR) in the MUSIC as a part of the first stage of the USTM. In this case, behaviour of the modelled treatment system depends on the number of CSTRs used. A treatment system model that has single CSTR means the inflow directly and fully mixed with actual content. A higher CSTR number represents the limited dispersion for inflow. In other words, when the number of CSTRs increases, the pug-flow condition is more likely to occur in the treatment system. (Wong et al., 2006).

Fair and Geyer's (1954) short-circuiting parameter (n) or hydraulic efficiency (λ) from Persson et al (1999) can be a good representative for the number of CSTRs used.

$$N \sim \frac{1}{1-n} ; \quad N \sim \frac{1}{1-\lambda} \quad (3.1)$$

Persson et al (1999) provided several two-dimensional models to obtain λ values for 13 pond designs which have different inlet/outlet properties and physical characteristics (Figure 3-5).

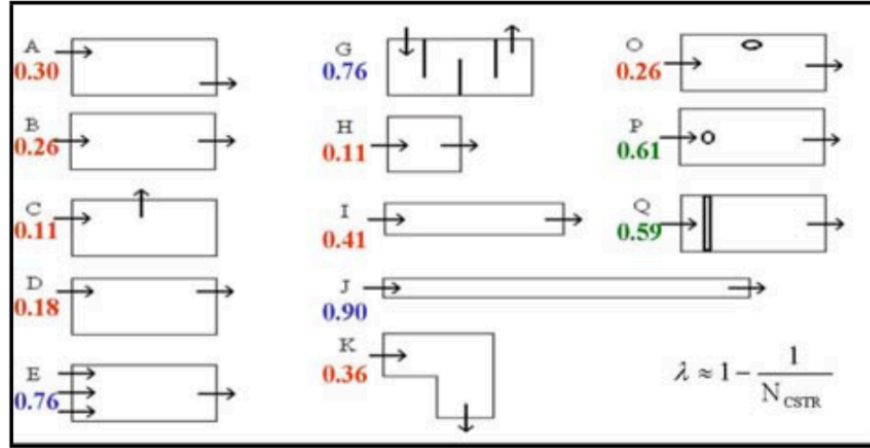


Figure 3.5: Hydraulic efficiencies (λ) of treatment systems (adapted from Wong et al., 2006)

When the inflow with different pollutants moves through the treatment system, or one CSTR moves to another, the quality of the inflow depends on multifarious factors. Likewise, completely and detailed model to represent flow behaviour may be very complex. However, the entire effect can be described as the pollutant concentration in a section has the tendency to approach an equilibrium by way of an exponential decay process for a specific time and site. This action is defined as the first order kinetic model in USTM and demonstrated in equation (3.2).

$$C_{out} = C^* + (C_{in} - C^*)e^{-\frac{k}{q}} \quad (3.2)$$

C^* = background concentration (mg/L)

C_{in} = input concentration (mg/L)

C_{out} = output concentration. (mg/L)

k = rate constant (decay) (m/y)

q = hydraulic loading (m/y)

The USTM applies the first order kinetic model to make simulation of contaminant's actions as the movement from one CSTR to another through the treatment system. This approach is mostly used for the prediction of wastewater treatment systems and the combined-sewer systems effectiveness (Kadlec and Knight, 1996), (Wong and Geiger, 1997), (Wong et al., 1999), (Wong et al., 2001). Particle size and settling velocity distributions are the main factors that influence the decay rate constant (k) and the background concentration (C^*). Theoretically, if the inflow includes large particles, the decay rate will be higher (large particles settle quickly). Similarly, the background concentration will be higher as a result of the detention time of finer particles being shorter. However, field experiments demonstrate that the settling velocity does not completely synchronize with the constant decay rate (k) due to bio-chemical processes and other external factors during the treatment. Initially, related k and C^* values for TSS, TN and TP for this project were adapted from calibrated values for Melbourne and Sydney catchments (Duncan et al., 2004) and demonstrated in Table (3-4).

Table 3-4: k-C* values for water quality parameters, adapted from (Duncan et al., 2004)

Treatment System	k (m/y)	C*(mg/l)	k (m/y)	C*(mg/l)	k (m/y)	C*(mg/l)
	TSS		TP		TN	
Ponds	300	30	200	0.2	50	1.3
Tanks	400	12	300	0.13	40	1.4
Swales	8000	20	6000	0.13	500	1.4

3.2.4 Sustainable Drainage System Design Scenarios

In this section of the project, five different treatment system scenarios were built to examine how stormwater quality influences the groundwater quality. The main focus of the project in this section and previous sections was to examine the relationship between stormwater quality and groundwater quality. Therefore, two infiltration, detention ponds were designed as fixed system components. Pond 1 was placed in the Area-21 to treat the runoff from sub-catchment 1 and Pond 2 was designed in Area-30 to treat runoff from sub-catchment 2. The properties of ponds are demonstrated in Table (3-5). The physical properties of the ponds were chosen due to pollutant reduction rates. After several models, the critical surface area of the ponds was surveyed as being between 4000-6000m². Ponds with smaller surface area from 4000m² were liable to generate negative pollutant reduction rates due to heavy rainfall during the wet-period in the case study area and do not represent a good fixed design component.

Table 3-5: Properties of Pond 1 and Pond 2

Ponds	Surface Area (m ²)	Detention Depth (m)	Permanent Pool Volume (m ³)	Exfiltration Rate (mm/hr)	Number of CSTR Cells
Pond 1	4000	2	1000	0.36	4
Pond 2	5500	2	1375	0.36	4

3.2.4.1 Scenario 1

Scenario 1 included just two fixed ponds as shown in Figure 3-6. As mentioned before, Pond 1 was designed to collect and treat the stormwater which was generated by sub-catchment 1. Pond 2 was designed to collect and treat the stormwater which was generated by sub-catchment 2.

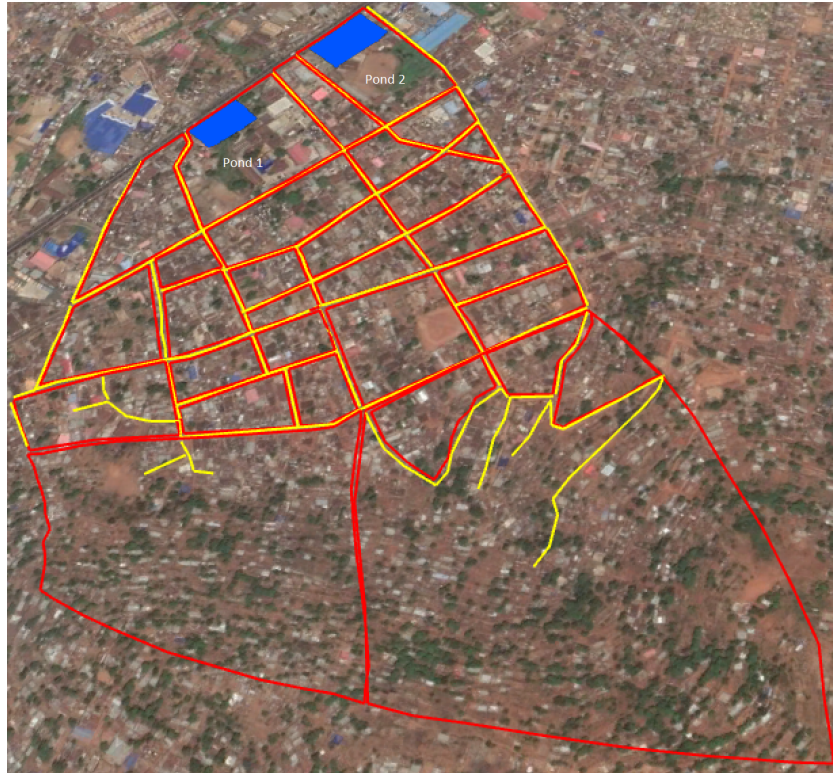


Figure 3.6: Conceptual illustration of scenario 1

3.2.4.2 Scenario 2

Scenario 2 included fixed ponds and 20 vegetated swales in different locations as shown in Figure 3-7. All swales are designed to treat the stormwater from adjacent roads. The properties of the swales are demonstrated in Table 3-6.

Table 3-6: Properties of swales

Swale	Length (m)	Swale	Length (m)	Swale	Length (m)	Swale	Length (m)
Swale 1	141	Swale 6	67.3	Swale 11	32	Swale 16	162
Swale 2	147	Swale 7	64.6	Swale 12	105	Swale 17	76
Swale 3	166	Swale 8	110	Swale 13	87.8	Swale 18	93.4
Swale 4	74.6	Swale 9	65.8	Swale 14	62.6	Swale 19	74.6
Swale 5	89.1	Swale 10	40.3	Swale 15	78	Swale 20	164
Swales Fixed Properties							
Bed Slope (%)	Base Width (m)		Top Width (m)		Depth (m)	Vegetation Height (m)	
1	1		3		0.5	0.25	

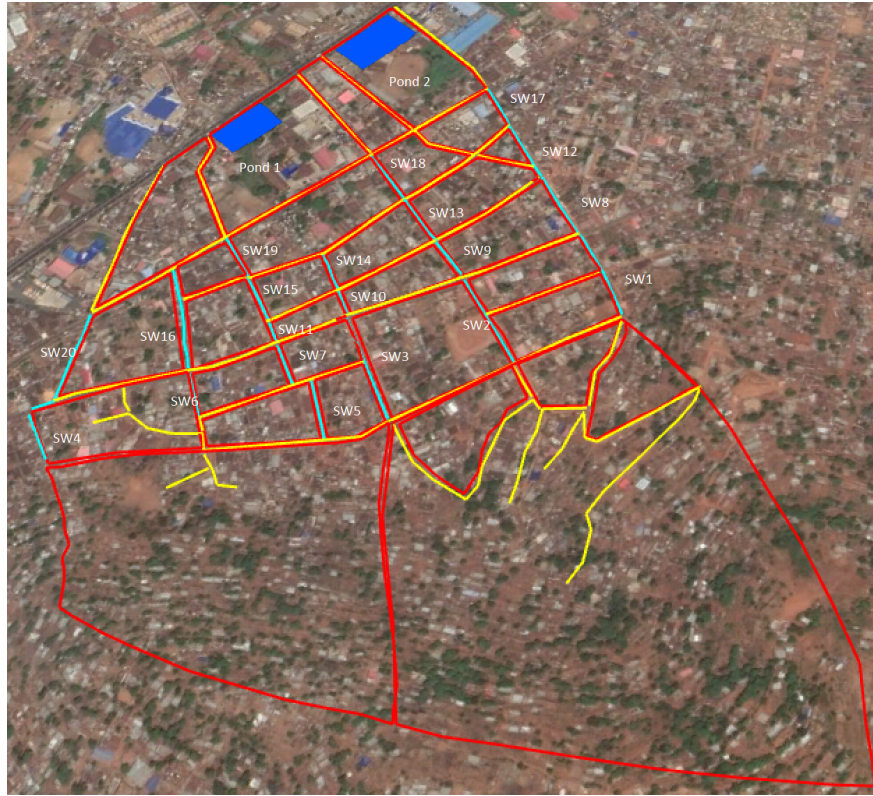


Figure 3.7: Conceptual illustration of scenario 2

3.2.4.3 Scenario 3

Scenario 3 included two fixed ponds and ten stormwater storage tanks in the downstream of Area-1 to treat the stormwater directly generated there. Similarly, ten stormwater storage tanks in the downstream of Area 1 and Area 4-6 to treat stormwater directly from them. All 20 stormwater tanks were assigned the water volume loss as water re-use $0.1\text{m}^3/\text{day}$. The volume of all the tanks was defined as 100m^3 . The stormwater storage capacity of per two sub-catchments is 500m^3 and was 1000 m^3 for total catchment (Figure 3-8).

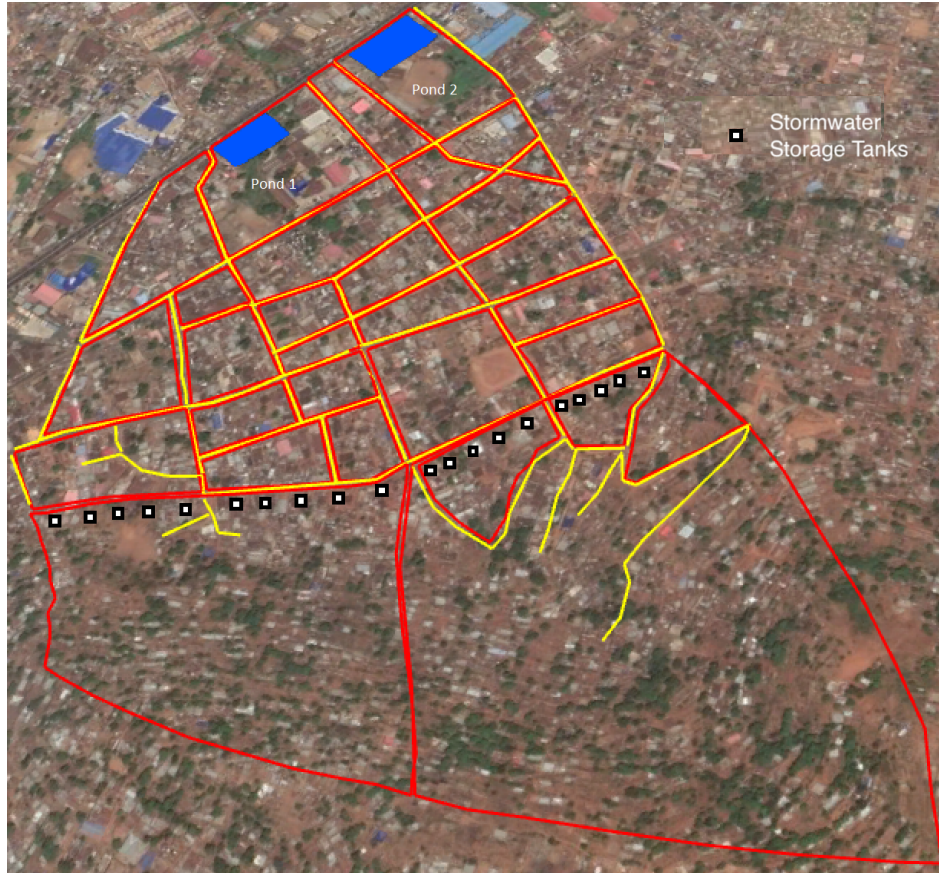


Figure 3.8: Conceptual illustration of scenario 3

3.2.4.4 Scenario 4

Scenario 4 includes two fixed ponds and 147 relatively small stormwater storage tanks. These stormwater storage tanks were in a variety of areas as shown in Figure 3-9. Each area included 7 stormwater storage tanks and the volume of each tank was designed as 7m^3 (total tank volume per area is 49m^3). The stormwater storage tanks in such areas were designed to directly treat the stormwater generated from this area. All 147 stormwater tanks were assigned the water volume loss as water re-use $0.01\text{m}^3/\text{day}$. The total stormwater storage volume in the catchment is 1029m^3 .

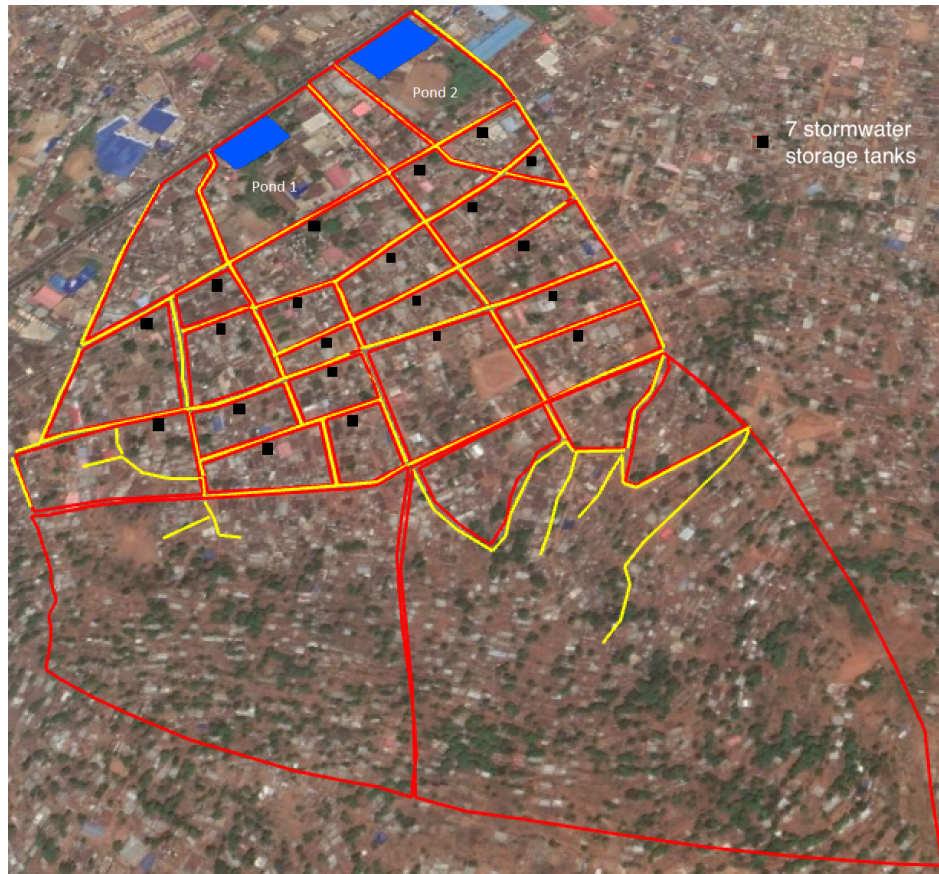


Figure 3.9: Conceptual illustration of scenario 4

3.2.4.5 Scenario 5

Scenario 5 included fixed ponds, the same vegetated swale design as in scenario 2 and stormwater storage tanks in the same areas as scenario 4. The difference of the design of the stormwater storage tanks in this scenario was that each area includes three tanks, 63 in total. Each tank was designed as 7m^3 and total stormwater storage volume is 441m^3 in the catchment.

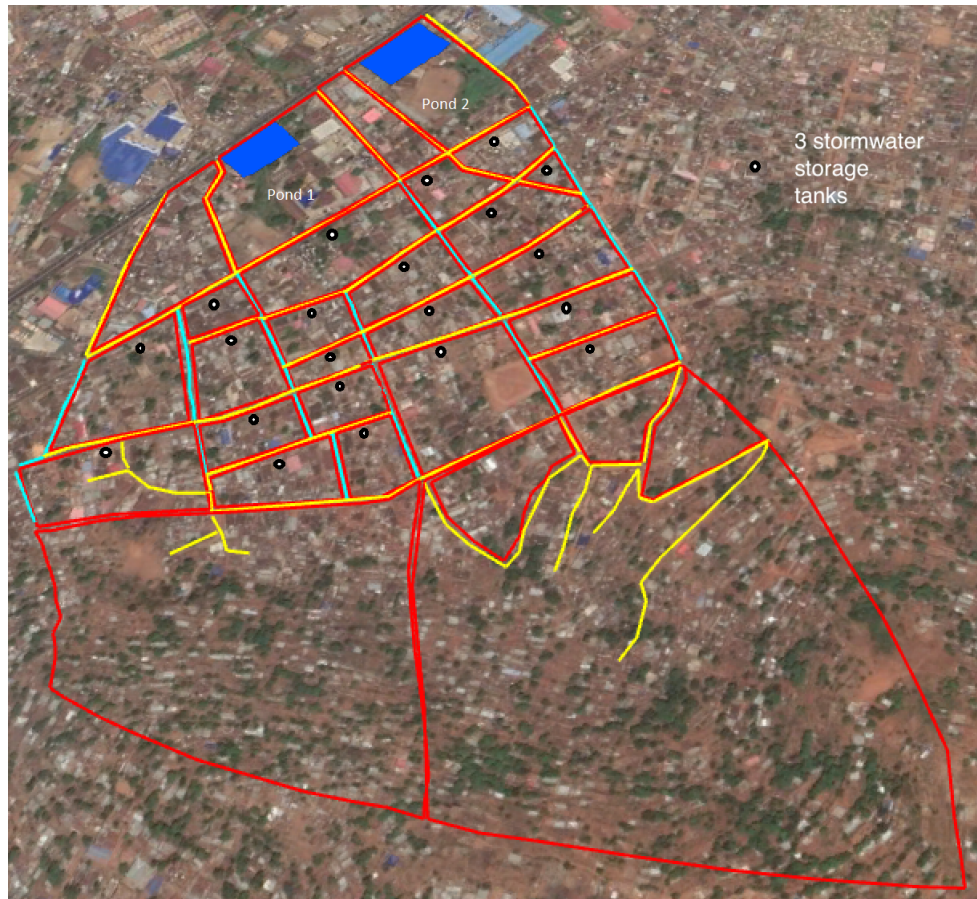


Figure 3.10: Conceptual illustration of scenario 5

3.2.5 Ponds Design Scenarios

In this section, ponds, or infiltration devices, were taken into consideration in detail. Three significant properties of ponds and their influence on groundwater quality were examined. Initially, sustainable drainage systems design scenario 1 was examined to observe how the initial and permanent volume of the ponds influence the exfiltrated water quality from ponds to groundwater. The initial volumes were chosen to be 0m^3 , 100m^3 , 200m^3 , 300m^3 and 400m^3 in order. Second, the sustainable drainage system in scenario 5 was examined to observe how different hydraulic efficiency values (different number of CSTR cells) influence the groundwater quality. The chosen hydraulic efficiency values are 0.11, 0.26, 0.61 and 0.76. Similarly, scenario 5 was examined to observe how different geological properties influence the exfiltrated water quality. The chosen infiltration rates values are 0.36mm/hr (heavy clay), 3.6 mm/hr (medium clay), 36 mm/hr (sandy clay), 180 mm/hr (sandy loam), 360 mm/hr (sand), 3600 mm/hr (coarse sand).

3.2.6 k-C* scenarios

The aim of this section is to examine how different constant decay rates and the background concentration of sustainable drainage system devices influence the groundwater quality. The adapted values for k-C* in previous sections were calibrated and were recommended values for the urban catchments in Melbourne and Sydney. However, the calibration process is undertaken by only focusing the during rainfall event operation. Although the constant decay rate (k) and background concentration (C*) changes were mainly due to the physical removal factors in the treatment system, other factors could have a significant impact on the treatment performance of the system such as bio-chemical processes, re-mobilisation of particles, maintenance of the treatment system or unexpected pollutant loads to the treatment system. The current version of the universal stormwater treatment model does not include these factors. Therefore, k- C* values are semi-hypothetically manipulated firstly just for ponds and secondly for all treatment devices for sustainable drainage system design scenario 5 to observe their influence on groundwater quality (Table 3-7). Scenarios were built with relatively lower k and higher C* values and continued with increasing k and decreasing C* values in order.

Table 3-7: k-C* values scenarios

k-C* scenarios just for ponds							
Scenario 1				Scenario 2			
Ponds	TSS	TP	TN	Ponds	TSS	TP	TN
k (m/y)	30	20	5	k (m/y)	300	200	50
C* (mg/l)	150	0.3	2.5	C* (mg/l)	130	0.25	2.2
Tank	TSS	TP	TN	Tank	TSS	TP	TN
k (m/y)	400	300	40	k (m/y)	400	300	40
C* (mg/l)	12	0.13	1.4	C* (mg/l)	12	0.13	1.4
Swales	TSS	TP	TN	Swales	TSS	TP	TN
k (m/y)	8000	6000	500	k (m/y)	8000	6000	500
C* (mg/l)	20	0.13	1.4	C* (mg/l)	20	0.13	1.4
Scenario 3				Scenario 4			
Ponds	TSS	TP	TN	Ponds	TSS	TP	TN
k (m/y)	3000	2000	500	k (m/y)	30000	20000	5000
C* (mg/l)	100	0.2	2	C* (mg/l)	70	0.15	1.5
Tank	TSS	TP	TN	Tank	TSS	TP	TN
k (m/y)	400	300	40	k (m/y)	400	300	40
C* (mg/l)	12	0.13	1.4	C* (mg/l)	12	0.13	1.4
Swales	TSS	TP	TN	Swales	TSS	TP	TN
k (m/y)	8000	6000	500	k (m/y)	8000	6000	500
C* (mg/l)	20	0.13	1.4	C* (mg/l)	20	0.13	1.4

k-C* scenarios for ponds, tanks and swales							
Scenario 1				Scenario 2			
Ponds	TSS	TP	TN	Ponds	TSS	TP	TN
k (m/y)	30	20	5	k (m/y)	300	200	50
C* (mg/l)	150	0.3	2.5	C* (mg/l)	130	0.25	2.2
Tank	TSS	TP	TN	Tank	TSS	TP	TN
k (m/y)	40	30	4	k (m/y)	400	300	40
C* (mg/l)	150	0.3	2.5	C* (mg/l)	130	0.25	2.2
Swales	TSS	TP	TN	Swales	TSS	TP	TN
k (m/y)	800	600	50	k (m/y)	8000	6000	500
C* (mg/l)	150	0.3	2.5	C* (mg/l)	130	0.25	2.2
Scenario 3				Scenario 4			
Ponds	TSS	TP	TN	Ponds	TSS	TP	TN
k (m/y)	3000	2000	500	k (m/y)	30000	20000	5000
C* (mg/l)	100	0.2	2	C* (mg/l)	70	0.15	1.5
Tank	TSS	TP	TN	Tank	TSS	TP	TN
k (m/y)	4000	3000	400	k (m/y)	40000	30000	4000
C* (mg/l)	100	0.2	2	C* (mg/l)	70	0.15	1.5
Swales	TSS	TP	TN	Swales	TSS	TP	TN
k (m/y)	80000	60000	5000	k (m/y)	800000	600000	50000
C* (mg/l)	100	0.2	2	C* (mg/l)	70	0.15	1.5

3.3 Groundwater quality modelling

In this section of the project, relatively worse scenarios among stormwater quality models which have more likely to create serious negative impacts on groundwater quality were chosen to observe how groundwater quality is affected by stormwater when the sustainable drainage system design scenarios were implemented in the case study area. As well as the total suspended solids, total phosphorus, total nitrogen, three heavy metal pollutants which are Iron (Fe), Copper (Cu) and Manganese (Mn) were also applied to stormwater model for the chosen scenario.

The chosen scenario for the stormwater quality model included relatively higher background concentrations for related water quality parameters (k-C* values scenario 2). It was intended to achieve more representative models for the case study area so that related k-C* values were assigned semi-hypothetically. k-C* values for heavy metals (Fe, Cu, Mn) were assigned after a comprehensive literature review according to their settling velocity in the treatment device and particle size distribution from China, the UK, Europe, the US, Africa South America and South Asia. (main factors for k value) (MPCA, 2008), (Institute of Ecology & Resource Management University of Edinburgh, 2019), (Tedoldi et al., 2016), (Ellis et al., 1987), (Wang et al., 2014), (Stagge et al., 2012), (Li et al., 2008), (Chubaka et al., 2018), (Sadeghi, Harchegani and Younesi, 2012), (Zonta, Zaggia and Argese, 1994), (Adiyiah et al., 2014), (Diop et al., 2015), (Ayoubi, Soltani and Khademi, 2018), (Abbasi, 2014), (Silva et al., 2010), (Quinn and Dussailant, 2013)

(Boller,1997). Similarly, heavy metal pollutants generation from sources are adapted from Duncan (1999). Likewise, for this scenario, ponds were designed with permanent volumes which were 1000m³ for pond 1 and 1375m³ for pond 2.

Table 3-8: k-C* values for chosen stormwater model scenario

Ponds	TSS	TP	TN	Fe	Cu	Mn
k (mg/l)	300	200	50	50	70	60
C* (mg/l)	130	0.25	2.2	0.3	0.01	0.05
Tanks	TSS	TP	TN	Fe	Cu	Mn
k (mg/l)	400	300	40	40	60	50
C* (mg/l)	130	0.25	2.2	0.3	0.01	0.05
Swales	TSS	TP	TN	Fe	Cu	Mn
k (mg/l)	8000	6000	500	500	700	600
C* (mg/l)	130	0.25	2.2	0.3	0.01	0.05

Table 3-9: Heavy metal concentrations generated from sources, adapted from Duncan (1999)

Water Quality Parameters (mg/l)	Urban		Sealed Roads		Unsealed Roads	
	Log Transformed Data					
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Total Copper	-1.21	0.49	-1.09	0.44	-1.09	0.44
Total Iron	0.2	0.51	0.6	0.39	0.6	0.39
Total Manganese	-0.63	0.45	-0.63	0.45	-0.63	0.45

3.3.1 Modflow – Mt3dms

Modflow – Mt3dms software and related advection, dispersion and sink and source packages were used to build the groundwater quality model. Modflow was originally developed as a groundwater flow code and was published in 1984 by USGS (Hughes, Langevin and Banta, 2017). Mt3dms provides numerical models for three-dimensional contaminant transport which is relatively more complex and challenging than the groundwater flow model. Generally, the methodology of numerical models includes Eulerian, Lagrangian or mixed Eulerian-Lagrangian approach to solve related advective-dispersive equations (Neuman 1984). Mt3dms uses the mixed Eulerian-Lagrangian approach to combine the advantages of both approaches and to minimise their disadvantages. Advection terms are solved with a Lagrangian method and dispersion and reaction terms are solved with Eulerian method. In the Lagrangian part of the model, the advection term is solved by applying forward tracking method of characteristics, backward tracking method of characteristics or mixed of them. For the Eulerian part, dispersion and reaction terms are solved by applying conventional block-centered finite-difference approach (Zheng and Papadopoulos, 1990). The main governing equation of Mt3dms defining three-dimensional contaminant transport model in aquifers is demonstrated in equation (3-3) (Javandel, Doughty, and Tsang, 1984).

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (v_i C) + \frac{q_s}{\theta} C_s + \sum_{k=1}^N R_k \quad (3.3)$$

C = concentration of contaminants, ML^{-3} ;
 t = time, T ;
 X_i = the distance along the respective Cartesian coordinate axis, L ;
 D_{ij} = hydrodynamic dispersion coefficient, L^2T^{-1} ;
 v_j = seepage or linear pore water velocity, LT^{-1} ;
 q_s = volumetric flux of water per unit volume of aquifer representing sources (positive) or sinks (negative), T^{-1} ;
 C_s = concentration of the sources or sinks, ML^{-3} ;
 θ = porosity of the subsurface medium, dimensionless ;
 $\sum_{k=1}^N R_k$ = chemical reaction term, $ML^{-3}T^{-1}$.

The relationship between the transport equation and the flow equation is demonstrated in equation (3-4).

$$v_i = -\frac{K_{ii}}{\theta} \frac{\partial h}{\partial x_i} \quad (3.4)$$

K_{ii} = principal component of the hydraulic conductivity tensor, LT^{-1} ;
 h = hydraulic head, L .

3.3.2 Time-steps of Groundwater Quality Model

The groundwater quality model was simulated as two time-steps. The first one was a contaminant transport model for all stormwater model periods which was from 01/01/2010 to 31/12/2010. The second one is a contaminant transport model for 30 days from 15/04/2010 to 15/05/2010. The second one approximately covers the first 30 days of the wet-period in the case study area.

3.3.3 Model Properties

The geological properties of the aquifer were adapted from four borehole drilling reports from Freetown, Sierra Leone. The reports were prepared from water companies by the purpose of Ministry of Water Resources, Sierra Leone (provided as appendix). The geological model was designed as 1.5km length, 1.5km width and 60m depth. It consisted of three layers with different permeable features. The first layer was between 0-25m is clay with the permeability of 0.36mm/h, between 25-35m is sandstone with the permeability of 36 mm/h and between 35-60m was fractionated gabbroic rock with the permeability of 3600 mm/h. The static water level was at the 10m depth (Figure 3.11).

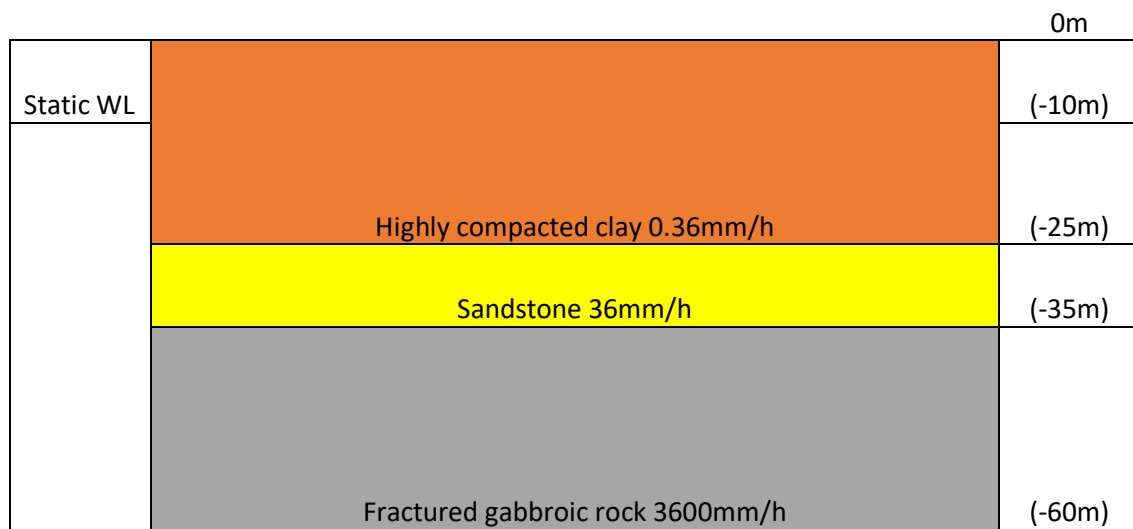


Figure 3.11: Conceptual illustration of modelled aquifer

Chapter 4. Case study

4.1 Introduction

Freetown peninsula is located on the west coast of Sierra Leone near the Atlantic Ocean. Freetown is the capitol of Sierra Leone and the largest city in the country with population of 1,055,964 in the 2015 census (Statistics Sierra Leone, 2019). Freetown initially attracted the attention of European navigators in sixteenth century because of its natural harbour and location on the trade routes (Jarrett, 1956). Since then, it has maintained its distinction as an important port for Western Africa, even though certain fluctuations have taken place, such as the civil war in the 1990s. Today, the city's economy revolves largely around its natural harbour. This port is the fourth largest natural port in the world.

Like the general climate in Sierra Leone, the dominant climate in Freetown is the tropical climate. While the rainy season is experienced from May to October throughout the year, the climate is generally dry. In the cool period from November to February, the most important factor that softens the city's air is the humid air and warm winds called 'Harmattan', and blowing from the Sahara Desert towards the country. One of the main water sources of Freetown is groundwater (Fileccia, 2018). The official number of the number of boreholes and hand-dug wells which hydrogeological details have been processed is 79 in Freetown by 2017. However, the provided data does not consist of the recording or estimation of transmissivity, permeability, storage/porosity, influence radius or related water quality parameters. Moreover, reliable data limitation is the main concern for the studies about water management and hydrogeology at the regional or national level. Monitoring surface water even for rivers is very limited and hydrographs and pollutographs do not exist. Stratigraphic logs are not complete. Calibration for statistical models are not carried out and there are uncertainties for units even for some official borehole tests. (Fileccia et al., 2017).

The polluted water consumption for drinking and bathing is a significant cause for infectious diseases especially for children under 14 years of age. According to the World Bank (1993), 40% of the children aged between 5-14 died as a result of waterborne diseases such as malaria, diarrhoeal and cholera. Another water related risk is floods during the wet period and the mudslides due to deforestation and inadequate drainage systems (Figure 4.3), (Figure 4.4).

The semi-hypothetical case study area is the Maeba Town urban catchment which is located at north west of Freetown peninsula (Figure 4.1), (Figure 4.2). The Maeba Town urban catchment as rapidly urbanised and covered by impermeable laterite crust (Wells, 1962). Nearly all rainfall is discharged promptly into the sea as stormwater runoff due to very low permeability clay soils as well as a high number of paved surfaces in the urban area (SLRSA, 1995). Similarly, the Maeba Town urban surface is classified as impermeable cover by the Sierra Leone Groundwater Resources Database and the Ministry of Water Resources (SALGRID) in 2017. Therefore, the urban catchment surface is modelled as completely impermeable.

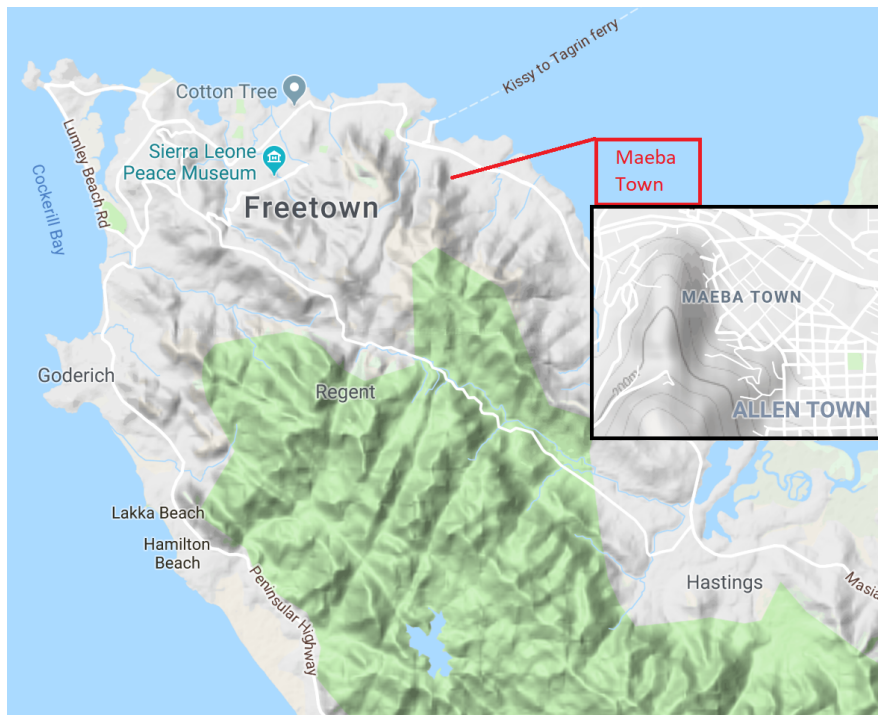


Figure 4.1: Location of Meaba Town in Freetown peninsula (adapted from Google Earth)



Figure 4.2: General overview of Freetown (adapted from Financial Times)



Figure 4.3: Maeba Town during wet-period (adapted from Financial Times)



Figure 4.4: Maeba Town during mudslide in August 2017 (adapted from Financial Times)

4.2 Case Study Set-up

4.2.1 Catchment Model Results

The inflow statistics of the receiving node which was located on the downstream of urban catchment are demonstrated in Table 4.1. The receiving node was modelled to collect all flow of the urban catchment. High flow rates and pollutant concentrations showed that the wet-period of tropical climate have a direct influence of stormwater in urban catchments. Likewise, the high amount of fluctuations, in other words, standard deviation, was the result of the difference of the daily rainfall rates between dry and wet periods.

Table 4.1 Downstream of urban catchment, receiving node statistics

Freetown / Maeba Town	Downstream Receiving Node Statistics						
Inflow	mean	standard deviation	median	maximum	minimum	10 percentile	90 percentile
Flow (cubic metres/sec)	6.86E-02	7.59E-02	3.94E-02	0.236	0	0	0.197
TSS Concentration (mg/L)	185	182	195	1.57E+03	0	0	379
TP Concentration (mg/L)	0.355	0.294	0.405	1.46	0	0	0.693
TN Concentration (mg/L)	2.16	1.7	2.69	6.25	0	0	4.07
TSS Load (kg/Day)	1.66E+03	2.21E+03	945	1.51E+04	0	0	4.42E+03
TP Load (kg/Day)	3.19	3.98	1.77	27.3	0	0	8.94
TN Load (kg/Day)	19.8	23.6	10.9	122	0	0	56.9
Gross Pollutant Load (kg/Day)	181	150	203	394	0	0	375

Table 4.1 shows that the flow rate of the catchment and the pollutant concentrations can reach significant levels, although the catchment area was relatively small. The other remarkable point about the results is the standard deviation. Due to the tropical climate rainfall characteristics, the difference between the maximum and the minimum value for each examined parameter was considerably high. In other words, this is the representative of the difference between dry and wet period during a year. These significant fluctuations were not observed for infiltrated water from ponds to groundwater because the main influencer for infiltrated water quality is particle size distribution, settling velocity of pollutants and background concentration of ponds instead of pollutant concentrations in stormwater. In fact, the pollutant concentration of the infiltrated water from ponds conveyed approximately the same number.

4.2.2 Sustainable Drainage System Design Scenarios

The results for five different sustainable drainage system design scenarios are demonstrated in Figure 4.5. These results are annual pollutant concentrations for infiltrated water from ponds.

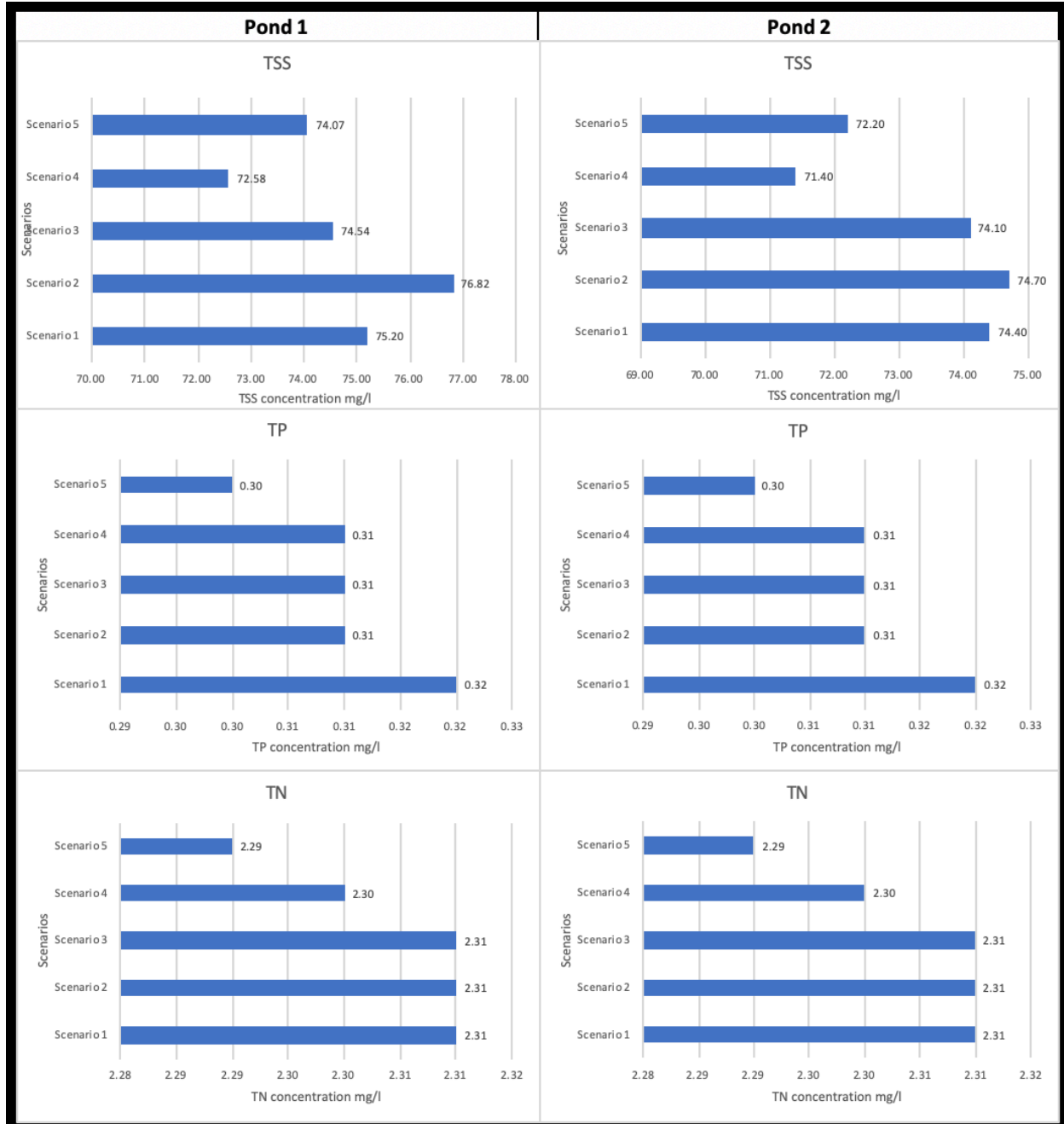


Figure 4.5: Pollutant concentrations for sustainable drainage system design scenarios

4.2.3 Different Initial Pond Volumes

The results for five different pond design scenarios with different initial volume are demonstrated in Figure 4.6. The results are annual pollutant concentrations for infiltrated water from ponds. The sustainable drainage system design in scenario 1 was used to observe the effect of the different initial pond volumes to infiltrated water quality.

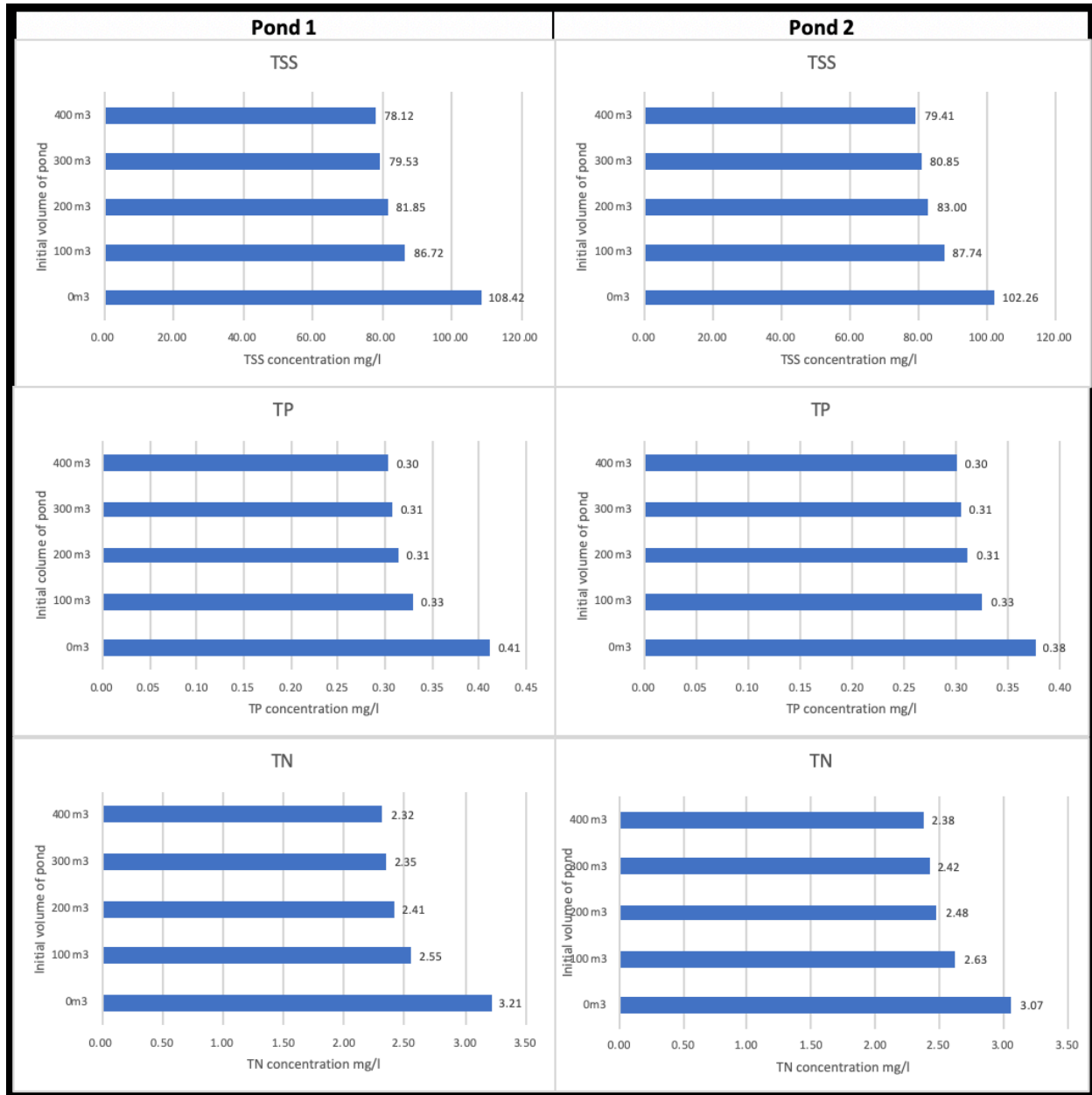


Figure 4.6: Pollutant concentrations for different initial pond volumes

4.2.4 Different Geological Properties of Pond Surface

The results for different geological properties of pond surface are demonstrated in Figure 4.7. The results are annual pollutant concentrations for infiltrated water from ponds. The sustainable drainage system scenario in 5 was used to observe the effect of different infiltration rates to infiltrated water quality.

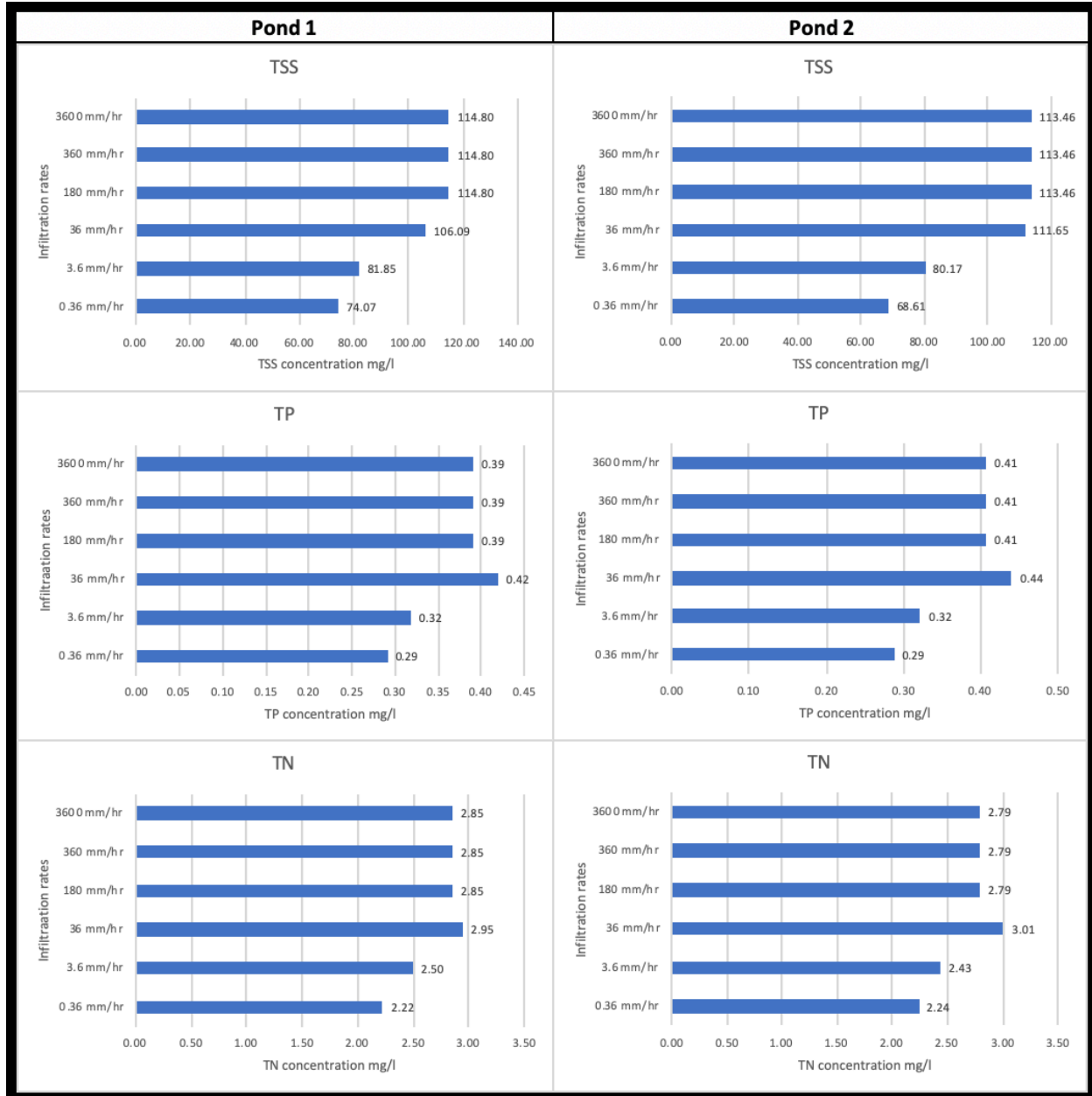


Figure 4.7: Pollutant concentrations for different infiltration rate scenarios for pond surface

4.2.5 Different Hydraulic Efficiency Values of Ponds

The results for different hydraulic efficiency values (λ) are demonstrated in Figure 4.8. The results are annual pollutant concentrations for infiltrated water from ponds. The sustainable drainage system scenario in 5 was used to observe the effect of different hydraulic efficiency values (λ) of ponds to infiltrated water quality.

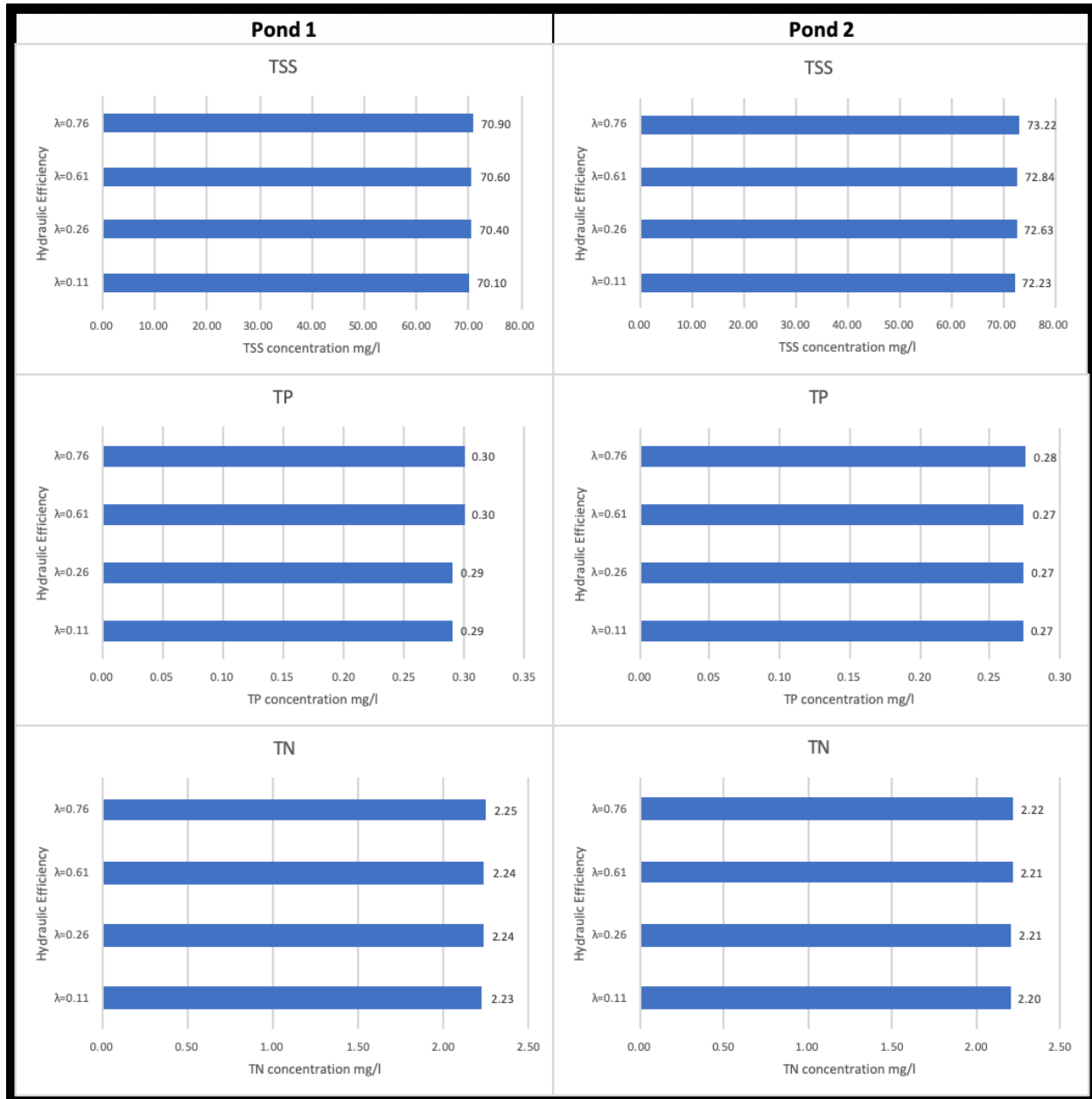


Figure 4.8: Pollutant concentrations for different hydraulic efficiency values (λ) for ponds.

4.2.6 k-C* Scenarios for Ponds

The results for different k-C* values scenarios for ponds are demonstrated in Figure 4.9. The results are annual pollutant concentrations for infiltrated water from ponds. The sustainable drainage system scenario in 5 was used to observe the effect of different k-C* values of ponds to infiltrated water quality.

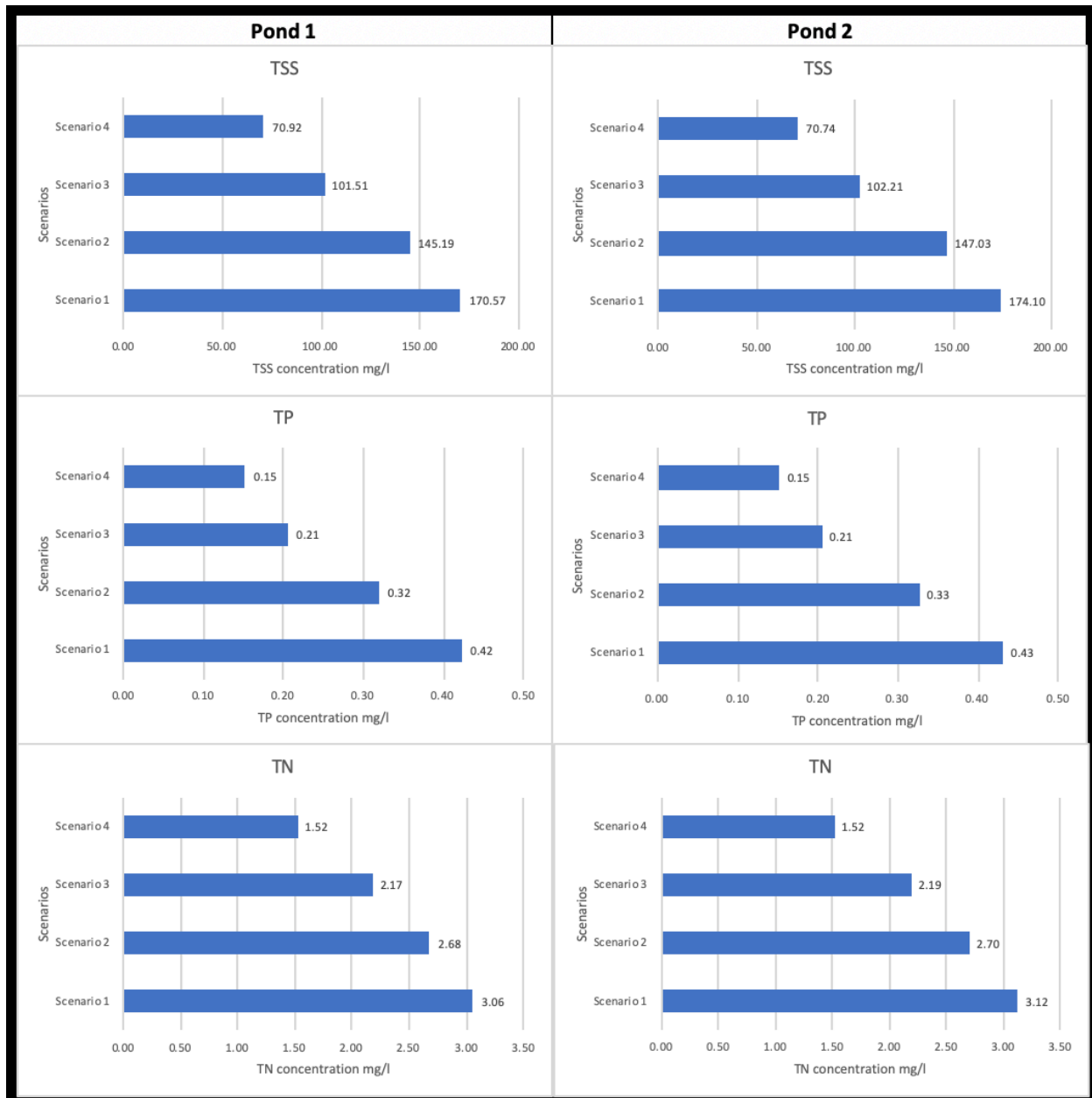


Figure 4.9: Pollutant concentrations for different k-C* values scenarios for ponds

4.2.7 k-C* scenarios for ponds, swales and tanks

The results for different k-C* values scenarios for ponds, swales and tanks are demonstrated in Figure 4.9. The results are annual pollutant concentrations for infiltrated water from ponds. The sustainable drainage system in scenario 5 was used to observe the effect of different k-C* values of ponds, swales and tanks to infiltrated water quality.

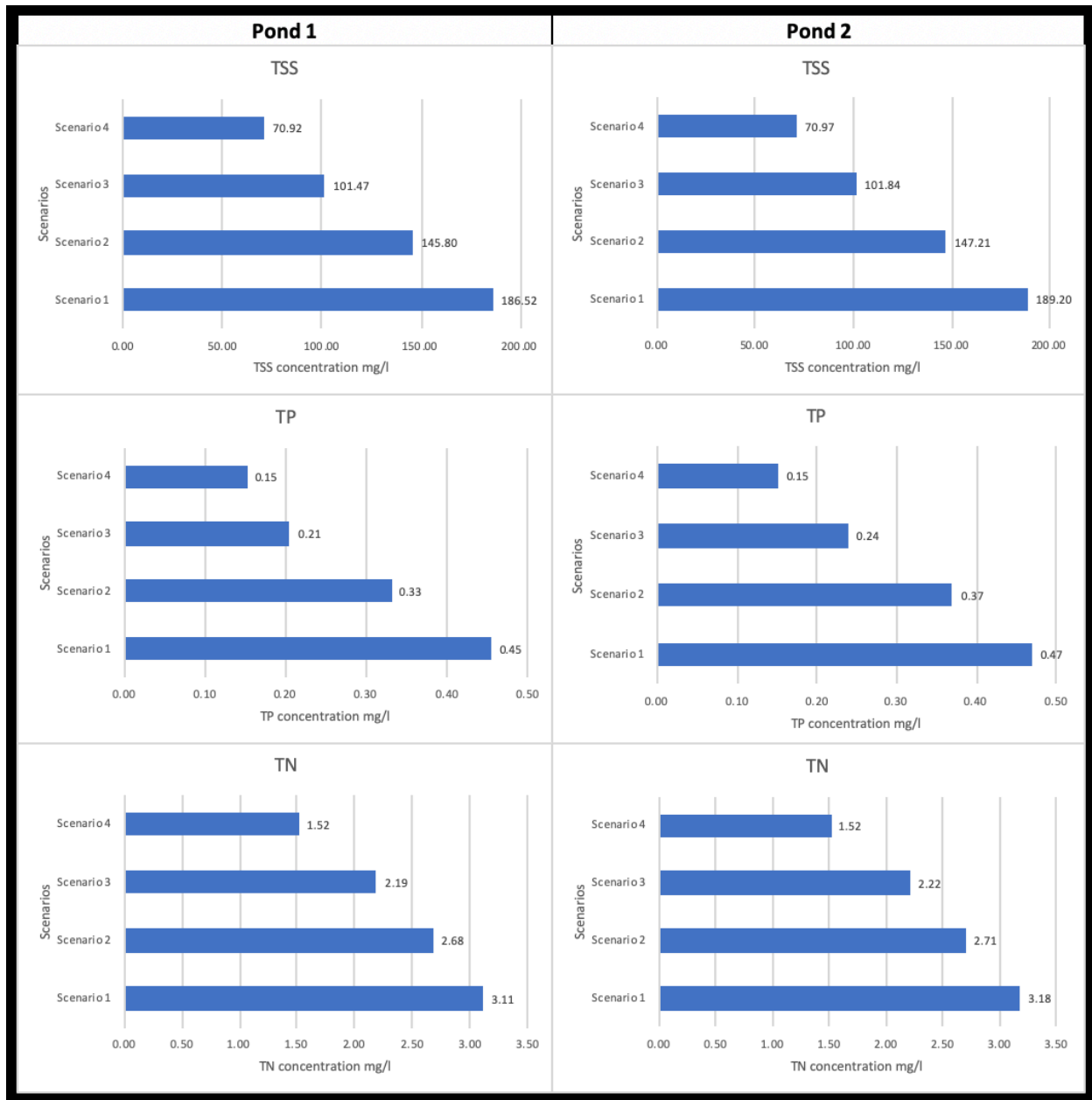


Figure 4.10: Pollutant concentrations for different k-C* values scenarios for ponds, swales and tanks

The different sustainable drainage system design scenario results show that stormwater storage tanks were the main devices to reduce TSS in the infiltrated water. The highest TSS concentration is observed for scenario 2 which does not include stormwater storage tank. For TP and TN, the results follow the expected trend which was more devices and more treatment although the results were very close to each other. However, it can be shown that there was no considerable difference between five scenarios.

The initial pond volume had a direct effect on infiltrated water quality as shown in Figure 4.6. Even 100m³ initial volume improves the infiltrated water quality significantly. The relationship between infiltrated water quality and initial pond volume first followed a linear relationship and then conveyed a certain number for each pollutant concentration. In contrast, hydraulic efficiency (λ) values had no effect on infiltrated water quality. Figure 4.7 shows that annual pollutant concentrations were nearly the same for the three pollutant types in infiltrated water. Permeability rates variance, in other words geological properties of the surface soil of ponds or the infiltration rates of stored water in ponds, demonstrate that high permeable soil created more serious results for groundwater. However, when the infiltration rate is 180mm/h or more, all inflow runoff was infiltrated which is not a good representation for a sustainable drainage system. For TN and TP, 36mm/h was the critical value for infiltrated water quality, although the pollutant concentrations were close to each other.

When it comes to k-C* values scenarios, Figure 4.9 and Figure 4.10 show that they are the most significant factors for infiltrated water quality from ponds for whole catchment between examined sustainable drainage system design scenarios and physical parameters of ponds. This means, even if the most effective sustainable drainage system design is built, even if the urban catchment resilience is high against stormwater pollution, and if the stormwater quality is at acceptable level, if the pollutants in stormwater is carried by fine particles and the background concentration of related treatment device is high, the system was critical for groundwater contamination.

4.2.8 Groundwater quality model results

As mentioned before, for this section of the project, three heavy metals (Fe, Cu, Mn) were integrated into the chosen relatively worse scenarios between different stormwater model scenarios. The first groundwater quality model was built as the 30 days from 15/04/2010-15/05/2010. The time step represents the beginning of the wet season on case study area. The second groundwater quality model is built as the 365 days from 01/01/2010 to 31/12/2010. The time step represents the whole year which was used for all stormwater quality models. Pollutant concentrations for 30 days model was relatively higher than the annual concentrations because of the rapid hydraulic loading at the beginning of the wet period. Table 4.2 shows the maximum pollutant concentration of the groundwater for each of the time-steps.

Table 4.2 Maximum pollutant concentrations for time-steps

Time-step	TSS (mg/l)	TP (mg/l)	TN (mg/l)	Fe (mg/l)	Cu (mg/l)	Mn (mg/l)
365 days	147.2	0.34	2.7	1.87	0.2	0.42
30 days	157	0.39	2.98	2.02	0.28	0.52

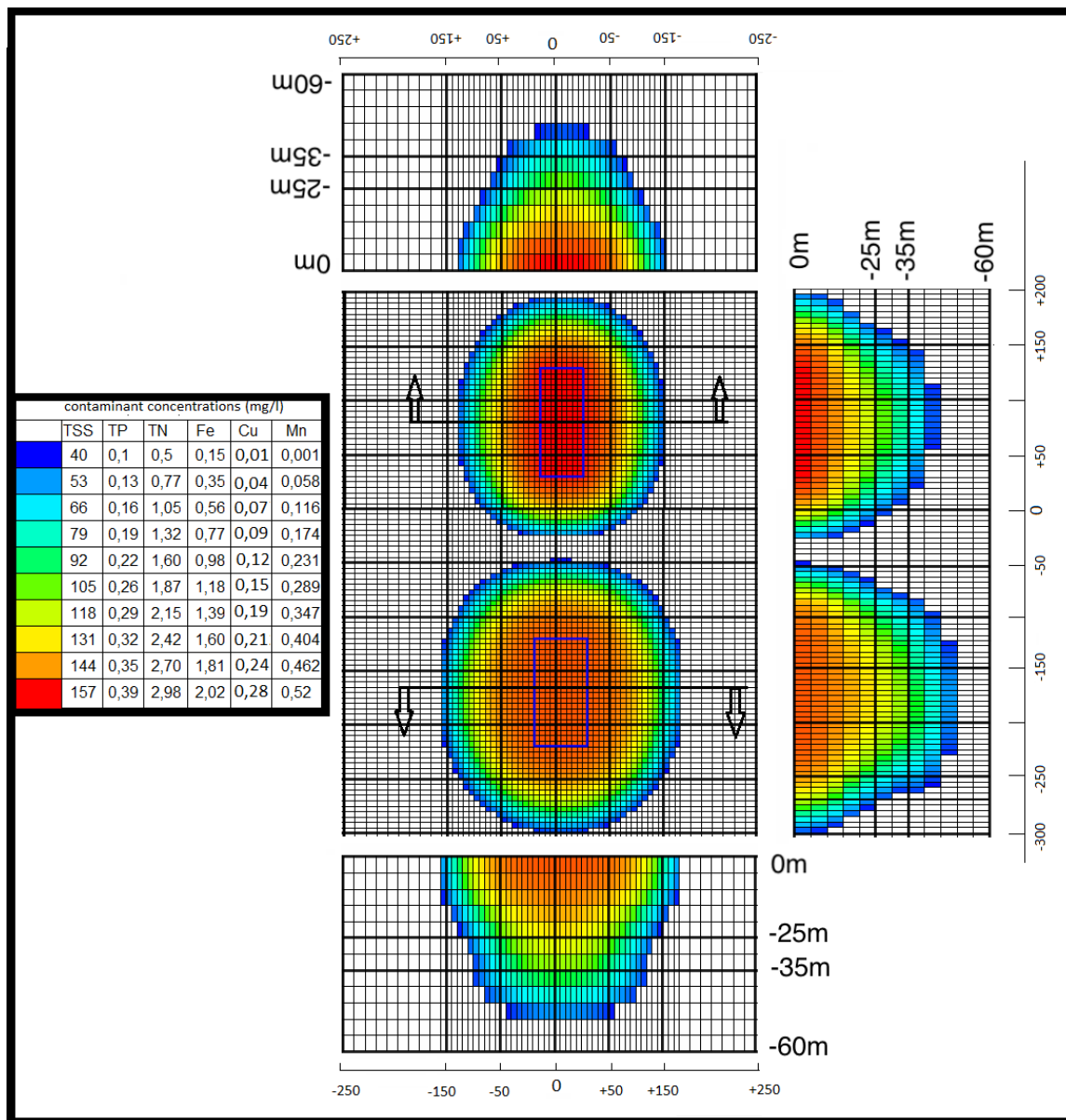


Figure 4.11: Contamination of groundwater for 30 days model

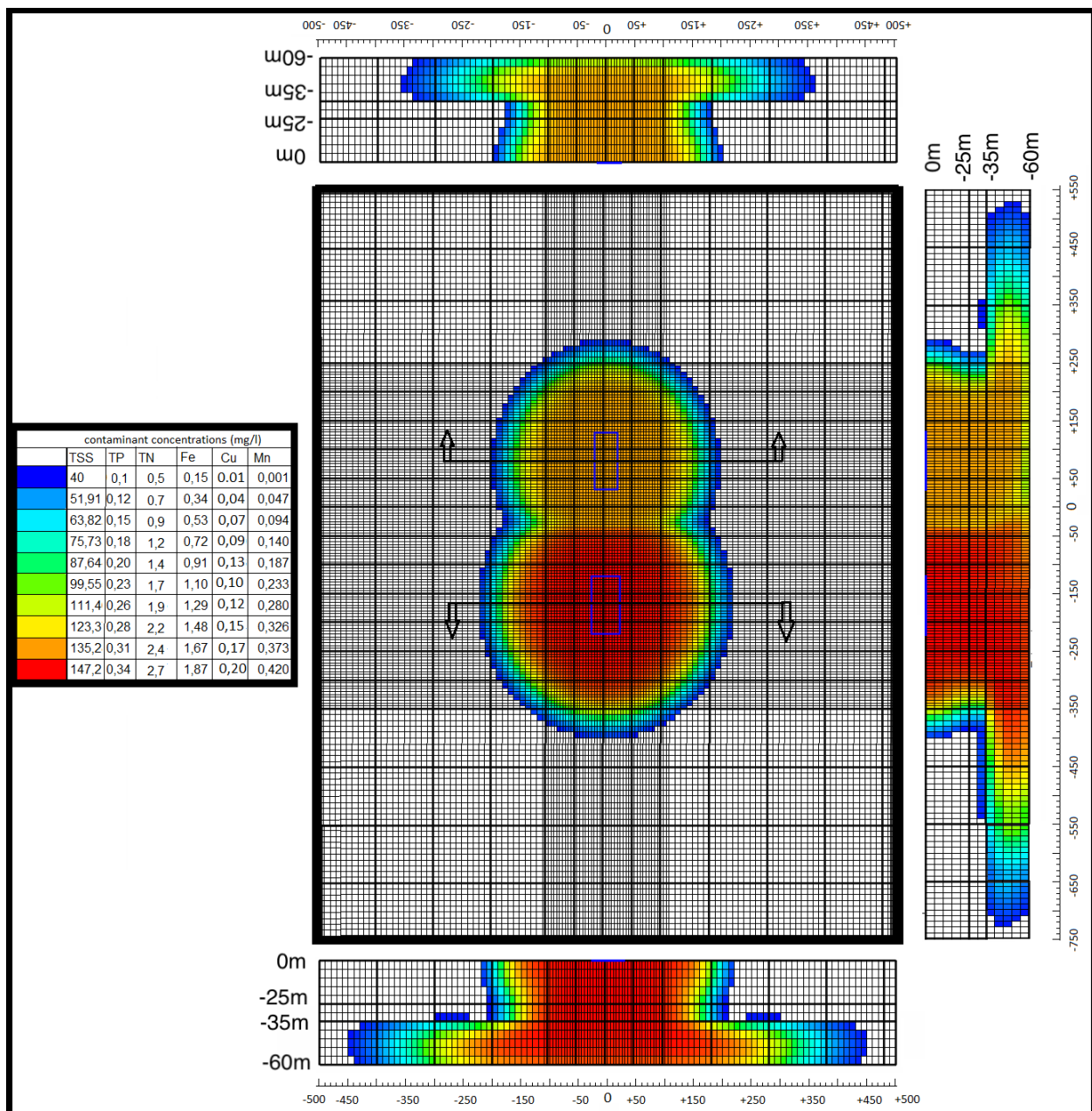


Figure 4.12: Contamination in groundwater for 365 days model.

The most remarkable thing about the groundwater quality model results is the pollutant concentration differences between the 30 and 365 day time-steps. The 30 day period, in other words the beginning of the wet season, represents a kind of wash of process. In the first 15 days of the 30 day time-step, there were some rainless days. The stormwater loading on ponds repeated after dry days and created more critical results on infiltrated water especially as the evaporation of the pond continued during those dry days. The other significant thing is the maximum pollutant concentration difference between time-steps. At the beginning of the wet period, Pond 1 created the critical pollutant concentration in the infiltrated water. However, Pond 2 was more critical for annual pollutant concentrations. The reason is that Pond 2 was designed to treat a larger area than the Pond 1. In other words, Pond 2 collected more water during the 30 days. These areal treatment difference become an influencer for 30 days period. However, when the ponds reached steady-state condition, Pond 2 had more serious effect on groundwater during the 365 days due to its larger surface area.

The water quality of infiltrated water from ponds to groundwater was compared with three different water quality standards to set a water quality goal. The related water quality standards are the World Health Organization (WHO) (2005), the Indian Council of Medical Research (ICMR) (1975) and the United States Public Health Service (USPHS) (1962). Existing groundwater quality parameters were taken into consideration from different regions in Sierra Leone which were Bo City (Kamara, Sundufu and Jacobsen, 2016), (Jimmy et al., 2012), Bombali District (Ibemenuga and Avoaja, 2014), Moriba Town, (Massally et al., 2017) and from other sub-saharan countries (Lapworth et al., 2017). The average results from the related literature showed that TN, Cu and Mn were very close or higher than the maximum acceptable limit. When it comes to Fe, some monitoring results showed that some concentrations have the potential to create fatal effects. Therefore, the water quality goals or the water quality criteria for the infiltrated water from ponds and transported in groundwater in the case study area was defined as shown in Table 4.3.

Table 4.3: Maximum limits of water quality parameters and chosen values for water quality goal

Standards	TSS (mg/l)	TP (mg/l)	TN (mg/l)	Cu (mg/l)	Fe (mg/l)	Mn (mg/l)
WHO	-	-	10	2	0.3	0.4
ICMR	-	-	20	3	0.3	0.1
USPHS	-	-	45	1	0.3	0.05
WQ Goal	40	0.1	0.5	0.01	0.15	0.001

As mentioned before, heavy metals are essential for human life in certain levels and depend on age, sex and physiological status. However, if the consumption of heavy metals exceeds a critical level, they become vitally dangerous. Copper has a density of 8.96g/cm^3 and can be used for various reasons in urban-environment interactions. For example, CuSO_4 is used to keep algae content constant in surface waters. In the human body, it is found in the structure of many enzymes such as ceruloplasmin, superoxide dismutase and cytochrome C oxide. Vomiting, abdominal pain, nausea and hepatic insufficiency are seen in overexposure. In deficiency, Menkes disease with pigment loss in hair, and Wilson's disease are seen (Luza and Speisky, 1996), (Whitacre, 2012).

Manganese is a heavy metal with a density of 7.21g/cm^3 . Manganese superoxide is found in cell enzymes, such as; dismutase, pyruvate carboxylase and kinase. It affects the central nervous system in overexposure and affects the weakness of the muscles. It can also cause a decrease in testosterone levels and drowsiness (Wright, 1986).

A high dose of iron consumption triggers chronic diseases due to excessive iron overloading. Although, literature generally considers 200-250mg/kg of body weight as a lethal dose, cases of death at a body weight of 40 mg/kg have been recorded (Aisen, Cohen and Kang, 1990), (McLaren, 1980).

In terms of the water quality goals, groundwater contamination can reach significant levels especially for a 365 days' time-step. Figure 4.12 demonstrates that pollutants can transport approximately 500m away from the side of ponds, in other words pollutant sources for groundwater, which have possible catastrophic effects on public health. When the boreholes, wells or general groundwater is taken into consideration as the main source of drinking water in the case study area, their application should be subject to permission. Figure 4.12 should be the basis of this permission process. Water quality goals are defined as the minimum value in the legend of Figure 4.12 to demonstrate how far from ponds are safe and includes the intended water quality for drinking water.

Chapter 5. Conclusions

5.1 Summary

Meaba Town, Freetown, Sierra Leone was selected as a case study. The main concentration of the project was to examine the qualitative relationship between stormwater and groundwater in terms of different sustainable drainage system design scenarios and different physical, geological and hydrological designs of infiltration ponds. In the first part of the project infiltrated water quality was examined to classify and compare scenarios. In the second part of the project, the chosen scenario, which was relatively worse among the scenarios in the first part of the project, and related infiltrated water quality was examined by focusing the contaminant transport processes in the groundwater. There were two time-steps for groundwater quality model. The first one was a 30-day model from 15/04/2010 to 15/05/2010. The second one was a 365-day model from 01/01/2010 to 31/12/2010. The first groundwater model was a built to examine the contaminant transportation process at the beginning of the wet season in the tropical climate of the case study area. Similarly, the second one was for annual examination. As the importance of the first model was that the contaminant concentration of infiltrated water was higher, due to wash off condition, the second model was important because of the third layer of the modelled aquifer, which had the highest permeability levels as a result of its geological properties, so it plays a main role in the contaminant transportation process.

The results show that for a tropical climate, the qualitative relationship between stormwater and groundwater needs a special attention, especially in terms of infiltration systems. The additional sustainable drainage systems at the upstream of the catchment did not have significant qualitative improvement on the infiltrated from infiltrated systems at the downstream of the catchment. The initial volume of the infiltration systems had a direct effect on the infiltrated water quality. Similarly, geological properties or the infiltration rate of the infiltration system surface need attention and should be key parameters of system design if there is groundwater contamination risk. Likewise, the background concentration of the treatment devices of the system, particle size distribution and settling velocity were the key points of the system's design in terms of the integrated stormwater-groundwater relationship. In contrast, hydraulic efficiency of the infiltration system had nearly no effect on infiltrated water quality.

Groundwater is one of the main sources for sustainable development in Sierra Leone like many other sub-Saharan countries. Water management in sub-Saharan countries should be taken into consideration as an integrated approach. This project focusses on the qualitative relationship between stormwater and groundwater for the hypothetically implemented sustainable drainage systems. Comprehensive integrated water management plans for the purpose of protecting our water sources by focusing on quantitative and qualitative integrations between different components of water-cycle both in macro and micro scale are essential in the twenty-first century, and the framework provided in this project might be a part of it.

5.2 Key Messages

The following key messages have been obtained from the case study conducted:

1. There is a direct relationship between stormwater and groundwater in terms of sustainable drainage systems. However, infiltration systems should be taken into consideration specifically rather than catchment base sustainable drainage system design in tropical climates.

2. Two main aspects of stormwater and sustainable drainage systems take the main role in terms of the qualitative integration of stormwater and groundwater. The correlation between the stormwater pollutants and related particle size distributions of suspended solids in the stormwater is significantly important. Likewise, settling velocity of related particle are equally important. The other major factor is background concentration of the infiltration systems. In other words, maintenance of the infiltration systems plays major role for the issue.

3. Dualistically, the geological properties of the surface soil of infiltration systems, and the initial and permanent water volume of the infiltration systems are likely to affect groundwater quality in the catchment. In fact, different permeability rates of layers of aquifer may become critical in terms of possible boreholes and wells for drinking water.

5.3 Future Research & Recommendations

The recommendations for further research for the project are as follows:

- Data monitoring processes should be started very seriously. With the data obtained, the models developed in this project and those developed in the future, can be sensitised by a more accurate calibration process. Therefore, more real-time results can be obtained.
- In this project, the stormwater quality models focus on the catchment surface as the main pollutant source. The rainwater is evaluated as perfectly clean and not including any pollutant concentration. However, previous studies reveal that different types of pollutants are available in rainwater before becoming a runoff in the catchment (Ahmed et al., 2008), (Amin and Han, 2009), (Chang, McBroom and Beasley, 2004), (Lee et al., 2010), (Lye, 2002). Likewise, Dr Eric Achterberg from the National Oceanography Centre University of Southampton (2008) shows that the Saharan winds from Africa trigger the huge plankton blooms in the eastern Atlantic. As mentioned before, the case study area is famous with the wind that is called ‘Harmattan’, and the wind blows from the Sahara. Examination of the same relationship could be a part of future studies especially for the integrated qualitative approach for water bodies in the region.
- Although this project focusses mainly on the quality of water, the quantity of the water might be studied in terms of groundwater flooding risk.

References

- Abbasi, M. (2014). Determination of Heavy Metal Settling Velocities with Respect to Particle Size and Density. *World Applied Sciences Journal*, 31 (12), pp.2024-2028.
- Adiyiah, J., Acheampong, M., Ansa, E. and Kelderman, P. (2014). Grain-Size Analysis and Heavy Metals Distribution in Sediment Fractions of Lake Markermeer in the Netherlands. *International Journal of Environmental Science and Toxicology*, 2(8), pp.160-167.
- Ahmed, W., Huygens, F., Goonetilleke, A. and Gardner, T. (2008). Real-Time PCR Detection of Pathogenic Microorganisms in Roof-Harvested Rainwater in Southeast Queensland, Australia. *Applied and Environmental Microbiology*, 74(17), pp.5490-5496.
- Aisen, P., Cohen, G. and Kang, J. (1990). Iron Toxicosis. *International Review of Experimental Pathology*, pp.1-46.
- Allen, H. (1993). The significance of trace metal speciation for water, sediment and soil quality criteria and standards. *Science of The Total Environment*, 134, pp.23-45.
- Amin, M. and Han, M. (2009). Roof-harvested rainwater for potable purposes: Application of solar collector disinfection (SOCO-DIS). *Water Research*, 43(20), pp.5225-5235.
- Arora, A. and Reddy, A. (2013). Multivariate analysis for assessing the quality of stormwater from different Urban surfaces of the Patiala city, Punjab (India). *Urban Water Journal*, 10(6), pp.422-433.
- Aryal, R., Vigneswaran, S., Kandasamy, J. and Naidu, R. (2010). Urban stormwater quality and treatment. *Korean Journal of Chemical Engineering*, 27(5), pp.1343-1359.
- Ayoubi, S., Soltani, Z. and Khademi, H. (2018). Particle Size Distribution of Heavy Metals and Magnetic Susceptibility in an Industrial Site. *Bulletin of Environmental Contamination and Toxicology*, 100(5), pp.708-714.

- Barry, D. and Bajracharya, K. (1995). On the Muskingum-Cunge flood routing method. *Environment International*, 21(5), pp.485-490.
- Bastani, M. and Harter, T. (2019). Source area management practices as remediation tool to address groundwater nitrate pollution in drinking supply wells. *Journal of Contaminant Hydrology*, p.103521.
- Boller, M. (1997). Tracking heavy metals reveals sustainability deficits of urban drainage systems. *Water Science and Technology*, 35(9).
- Bras, R. (1999). A Brief History of Hydrology*. *Bulletin of the American Meteorological Society*, 80(6), pp.1151-1164.
- Bruce, J. and Clark, R. (2013). *Introduction to Hydrometeorology*. Burlington: Elsevier Science.
- Butler, D. and Parkinson, J. (1997). Towards sustainable urban drainage. *Water Science and Technology*, 35(9), pp.53-63.
- Butler, D., James Digman, C., Makropoulos, C. and Davies, J. (2018). *Urban Drainage, Fourth Edition*. 4th ed.
- Chang, M., McBroom, M. and Beasley, R. (2004). Roofing as a source of nonpoint water pollution. *Journal of Environmental Management*, 73(4), pp.307-315.
- Charlesworth, S. (2010). A review of the adaptation and mitigation of global climate change using sustainable drainage in cities. *Journal of Water and Climate Change*, 1(3), pp.165-180.
- Chocat, B., Ashley, R., Marsalek, J., Matos, M., Rauch, W., Schilling, W. and Urbonas, B. (2007). Toward the Sustainable Management of Urban Storm-Water. *Indoor and Built Environment*, 16(3), pp.273-285.

Chubaka, C., Whiley, H., Edwards, J. and Ross, K. (2018). Lead, Zinc, Copper, and Cadmium Content of Water from South Australian Rainwater Tanks. *International Journal of Environmental Research and Public Health*, 15(7), p.1551.

CIRIA (2015). *The SuDS Manual*. London: CIRIA.

Ciria.org. (2019). *CIRIA*. [online] Available at: <https://www.ciria.org> [Accessed 17 Jul. 2019].

Cooperative Research Centre for Catchment Hydrology (2004). *Effectiveness of Non-Proprietary Stormwater Treatment Measures — A Review and Gap Analysis*.

Data.worldbank.org. (2019). *Sierra Leone | Data*. [online] Available at: <https://data.worldbank.org/country/sierra-leone> [Accessed 19 Jul. 2019].

Dawson, R., Ball, T., Werritty, J., Werritty, A., Hall, J. and Roche, N. (2011). Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change. *Global Environmental Change*, 21(2), pp.628-646.

Diop, C., Dewaelé, D., Cazier, F., Diouf, A. and Ouddane, B. (2015). Assessment of trace metals contamination level, bioavailability and toxicity in sediments from Dakar coast and Saint Louis estuary in Senegal, West Africa. *Chemosphere*, 138, pp.980-987.

Duncan, H. (1999). *Urban stormwater quality*. Clayton, Vic.: CRC for Catchment Hydrology.

Duncan, H., Fletcher, T., Poelsma, P. and Lloyd, S. (2004). *Stormwater flow and quality and the effectiveness of non-proprietary stormwater treatment measures*. Clayton, Vic.: CRC for Catchment Hydrology.

Elliott, A. and Trowsdale, S. (2007). A review of models for low impact urban stormwater drainage. *Environmental Modelling & Software*, 22(3), pp.394-405.

Ellis, J., Revitt, D., Harrop, D. and Beckwith, P. (1987). The contribution of highway surfaces to urban stormwater sediments and metal loadings. *Science of The Total Environment*, 59, pp.339-349.

Estèbe, A., Boudries, H., Mouchel, J. and Thévenot, D. (1997). Urban runoff impacts on particulate metal and hydrocarbon concentrations in river seine: suspended solid and sediment transport. *Water Science and Technology*, 36(8-9), pp.185-193.

Fileccia, A. (2018). Groundwater potential in Sierra Leone. *Acque Sotterranee - Italian Journal of Groundwater*, 7(2).

Fileccia, A., Teatini, P., Walther, C. and Mastrocola, P. (2017). *Hydrogeology of Sierra Leone*. Freetown, Sierra Leone: Ministry of Water Resources.

Fisher, T., Hayward, D., Stephens, R. and Stenstrom, M. (1999). Dioxins and Furans Urban Runoff. *Journal of Environmental Engineering*, 125(2), pp.185-191.

Forman, D., Al-Dabbagh, S. and Doll, R. (1985). Nitrates, nitrites and gastric cancer in Great Britain. *Nature*, 313(6004), pp.620-625.

Fry, C. (2008). *The impact of climate change*. London: New Holland.

Goldenfum, J., Tucci, C. and Parkinson, J. (2010). *Integrated urban water management*. Paris: UNESCO.

Gromaire, M., Garnaud, S., Saad, M. and Chebbo, G. (2001). Contribution of different sources to the pollution of wet weather flows in combined sewers. *Water Research*, 35(2), pp.521-533.

Gustafson, C., Key, K. and Evans, R. (2019). Aquifer systems extending far offshore on the U.S. Atlantic margin. *Scientific Reports*, 9(1).

Hatt, B., Fletcher, T., Walsh, C. and Taylor, S. (2004). The Influence of Urban Density and Drainage Infrastructure on the Concentrations and Loads of Pollutants in Small Streams. *Environmental Management*, 34(1).

Hellström, D., Jeppsson, U. and Kärrman, E. (2000). A framework for systems analysis of sustainable urban water management. *Environmental Impact Assessment Review*, 20(3), pp.311-321.

Hughes, J., Langevin, C. and Banta, E. (2017). Documentation for the MODFLOW 6 framework. *Techniques and Methods*.

Ibemenuga, K. and Avoaja, D. (2014). Assessment of Groundwater Quality in Wells within the Bombali District, Sierra Leone. *Animal Research International*, 11(1), pp.1905-1916.

Institute of Ecology & Resource Management University of Edinburgh (2019). [online] Available at: <https://www.geos.ed.ac.uk/homes/kheal/conconf.pdf> [Accessed 26 Jul. 2019].

Jarrett, H. (1956). Some Aspects of the Urban Geography of Freetown, Sierra Leone. *Geographical Review*, 46(3), p.334.

Javandel, I., Doughty, C. and Tsang, C. (1984). *Groundwater Transport: Handbook of Mathematical Models*. American Geophysical Union Water Resources Monogram, p.228.

Jimmy, D., Sundufu, A., Malanoski, A., Jacobsen, K., Ansumana, R., Leski, T., Bangura, U., Bockarie, A., Tejan, E., Lin, B. and Stenger, D. (2012). Water quality associated public health risk in Bo, Sierra Leone. *Environmental Monitoring and Assessment*, 185(1), pp.241-251.

Johnson, D., Ambrose, S., Bassett, T., Bowen, M., Crummey, D., Isaacson, J., Johnson, D., Lamb, P., Saul, M. and Winter-Nelson, A. (1997). Meanings of Environmental Terms. *Journal of Environment Quality*, 26(3), p.581.

Kadlec, R. and Knight, R. (1996). *Treatment Wetlands*. Boca Raton, Florida: CRC Press.

Kamara, A., Sundufu, A. and Jacobsen, K. (2016). Commercial Drinking Water Quality and Safety in Bo City, Sierra Leone. *Sierra Leone Journal of Biomedical Research*, 8(1), p.26.

Kamara, A., Sundufu, A. and Jacobsen, K. (2019). *Commercial Drinking Water Quality and Safety in BO City, Sierra Leone..*

Kennedy, P., Allen, G., Pennington, S., Hunt, S. and Wilson, N. (2016). *The Management of Hydrocarbons in Stormwater Runoff*. Auckland: Auckland Council.

Kumar, M., Singh, G., Chaminda, T., Van Quan, P. and Kuroda, K. (2014). Emerging Water Quality Problems in Developing Countries. *The Scientific World Journal*, 2014, pp.1-2.

Lapworth, D., Nkhuwa, D., Okotto-Okotto, J., Pedley, S., Stuart, M., Tijani, M. and Wright, J. (2017). Urban groundwater quality in sub-Saharan Africa: current status and implications for water security and public health. *Hydrogeology Journal*, 25(4), pp.1093-1116.

Larsen, T. and Gujer, W. (1997). The concept of sustainable urban water management. *Water Science and Technology*, 35(9), pp.3-10.

Lee, J., Yang, J., Han, M. and Choi, J. (2010). Comparison of the microbiological and chemical characterization of harvested rainwater and reservoir water as alternative water resources. *Science of The Total Environment*, 408(4), pp.896-905.

Lee, S., Min, K., Woo, N., Kim, Y. and Ahn, C. (2003). Statistical models for the assessment of nitrate contamination in urban groundwater using GIS. *Environmental Geology*, 44(2), pp.210-221.

Li, Y., Kang, J., Lau, S., Kayhanian, M. and Stenstrom, M. (2008). Optimization of Settling Tank Design to Remove Particles and Metals. *Journal of Environmental Engineering*, 134(11), pp.885-894.

Logeshwaran, P., Megharaj, M., Chadalavada, S., Bowman, M. and Naidu, R. (2018). Petroleum hydrocarbons (PH) in groundwater aquifers: An overview of environmental fate, toxicity,

microbial degradation and risk-based remediation approaches. *Environmental Technology & Innovation*, 10, pp.175-193.

Luza, S. and Speisky, H. (1996). Liver copper storage and transport during development: implications for cytotoxicity. *The American Journal of Clinical Nutrition*, 63(5), pp.812S-820S.

Lye, D. (2002). Health Risks Associated With Consumption of Untreated Water From Household Roof Catchment Systems. *Journal of the American Water Resources Association*, 38(5), pp.1301-1306.

Marshall, S. (2013). Hydrology. *Reference Module in Earth Systems and Environmental Sciences*.

Massally, R., Sheriff, A., Kaitibi, D., Abu, A., Barrie, M. and Taylor, E. (2017). Comprehensive Assessment of Groundwater Quality around a Major Mining Company in Southern Sierra Leone. *Journal of Water Resource and Protection*, 09(06), pp.601-613.

McLaren, D. (1980). Iron Metabolism in Man. *Quarterly Journal of Experimental Physiology and Cognate Medical Sciences*, 65(3), pp.255-256.

Minnesota Pollution Control Agency (2008). *Contamination of Soil and Groundwater Due to Stormwater Infiltration Practices*. 515. Minneapolis, Minnesota: University of Minnesota.

Nace, R. (1974). Pierre Perrault: The Man and His Contribution to Modern Hydrology. *Journal of the American Water Resources Association*, 10(4), pp.633-647.

Neuman, S. (1984). Adaptive Eulerian-Lagrangian finite element method for advection-dispersion. *International Journal for Numerical Methods in Engineering*, 20(2), pp.321-337.

NSTC (2003). *An Assessment of Coastal Hypoxia and Eutrophication in U.S. Waters*. Washington D.C.: National Science and Technology Council Committee on Environment and Natural Resources.

Ollivier, V., Fontugne, M., Hamon, C., Decaix, A., Hatté, C. and Jalabadze, M. (2018). Neolithic water management and flooding in the Lesser Caucasus (Georgia). *Quaternary Science Reviews*, 197, pp.267-287.

Pal, D. and Maiti, S. (2018). Heavy metal speciation, leaching and toxicity status of a tropical rain-fed river Damodar, India. *Environmental Geochemistry and Health*, 40(6), pp.2303-2324.

Pengchai, P., Nakajima, F. and Furumai, H. (2005). Estimation of origins of polycyclic aromatic hydrocarbons in size-fractionated road dust in Tokyo with multivariate analysis. *Water Science and Technology*, 51(3-4), pp.169-175.

Quigley, M., Strecker, E. and Urbonas, B. (2003). Urban Stormwater Bmp Performance: Application of Recent Findings from the National Stormwater Best Management Practices Database Project. *Proceedings of the Water Environment Federation*, 2003(4), pp.1265-1278.

Quinn, R. and Dussailant J., A. (2013). Modeling Heavy Metal Behavior in Sustainable Drainage Systems: A Case Study. *CLEAN - Soil, Air, Water*, 42(2), pp.160-168.

Reddy, K., Xie, T. and Dastgheibi, S. (2014). Removal of heavy metals from urban stormwater runoff using different filter materials. *Journal of Environmental Chemical Engineering*, 2(1), pp.282-292.

Roberts, W. and Pierce, J. (1976). Deposition in upper Patuxent estuary, Maryland, 1968–1969. *Estuarine and Coastal Marine Science*, 4(3), pp.267-280.

Roy, A., Wenger, S., Fletcher, T., Walsh, C., Ladson, A., Shuster, W., Thurston, H. and Brown, R. (2008). Impediments and Solutions to Sustainable, Watershed-Scale Urban Stormwater Management: Lessons from Australia and the United States. *Environmental Management*, 42(2), pp.344-359.

Sadeghi, S., Harchegani, M. and Younesi, H. (2012). Suspended sediment concentration and particle size distribution, and their relationship with heavy metal content. *Journal of Earth System Science*, 121(1), pp.63-71.

Salone Groundwater Resources Database (SALGRID), Coordinator, Ministry of Water Resources (2017). *Surface Permeability of Sierra Leone*. Freetown: Government of Sierra Leone, Ministry of Water Resources.

Sharma, A., Gray, S., Diaper, C., Liston, P. and Howe, C. (2008). Assessing integrated water management options for urban developments – Canberra case study. *Urban Water Journal*, 5(2), pp.147-159.

Sharma, M. (2012). *Evapotranspiration from Plant Communities*. Amsterdam: Elsevier Science.

Shmueli, D. (1999). Water quality in international river basins. *Political Geography*, 18(4), pp.437-476.

Showers, K. (2002). Water Scarcity and Urban Africa: An Overview of Urban–Rural Water Linkages. *World Development*, 30(4), pp.621-648.

Sierra Leone Roads Authority (1995). *Urban Water Supply Project*. Leatherhead, England.

Silva, A., Nascimento, N., Seidl, M. and Vieira, L. (2010). SWITCH in Belo Horizonte, Brazil: infiltration and detention systems for more sustainable stormwater control in Belo Horizonte. *Reviews in Environmental Science and Bio/Technology*, 9(1), pp.7-13.

Smith, K. (1984). Hydrology Hydrology. *Encyclopedia of Earth Sciences Series*, pp.296-303.

Stagge, J., Davis, A., Jamil, E. and Kim, H. (2012). Performance of grass swales for improving water quality from highway runoff. *Water Research*, 46(20), pp.6731-6742.

Statistics Sierra Leone (2019). [online] Available at:
https://www.statistics.sl/images/StatisticsSL/Documents/final-results_-_2015_population_and_housing_census.pdf [Accessed 27 Jul. 2019].

Stefania, G., Rotiroti, M., Buerge, I., Zanotti, C., Nava, V., Leoni, B., Fumagalli, L. and Bonomi, T. (2019). Identification of groundwater pollution sources in a landfill site using artificial sweeteners, multivariate analysis and transport modeling. *Waste Management*, 95, pp.116-128.

Tedoldi, D., Chebbo, G., Pierlot, D., Branchu, P., Kovacs, Y. and Gromaire, M. (2016). *Heavy metal accumulation in the surface soil of SUDS: spatial variability of contamination and inter-site comparison*. Lyon, France: Conférence NOVATECH 2016.

The Revision of the IUPAC Compendium of Chemical Terminology (The "Gold Book"). (2003). *Chemistry International -- Newsmagazine for IUPAC*, 25(2).

Tucci, C. (2001). *Urban Drainage in Specific Climates*. International Hydrological Programme. Paris: UNESCO.

Tuncok, I., Mays, L. and Briscoe, J. (1999). Water Resources Management in Developing Countries and the Role of World Bank. *WRPMD'99*.

UN (2011). *World Urbanization Prospects*. New York: UN.

UNESCO, UN-Water (2019). *The United Nations World Water Development Report 2019*. Paris: UNESCO on behalf of UN-Water.

US EPA. (2016). *Relationship between Water Quality Criteria and Water Quality Standards | US EPA*. [online] Available at: <https://www.epa.gov/standards-water-body-health/relationship-between-water-quality-criteria-and-water-quality-standards> [Accessed 7 Jul. 2019].

USGS (2001). *A Synopsis of Technical Issues for Monitoring Sediment in Highway and Urban Runoff*. National Highway Runoff Data and Methodology Synthesis. Massachusetts: USGS.

Van Der Kooij, L., Van De Meent, D., Van Leeuwen, C. and Bruggeman, W. (1991). Deriving quality criteria for water and sediment from the results of aquatic toxicity tests and product standards: Application of the equilibrium partitioning method. *Water Research*, 25(6), pp.697-705.

Vandibyer.dk. (2019). *Vand i Byer Innovationsnetværk for klimatilpasning*. [online] Available at: <http://www.vandibyer.dk> [Accessed 17 Jul. 2019].

Vardar, N., Odabasi, M. and Holsen, T. (2002). Particulate Dry Deposition and Overall Deposition Velocities of Polycyclic Aromatic Hydrocarbons. *Journal of Environmental Engineering*, 128(3), pp.269-274.

Wakida, F. and Lerner, D. (2005). Non-agricultural sources of groundwater nitrate: a review and case study. *Water Research*, 39(1), pp.3-16.

Wang, Z., Yao, L., Liu, G. and Liu, W. (2014). Heavy metals in water, sediments and submerged macrophytes in ponds around the Dianchi Lake, China. *Ecotoxicology and Environmental Safety*, 107, pp.200-206.

Wang, J., Da, L., Song, K. and Li, B. (2008). Temporal variations of surface water quality in urban, suburban and rural areas during rapid urbanization in Shanghai, China. *Environmental Pollution*, 152(2), pp.387-393.

Water.wa.gov.au. (2017). *Integrated urban water management*. [online] Available at: <http://www.water.wa.gov.au/planning-for-the-future/water-and-land-use-planning/better-urban-water-management> [Accessed 6 Jul. 2019].

Wells, M. (1962). Structure and Petrology of the Freetown Layered Basic Complex of Sierra Leone. *Overseas Geology and Mineral Resources Supplement Series - Her Majesty's Stationery Office*.

Westerlund, C. and Viklander, M. (2006). Particles and associated metals in road runoff during snowmelt and rainfall. *Science of The Total Environment*, 362(1-3), pp.143-156.

Whitacre, D. (2012). *Reviews of environmental contamination and toxicology*. New York: Springer.

WHO (2017). *Guidelines for drinking water quality: fourth edition incorporating the first addendum..* Geneva: World Health Organization.

Wong, T. and Geiger, W. (1997). Adaptation of wastewater surface flow wetland formulae for application in constructed stormwater wetlands. *Ecological Engineering*, 9(3-4), pp.187-202.

Wong, T., Duncan, H., Fletcher, T., Jenkins, G. and Coleman, J. (2001). A unified approach to modelling urban stormwater treatment. *2nd South Pacific Stormwater Conference, Auckland, New Zealand, 27 – 29*, pp.319-327.

Wong, T., Fletcher, T., Duncan, H. and Jenkins, G. (2006). Modelling urban stormwater treatment—A unified approach. *Ecological Engineering*, 27(1), pp.58-70.

Wong, T., Rodder, A. and Geiger, W. (1999). Geiger, Predicting the Performance of a Constructed Combined Sewer Overflow Wetland. *Proceedings of the Eighth International Conference on Urban Storm Drainage*, Sydney, Australia, pp.1947-1954.

World Meteorological Organization. (2019). *World Meteorological Organization*. [online] Available at: <https://public.wmo.int/en> [Accessed 6 Aug. 2019].

Wright, H. (1986). A Paleohydrology Project: Handbook of Holocene Palaeoecology and Palaeohydrology. *Science*, 233(4762), pp.482-482.

Yang, Y. and Lusk, M. (2018). Nutrients in Urban Stormwater Runoff: Current State of the Science and Potential Mitigation Options. *Current Pollution Reports*, 4(2), pp.112-127.

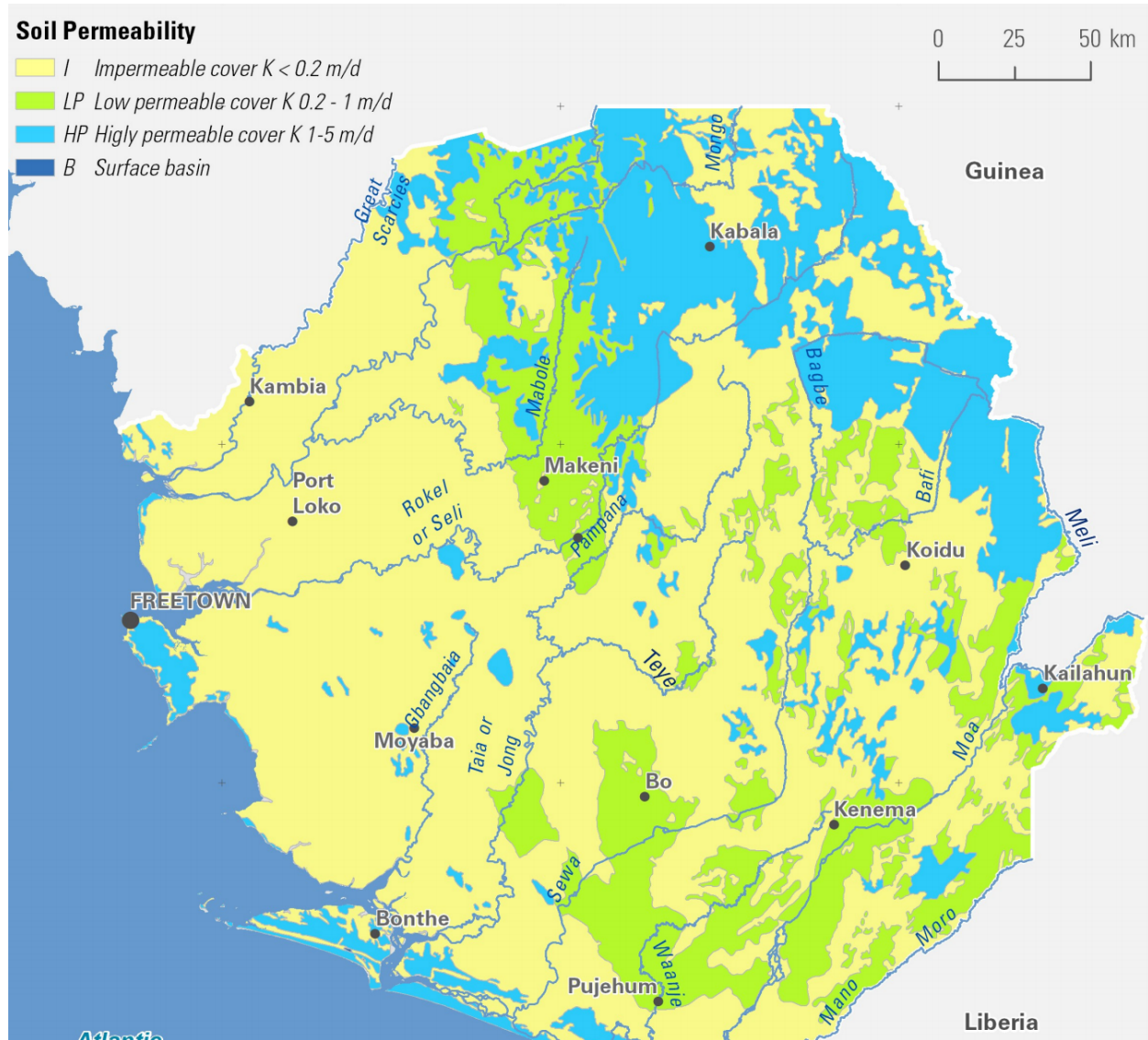
Yu, X. and Michael, H. (2019). Mechanisms, configuration typology, and vulnerability of pumping-induced seawater intrusion in heterogeneous aquifers. *Advances in Water Resources*, 128, pp.117-128.

Zanders, J. (2005). Road sediment: characterization and implications for the performance of vegetated strips for treating road run-off. *Science of The Total Environment*, 339(1-3), pp.41-47.

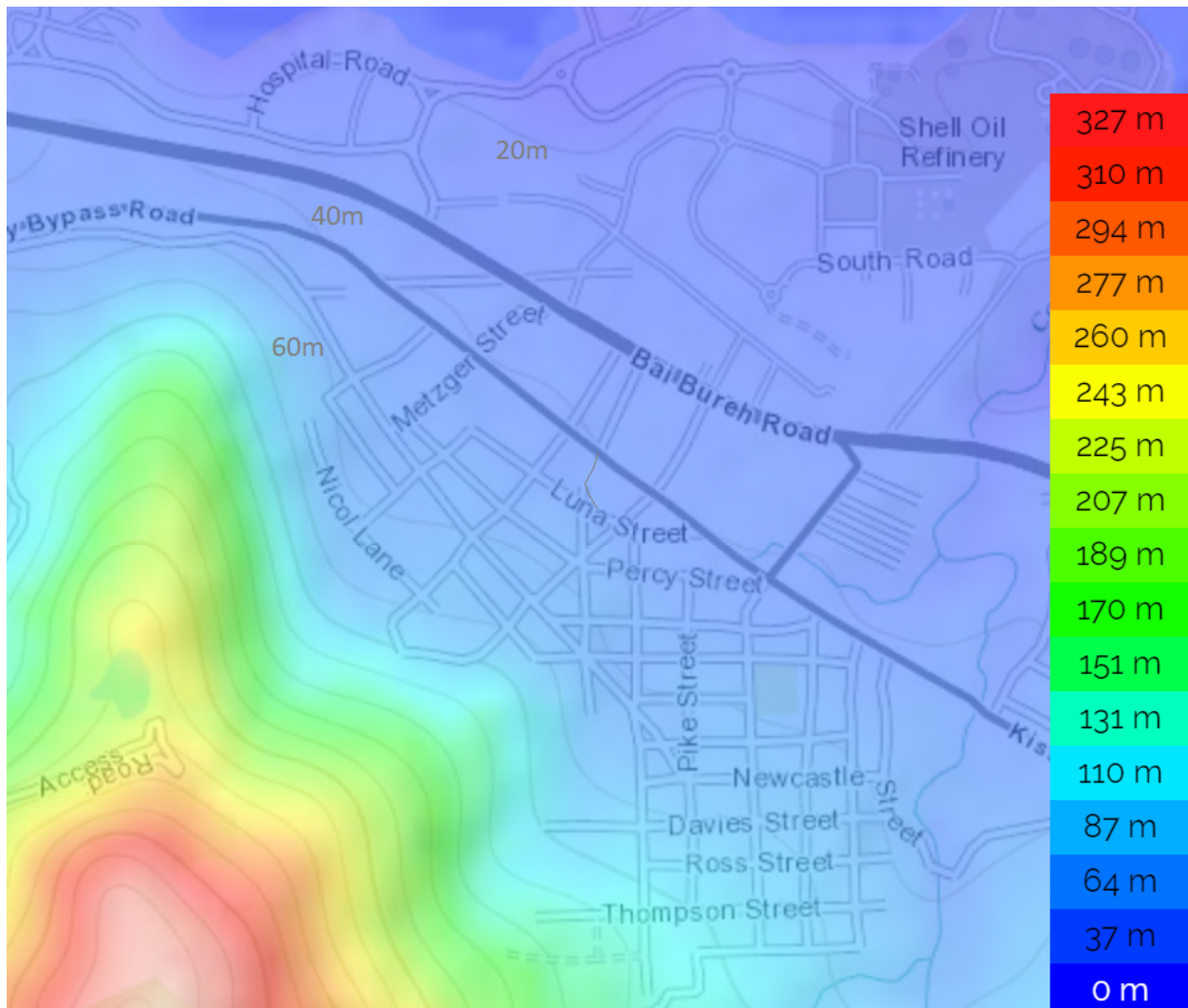
Zheng, C. and Papadopoulos, S. (1990). A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion and Chemical Reaction of Contaminants in Groundwater Systems. *The United States Environmental Protection Agency Robert S. Kerr Environmental Research Laboratory*.

Zonta, R., Zaggia, L. and Argese, E. (1994). Heavy metal and grain-size distributions in estuarine shallow water sediments of the Cona Marsh (Venice Lagoon, Italy). *Science of The Total Environment*, 151(1), pp.19-28.

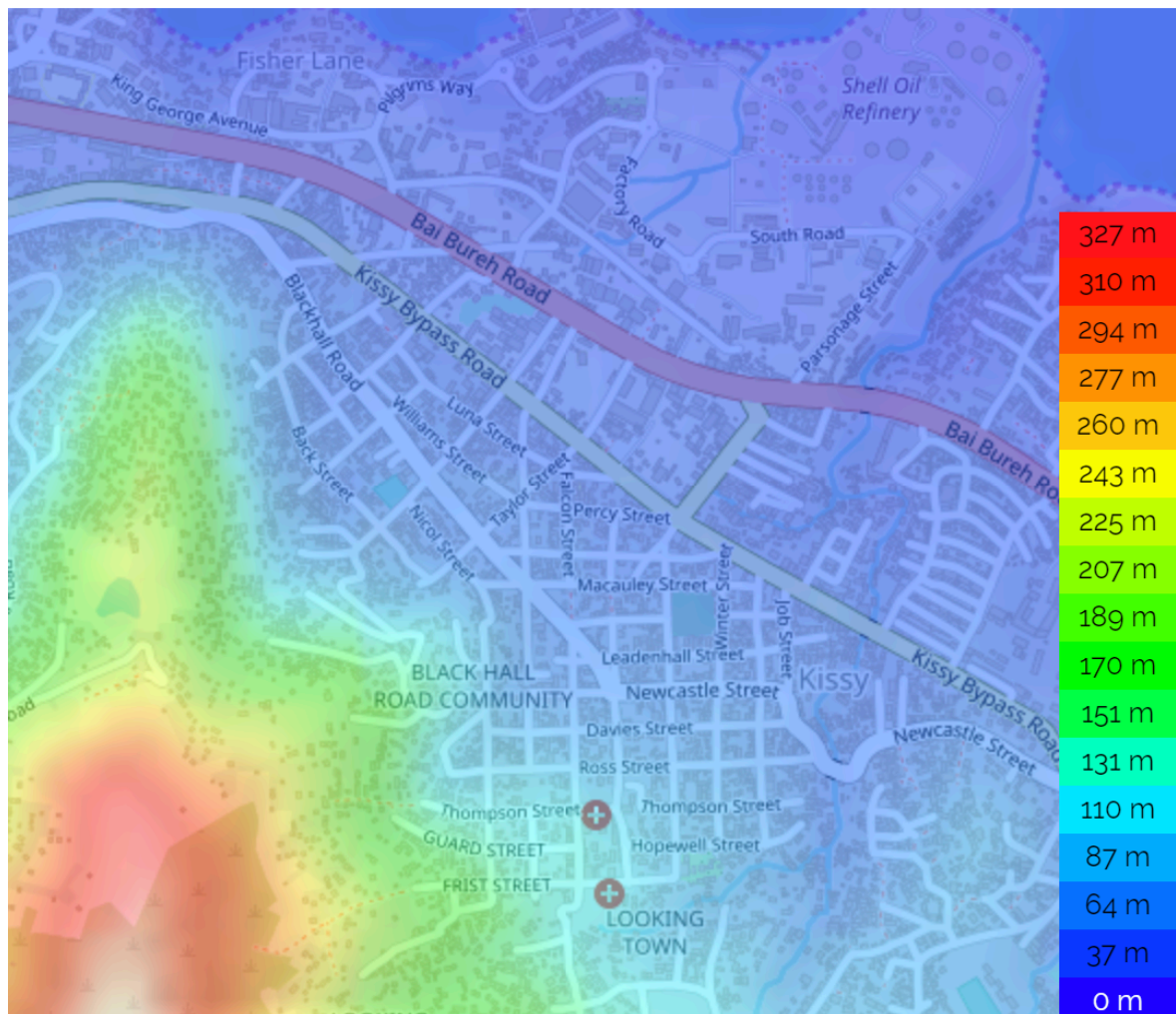
APPENDIX-B



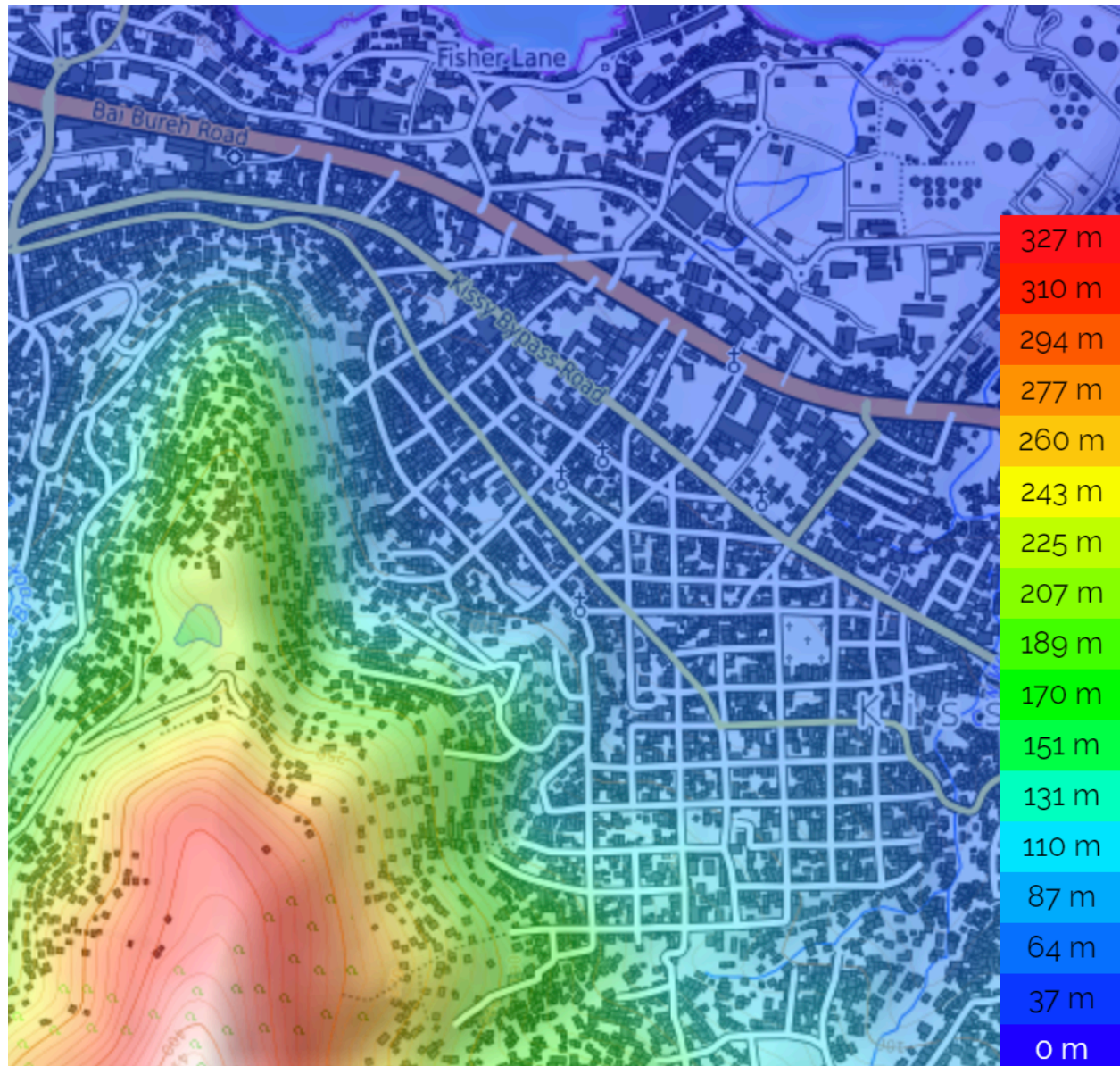
APPENDIX-B



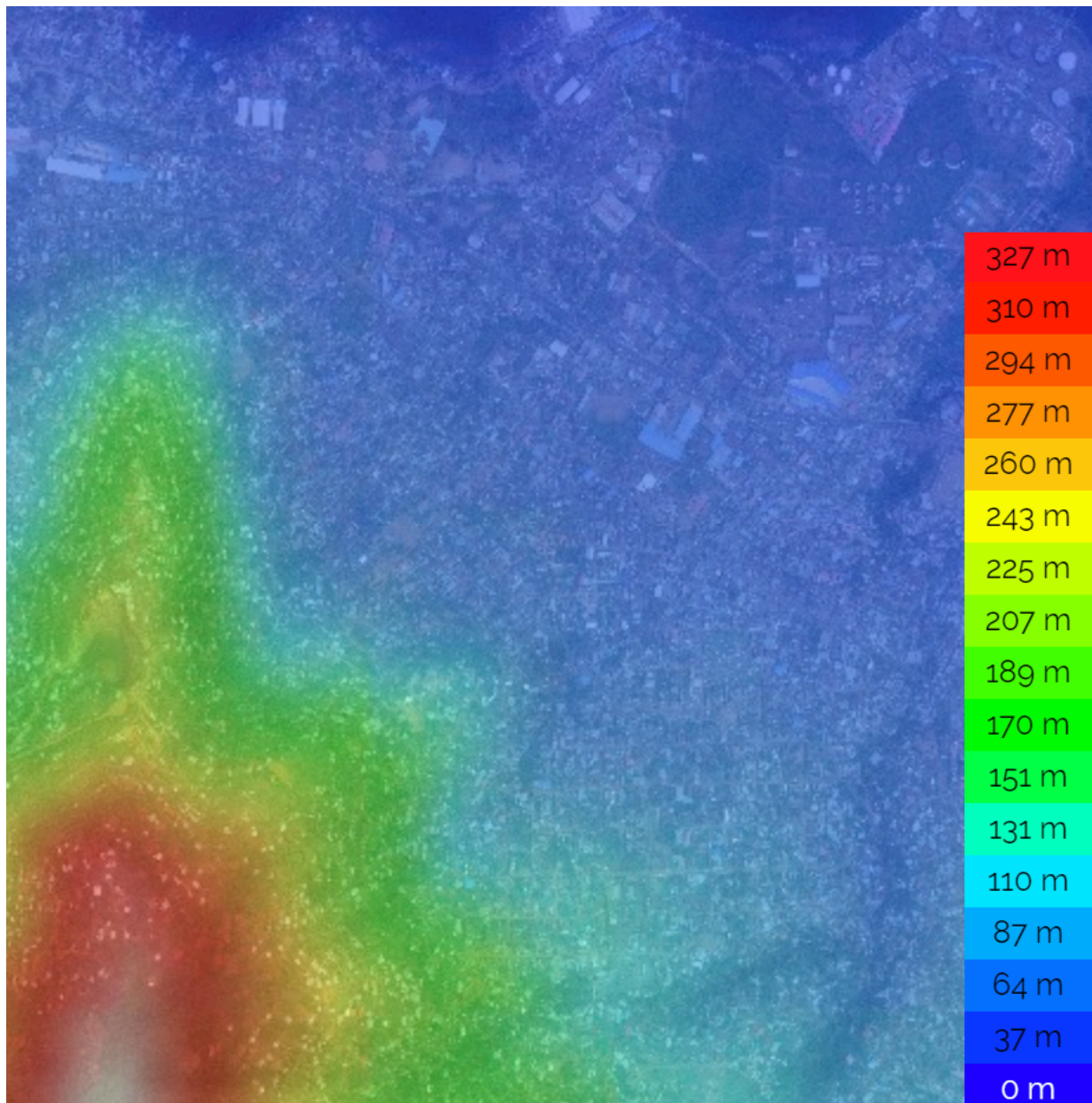
APPENDIX-B



APPENDIX-B

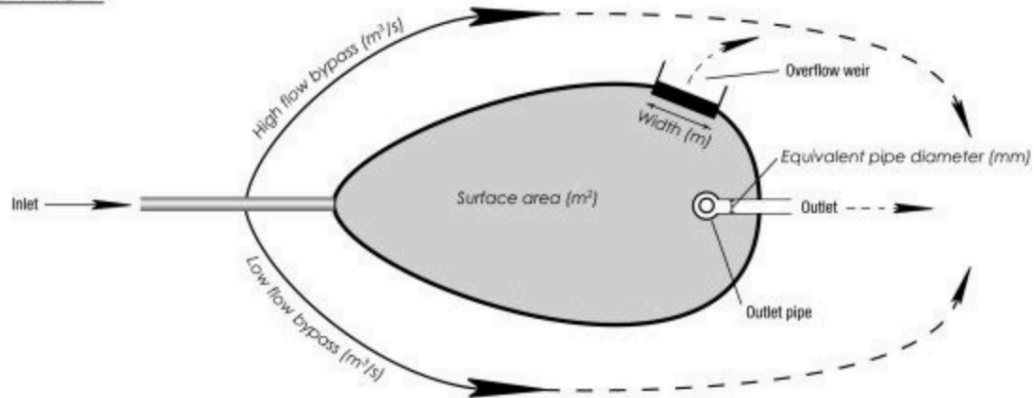


APPENDIX-B

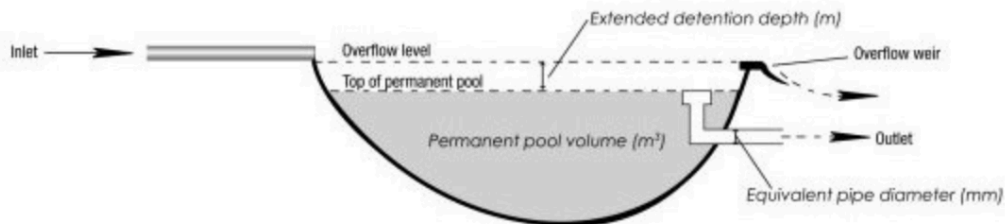


APPENDIX-B

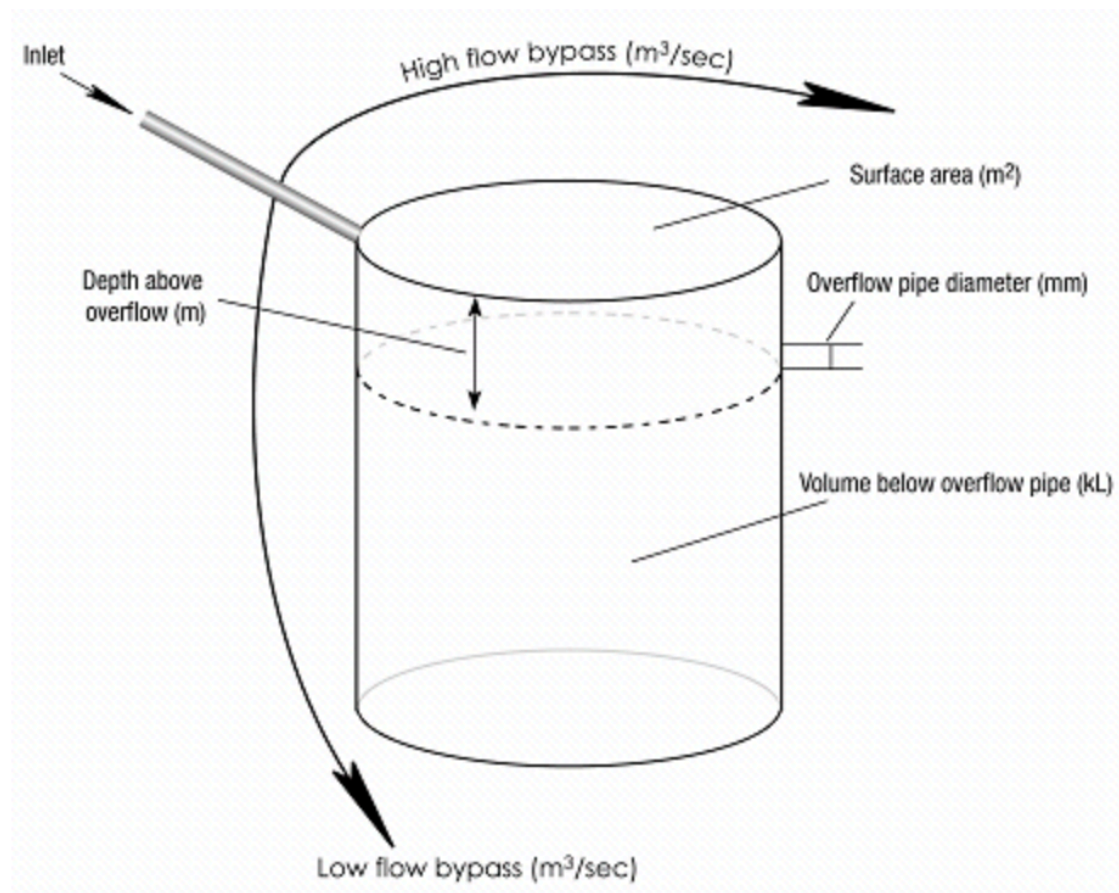
Plan View



Longitudinal Section

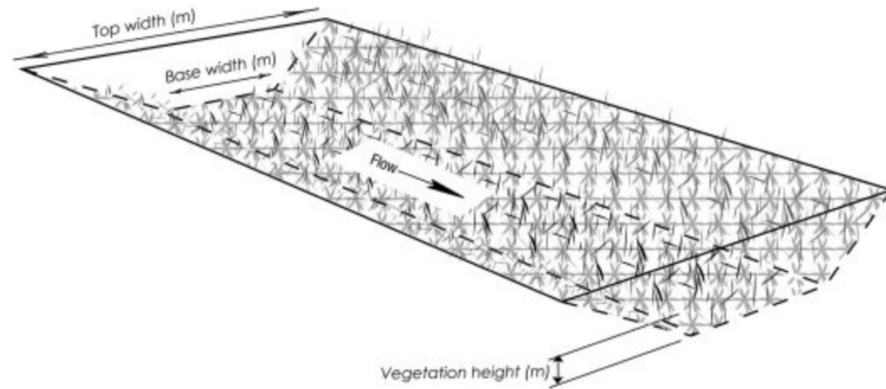


APPENDIX-B



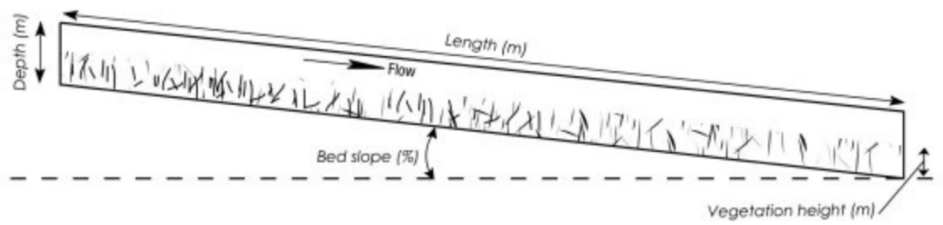
APPENDIX-B

3D Perspective



Swale

Longitudinal Section



APPENDIX-B

EDAL DRILLING COMPANY							BH status:	Succesful Dry
Geophysics ref No		BOREHOLE RECORD						
VES								
Community:		Shell Kivuvu	BH ref. No.	MY - BH - 01	Nat. grid ref.			
Drilling contractor		Edal Drilling Company	Drill rig	29th July 2015	Method	road and air		
Drilling start date		20th July 2015	Compl. date	29th July 2015	Operator	Barahm Bangura		
TEST PUMPING		Date:	Top of screen *		36	m		
DYNAMIC WL *	47.63	Pump type	Pedrollo		10.08	m		
Static WL *	10.08	Pumping rate (Q)	1.8 m³/h		Potential drawdown		m	
Drawdown(s)	37.55	Duration	6 hrs		Potential yield		m³/h	
* Levels to ground level datum		Specific capacity (Q/s)	6 m³/hr		Depth of borehole *	65	m	
BIT SIZE & TYPE		PROFILE	TIME DEPTH M MIN	WATER ZONES CUMULATIVE Q L/min	WELL DIAGRAM with STATIC AND DYNAMIC WATER LEVELS			
12" DTH		Upper gravel pack and cement			Upper grout seal (cement)			
		Highly compacted reddish-brown clay			Main plain PVC			
		Highly compacted reddish-brown clay			Back fill with drill cuttings			
		Standsone			Lower grouting bentonite			
		Standsone		Muddy	Lower grouting bentonite			
		Hard Gabbroic rock			36mm plain PVC			
		Hard Gabbroic rock			Gravel			
		Hard Gabbroic rock			9m screen PVC			
		Hard Gabbroic rock			6m Plain PVC (165mm)			
		Hard Gabbroic rock			6m Screen PVC(165mm)			
		Hard Gabbroic rock			3m sandstone			
8" Hammer bit								
Remarks: We stop at 65m because we had sufficient water after measuring the yild								
Prepared by: Edal drilling Company		(Contractor)						
Certified: KEMOH ALIE BAYOH								
Approved:								
Approved:								

APPENDIX-B

3.1 DAILY LOG FOR DRILLING SUPERVISION

CONTRACT		CONTRACTION		EDAL DRILING COMPANY LIMITED	
OWNER NAME	KING'S FOAM AND MATTRESS	DEPTH OF HOLES	65m		
OWNER ADDRESS	SHELL KISSY	WEATHER	RAINY AND SUNNY		
RIG MAKE	PRD OZ	USE			
COMPRESSOR MAKE	ELGI 1100 cfm/ 350 psi	DATE	START DATE:	20/07/15	
			COMPLETION DATE:	25/07/15	
BORE-HOLE REFERENCE NO.	BORE-HOLE ONE(1)	DRILLING METHOD	MUD CIRCULATION AND AIR		
LITHOLOGICAL BOUNDARIES AND SAMPLE FORMATION.					
DEPTH OF CONTACT ZONE		DRILLING PROCESS			DESCRIPTION OF FORMATION
DEPTH (m)	SAMPLE	FROM	TO	PENETRATION RATE (min/m)	SAMPLES COLLECTED
0-5	5	09:10	09:15	1.0	Brownish-red laterite and sandstone
5-10	5	09:22	09:28	1.2	Reddish-brown highly compacted clay
10-15	5	09:32	09:37	1.0	" " " " "
15-20	5	10:07	10:10	0.6	" " " " "
20-25	5	10:50	10:52	0.4	
25-30	5	16:00	16:04	0.8	
30-35	5	16:05	16:08	0.6	Sandstone
35-40	5	11:36	11:52	3.2	Hard gabbroic rock
40-45	5	12:04	12:18	2.8	" " " " "
45-50	5	12:25	12:40	3.0	" " " " "
50-55	5	13:37	13:56	3.8	
55-60	5	14:00	14:11	2.2	
60-65		14:15	14:28	2.6	
					REMARKS(Drilling Method including change of bit)
					Rock roller 12" Throughout

APPENDIX-B

CONTRACTOR		BABA DRILLING & EXPLORATION COMPANY			CLIENT		Mr. Ibrahim Sowe	
GPS CO-ORDINATES		0702379 - EAST			DEPTH OF HOLE		74m	
		0933226 - NORTH						
LOCATION		Hill Stations			START DATE		17 th January, 2016	
BORE-HOLE REFERENCE NO.		One (1)			COMPLETION DATE		23 rd January, 2016	
DEPTH STRUCK WATER		40m			DRILLING METHOD		Air Drilling	
DRILLING DEPTH (m)		DRILLING PROCESS				SAMPLE DSCRIPTION		
DEPTH (m)	INTERVAL	FROM	TO	PENETRATION RATE (m/min)		SAMPLES	DRILLING DIAMETER/CHANGE OF BIT (inches)	
0 - 4.6	4.6	10:06	10:11	0.9		Reddish Brown Laterites	14"	
4.6 - 9.2	4.6	10:26	10:32	0.8				
9.2 - 13.8	4.6	10:53	11:03	0.5				
13.8 - 18.4	4.6	11:23	11:35	0.4				
18.4 - 23	4.6	11:40	11:53	0.4		Grey Gabbroic Rocks	6"	
23 - 27.6	4.6	13:35	13:39	1				
27.6 - 32.2	4.6	13:41	13:46	0.9				
32.2 - 36.8	4.6	13:50	13:56	0.8				
36.8 - 41.4	4.6	13:59	14:07	0.6				
41.4 - 46	4.6	14:10	14:16	0.8				
46 - 50.6	4.6	14:19	14:27	0.6				
50.6 - 55.2	4.6	14:30	14:38	0.6				
55.2 - 59.8	4.6	14:40	14:47	0.7				
59.8 - 64.4	4.6	14:51	15:00	0.5				
64.4 - 69	4.6	15:03	15:11	0.6				
69 – 73.6	4.6	15:16	15:22	0.8				

APPENDIX-B

Geotechnical ref. No.		BABA DRILLING				BH status: Successful	
VES		BOREHOLE RECORD					
Community:		WELLINGTON FREETOWN		BH ref. No.	1	MY - BH - 01	Net. grid ref.
Drilling contractor:		BABA DRILLING		Drill rig:			Alt.
Drilling start date:		11th February, 2016		Compd. date:	12 February, 2016		Madhabudan / Saidho
TEST PUMPING				Date:	24th February, 2016		Top of screen *
Dynamic WL *				Pump type:			Static WL *
Static WL *		13.59		Pumping rate (Q)			Potential drawdown
Drawdown (s)				Duration:			Potential yield
* Levels to ground level datum				Specific capacity (Q/s)			Depth of borehole *
							74 m
BIT SIZE & TYPE		PROFILE		TIME / DEPTH (MIN)	WATER ZONES CUMULATIVE (CUMULATIVE)	WELL DIAGRAM with STATIC AND DYNAMIC WATER LEVELS	
10" DTH BIT							
7" DTH BIT							
Throughout							
Gravel for gravel pack		2 - 4mm		M		Remarks: We stop at 74m because of sufficient and sustainable water	
Cement for grouting		50		KG			
Bentonite for grouting				M			
Installation of grout seal				M			
Cleaning & development				HRS			
Centralisers fitted		Yes		No		Prepared by: BABA DRILLING & EXPLORATION COMPANY LIMITED (Contractor)	
Safety cap fitted		Yes		No			
Backfill around BH		Yes		No			
Disinfection date							
Platform construct date						Certified by: MORLIA KANU	
Platform transport adjust							
Cut access to site							
				KM		Approved by: V. MAHESH REDDY	
				KM			

APPENDIX-B

3.0 BOREHOLE LOG SHEET

CONTRACTOR	BABA DRILLING & EXPLORATION COMPANY				CLIENT	BLUE MOON INDUSTRIES	
COMMUNITY	WELLINGTON, FREETOWN				DEPTH OF HOLE	74m	
					START DATE	11 th February, 2016	
BORE-HOLE REFERENCE NO.	One (1)				COMPLETION DATE	13 st February, 2016	
DEPTH STRUCK WATER	29m,38m & 60m				DRILLING METHOD	Air Drilling	
DRILLING DEPTH (m)		DRILLING PROCESS				SAMPLE DSCRIPTION	
DEPTH (m)	INTERVAL	FROM	TO	PENETRATION RATE (m/min)	SAMPLES	DRILLING DIAMETER/CHANGE OF BIT (inches)	
0 - 4.6	4.6	09:00	09:03	1.5	} Reddish Brown Laterites	} 10"	
4.6 - 9.2	4.6	09:04	09:06	2.3			
9.2 - 13.8	4.6	09:09	09:12	1.5	} Light Yellow Lateritic Clay		
13.8 - 18.4	4.6	09:17	09:20	1.5			
18.4 - 23	4.6	09:22	09:25	1.5			
23 - 27.6	4.6	09:27	09:31	1.2			
27.6 - 32.2	4.6	08:22	08:25	1.5			
32.2 - 36.8	4.6	08:27	08:30	1.5			
36.8 - 41.4	4.6	08:30	08:33	1.5			
41.4 - 46	4.6	08:42	08:44	2.3			
46 - 50.6	4.6	08:46	08:48	2.3	} Grey Gabbroic Rock	} 7"	
50.6 - 55.2	4.6	08:51	09:00	0.5			
55.2 - 59.8	4.6	09:03	09:13	0.5			
59.8 - 64.4	4.6	09:15	09:26	0.4			
64.4 - 69	4.6	09:27	09:37	0.5			
69 - 73.6	4.6	09:41	09:52	0.4			

First Water Strike: **29m**

Second Water Strike: **38m**

APPENDIX-B

3.4: BOREHOLE DEVELOPMENT RECORD

COMMUNITY: **Osman Lane, Calaba Town**

BOREHOLE REF. No: **One (1)**

DEPTH: **60m**

DATE: **08/03/2017**

TOTAL TIME OF DEVELOPMENT: **3hrs.**

STATIC WATER LEVEL: **14.96m**

TIME		YEILD (m ³ /hr.)	OBSERVATION
From	To		
12:15	13: 15	2.3m ³ /hr	Muddy water flushed out
13:15	14:30		Cloudy water flushed out
14:30	15:15		Clean water flushed out