Stormwater management in Gaborone

A Minor Field Study of the quality and quantity of water in Segoditshane River

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by

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Picture on front page: Segoditshane River. Photo by Hanna Palm Johansson and Elin Andersson

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Minor Field Study

This study has been carried out within the framework of the Minor Field Studies (MFS) Scholarship Programme, which is funded by the Swedish International Development Cooperation Agency, Sida.

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The responsibility for the accuracy of the information presented in this MFS report rests entirely with the authors and their supervisors.

Preface

This master thesis has been performed by Elin Andersson and Hanna Palm Johansson, Environmental Engineering students with a specialization in Water Resources at the Faculty of Engineering at Lund University, Sweden. The thesis is the final part of the education and was performed at Water and Environmental Engineering at the Department of Chemical Engineering at the Faculty of Engineering, Lund University. The time for the master thesis was January to September 2015 and the field study was performed at University of Botswana in Gaborone, Botswana, during March and April 2015. The departments connected to the master thesis at University of Botswana were the Department of Civil Engineering, the Department of Chemistry, the Department of Environmental Science and the Department of Biology.

Before and during this project we have got great help from several persons. Hereby we would like to say Thank You to all of you in no particular order.

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Lund, September 2015

Elin Andersson and Hanna Palm Johansson

Abstract

This master thesis was partly performed as a field study in Gaborone, the capital city of Botswana, located in southern Africa. The semi-arid climate in Botswana together with a rapid financial development in the country during the last decades has increased the need for water. The last years the water situation has been strained in Gaborone, and Gaborone dam which used to be one of the city's drinking water sources has come down to a level of only a few per cent of its total capacity. The water scarcity results in a need for the country to transport water from northern Botswana as well as from South Africa to meet the need for water in Gaborone. The severe water situation results in need for alternative water sources for Gaborone. Reuse of urban stormwater is one alternative water source worth to investigate. A large amount of the stormwater from Gaborone discharges into Segoditshane River, a watercourse which flows through Gaborone. The aim with this project was to investigate the quality and quantity of water from Segoditshane River and the possibilities of collection and reuse of the water.

Water samples were collected from Segoditshane River at three times and at two locations each time. One sample of stormwater was also collected from a parking lot at University of Botswana and another water sample was collected from a roof at Motheo Apartments, both located in Gaborone. Quality parameters for the water samples were measured at the sample sites and in laboratories at University of Botswana. The water contained several metals. Most outstanding were arsenic, lead, cadmium and aluminium. Hydrocarbons connected to traffic pollution were also noticed in the water. When water from Segoditshane River was tested for pollution of microorganisms no *E. Coli* was found but other enteric bacteria were found and hence possible inflow of sewage water in Segoditshane River cannot be disregarded. However, the enteric bacteria may also origin from faeces from animals. Depending on the planned reuse of the water, different water treatment would be needed. Drinking water needs more treatment than irrigation water. Biological treatment methods along Segoditshane River may improve the quality of the water. A stormwater dam downstream can store the water and prevent flooding as well as further improve the water quality through settling.

Rainfall data for the years 2001-2010 was given from Department of Meteorological Services in Botswana and were processed in order to estimate the water volume possible to collect in the urban part of Segoditshane River catchment. In the quantity calculations the evaporation is not included and the annual water volumes originating from stormwater will therefore be lower than the volumes presented below. Three scenarios were set up to describe potential situations for the stormwater in the catchment. Scenario 1 includes the stormwater runoff from larger roads and gravel areas and according to this scenario a water volume of less than 4.8 Mm^3 is possible to collect. This corresponds to 15% of the total annual water usage in Gaborone. Scenario 2 includes the stormwater runoff from all house roofs in the city and in this scenario a water volume of less than 3.6 Mm^3 is possible to collect, 10% of the total water usage in Gaborone. Scenario 3 describes the amount of stormwater runoff from large roads, gravel areas and house roofs ending up in Segoditshane River and in this scenario a water volume of less than 7.2 Mm^3, 23% of the total water usage in Gaborone, can be collected.

There is a potential worth considering of collecting stormwater from Segoditshane River and rainwater from house roofs in Gaborone in order to reuse the water and hence improve the stressed water situation in Gaborone.

Sammanfattning

Det här examensarbetet utfördes delvis som en fältstudie i Gaborone, Botswanas huvudstad, i södra Afrika. Botswanas semiarida klimat kombinerat med snabb ekonomisk tillväxt de senaste decennierna har bidragit till ett ökat vattenbehov i landet. Vattensituationen i Gaborone har de senaste åren varit ansträngd och kapaciteten i Gaborone-dammen, den tidigare dricksvattenreservoaren för Gaborone, är nu nere på bara några få procent av den totala kapaciteten. Vattenbristen resulterar i att Botswana tvingas transportera vatten från norra delen av landet samt från Sydafrika för att möta vattenbehovet i Gaborone. Den allvarliga vattensituationen medför ett behov av alternativa vattenkällor, där återanvändning av dagvatten är ett alternativ värt att undersöka. En stor del av dagvattnet från Gaborone rinner ut i Segoditshane River, ett vattendrag som rinner genom Gaborone. Syftet med detta projekt var att undersöka kvaliteten och kvantiteten av, samt möjligheterna att samla upp och återanvända, vattnet från Segoditshane River.

Från Segoditshane River togs vattenprover på två olika platser vid tre olika tillfällen. Ytterligare två vattenprover togs i Gaborone, ett från en parkeringsplats på University of Botswana och ett annat från ett tak på Motheo Apartments. Olika kvalitetsparametrar mättes, dels i fält och dels i laboratorier på University of Botswana. Vattenproverna innehöll flera metaller där de mest utmärkande var arsenik, bly, kadmium och aluminium. Även kolväten med möjligt ursprung från trafikföroreningar upptäcktes i vattnet. En mikrobiologisk analys genomfördes på två av proverna från Segoditshane River. *E. Coli* påvisades inte i vattenproverna men däremot andra tarmbakterier varför tillflöde av spillvatten till Segoditshane River inte kan uteslutas och bör utredas vidare. Tarmbakterierna kan även komma från djur som lever längs vattendraget.

Beroende på hur det uppsamlade vattnet ska användas så behövs olika reningsmetoder. Dricksvatten kräver mer avancerad rening än vatten som ska användas till bevattning. Biologisk rening längs Segoditshane River kan förbättra vattenkvaliteten i vattendraget. En dagvattendamm nedströms ån kan samla upp och lagra vattnet samt förhindra översvämning och i viss mån förbättra vattenkvaliteten genom sedimentering.

Regndata från åren 2001-2010 från Botswanas meteorologiska myndighet användes för att uppskatta storleken på vattenvolymer möjliga att samla upp från den urbana delen av Segoditshane Rivers avrinningsområde. I de kvantitetsberäkningar som gjorts har avdunstning inte inkluderats vilket medför att de faktiska vattenvolymerna är mindre än de som presenteras här. Tre scenarion sattes upp för att beskriva olika dagvattensituationer i avrinningsområdet. Enligt scenario 1 antas allt dagvatten komma från större vägar och grusarealer och därifrån rinna ut i Segoditshane och samlas upp. Scenario 2 beskriver hur mycket avrinning som kan förväntas från hustak. Scenario 3 beskriver hur mycket vatten som kan samlas upp om vattnet från stora vägar, grusarealer och hustak rinner ut i Segoditshane och samlas upp. Enligt scenario 1 kan mindre än 4.8 Mm^3 vatten samlas upp från vägar och grusarealer. Det motsvarar 15 % av den totala årliga vattenanvändningen i Gaborone. Enligt scenario 2 kan mindre än 3.6 Mm^3 vatten samlas upp från hustak i Gaborone vilket motsvarar 10 % av den totala årliga vattenanvändningen i Gaborone. Scenario 3 ger en årlig vattenvolym av mindre än 7.2 Mm^3 vilket motsvarar 23% av Gaborones totala vattenanvändning per år.

Det finns en potential för uppsamling av dagvatten från Segoditshane River och regnvatten från hustak i Gaborone som är värd att undersöka vidare för att förbättra den ansträngda vattensituationen i Gaborone.

Abbreviations

BOD	Biological Oxygen Demand
BTV	Botswana Television
BWP	Botswana Pula
CASL	Community Adaptation and Sustainable Livelihoods
CBRNE	Chemical, Biological, Radiological, Nuclear and Explosive
CFU	Colony Forming Units
COD	Chemical Oxygen Demand
CPP	Civil & Planning Partnership
CSO	Combined Sewer Overflow
DMS	Department of Meteorological Services
DO	Dissolved Oxygen
DWA	Department of Water Affairs
GC TOF MS	Gas Chromatography Time of Flight Mass Spectrometer
GDP	Gross Domestic Product
MMEWR	Ministry of Minerals, Energy and Water Resources
MP-AES	Microwave Plasma - Atomic Emission Spectrometer
MPN	Most Probable Number
PCA	Plate Count Agar
PAH	Polycyclic Aromatic Hydrocarbons
TSS	Total Suspended Solids
UB	University of Botswana
VSS	Volatile Suspended Solids
WHO	World Health Organization
WUC	Water Utilities Cooperation

Contents

1 Introduction

In Botswana, located in southern Africa, water issues are generally a current topic due to the water scarcity in the country. How to secure a proper water supply to the inhabitants and the country as a whole has been, is and will probably in the future be one of the most important issues in the country. Factors such as unpredictable rainfall, rainfall deficiency and high evaporation rates strictly limit the possibilities for an uncomplicated water management. Many projects have been carried out and alternative water sources investigated in order to secure the water supply (MMEWR & DWA, 2013).

Gaborone, the capital of Botswana, located in the south-eastern part of the country is strongly affected by the stressed water situation. With an increasing and fast growing population in a particularly dry area of the country the water shortage is strongly apparent in Gaborone (MMEWR & DWA, 2013). The lack of water increases the interest in alternative water sources, stormwater being one of them. Today a watercourse called Segoditshane River that runs through central Gaborone receives a large part of the stormwater from the city. Collection and reuse of water from this river could be one way to improve the water situation in Gaborone.

1.1 Aim

The aim of this project is to investigate the quality and quantity of stormwater from Segoditshane River, Gaborone, and the possibilities of collection and reuse.

From the aim, four research questions for the work were compiled:

- How is the present state of the water quality in Segoditshane River?
- From the present state of the water quality in Segoditshane River; Are water quality improvements motivated and how can those improvements be arranged?
- What quantity of stormwater can be expected from Segoditshane River catchment area?
- In what way can the water from Segoditshane River catchment area be collected and reused?

1.2 Minor Field Study

This master thesis was carried out as a Minor Field Study financed by Sida, the Swedish International Development Cooperation Agency. The field study was performed in Gaborone, Botswana, during March and April 2015.

1.3 Limitations

The field study of this master thesis was limited to eight weeks in time. The thesis only includes the Segoditshane River and not the tributary streams. The quality analysis of the water from Segoditshane River was based on samples from only two sites along the river and at only three sampling occasions. In the quantity calculations evaporation was not included. The thesis does not include climate changes and their effects on the precipitation in Botswana.

2 Background

This chapter aims to give useful background information about Botswana and more specifically Gaborone and Segoditshane River. The overall focus is on the water situation in Botswana.

2.1 Botswana

Botswana is located in southern Africa and borders to South Africa in the south, Namibia in the west, Zimbabwe in the north-east and a minor part of the northern border is towards Zambia, see Figure 2.1. The country has no coast and is hence a land-locked country. Botswana has an area of 582 000 km^2 (Ganesan, 2001). For comparison, the area of Sweden is 439 000 km^2 (EU, 2015). The population of Botswana was in January 2015 around 2.1 million people (Countrymeters, 2015).

Figure 2.1. Botswana's location in southern Africa (Google Maps, 2015a).

The economy in Botswana is mainly based on mining, and livestock and diamonds are the main export product (Ganesan, 2001). Since the Independence in 1966 the economy has grown fast which, in combination with a rapid increase in population, has contributed to the water resources management being stressed (MMEWR & DWA, 2013). At several places the water resources are insufficient (Worldbankgroup, 2014). How to provide safe water for the people, industries and mines, now as well as in the future, is a very important and urgent question in Botswana today. Improvements in standards of living as well as changes in household income also affect the water consumption since people living in high cost homes tend to consume more water. Due to expected increase in population and increased standards of living in Botswana the water demand in the country is expected to increase. Botswana experiences an increasing urbanization with more and more people living in urban areas. This also affects the water consumption since people living in urban areas tend to use more water than people living in the countryside in Botswana (Ganesan, 2001). In the "Botswana Integrated Water Resources Management & Water Efficiency Plan" from 2013 the importance of proper water resources development and management to secure a sustainable development of the society is emphasized (MMEWR & DWA, 2013).

2.1.1 Climate

The southern Africa region is a drought prone area and the climate in Botswana is semi-arid[1] (Ganesan, 2001). The summer season in Botswana is between December and March and this is when most of the rainfall occurs (Ganesan, 2001). The rainfall in Botswana is generally low and the mean annual rainfall varies from a maximum of 650 mm to a minimum of 250 mm (MMEWR & DWA, 2013). The majority of the towns in Botswana are located in the eastern part of the country which hence is most populated and here the mean annual rainfall is between 400 and 550 mm. At the same time the potential evaporation is around 2 000 mm per year and hence four times higher than the average precipitation each year. The potential evaporation exceeding the average rainfall results in the evaporation being controlled by the actual rainfall (De Vroes & Gieske, 1990). The evaporation being so much higher than the precipitation results in a water shortage in Botswana (Ganesan, 2001). Although Botswana being a semi-arid country with a low number of rainfalls, the intensity of the rainfalls can be very high. The rainfalls can also be highly variable over time. Where the number of rainfalls is lower the variability is higher and it is expected that the climate change will increase the variability (MMEWR & DWA, 2013). Since the rainfall can vary from year to year the runoff from rivers are also likely to vary. The climate, unpredictable and patchy rainfall and hence unpredictable run-off events as well as losses due to high rates of evaporation and evapotranspiration make modeling of hydrological processes in Botswana very difficult (Ganesan, 2001).

2.1.2 Surface water

In large parts of Botswana the topography is flat which makes it difficult to use surface water as a water source. Not only unsuitable dam sites but also other parameters such as high evaporation rates, erratic rainfall contributing to even more erratic runoff and poor soil conditions (sandy and pervious soils) limit the use of surface water in Botswana. Most of the rivers in Botswana are in the eastern part of the country and are not perennial. Only two rivers are perennial, Chobe and Okavango, and they are located in the northern parts of the country which are less populated (Ganesan, 2001; MMEWR & DWA, 2013). The Chobe and Okavango rivers represent 95% of the total surface water resources in Botswana (Ganesan, 2001). Although there are parameters limiting the use of surface water in Botswana, around half the amount of total water consumed comes from surface water (Worldbankgroup, 2014).

2.1.3 Groundwater

Groundwater represents around half of the total water use in Botswana (Worldbankgroup, 2014). Deep boreholes are needed to access the groundwater but unfortunately the quality can often be bad (MMEWR & DWA, 2013). The recharge of groundwater is also very low and many boreholes are depleted after some years of usage. Surface water is generally used as a water source in cities while groundwater is commonly used in smaller villages (Ganesan, 2001).

2.1.4 Recycled water

Recycled water represents only a small part of the total water use in Botswana (Worldbankgroup, 2014). Recycled water, especially from wastewater treatment plants, may in the future be used for irrigation. Due to the stressed water situation in Botswana, large scale irrigation is not prioritized (Ganesan, 2001).

[1] Semi-arid climate is characterized by low erratic rainfall and periodic droughts (CASL, 2015).

2.1.5 Water use

The most water consuming sectors are the agricultural and the mining sectors representing 44% and 21%, respectively, of the total water use. At the same time the agricultural sector contributes to a relatively small extent to the economy and the gross domestic product, GDP. The mining sector stands for a relatively large part of the GDP but represents at the same time a relatively small part of the employment (Worldbankgroup, 2014). The trend shows that urban centers will be the significantly largest water consuming sector followed by the mining sector (MMEWR & DWA, 2013).

The total water use in Botswana was about 200 Mm^3 and the average annual water use per capita was about 95 m^3/person in 2011. The water charge was then 0.37 BWP/m^3 (Worldbankgroup, 2014). In Sweden the total annual water use per capita was 344 m^3 in 2010 (Statistics Sweden, 2015). The water volume of 95 m^3/person in Botswana for 2011 is the national water use divided by the national population size. The water volume of 344 m^3/person was the total water use in Sweden for 2010, including household, industrial and agricultural water use. During the last twenty years the water charge has increased considerably in Botswana. Due to increased efficiency in water use and changes in economic structures the relative increase in water use has been slower than population and economic growth (Worldbankgroup, 2014).

2.1.6 Water quality

The Botswana Integrated Water Resources Management & Water Efficiency Plan heavily emphasizes the importance of good quality of both surface water and groundwater. Poor water quality can cause problems for human and animal health and the environment can also be affected. Examples of parameters connected to water quality are salinity, odor, colour and water pollution. It is likely that pollution of different kinds increases when the economy grows which makes control measures even more important in order to prevent the pollutions on an early stage (MMEWR & DWA, 2013).

2.2 Gaborone

Gaborone, the capital of Botswana, is located in the southeastern part of the country, see Figure 2.2. The surface of the city is about 210 km^2 (CPP, 2002) and it has around 230 000 inhabitants (Brinkhoff, 2014). Gaborone started to develop rapidly in the 1960's and since then the population has increased quickly (CPP, 2002). Today, Gaborone is the city where the population grows fastest in Botswana (MMEWR & DWA, 2013). Sanitary facilities and services, such as storm drainage, have not been developed in the same rate as the increase in population. With its location in the southeastern part of the country, Gaborone is not located where the main water recourses in Botswana are (CPP, 2002).

The present water consumption in Gaborone is on average 90 000 m^3 per day which corresponds to 2.7 Mm^3 per month or 32.4 Mm^3 per year or 0.39 m^3 per person and day. However there are restrictions regarding the water consumption, e.g. the water distribution is cut off in different parts of the city at different days of the week. Without those restrictions the expected water consumption would be 110 000 m^3 per day[2].

[2] Pule, O. B. Department of Water Affairs, e-mail May 29, 2015

2.2.1 Gaborone dam

There are several dams in Botswana where water is stored. The largest one is Gaborone dam with a catchment area of 4 300 km^2 and a total capacity of around 144 Mm^3 (MMEWR & DWA, 2013). The current water content of the dam is around 2% of the total capacity due to very low rainfall the last years, see Figure 2.3 (WUC, 2015a). The dam is not used as a water source today since the water went below the lowest abstraction point in February 2015[3]. Botswana is in total divided in six larger catchments and Gaborone belongs to the Limpopo River catchment with a total area of 80 000 km^2. Gaborone dam is one of several dams in this catchment (MMEWR & DWA, 2013).

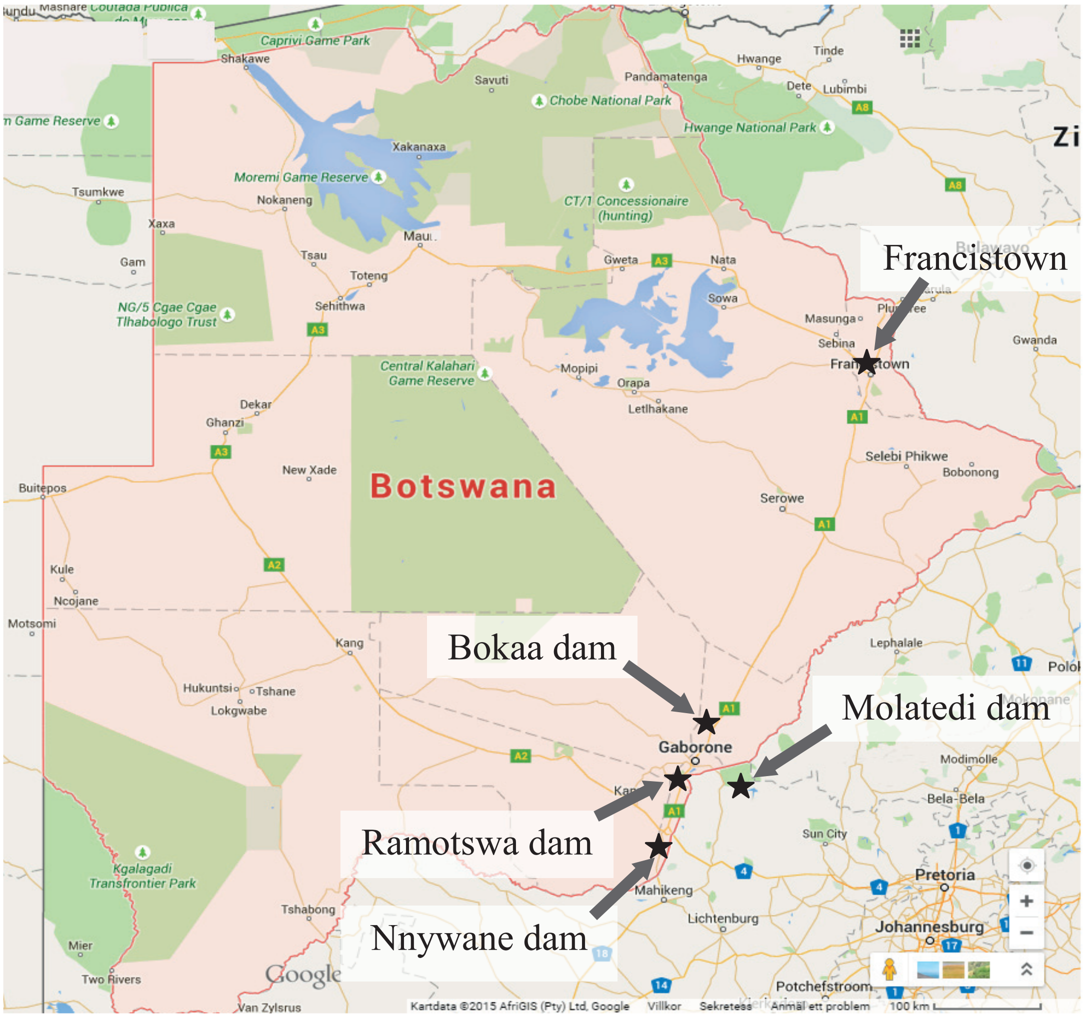

Figure 2.2. Map of Botswana with the capital Gaborone in the southeastern part of the country (Google Maps, 2015b). Figure modified by authors.

[3] Pule, O. B. Department of Water Affairs, e-mail May 29, 2015

Figure 2.3. Air photo of Gaborone dam taken on March 4, 2015.

2.2.2 Gaborone climate

Gaborone has a continental climate with cloudy weather, high temperatures and high humidity during summers. The winters are very dry with extremely low rainfall and mild temperatures. The temperature and humidity vary relatively little between the months (CPP, 2002). December and January are the hottest months at the peak of the summer season with an average daily maximum temperature around 32°C and the maximum temperatures reaching around 40°C. June and July represent the coldest months with an average daily maximum temperature around 21°C and the lowest temperatures around -5°C (DMS, 2015). The daily temperatures vary a lot due to the continental climate. The Gaborone climate is also influenced by convection processes due to the ascent and subsequent condensation of hot air masses. These processes generate storms of high intensity and short duration. The evaporation is connected to the temperatures and during the summer the evaporation reaches the highest values. During the colder winter the evaporation is lower but it does vary a lot also within the seasons. The relatively humidity is usually compartively low in Gaborone even during the wet and hot summer (CPP, 2002).

2.2.3 Gaborone rainfall characteristics

In the catchment as well as in Botswana the rains often occur in spells of 2-4 days. In February 2000 and 2001 there were prolonged periods of rainfall but these are usually very rare. In and around Gaborone there are several rain gauge stations. In Gaborone there is one station at DMS offices and one at Sir Seretse Khama Airport. There are also three other stations at Kgale, Sebele and the Gaborone dam. In addition to those there are also several rain gauges installed in villages around Gaborone, including Mogoditshane, Tlokweng, Gabane and Oodi (CPP, 2002).

The rainfall is more frequent during the summer from November to March and very low during winter. For the Gaborone area the mean annual rainfall is about 510 mm. Around 60-

65% of the total rainy days record significant storms which yields a depth exceeding a threshold value of 1 mm. Only 25% of the rainfalls yield amounts in excess of 10 mm on each rainy day. The rainfall events have considerable differences in spatial variability due to the characteristics of the convective processes. Most rainfalls in the catchment are characterized by these processes (CPP, 2002).

The streams in Gaborone, including Segoditshane, have a well-defined seasonal pattern from the rainfall. Generally the recession time for the streamflows is very short, usually only a few hours after the rains. During the dry season the rivers run completely dry except those fed by flows from settlements in the catchments. Segoditshane discharges into Notwane river coming from Gaborone dam, see Figure 2.4 (CPP, 2002).

2.2.4 Gaborone geology

The geology in Gaborone includes the Gaborone Granite Complex Supergroup. It is divided into four units; The Kanye Volcanics, The Ntlanthe Microgranite, The Kgale Granite and the Thamaga Granite. Most of the rocks are not exposed but covered with residual gravel and alluvial soils originating from weathering of the rocks. On low-lying areas and along rivers the alluvial soils are mostly clays. The soils underlain Segoditshane river are mainly consolidated clay with some surfaced rock. There is evidence of sediment transport in the stream channel which presumably emerge from sources at the hills in the catchment (CPP, 2002).

2.2.5 Segoditshane River

Segoditshane River is the largest tributary river of the Notwane River and originates from Gabane hills, approximately 11 km west of Gaborone. In the more upstream part of Segoditshane River, directly after Gabane hills the catchment is predominantly rural with almost no infrastructural development. That part of the river catchment is mostly covered with shrubs and grass. In the Segoditshane River catchment nearly all areas are developed land with only a few areas of undeveloped land in the upstream parts. In a few years the river catchment is however expected to be very close to saturated in terms of development. Segoditshane River flows in an almost easterly direction. The river flows almost centrally through the city and several principal roads crosses the river. Segoditshane River finally enters Notwane River about 200 m upstream the city's waste water treatment plant in the northern part of the city. Segoditshane River is approximately 22 km long. The Segoditshane River catchment holds more than 70% of the residential areas of the city (CPP, 2002).

The Segoditshane River catchment area, shown in Figure 2.4, is about 100 km^2 (DWA, 2010) and has the shape of an elongated crescent. It is 4.2 km at its broadest section. The length-width ratio for the catchment area is about 2.5. Kgale hill is the southern catchment boundary whereas the Nkoyaphiri hills represent the northern boundary. The average overland slope in the catchment is approximately 1%. In the northern part of the river catchment the average overland slope is 0.8% while the southern half of the catchment has a steeper slope of 2%. The overland width of the southern half is on average one third smaller than the northern half (CPP, 2002). There are no flow data records for Segoditshane River.

Heavy and patchy rainfalls often lead to flooding in different parts of Gaborone. Not only the amounts of rain cause floods but also factors such as insufficient drainage, e.g. due to lack of maintenance or due to the flat terrain, in some parts of the town limits the runoff. The most flood prone areas in Gaborone lie close to the floodplains of Segoditshane River (CPP, 2002).

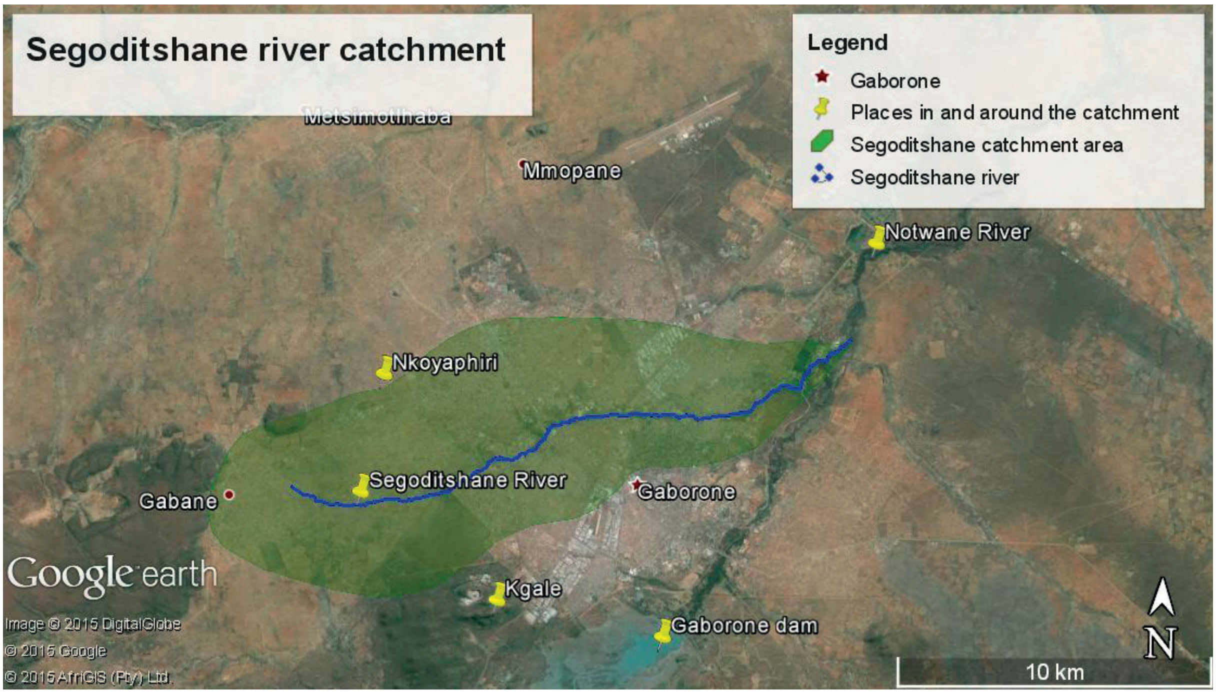

Figure 2.4. Segoditshane River catchment including Segoditshane River, delineated in Google Earth (Google Earth, 2015a). Photo modified by the authors.

2.2.6 Water Utilities Corporation

Water Utilities Corporation (WUC) is an organization established in 1970 and owned by the government of Botswana. This organization is responsible for delivery of potable water to the country and for management of wastewater treatment services (MMEWR & DWA, 2013; WUC, 2010). The main focus is the water management in urban areas and more exactly the six major towns in Botswana (Ganesan, 2001).

2.2.7 Department of Water Affairs

The Department of Water Affairs (DWA) is responsible for development and protection of water resources in Botswana in order to support a sustainable social-economic growth. Assessment, planning, development and management of water resources for short as well as long term purposes is part of the work at the department. Also administration of the water law and other water related legislations and management of international water sources lies under the department (MMEWR, 2013). DWA is entirely financed by the central government (MMEWR & DWA, 2013). While WUC is responsible for the water supply in the larger cities DWA is responsible for the water management in most of the smaller villages in Botswana (Ganesan, 2001). Except WUC and DWA also some smaller institutions take care of the water supply for livestock, mines and wildlife.

2.3 Previous studies regarding Segoditshane

Previous studies conducted regarding Segoditshane River includes one finished in May 2010 by the Department of Water Affairs – Ministry of minerals, energy and water resources. The title is Water from the Segoditshane River and is written by Professor D Stephenson (Stephenson, 2010). Stephensons's report was found and studied for this master thesis late in the working process and there are similarities with the aim and the questions asked in this master thesis.

In the report the possibilities of utilizing the water from Segoditshane River was investigated. In the report it was concluded that the runoff to Segoditshane River averages up to 5 Mm^3 of water per year. A dam structure and treatment of the water would be needed to balance flow and secure the water quality. Further the report concluded that, in order to improve the water situation in Segoditshane River, there will be need for stream gauging, testing of water samples for pollution levels as well as investigations for dam sites. In this master thesis analysis of water samples for quality parameters are studied which complement Stephenson's report.

The runoff to Segoditshane River has both domestic and industrial contributions. Sewage water is led separately to the waste water treatment plant for treatment. The treated sewage water is then discharged into the Notwane River. Segoditshane River is expected to have a high pollution load originating from the city and this water would need treatment before it can be used for domestic purposes (Stephenson, 2010).

Along the Segoditshane River there are no gauging for water flows and the river is not monitored for the pollution levels. Testing for presence of wastewater and chemical contaminants would be needed to select the most appropriate way of treatment (Stephenson, 2010).

In 2010 a pre-feasibility study of potential dam sites and off-river storages on the lower Notwane River was performed by DWA (DWA, 2010). In the report potential dam sites for storages in the lower Notwane River catchment was investigated. Segoditshane River catchment is a sub-catchment to Notwane River catchment but was in the Notwane River report from 2010 not studied in detail. Two dam sites in lower Notwane River catchment were chosen for further studies. The water stored in the dams should be stored less than a month due to high evaporation rates. The water from the dams could be transferred to Bokaa dam (located north of Gaborone) or Gaborone dam for further usage.

3 Theory

The theory includes four major parts; Stormwater - background and management, Stormwater quality, Stormwater quantity and lastly Treatment methods, collecting systems and areas of reuse.

3.1 Stormwater – background and management

Stormwater is defined as the part of the rainfall that runs off from urban surfaces. Stormwater is also called surface runoff but not all the rainwater that reaches the ground actually runs off. The water can be lost due to different reasons. The water can be stored in depressions on the catchment surface and is hence prevented to run off. Also water vaporized from plants and open water bodies, so called evapotranspiration, results in less water reaching the stormwater system. Part of the rainfall also infiltrates into the ground where it can enter the groundwater. Different soils have different infiltration capacity which depends on the soil type, the structure of the soil, the initial moisture content and the depth of water covering the soil. The initial infiltration rate is high but decreases exponentially until it reaches a final steady rate which is when the upper soil zone is saturated. The part of the rainfall in urban areas that is not captured by vegetation or infiltrated into the ground is accumulated on the catchment surface. After some distance of overland flow this water will end up in underground storm sewers or natural drainage channels (WEF & ASCE, 1992).

The purpose with stormwater management has varied over the years and does vary between different cities and countries regarding the local conditions. At places where large amounts of stormwater are received, the main focus with stormwater management was for a long time to remove water from e.g. a city. However, during the last 20-30 years another purpose has been the quality of the stormwater, and treatment of stormwater has become more common. Treatment of stormwater has, during the last 10 years, also been combined with an aesthetic value of stormwater since treatment ponds and wetlands may have a recreational value. Sustainable urban drainage has become a concept where stormwater is seen as a resource and not only something to remove (Stahre, 2008).

At places which are more dry, on the other hand, there is an interest in collection and reuse of stormwater. Droughts and climate change may lead to water scarcity and then stormwater conservation and water reuse get more and more important to secure the water supply. The conservation of stormwater reduces the volumes and peak flows of stormwater that reach the receiving streams. Also measurements like reducing the impervious areas in order to prevent stormwater to infiltrate and hence collect more water can be used. These are measurements that are avoided in areas where the purpose of stormwater management is to remove the water as quick as possible (Gautam *et al*., 2010).

3.2 Stormwater quality

Urban stormwater can be heavily polluted with a range of substances. These can be natural organic and inorganic substances as well as man-made substances. The man-made substances can originate from transport as well as from commercial and industrial practices. Pollutants in stormwater originate from atmospheric downfall and substances present on the runoff surfaces. The concentration of pollutants can differ greatly in time due to the frequency and intensity of rain and use of the area (Butler & Davies, 2004). During periods with no rain contaminants like dust, inert solids and other pollutants are accumulated on roofs and other impermeable surfaces. During the first rain after a dry period the runoff water may contain higher loads of contaminants compared to the runoff later during the rain event. This is called the first-flush (Gikas & Tsihrintzis, 2012).

Pollutants in the atmosphere originate from human activities such as heating, traffic, industry or waste incineration etc. These have come in contact with stormwater as wet outfall from precipitation or as dry outfall from settling on land surfaces (Butler & Davies, 2004).

Pollutants from traffic also add to the total amount of pollutants in stormwater. Unburned fuel from vehicles can emit volatile solids and polycyclic aromatic hydrocarbons (PAH). Tires wearing off release zinc and hydrocarbons. Corrosion of vehicles release pollutants like iron, chromium, lead and zinc. Degradation of roads and paved surfaces will also release particles of various sizes that eventually reach the stormwater (Butler & Davies, 2004).

In the following sections different quality aspects and pollutants connected to stormwater are presented.

3.2.1 Solids

Solids in water can be divided into four groups: gross, grit, suspended and dissolved. The gross particles are the particles larger than approximately 6 mm in two dimensions. In stormwater gross particles can consist of debris like bricks, wood, cans, paper etc. These particles can beside aesthetic impact in the environment cause maintenance problems by deposition and blockages of screens and pipes. Grit can be defined as inert, granular material larger than 150 µm. The main mass of the material in sewer sediment can be counted as grit. The suspended solids in stormwater mainly origins from construction activities, unpaved surfaces and agriculture. Traffic also contributes to the amount of suspended solids in stormwater and the largest sources are parking lots and roads (Feng *et al.*, 2012). Suspended solids (SS) are the particles maintained in suspension and what is left after filtering through a filter with pore size 0.45 µm. Suspended solids consist of both organic and inorganic compounds. The organic suspended solids are volatile and therefore also called volatile suspended solids, VSS. VSS and SS together make TSS – Total Suspended Solids. Suspended solids may cause problems in surface waters since they are good carriers of pollutants (Butler & Davies, 2004). Pollutants carried by suspended solids can be hydrocarbons, heavy metals, pesticides and PCB (Deletic *et al.*, 2011). High concentration of SS may affect the receiving water by increasing the turbidity, and hence reducing light penetration, which disturbs fish and aquatic invertebrates (Butler & Davies, 2004). High amounts of total suspended solids are often related to higher amounts of disease-causing microorganisms like viruses, parasites and bacteria (EPA, 2014).

3.2.2 Dissolved oxygen

The levels of dissolved oxygen (DO) depend on physical, chemical and biochemical processes in the water. The solubility of oxygen in water depends on temperature and purity. Water with higher temperature can hold less oxygen than cold water. The DO saturation value also decreases with increase of purity (e.g. salinity, solids content) and decrease in atmospheric pressure. Dissolved oxygen can be seen as a health indicator of receiving waters. All higher forms of water organisms require oxygen and coarse fish need 3 mg/l. In absence of toxic compounds, DO and biodiversity are closely correlated (Butler & Davies, 2004).

3.2.3 Organic compounds

Stormwater contain significant amounts of organic compounds in both particulate and soluble form. The biodegradable organics consist of carbohydrates (sugars, starch and cellulose), proteins (built up of amino acids and urea) and lipids and fats. DO is consumed by microorganisms and animals when eating and degrading organic matter which can lead to oxygen depletion in sewers and receiving waters. The amount of organic matter in a water sample can be estimated by measuring the biochemical oxygen demand (BOD), the chemical oxygen demand (COD) or the total organic carbon (TOC). The three methods are carried out in three different ways and give somewhat different estimates of the content of organic matter (Butler & Davies, 2004).

3.2.4 Turbidity

Suspended particles or colloidal matter that blocks light transmission through water is called turbidity. The particles can be both inorganic and organic matter. It is common for microorganisms to attach to particles. Hence removal of turbidity through filtration will also reduce microbial contamination to some extent. Due to the easy attachment of microorganisms on particles, turbidity is acting as an indicator of possible microbial contamination and turbidity therefore correlates with increasing risk of gastrointestinal infections. However turbidity can also be caused by minerals or from post-precipitation of calcium carbonate which is not necessarily a threat to health. Turbidity can occasionally also be caused by small air bubbles released when there is a high dissolved air content in the water. Turbidity plays an important role in decisions regarding water sources and treatment for water supplies (WHO, 2011).

Turbidity can be expressed in Nephelometric Turbidity Units (NTU) as well as Formazine Turbidity Unit (FTU). The relation between NTU and FTU is 1:1 (Daly, 2015).

A human eye can notice turbidity above 4 NTU. After disinfection of drinking water, turbidity in the water should not be above 1 NTU. At small water supplies with limited treatment it may not be possible to reach that low turbidity levels. Then the water should have a turbidity of less than 5 NTU and if possible, less than 1 NTU (WHO, 2011).

3.2.5 Electrical conductivity

The conductivity for water represents the ability of the water to conduct electrical current and is affected by different compounds in the water. Inorganic dissolved solids that are either cations or anions affect the conductivity since the ions can conduct electrical current. Organic compounds, e.g. oil, sugar and alcohol do not conduct electrical current and hence reduce the conductivity in water. Temperature also affects the conductivity and the higher the temperature of the water the higher the conductivity. To get comparable results conductivity should be measured at 25°C (EPA, 2012).

The conductivity being affected by several compounds in the water makes it a good quality measure. Inflow of sewage water can change the conductivity in a stream since sewage water contain e.g. phosphate and nitrate; ions that increases the conductivity. An oil spill on the other hand would decrease the conductivity (EPA, 2012).

The surrounding geology is the primary factor that affects the conductivity in a stream or a river. A hard bedrock, e.g. granite, does not release ions to the water while softer materials, e.g. clay, does release particles that ionize in the water. Inflow of groundwater to surface water can also affect the conductivity depending on what kind of bedrock the groundwater has passed (EPA, 2012).

3.2.6 Metals

Heavy metals and other toxic metals can be found in considerable amounts in stormwater. Some of the metals present can be arsenic, lead, cadmium, iron, copper, zinc and mercury.

Depending on the redox and pH conditions these can be in different phases such as particulate, colloidal and dissolved. In stormwater, metals are mostly found in particulate phase. Heavy metals can have toxic effects on aquatic life (Butler & Davies, 2004).

Health effects from heavy metals are mostly associated with exposure to lead, mercury, cadmium and arsenic. Several severe health effects are known from heavy metals but they are still used in many parts of the world, especially in developing countries. In developed countries the emissions of heavy metals have decreased the last 100 years (Järup, 2003).

Analyses of metal concentrations are important in order to detect levels of metals that can be harmful to humans and the environment. To find out about the concentrations of metals at a specific site there are different analyzing methods which can be used. One of them is the MP-AES which stands for Microwave plasma – Atomic Emission Spectrometry which is an atomic emission technique (John Wiley & Sons, 2011). The MP-AES consists of both a microwave induced plasma as well as an atomic emission spectrophotometer (AES). The MP-AES can determine major and minor elements through simultaneous multi-analysis (CBRNETechIndex, 2014). The plasma is based on nitrogen from a compressed air supply and nitrogen generator (John Wiley & Sons, 2011).

The nitrogen can be supplied from a gas cylinder or be extracted from surrounding air. Through the MP-AES technique ions in the sample pass through the plasma. Electrons are put in excited state and the resulting light when the electrons return to the ground state is separated in a spectrum. The intensity of each emission can then be measured by a detector and hence the present elements can be determined (CBRNETechIndex, 2014).

The metals studied in this report are presented in the following text. Almost all metals presented have guideline values from WHO regarding drinking water and those are presented for each metal respectively.

Cadmium (Cd)

Cadmium is a heavy metal found naturally in ores together with zinc, copper and lead. Cadmium is mostly used in rechargeable nickel-cadmium batteries and can also be found used as stabilizers in PVC plastic products and in colour pigment. It is also a pollutant found in phosphate fertilizers. During the 20^{th} century emissions from cadmium have increased dramatically. One reason to the high emissions may be that cadmium compounds rarely are recycled and instead dumped together with household waste. It is especially contaminating the environment when the waste is being incinerated. The application of cadmium-containing fertilizers may lead to uptake of cadmium by crops and vegetables grown for human consumption. New information states that cadmium is more harmful in lower concentrations than thought before. Exposure may lead to kidney damage and bone effects. Long-term exposure of high cadmium levels may also cause skeletal damage (Järup, 2003). WHO's guideline value for drinking water regarding cadmium is 0.003 mg/l (WHO, 2011).

Lead (Pb)

Lead is a heavy metal which has been used for 5000 years as building material and in water pipes. Lead emissions have caused large pollution the last century mostly originating from petrol sources. However, lead emissions have decreased distinctly the last decades due to introduction of unleaded petrol. The lead transferred via air can be deposited on soil and water and thus reaching the human food chain. Lead is accumulated in the skeleton and is very slowly released. Children are especially vulnerable to lead exposure which may cause brain damage. Long-term exposure for adults may cause anaemia and in earlier stages disturbance of haemoglobin synthesis (Järup, 2003). WHO's guideline value for drinking water regarding lead is 0.01 mg/l (WHO, 2011).

Arsenic (As)
Arsenic is a widely distributed metalloid but usually classified as a heavy metal. Arsenic occurs in rock, soil, water and air. Inorganic arsenic can be found contaminating ground water in several countries in the world. Organic arsenic can be found in fish and therefore exposed to humans via the food chain. The metal is common in wood preservatives and is still used as an additive to petrol in some parts of the world. Energy production from fossil fuel and smelting of non-ferrous metals lead to contamination from arsenic of air, water and soil. Pesticides may also contain arsenic. Concentrations of arsenic in air is often higher in cities than in rural areas and even higher near certain industrial sources. Humans are mainly exposed to arsenic via food and drinking water. Inorganic arsenic is acutely toxic and may cause severe symptoms and disturbances in the human body. Humans exposed to arsenic via drinking water have a risk of mortality from lung, bladder, kidney and skin cancer. Drinking water with arsenic concentrations of approximately 0.1 mg/l have lead to cancer and precursors of skin cancer have been linked with levels of 0.05-0.1 mg/l (Järup, 2003). WHO's guideline value for drinking water regarding arsenic is 0.01 mg/l (WHO, 2011).

Nickel (Ni)
Nickel is a heavy metal used to produce stainless steel and nickel alloys. Intake of nickel by food is much more common than intake from water. Nickel is carcinogenic both if inhaled and in metallic form. Increase in pH may reduce leaching of nickel. WHO's guideline value for drinking water regarding nickel in drinking water is 0.07 mg/l (WHO, 2011).

Zinc (Zn)
Zinc is a heavy metal which can be found in almost all food and potable water as salts and organic complexes. Zinc is a trace element. There is no guideline value for drinking water from WHO regarding zinc in drinking water due to that the levels found in drinking water is of no health concern. However it might give the water some bad taste in concentrations above 4 mg/l and it may not be acceptable to consumers at levels above 3 mg/l. Zinc in surface water and groundwater is normally not found in concentrations higher than 0.01 and 0.05 mg/l, respectively (WHO, 2011).

Chromium (Cr)
Chromium is a widely distributed heavy metal in the earth's crust and it exists in different valences. The major intake source for chromium is through food and chromium (III) is an essential nutrient. The WHO guideline-value for drinking water regarding chromium is 0.05 mg/l. In drinking water chromium is mostly lower than 0.002 mg/l but concentrations up to 0.12 mg/l have been reported. Chromium (VI) via inhalation is stated carcinogenic (WHO, 2011).

Manganese (Mn)
Manganese is a very common heavy metal in the earth's crust and usually found together with iron. Manganese is used as an oxidant for cleaning, bleaching and disinfection in production of iron and steel alloys. Manganese often occurs naturally in surface water and groundwater. It is more common in anaerobic or low oxidation condition which is an important source for drinking water. Manganese is naturally present in many food sources, why intake by food is also the most common way of exposure. The levels of manganese found in drinking water are not of health concern and therefore WHO has no guideline value for manganese in drinking water. Instead manganese is an essential element for both humans and animals. There is

however a health based value of 0.4 mg/l but because that level is usually not found in drinking water, there is no formal guideline value. To consumers a manganese concentration of 0.1 mg/l is usually acceptable but at concentrations exceeding 0.1 mg/l the manganese may cause a bad taste and the water can stain sanitary ware and laundry (WHO, 2011).

Copper (Cu)
Copper is a heavy metal and also an essential element but can also be a water contaminant. Copper in drinking water can originate from leaching of copper water-pipes. Copper concentrations over 5 mg/l can color and give a bitter taste to the water. The health-based guideline value for copper in drinking water is 2 mg/l even if it at this level may give rise to some bad taste. Copper is normally not a raw water contaminant and hence is not in need of treatment processes (WHO, 2011).

Aluminium (Al)
Aluminium is the most common metallic element in the earth's crust, and it is not a heavy metal. It occurs naturally as silicates, hydroxides, oxides and together with organic matter. Aluminium salts can be used as coagulants in water treatment which may cause increased aluminium levels in treated water. Aluminium is used in the structural and electrical industry for production of vehicles and also for food packaging and antiperspirants. Aluminium can occur in different forms in water, both alone and together with other compounds. Aluminium dissolved in natural water which has close to neutral pH usually range from 0.001 to 0.05 mg/l but concentrations can be as high as 0.5-1 mg/l if the water is more acidic or contains more organic matter (WHO, 1998). The health value for aluminium in drinking water is 0.9 mg/l (WHO, 2011).

The guideline values from WHO for drinking water for each metal presented can be seen in Table 3.1.

Table 3.1. WHO's guideline values for drinking water for concentrations of different metals.

Metal	WHO guideline value (mg/l)
Cadmium	0.003
Lead	0.01
Arsenic	0.01
Nickel	0.07
Zinc	3.0*
Chromium	0.05
Manganese	0.4*
Copper	2
Aluminium	0.9*

*No guideline value but only a health based value.

3.2.7 Hydrocarbons

Hydrocarbons, organic compounds only consisting of carbon and hydrogen, are commonly present in stormwater and can origin from biological oils and soaps but the most common source is petroleum. The traffic in general is a big source of hydrocarbons but the highest concentration come from places like parking lots and gas stations (Denton, 2006; Butler &

Davies, 2004). Most hydrocarbons are stable organic compounds and not easily biodegradable (Butler & Davies, 2004).

Higher chain alkanes, alkanes having nine or more carbon atoms, have a high flash point which makes them inefficient as fuels and they are hence less used in the petrochemical industry. Instead they can be used as lubricants, transformer oils and anti-corrosion agents. Higher chain alkanes are also chemically inactive and can occur naturally (Chemicalland21, 2015).

Studies have shown that crankcase and lubricant oils are the petroleum-related hydrocarbons most often present in stormwater (Butler & Davies, 2004). Not only petroleum and oil residues contribute to hydrocarbon in stormwater. The hydrocarbons can also origin from asphalt and wearing off rubber tires (EPA, 2013).

Earlier studies regarding hydrocarbon in stormwater have also shown that hydrocarbons are more present in stormwater sediment than in the actual water. The reason for this is mainly that many hydrocarbons have low water solubility and tend to bind to solid particles (Sweco, 2009; Butler & Davies, 2004). As much as 80-90% of the hydrocarbons in stormwater are attached to particles (Denton, 2006). Hydrocarbons accumulated in sediments often persist for a long time affecting bottom-living organisms and may be re-suspended by storm events (Butler & Davies, 2004).

The health effects connected to exposure of hydrocarbons vary considerably between different hydrocarbons and the type of exposure. Insufficient oxygen supply to the body, depression of the central nervous system and heart problems are some effects that can be caused by exposure to hydrocarbons. For a hydrocarbon to cause severe health effects the concentrations of exposure are generally thousands of ppm (HSE, 2004).

To get information about the effects different hydrocarbons have on the human health and the environment, the type of hydrocarbons present in a sample must be determined. One way is to use a Gas Chromatography Time of Flight Mass Spectrometer, GC TOF MS. The TOF equipment measure the time it takes for the ions to pass along an evacuated tube, small ions travel faster than larger ions, and from this information a mass spectrum can be obtained and the compounds determined (Chromservis, 2015).

3.2.8 Microorganisms

Escherichia coli (*E. coli*) is a coliform bacteria belonging to the family Enterobacteriaceae. Around 10% of the intestinal microorganisms in humans and warm blooded animals are represented by these bacteria and are therefore used as indicator organisms. In fresh water they are viable for a longer time than other intestinal bacterial pathogens. A water sample is considered potable if no such indicator bacteria are detectable in a specific volume of water which is generally 100 ml (Willey *et al.,* 2011; WHO, 2011). High water temperatures increase the growth of microorganisms (WHO, 2011). There are limits of how high concentrations of *E. coli* that are acceptable for different standards of bathing waters in Sweden and EU. To reach a good bathing water quality in inland surface water the *E. coli* concentration must be below 1000 cfu/100 ml (HaV, 2012).

Bacterial indicator organisms such as *E. coli* have been found in large numbers not only in wastewater but also in stormwater. These may be found in receiving waters due to discharges from CSOs and misconnections of sewer pipes. Urine and faeces from animals is another source of bacterial pollution (Butler & Davies, 2004).

Presence of pathogens in stormwater for reuse may be a health risk for the public. To decrease the health risks, treatment and disinfection of the harvested stormwater is needed. Some reuse applications of the water must also be limited for the public (DECNSW, 2006).

3.2.9 Case studies regarding stormwater quality

In Stormwater Effects Handbook (Burton & Pitt, 2002) two case studies regarding stormwater quality are described. A few water quality parameters; pH, turbidity, BOD_5 and suspended solids, from two different studies are presented in Table 3.2. One of the studies was performed by the U.S. Geological Survey (USGS) and the results are mean values from a sample series of around 1000 samples. The other study was performed in the City of Bellevue in the U.S. and the values are mean values from around 200 sampling occasions during two years (Burton & Pitt, 2002). The quality results from these studies will be used for comparison of the stormwater sample results.

Table 3.2. Quality parameters from Stormwater Effects Handbook regarding U.S. Geological Survey (USGS) and the City of Bellevue (Burton & Pitt, 2002).

Study	pH	Turbidity, (FTU)	BOD_5 (mg/l)	COD (mg/l)	Suspended solids (mg/l)
USGS	6.7	-	6.6	60	50
Bellevue	6.3	19	-	46	-

3.3 Stormwater quantity

3.3.1 Catchment characteristics

The initial step when analyzing surface runoff is to identify the points where flow will be determined and the corresponding catchments. A catchment is often divided into sub-catchments when the runoff is to be analyzed. A sub-catchment should have homogenous physical characteristics. When a catchment is to be defined parameters like the drainage patterns, the slopes of the surface and the land use are considered. It is important to define these characteristics of the sub-catchments as accurate as possible. When the current conditions are to be defined, field inspections can be performed as well as surveying different kinds of maps including topographical maps, soil maps and drainage-system maps. Aerial photographs can also be useful. An important factor when analyzing a catchment regarding surface runoff is the amount of impervious surface area. The impervious areas can be further divided into directly connected impervious area and non-connected impervious area. Water from directly connected impervious surfaces is directly transported to storm sewers, e.g. water from parking lots, whereas rainwater from non-connected impervious surfaces such as e.g. roofs drain onto pervious surfaces. The directly connected impervious surfaces are the ones that, to the largest extent, contribute to peak discharges on small urban catchments (WEF & ASCE, 1992).

3.3.2 Evaporation

Evaporation is the transition of a liquid to gas. In terms of water it is the transition of liquid water to water vapor. Evaporation occurs from open water, soil and from vegetation. How much water that evaporates depends on the availability of water and hence there is a higher evaporation rate from a lake than from dry soil. The evaporation rate from a land surface depends on the amount of water in the soil (WEF & ASCE, 1992).

Water molecules are constantly moving and when energy is added the molecules start to move more rapidly and hence move even further away from each other. The reverse process to evaporation is called condensation and is the transition from water vapor to liquid water. Condensation is determined by the vapor pressure. Warm air can hold more moisture than cold air and evaporation is hence directly connected to temperature. The energy needed for evaporation comes from the sun and the higher the temperature the higher the rate of evaporation. Except the energy in terms of heat, evaporation is also affected by wind and the humidity of the air (WEF & ASCE, 1992).

3.3.3 Infiltration

In areas with pervious surfaces the infiltration is an important factor when the runoff is to be determined. Factors affecting the rainfall infiltration are primarily the initial soil wetness, the soil type, the slope of the surface, the vegetation cover, the rainfall intensity and how the intensity changes over time. The potential infiltration rate is the maximum rate at which the soil surface can absorb water. All rainfall reaching the soil surface in the beginning of a storm infiltrates. When the rain reaches the surface with a rate that exceeds the potential infiltration rate, water will stay on the surface and runoff begins. The infiltration capacity decreases during a rainfall. In the beginning of the rain it decreases rapidly and then more slowly until a stable capacity is attained when the upper soil is saturated. Vegetation tends to increase the infiltration capacity of a soil, e.g. plants help to stabilize loose particles and decrease the speed of the surface water (Ward & Robinson, 2000). Different soils also have different infiltration capacities which depend on the soil type, the structure of the soil, the initial moisture content and the depth of water covering the soil (WEF & ASCE, 1992).

The relationship between the rainfall intensity and infiltration capacity will determine how much of the rain that falls on a surface that will generate runoff and how much that will infiltrate into the ground. In semi-arid areas it is common that rainfall intensity exceeds infiltration capacity which results in surface ponding and overland flow (Ward & Robinson, 2000).

3.3.4 Runoff coefficient

The runoff coefficient, C, represents the effects of rainfall interception, infiltration, depression storage and temporary storage on the runoff. Land use, soil and vegetation type and slope affect the runoff coefficient as well as rainfall characteristics such as intensity and duration. For impervious surfaces such as pavements and roofs the runoff coefficient can vary between 0.70 and 0.95. Pervious surfaces can have a runoff coefficient between 0.05 and 0.35 (WEF & ASCE, 1992).

3.3.5 Rational method

One way of calculating the peak discharge from a certain area where the runoff coefficient, rain intensity and the surface area are known is by the rational method, see Equation 1.

$$Q = CiA \tag{1}$$

Where,
$Q = Flow$
$C = Runoff\ coefficient$
$i = Rainfall\ intensity$
$A = Contributing\ area$

There are four main assumptions connected to the rational method:

- The duration of the intensity is equal to the time of concentration for the area.
- The time of concentration is the time it takes for the water to travel from the point furthest away (in terms of time) from the point of study to the point of study.
- The return period of the discharge should be equal to the return period of the average rainfall intensity.
- The contributing area is the total drainage area upstream the point of study or a part of that area.

When applied properly the rational method can provide reasonable estimates of the peak discharge from a catchment. The method has, however, two main limitations; the storage effects in the catchment should be insignificant and the drainage area should be around 0.4-0.8 km^2 (WEF & ASCE, 1992).

3.4 Treatment methods, collecting systems and areas of reuse

In this part different treatment methods, collecting systems for stormwater and areas of reuse of stormwater are presented.

3.4.1 Biological treatment

Treating stormwater in a natural way is getting more and more common. Bioremediation and phytoremediation are two types of biological treatment. The purpose of the remediation is to change or totally remove the pollutants present in the water to prevent them from damaging the environment in the recipient and improve the water quality (Fulekar, 2010).

Bioremediation

In bioremediation processes microorganisms are used to reduce, transform or eliminate contaminants that are present in water, sediments or soils. Biotransformation and biodegradation are two different types of bioremediation. In biotransformation the structure of the contaminants changes into less harmful compounds and biodegradation means the breaking down of harmful compounds into environmental friendly compounds. Carbon dioxide or methane as well as water and biomass are produced during the microorganisms' metabolism (Fulekar, 2010).

Compounds that are usually present in stormwater from urban areas and can be treated by using bioremediation are e.g. hydrocarbons, oil, suspended solids and nutrients. Heavy metals are persistent in the environment and cannot be degraded. Removing of heavy metals from a contaminated site is very complicated but studies have shown that also removal of heavy metals, to a certain extent, can be done by bioremediation (Fulekar, 2010). Depending on e.g. the concentration of pollution, bioremediation can also be useful when hydrocarbons are to be removed from a site (Bamforth & Singleton, 2005).

Phytoremediation

Plants have a natural ability to degrade and remove toxic chemicals and pollutants from soil or water. The process is called phytoremediation and can be used to remove contaminants like metals, pesticides and crude oil. Some metals, e.g. Cu, Mn and Zn, are essential for plant growth and can be accumulated in the plants. Other metals, e.g. Cd, Cr and Pb, do not have any biological functions but can still be accumulated by plants (Fulekar, 2010).

The rate of phytoremediation is directly proportional to the rate of plant growth which makes the process dependent on the conditions for growth of the plants. To make the process more efficient fast growing plants are needed and if e.g. removal of metals is the specific focus, plants good at accumulating metals are needed (Fulekar, 2010).

At regular intervals the plants need to be harvested. The most common way to dispose the plants is through incineration and the ash produced should be put on appropriate waste-disposal sites (Fulekar, 2010).

Bioremediation and phytoremediation in combination
Bioremediation and phytoremediation can also be combined and is then called phytobial remediation. The benefits of both microbes and plants are used in phytobial remediation. The microorganisms and plant roots interact in the plants rhizosphere, the soil closest to the plant roots, and organic compounds as well as metals are taken up by and accumulated in the plants (Fulekar, 2010).

Implementation
Bioremediation and phytoremediation can be implemented with different solutions e.g. vegetated swales and wetlands. A vegetated swale is a broad and shallow channel where the speed of the flow is reduced. Along the side slopes and the bottom there is vegetation where the bioremediation can take place. Vegetated swales are especially efficient in taking up pollutants like suspended solids and trace metals. If a vegetated swale is suitable as treatment method depends on the local climate and soils. A vegetated swale is most efficient if used together with other treatment solutions, e.g. wetlands (EPA, 1999a). Wetlands are water-saturated areas with low concentrations of oxygen in the soil. In a wetland the speed of the flow is reduced and the soil and the vegetation in the wetlands work as natural filters treating the water (Banner & MacKenzie, 2000).

3.4.2 Rainwater harvesting
There are different opinions of what the definition of rainwater harvesting is. Abdulla & Al-Shareef (2009) state that rainwater harvesting is the collection and storage of rainwater from surfaces like roofs, land and roads and from rock catchments using simple techniques like pots, tanks, cisterns and sometimes underground dams as collecting systems (Abdulla & Al-Shareef, 2009). However, DECNSW (2006) stated that the water collected from ground surfaces like land and roads is called stormwater harvesting. In this report the terms are divided by calling the rainwater that have not yet reached the ground, rainwater harvesting – i.e. water collected from roofs.

The water collected from roofs and stored in rainwater tanks is often used as non-potable water for domestic purposes. The storage is located near the use and can be incorporated for most residential blocks (DECNSW, 2006). In Gaborone usage of rainwater tanks at households can be seen at several locations.

3.4.3 Stormwater harvesting
The term stormwater harvesting includes collecting, storing and treating water from urban areas. This can then be used as recycled water. The stormwater is usually collected from stormwater drains and creeks and the recycled water is often used for irrigation of both public and domestic areas (Sydney Water, 2013).

Stormwater harvesting is a relatively new way of reusing water whereas using rainwater tanks and reuse effluents from sewage treatment plants are older ways. Several benefits may be given from stormwater harvesting such as reduction in stormwater volumes, flows and frequency of runoff and reduction in stormwater pollution loads to downstream waterways.

The benefits from different stormwater solutions will vary due to climate – especially rainfall, catchment land-uses, condition of drainage system and demand for reuse of water (DECNSW, 2006).

Limitations of stormwater harvesting can, for example, be variable rainfall patterns, environmental impact of storages and a high relative unit cost of treated stormwater. Variations in rainfall patterns can increase the demand for back-up water when the demand cannot be met by harvested stormwater. The required storage volume can increase due to intense rainfalls. However, the fluctuations in water level in storages can cause more turbid water (DECNSW, 2006).

Stormwater harvesting and rainwater harvesting through rainwater tanks can have similar benefits in reducing pollution loads and downstream stormwater flows. Both techniques however have their own advantages and disadvantages and none of them is clearly more preferable. The risk of pathogen pollution is potentially higher in raw stormwater than in rainwater and collection of rainwater in tanks may therefore be a better alternative to reduce the risk of pathogen pollution. In open stormwater harvesting storages there is also a risk of mosquito breeding with associated diseases whereas in rainwater tanks there is limited potential for mosquito breeding. Stormwater harvesting has potential of significant reduction in pollution loads as runoff from road areas is collected. Regarding rainwater tanks, relatively clean roof runoff is collected which results in limited reduction in pollution loads (DECNSW, 2006).

Stormwater harvesting can reduce stormwater flows from a whole catchment whereas rainwater tanks only reduce flows from specific roofs. Above ground storage for stormwater harvesting can be relatively space-consuming whereas rainwater tanks can be easily incorporated for most residential blocks. Each householder cares for the maintenance of each rainwater tank and therefore the quality of the maintenance may vary. The stormwater harvesting storages is maintained by a single organization and is thus likely not to vary as much in maintenance quality (DECNSW, 2006).

Combining the two techniques has been found successful but if rainwater tanks are installed in the same area as the stormwater harvesting is implemented, less stormwater may be available for harvesting and reuse (DECNSW, 2006).

3.4.4 Dams

A dam may provide both detention and treatment of stormwater. Constructed along a watercourse the dam may store the water passing by for later use. The storage capacity of the dam may reduce the flow peaks after heavy rains. The risk of flooding downstream the dam is reduced. Due to reduced flow speed in the dam, sedimentation processes where e.g. particles, organic matter and metals may settle are supported. Biological processes stand for the removal of dissolved metals and nutrients in the water (EPA, 1999b).

3.4.5 Areas of reuse

Depending on how the stormwater should be reused different types of treatments are needed. Drinking water is strongly connected to human health and the quality is of great importance. According to the WHO Guidelines for drinking water quality, safe drinking water should not cause any significant risks to health over a lifetime of consumption. Pathogens and chemicals are two of the most important aspects regarding drinking water quality (WHO, 2011).

Water from sources that, to some extent, are polluted, e.g. stormwater, may need more comprehensive treatment than water from a relatively clean source. This kind of water could preferably be used for purposes where high quality of the water is not as important as for drinking water, e.g. irrigation, cloth washing and toilet flushing (WHO, 2011).

4 Materials and Methods

All methods used are described in the following chapter. The method is divided in two main parts; the Quality part and the Quantity part and from there follows the parameters measured in each part.

4.1 Quality

The quality of the water from Segoditshane River was investigated by taking samples which were analyzed for several parameters, both at the site and in laboratory.

4.1.1 Sampling

The main focus for the quality analysis was on the water from Segoditshane River. Along the river two sites were used for sampling. Segoditshane site 1 is located behind Broadhurst clinic and Segoditshane site 2 is located behind BTV offices. The sites were chosen due to accessibility and sampling was repeated at these sites to get time series.

Two more sample sites were chosen as references to the sample sites in the river. One sample was taken at a site at UB campus and another one from water discharging from a roof at Motheo Apartments, both located outside the delineated catchment area of Segoditshane River. These were used as reference samples for stormwater from parking areas with much impermeable area, as well as rainwater from a roof. The rainwater at Motheo Apartments was collected before reaching the ground and thus had not been polluted by compounds in the soil. All the sampling sites and the catchment area of Segoditshane River can be seen in Figure 4.1.

Figure 4.1. Map showing the four sampling sites in Gaborone. Two in the catchment area along Segoditshane River and two just outside the area; a roof at Motheo Apartments and a drainage channel from a parking lot at UB campus (Google Earth, 2015b). Photo modified by the authors.

Water samples from Segoditshane River were taken at three different times at the two sites. The first samples were taken before the startup of the project and during the field study in Gaborone two more sample sessions were carried out. The date, time and site description for all samples are described in Table 4.1.

Table 4.1. Information about the sampling sites in Gaborone. Sample 1, 3 and 7 were collected before the start of the field work and the area are therefore described with figures.

Sample	Sampling date	Sampling time	Site description
Segoditshane 1			
1	Jan 15, 2015	11:00 am	See Figure 4.2.
2	Mar 11, 2015	10:45 am	Stagnant, shallow water. Depth: 0.1-0.15 m, Width: 0.5 m. Turbid water with a light brown colour. Vegetation: grass and small bushes along the water course. The vegetation does not prevent the sunlight from reaching the water.
3	Apr 13, 2015	10:30 am	Flowing water, Depth: 0.05 m, Width: 0.5 m. Turbid water. Vegetation: grass and small bushes along the water course. The vegetation does not prevent the sunlight from reaching the water.
Segoditshane 2			
4	Jan 15, 2015	12:00 am	See Figure 4.3.
5	Mar 11, 2015	11:00 am	Depth: 0.1-1 m, Width: 5 m. Turbid water with a light brown colour. Small animals in the water. High vegetation surrounding the watercourse such a grass, bushes and trees. The vegetation does not prevent the sunlight from reaching the water.
6	Apr 13, 2015	11:00 am	Brown/grey/yellow water, Depth: 1.5 m, Width: 4 m. Stagnant water, some litter in the water, small insects/animals.
UB campus			
7	Jan 14, 2015	4:00 pm	Open stormwater drainage channel, see Figure 4.5.
Motheo Apartments			
8	Mar 8, 2015	5:00 pm	Rain water collected from a cement roof during rain.

Sample 1-2, 4-5 and 7 were taken and stored in plastic bottles directly from the river and stormwater drainage channel. Sample 8 was collected in a stainless steel bucket and then stored in plastic bottles. Sample 3 and 6 were collected in autoclaved glass bottles. All samples were stored in refrigerators at the laboratory after sampling and before the analyses.

4.1.2 Sample pictures

Figure 4.2 to Figure 4.5 show sample site 1 and sample site 2 in Segoditshane River at two different times and the UB campus sampling site.

Figure 4.2. Segoditshane River behind Broadhurst clinic, sampling site 1, at the first sampling time in January. Photo: Ditebogo Nage.

Figure 4.3. Sample site 2 in Segoditshane River at the first sampling time in January 2015. Photo: Ditebogo Nage.

Figure 4.4. Two sample sites in Segoditshane River when sampling in April 2015. Sample site 1 (to the left) with almost no water and sample site 2 (to the right).

Figure 4.5. Sample site 7; an open storm water drainage channel at the University of Botswana campus in January 2015. Photo: Ditebogo Nage.

4.1.3 Physical parameters

The physical parameters pH, temperature, dissolved oxygen (DO), electrical conductivity and turbidity were measured on site directly after sampling or in the laboratory a few hours after sampling for most of the samples. Some parameters for some of the samples were measured a couple of days later than the sampling occasion, see Chapter 5 for the specific number of days. The measuring equipment used for the pH and the conductivity were ELE international 370 pH meter and ELE international 470 conductivity meters and both of them also measured the temperature. Turbidity was measured with a HI 93703 Microprocessor turbidity meter from Hanna instruments. The turbidity measurements were performed in a laboratory at UB campus about one hour after sampling. All samples were stored in a refrigerator after sampling. The parameters measured for the different samples are presented in Table 4.2.

Table 4.2. Measured physical parameters in each sample. Measured parameters are marked with an X.

Sample	pH	Temperature	DO	Turbidity	Conductivity
Segoditshane 1					
1	X	X	X	X	X
2	X	X		X	X
3	X	X			X*
Segoditshane 2					
4	X	X	X	X	X
5	X	X			X
6	X	X			X*
UB campus					
7	X	X	X	X	X
Motheo Apartments					
8	X*			X*	X*

* The values were measured later than the sampling occasion.

After the physical parameters were measured, the water samples were analyzed for several other parameters. Those were metals, hydrocarbons, BOD, COD, TSS, VSS and microorganisms. The parameters measured for every water sample are shown in Table 4.3.

4.1.4 Metals

Samples 1-2, 4-5, and 7-8 were analyzed for metals, see Table 4.3. That includes two samples from each site in Segoditshane River and the sample from the roof of Motheo Apartments as well as the sample from the UB campus drainage channel. Sample 3 and 6 were taken later and not included in the metal analysis. The samples were prepared for the metal analysis by first being filtered through filter paper with a pore size of 11 µm (SigmaAldrich, 2015) and then with a squirt through syringe filters with a pore size of 0.45 µm, see Figure 4.7. The samples were then analyzed in a Microwave Plasma – Atomic Emission Spectrometer (MP-AES) (see Figure 4.6), and compared to a standard solution with assistance from laboratory technicians. The standard solution contained a concentration of 50 mg/l of aluminium, arsenic, barium, cadmium, cobalt, chromium, copper, magnesium, manganese, nickel, lead, selenium, strontium and zinc and also 500 mg/l of potassium. Triplicate measurements were done for each sample.

Table 4.3. Analyzed water quality parameters. Analyzed parameter is marked with an X for each sample.

Sample	BOD	COD	TSS	VSS	Metals	Hydrocarbons	Microbiology
Segoditshane 1							
1	X	X	X	X	X	X	
2	X	X	X	X	X	X	
3		X					X
Segoditshane 2							
4	X	X	X	X	X	X	
5	X	X	X	X	X	X	
6		X					X
UB campus							
7	X	X	X	X	X	X	
Motheo Apartments							
8	X	X	X	X	X	X	

Figure 4.6. Microwave Plasma – Atomic Emission Spectrometer (MP-AES) for analysis of heavy metal.

4.1.5 Hydrocarbons

Sample 1-2, 4-5, 7-8 were analyzed for hydrocarbons. While preparing the analysis 50 ml of each water sample were evaporated in a water bath and then heated at 105° C for one hour. The residues were then diluted with 10 ml of the solvent acetonitrile and stored in beakers over night. The samples were then filtrated, using a squirt through Syringe filter with a pore size of 0.45µm into 1 ml test tubes, see Figure 4.7. To perform the actual analysis of the prepared samples assistance was given from laboratory technicians and a Gas Chromatography Time of Flight Mass Spectrometer, GC TOF MS, was used, see Figure 4.8.

The water samples were collected and stored in plastic bottles. Plastic contains several types of hydrocarbons and hence plastic related hydrocarbons, e.g. phthalates, were excluded from the results. This was done in order to eliminate the contribution of plastic compounds from the bottles.

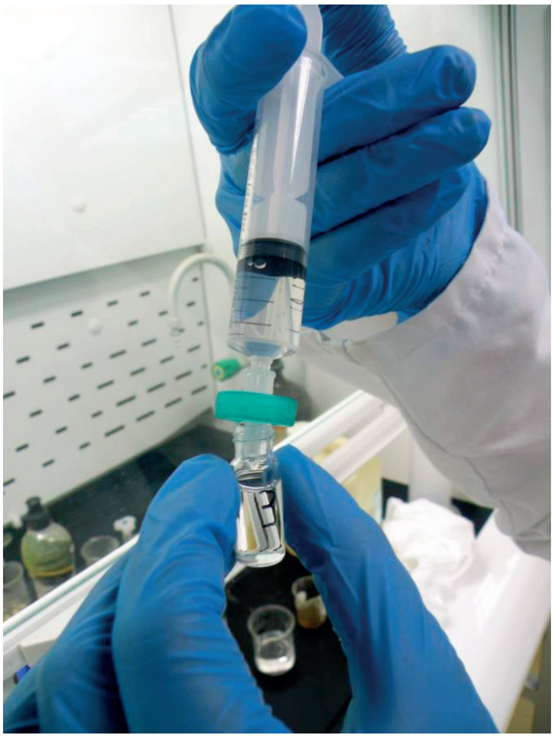

Figure 4.7. to the left and Figure 4.8. to the right.. Filling of the small test tubes with sample to analyse for hydrocarbons in GC TOF MS (Figure 4.7.). Gas Chromatography Time of Flight Mass Spectrometer, GC TOF MS, analyzing several substances in water samples, e.g. hydrocarbons (Figure 4.8.).

4.1.6 Total Suspended Solids and Volatile Suspended Solids

The TSS and VSS analyses were performed for sample 1-2, 4-5, 7-8, see Table 4.3. The number of days between the sampling occasion and the analysis for each sample respectively is shown in Table 9.9 in Appendix II. Porcelain bowls and membrane filters (Supor-450 filters with a 47 mm diameter and pore size of 0.45 µm) were weighed before filtering the water samples through the filters using a vacuum pump. A sub-sample of 20 ml from each sample was used. The filters and the bowls were placed in an oven in 105°C for one hour. The filters then cooled down in a desiccator before weighed again and then put in another oven in 550°C for one hour. The filters were then weighed again and the TSS and VSS calculated according to Equation 2 and Equation 3 respectively from the Swedish Standards Institute (SIS, 1981).

$$Total\ Suspended\ Solids, \left(\frac{mg}{l}\right) = \frac{(A_1 - B) \times 1\,000}{C} \qquad (2)$$

$$Volatile\ Suspended\ Solids, \left(\frac{mg}{l}\right) = \frac{(A_2 - B) \times 1\,000}{C} \qquad (3)$$

Where:
A_1 = Weight of sample and filter after 105°C, mg
A_2 = Weight of sample and filter after 550°C, mg
B = Filter weight, mg
C = Sample volume, ml

4.1.7 Biochemical Oxygen Demand

The BOD analysis was performed for sample 1-2, 4-5, 7-8, see Table 4.3. The number of days between the sampling occasion and the analysis for each sample respectively is shown in Table 9.7 in Appendix II. To perform the BOD analysis, 300 ml of each water sample were put in glass bottles. Five drops of Tintometer GmbH Bereich Aqualytic nitrification inhibitor were added into the bottles and two pellets of sodium hydroxide from Rochelle chemicals were put just under the lid of the bottles to prevent production of carbon dioxide. One magnetic stirrer was also put in each bottle. The bottles were then put in a BOD analyzing equipment (Oxidirect by Aqualytic) in a refrigerator for five days before the BOD values were read.

4.1.8 Chemical Oxygen Demand

The COD analysis was performed for sample 1-8, see Table 4.3. The number of days between the sampling occasion and the analysis for each sample respectively is shown in Table 9.8 in Appendix II. To perform the COD measurements 0.3 ml for ultra high range, or 2.0 ml for the high range test, of each water sample was put in Hach Lange cuvettes (TNT 823) that were heated in 150°C for two hours. The samples were allowed to cool down and the resulting numbers were then read in the COD Hach reactor.

4.1.9 Microbiology analysis

The water collected from Segoditshane River had some colour and smell which indicated that it might contain sewage water. Testing for *Escherichia- coli (E. coli)* bacteria as an indicator of sewage (e.g. fecal contamination) was, with supervision from laboratory technicians, performed at department of biological sciences at University of Botswana. The testing for *E. coli* was performed during five days which included sampling in autoclaved bottles and several techniques to determine possible *E. coli* presence. The method for analyzing pathogens is based on the fact that coliform bacteria like *E. coli* are anaerobic, gram-negative, rod-shaped bacteria which ferment lactose with gas fermentation within 48 hours at 35°C. A detailed description of the method can be found in Appendix V.

4.2 Quantity

The Segoditshane River catchment was delineated using information from Gaborone city drainage master plan and the different boundary places is shown in the background in Figure 2.4. The size of the catchment area was stated differently in different reports. In the Segoditshane River report from DWA (Stephenson, 2010) the catchment size was said to be 100 km^2 whereas the Drainage master plan stated 30 km^2. During delineation of the catchment in Google Earth 30 km^2, according to the description of the catchment in the Drainage master plan, a total area of 30 km^2 seemed unrealistically small. Therefore the delineation of the catchment was fitted to be approximately 100 km^2 according to the DWA report from 2010.

The quantity of water in Segoditshane River catchment was estimated by using rainfall data collected by DMS at the Gaborone rain gauge station as well as some from Mogoditshane rain gauge station. The Gaborone rain gauge station is located at DMS in the southeastern part of the city outside the Segoditshane River catchment whereas the Mogoditshane station is located in Mogoditshane in the western part of Gaborone.

From the Gaborone rainfall station data, the years 2001-2010 were chosen due to the connected period of daily rainfall data. From this data the variations in rainfall between different years and months were calculated and presented in diagrams.

Different runoff coefficients were estimated by studying the map over the Gaborone area and the Segoditshane River catchment in Google Earth.

In order to investigate the runoff coefficient, the Segoditshane River catchment was divided into two parts – one more urban and one more rural. Due to the larger parts of impervious areas in the urban Segoditshane River catchment, this one was assumed to have the major contribution of stormwater runoff and was therefore chosen for further calculations. A map showing the urban and rural part of Segoditshane River catchment is shown in Figure 4.9.

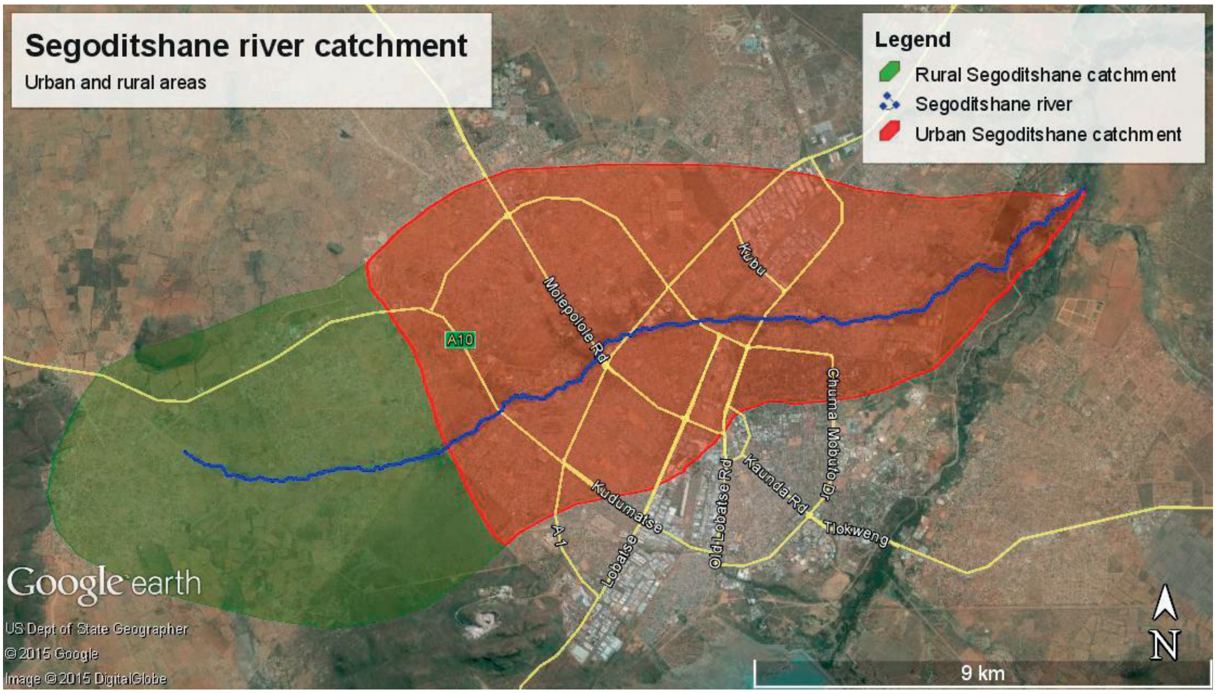

Figure 4.9. Segoditshane River catchment divided into urban and rural parts due to different density in roads and residential areas (Google Earth, 2015c). Photo modified by the authors.

The rainfall data was multiplied by the urban catchment area of Segoditshane River to get the possible volume of water falling on that area. The variations in volume between years and months were calculated and presented in graphs in Chapter 5.

In the urban Segoditshane River catchment the approximate area of all large roads were estimated by measuring the length and width of the roads in Google Earth. A few smaller residential areas in the urban Segoditshane River catchment were chosen in order to estimate the percentage of the total impervious roof areas in the whole urban Segoditshane River catchment using Google Earth. The rest of the areas which was not impervious area like roads or roofs were assumed to be gravel areas. One small residential area is shown in Figure 4.10.

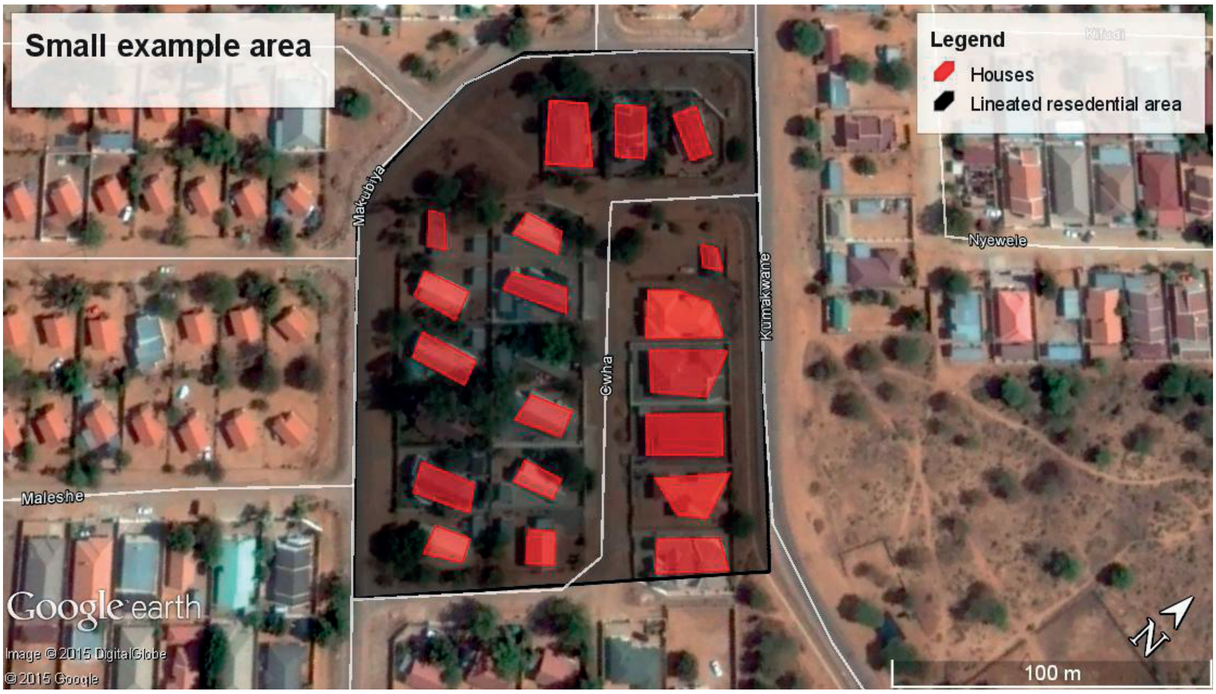

Figure 4.10. Small residential area in Segoditshane River catchment used to calculate percentage of house roofs in the big catchment. Red squares represent house roofs (Google Earth, 2015d). Photo modified by the authors.

The runoff coefficients for the different types of surfaces were taken from Svenskt Vatten (2004), and are presented in Table 4.4. To get the total volume discharging to Segoditshane River, the rainfall per day (h) was multiplied with the area (A) and the total runoff coefficient (C_x) as shown in Equation 4.

$$V = hAC_x \qquad (4)$$

Table 4.4. Runoff coefficients for three different types of surfaces (Svenskt Vatten, 2004).

Surface	Runoff coefficient, C
Roof	0.9
Road	0.8
Gravel	0.2

The further calculations of the water volume possible to collect in Segoditshane River catchment were divided into three scenarios.

Scenario 1

Scenario 1 includes all larger roads and the gravel areas in between using the percentages for road areas, assuming that the rest is gravel areas. This scenario states that only the water from the roads, and from the gravel areas, is discharging to the Segoditshane River. The water from the house roofs is assumed to infiltrate in the ground and are hence included in the calculated gravel area.

Scenario 2

Scenario 2 includes all roof area and estimates how much rainwater that can be collected directly from the roofs. Here only the percentage and runoff coefficient for the roof area is used.

Scenario 3

Scenario 3 includes the larger roads, the roof areas and the gravel areas in between. This scenario estimates how much water that can be collected if all the water from the roads and the roofs discharges into the Segoditshane River and is being collected.

Calculation of total runoff coefficients

The different percentages for each type of surface were multiplied with the runoff coefficient for each type of surface to get the final runoff coefficient for the catchment in each type of scenario. The final runoff coefficients are shown in Table 4.5.

Table 4.5. The three different runoff scenarios in urban Segoditshane River catchment with their different types of surfaces, their percentages of the catchment as well as the total runoff coefficient for each scenario.

Scenario	Surface	Part of catchment	Runoff coefficient, C	Total runoff coefficient, C_x
1	Road	2%	0.8	0.21
	Gravel	98%	0.2	
2	Roof	15%	0.9	0.14
3	Road	2%	0.8	0.32
	Roof	15%	0.9	
	Gravel	83%	0.2	

5 Results and Discussion

In the following chapter the results from the quality analyses and the quantity calculations are presented separately. The results are discussed while presented. In the end of the chapter the quality and the quantity parts are discussed based on the aim and research questions asked in the introduction.

5.1 Quality

The quality of the water from Segoditshane River was examined by taking and analyzing water samples. The results from the analyses are presented in their different categories in the following sections.

5.1.1 Physical parameters

The physical parameters measured at site and in the laboratory, either directly after sampling or some days later, are presented in Table 5.1. The samples that were not analyzed directly after sampling are marked in the table and they were stored in a refrigerator between sampling and analysis. The parameters analyzed are pH, electrical conductivity, temperature and turbidity. The dissolved oxygen, DO, was also measured in the stormwater samples but due to unreliable analyzing equipment the results are not presented.

Table 5.1. Physical parameters for each water sample and values from the U.S. Geological Survey (Burton & Pitt, 2002). The temperature for sample 8 was not measured. The turbidity for sample 1, 4 and 7 was measured in TDU.

Sample	pH	EC (µS/cm)	Temp (^oC)	Turbidity (FTU)
Segoditshane 1				
1	7.14	21.4	27.9	144 TDU
2	7.62	6280	24.7	35.9
3	7.79	678*	20.4	23.1**
Segoditshane 2				
4	7.44	24.4	24.9	185 TDU
5	7.58	7420	28.7	56.5
6	7.46	792*	22.5	37.6**
UB campus				
7	8.22	5.83	25.8	684 TDU
Motheo Apartments				
8	7.57***	1810***	-	2.03***
Other study				
USGS	6.7	-	-	-
Bellevue	6.3	-	-	19

* The sample was stored for 2 days before analyzed

** The sample was stored for 7 days before analyzed.

*** The sample was stored for 12 days before analyzed.

The pH values for sample 1-8 are shown in Figure 5.1. and the temperature for sample 1-7 is shown in Figure 5.2.

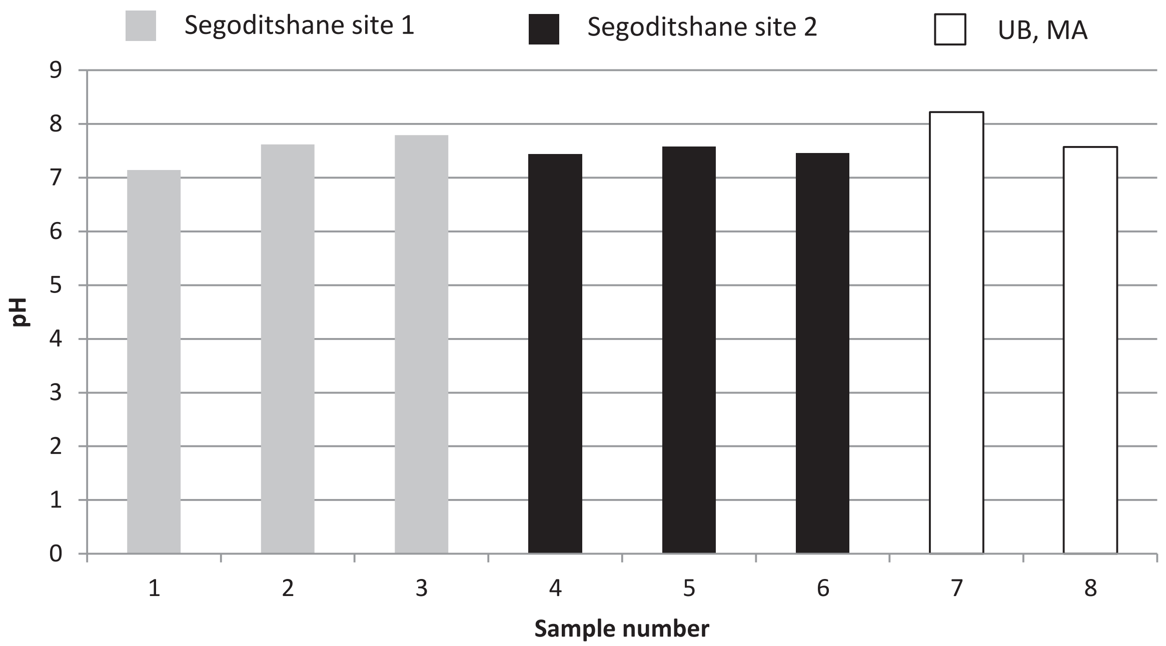

Figure 5.1. pH for samples 1-8.

The pH varied between just over 7 to a little above 8 for the different water samples, see Figure 5.1. The pH for sample 8 was measured 12 days after sampling.

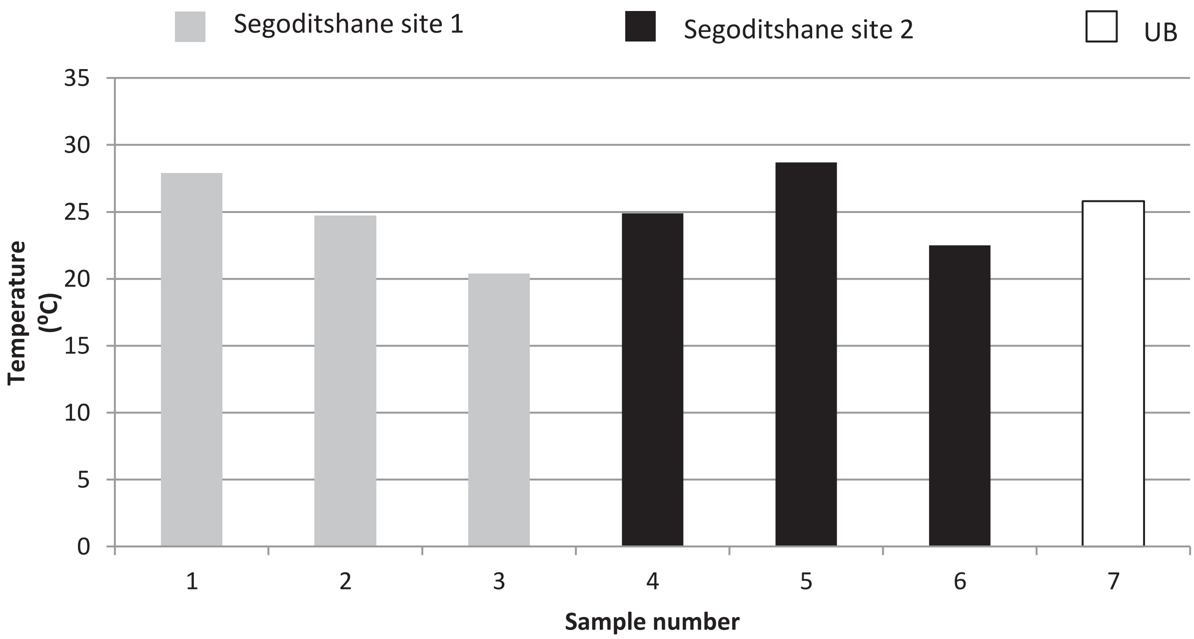

Figure 5.2. Water temperatures for sample 1-7.

The water temperatures at the sampling sites were relatively high at all sampling occasions not falling below 20 ^{o}C, see Figure 5.2. This may influence the climate in the water and the high temperature may favour growth of microorganisms which are pathogenic to humans. The temperature was not measured for sample 8.

The turbidity and electrical conductivity values vary between different samples as can be seen in Figure 5.3 and Figure 5.4. The reason for this could be leakage of pollution from a point source or error in measurements. The turbidity and conductivity for sample 8 was measured 12 days after sampling. The turbidity for sample 3 and 6 was measured 7 days after sampling.

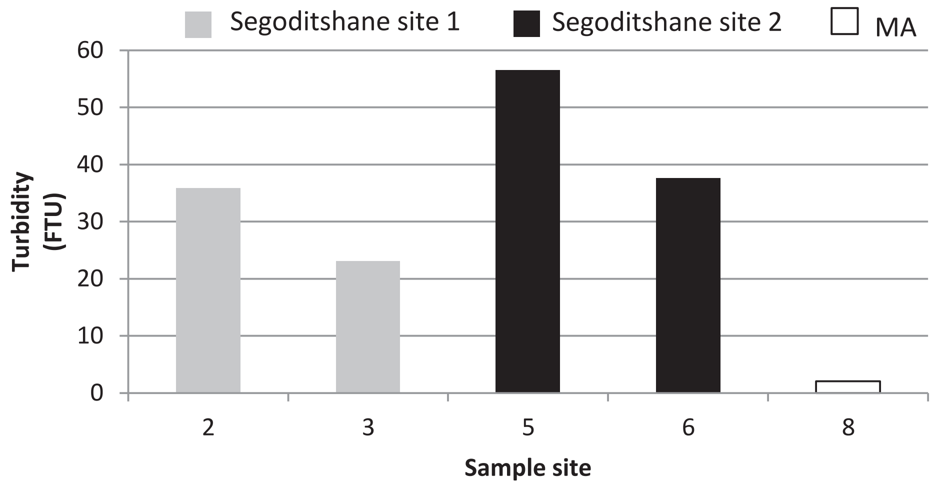

Figure 5.3. Turbidity for sample 2-3, 5-6, 8 measured in FTU.

The turbidity from the study in Bellevue is in the same range as the turbidity for sample 2-3, 5-6 and 8 according to Table 5.1.

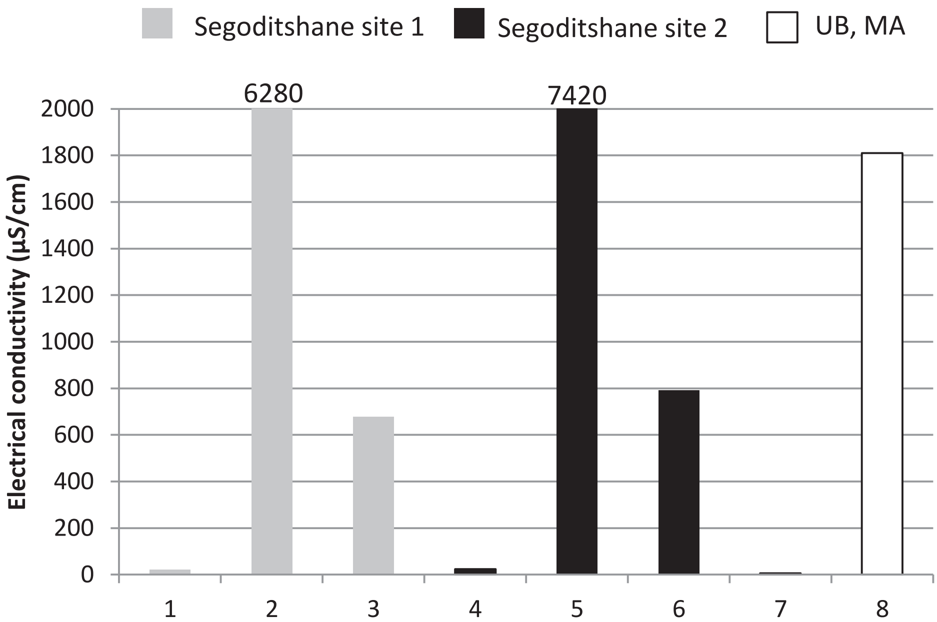

Figure 5.4. Electrical conductivity results for sample 1-8.

The electrical conductivity for sample 1-8 varies significantly. The differences could be due to changed conditions in Segoditshane River between the sampling occasions or errors in measurements.

5.1.2 Metals

The concentrations of heavy metals were measured and analyzed for sample 1-2, 4-5 and 7-8 and the results are presented in Table 5.2. The concentrations of lead, arsenic, copper, aluminium and manganese are remarkably high at one or several of the sample sites. To get an idea of how high the concentrations are, they are compared to limit values in drinking water standards from WUC (2015b) and guidelines from WHO (2011). Regardless if the water will be used as drinking water or not, it is interesting to compare the measured concentrations with standards and guidelines.

Table 5.2. Metal concentrations measured in the water samples, WUC drinking water standards and WHO guideline values. The values inside boxes exceed the WUC drinking water standards or the WHO guideline values for drinking water.

Sample	Ni	Cr	Pb	Zn	As (µg/l)	Cd	Cu	Al	Mn
Segoditshane 1									
1	-	0	363	0	1843	10	50	23	7
2	-	0	243	3	1917	10	30	7	10
Segoditshane 2									
4	1	0	0	0	1943	10	50	13	30
5	7	0	0	0	1957	13	37	327	207
UB campus									
7	-	0	547	7	1807	10	33	1007	20
Motheo Apartments									
8	-	7	157	0	1990	10	20	0	0
Reference values									
WUC Drinking water standards	*	*	*	3000	*	*	1000	100	500
WHO Guideline value	70	50	10	3000**	10	3	2000	900**	400**

*No drinking water standards or guideline values available for those metals (WUC, 2015b).
**No guideline values exist for those metals but only health based values (WHO, 2011).

The metals that exceed the WUC drinking water standards and/or the WHO guideline values for one or several samples are lead, arsenic, cadmium and aluminium.

Lead

At sample site 1 in Segoditshane River the lead concentrations exceeded the WHO guideline value (10 µg/l) considerably, 363 µg/l at the first sampling occasion and 243 µg/l at the second. At sample site 2, upstream site 1, there were however no concentrations of lead at any of the sampling occasions. There could be a point source of lead between the two sampling sites explaining the difference. The highest concentration of lead was recorded at UB campus. The high concentration may be explained by the water coming from a parking lot and being connected to traffic.

Arsenic

The most notable metal regarding high concentrations was arsenic which exceeded the WHO guideline value with almost 200 times at all sampling sites. Arsenic can have natural sources and origin from the soil. Other sources could be industries and traffic. The water in Segoditshane River could be influenced by possible high arsenic concentrations in the soil. The high arsenic concentrations in the water from UB campus and Motheo Apartments are more difficult to find a possible origin for. In the results, the sample from Motheo Apartments showed the highest arsenic concentration but it is still in the same range as the other samples. The high concentration of arsenic in the sample from Motheo Apartments is remarkable since that water was runoff from a roof. Roof runoff is expected to have relatively low pollution load since it is rain water which has only been in contact with the roof. There is need for more analyzing of metals especially arsenic since it exists in very high concentrations in all samples. This is in order to minimise the risk for analyzing errors, which cannot be excluded in this study. At the time of the metal analysis another master thesis where metals were analysed in sludge from the Glen Valley waste water treatment plant in Gaborone was also performed at University of Botswana. Like in the stormwater, the concentrations of arsenic were remarkably high also in the sludge. The sludge in the master thesis was also analysed in a laboratory at Lund University, Sweden. The arsenic concentrations from the two analyses differed and were around ten times lower when analysed in Lund (Norup & Åberg, 2015). Different preparation methods as well as different analysis methods were used but these differences still indicate that there might have been errors in the analysis in this study regarding stormwater and more analyses would be needed to secure the results. Still notable is that even if the arsenic analysis would contain errors, the concentrations must be divided by more than 100 to fall below the drinking water standard for arsenic from WHO.

Cadmium

The cadmium concentrations were exceeding the WHO guideline value for drinking water around 3-4 times for all samples. High cadmium concentrations are remarkable since exposure to cadmium, even low concentrations, may have severe health effects.

Aluminium

At the second sampling occasion at site 2 in Segoditshane River, sample 5, the aluminium concentration (327 µg/l) exceeded the aluminium standard from WUC (100 µg/l). It is also considerably higher than at the first sampling occasion at the same location (13 µg/l). It is also higher than the concentration at the downstream sampling location at the same sampling occasion, sample 2 (7 µg/l). This could be due to a point source close to sampling site 2 just before the second sampling occasion. Either the emission has not reached sample site 1 yet at the sampling occasion or the concentration is strongly reduced between the two sampling sites. At UB campus the aluminium concentration is about ten times higher (1007 µg/l) than the WUC standards which could probably be explained by the water coming from a parking lot and the aluminium originating from the cars. The water from UB campus has overall the highest concentrations for all heavy metals respectively, except arsenic. One should keep in mind that aluminium is often used in drinking water treatment and since the standards and guideline values from WUC and WHO concerns drinking water, the amount of aluminium can, to some extent, originate from the treatment process. However, it is still remarkable that the aluminium concentration at UB campus is ten times higher the WUC standard. Compared to the WHO health based value for aluminium the concentration at UB campus is higher but still in the same range.

Results from other analyzed metals
The other metals analyzed, Ni, Cr, Zn, Cu and Mn, were all below the WUC and WHO limit values, see Table 5.2. For most of the metals the lowest concentrations are found at the sampling site Motheo Apartments. This is reasonable since this is rainwater that has only been in contact with the roof. The high arsenic concentration at this site is however notable. The fact that the samples had been stored for some time could affect the results. Sample 1, 4 and 7 had been stored for almost two months and sample 2, 5 and 8 for a couple of days. Other

The metal analysis gives an idea of the metal concentrations at the different sampling sites but it does not tell in which forms/states the metals occur. All forms of e.g. arsenic are not equally toxic so the results can not totally tell to what extent the metals cause problems if and how the water in Segoditshane River is to be collected and reused. Also, metals can stick to particles and since the water samples were filtered before analyzed there could have been higher amounts of metals in the water which are not shown in these results. There can also be metals in the sediment on the riverbed that are neither included in these results.

Metals and pH
As seen in Table 5.2 the metals with the highest concentrations are aluminium, arsenic and lead. The concentration of metals can be related to pH and the relationship between metal concentration and pH for aluminium, arsenic and lead are presented in Figure 5.5 to Figure 5.7. The numbers in boxes in the diagram represent the different sampling sites. The Motheo Apartment site is excluded in the diagrams since the pH measurement at this site is probably inaccurate.

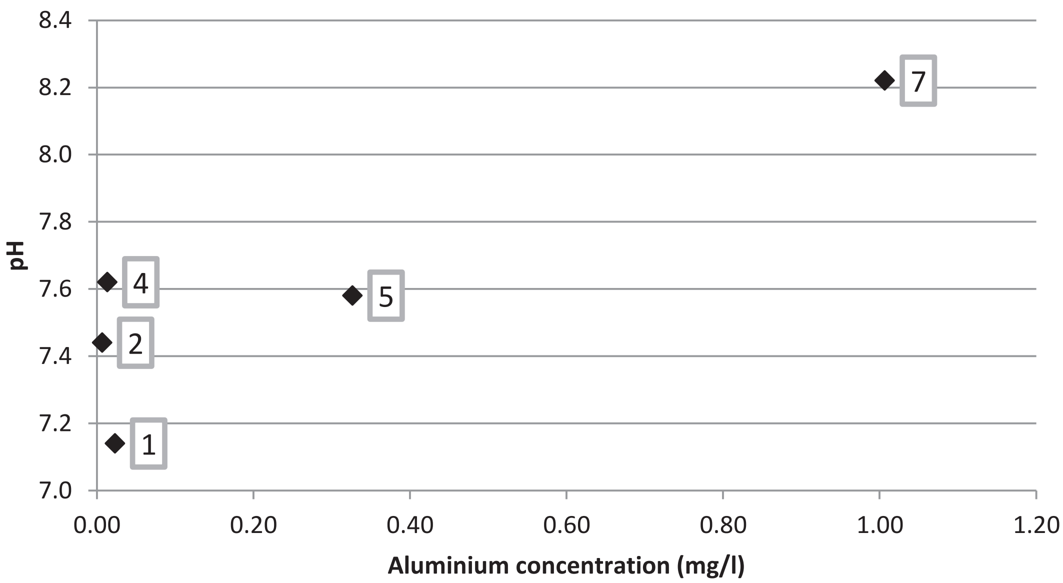

Figure 5.5. Relationship between pH and aluminium concentration.

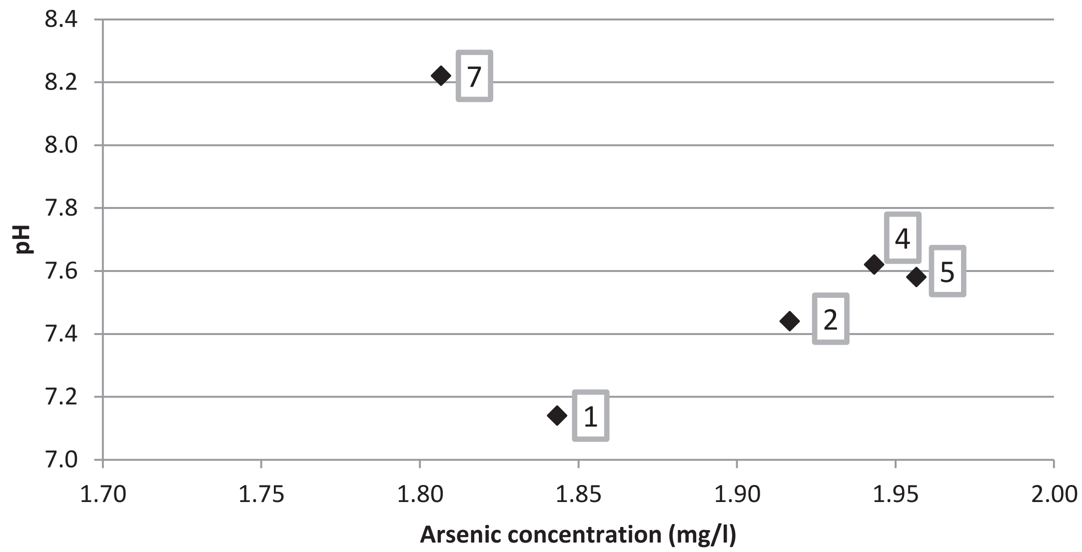

Figure 5.6. Relationship between pH and arsenic concentration.

The relationship between concentration of aluminium and pH, Figure 5.5, shows a relatively low aluminium concentration at around pH 7.1 – 7.6. At the UB campus site there is considerably higher aluminium concentration as well as higher pH compared to the Segoditshane River sites.

Regarding the relationship between pH and concentration of arsenic, Figure 5.6, there is a small tendency of increasing concentration with increasing pH. The UB campus site does, however, not follow this trend.

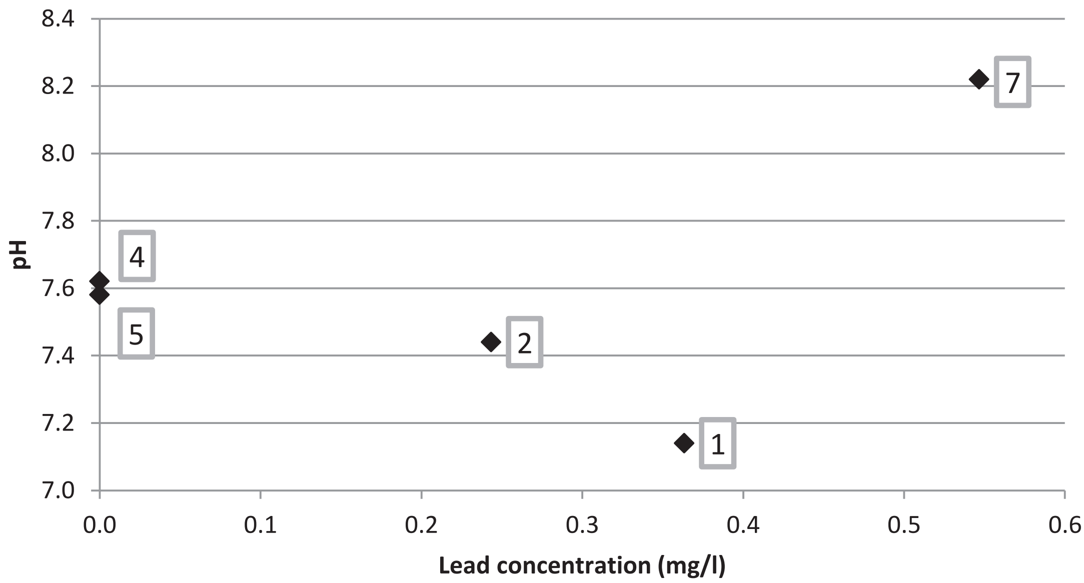

Figure 5.7. Relationship between pH and lead concentration.

Regarding lead, Figure 5.7, there could be a small trend of higher concentration while pH decreases. The sample from UB campus does not follow this possible trend.

For all the three heavy metals focused on here, aluminium, arsenic and lead, there is no obvious relationship between heavy metal concentration and pH. The Segoditshane sampling sites are more or less close to each other while the UB campus site is the odd one. Looking at the two sites along Segoditshane River respectively they are most often close to each other in terms of pH and metal concentration from the first sampling occasion to the second. The differences in concentration could overall be due to other factors than pH as well.

5.1.3 Hydrocarbons

From the GC TOF MS analysis only the hydrocarbons with more than 90% similarity to the theoretical composition of the compounds were further studied and these results are presented in Appendix I. Three hydrocarbons were chosen and focused on since they are oil compounds with an assumed connection to petroleum and can originate from traffic. The three hydrocarbons are octadecane, nonadecane and pentadecane. In which samples they occurred can be seen in Table 5.3. Plastic bottles were used as sampling container for all samples. Compounds from the plastic bottles have probably contaminated the samples and hence all plastic related compounds found in the hydrocarbon analysis have been ignored. To use glass bottles instead of plastic bottles during the hydrocarbon analysis would have enabled studies regarding the impact of plastic contamination from e.g. litter in the stormwater.

Table 5.3. Presence of the hydrocarbons octadecane, nonadecane and pentadecane in the different samples. The presence is marked with an X.

Sample	Octadecane	Nonadecane	Pentadecane
Segoditshane 1			
1	X	X	
2	X	X	
Segoditshane 2			
4			
5	X		
UB campus			
7			
Motheo Apartments			
8	X	X	X

Octadecane and nonadecane were found at sampling site 1 in Segoditshane River at both sampling occasions. At sampling site 2 in Segoditshane River none of the three hydrocarbons were found at the first sampling occasion and only octadecane at the second occasion. In the rainwater from the apartment roof all the three hydrocarbons were found. In the stormwater from UB campus, sample 7, none of the chosen hydrocarbons were found which is notable since the water has been in contact with a parking lot.

Using the GC TOF MS to detect hydrocarbons in water samples gives an indication of what compounds that are present in the water but it does not tell in what concentrations they occur. In this study it would have been interesting to know in what concentrations the different hydrocarbons occurred and not only which hydrocarbons that were present. This could have given an indication of where and if certainly high concentrations occurred. It is not unlikely to find hydrocarbons in stormwater but certainly high concentrations are remarkable and a good reason to investigate possible sources.

Hydrocarbons do not only occur in the free water mass but can be bound to particles and present in the sediment of the river. Since only the filtered water and not the sediment is analyzed for hydrocarbons the presented results do not give the entire picture of the hydrocarbons present in the Segoditshane River. It would have been interesting to analyse the hydrocarbon levels in the sediment since the hydrocarbons tend to stick to particles.

One possible way of removing the suspended hydrocarbons from the water is to construct a dam allowing the particles to sediment due to reduced flow speed. Since the hydrocarbons to a large extent are attached to the particles they can be removed from the water if the sediment is removed. Proper treatment of the sediment is needed in order to prevent the hydrocarbons from causing damage at other places downstream in the river.

To verify the hydrocarbon analysis of the stormwater, further analysis would have been needed. More samples from different points along Segoditshane River during a longer period of time would have given a more accurate picture of the hydrocarbons present in the river. This could also give indications of possible and certain sources of hydrocarbons along the river. It would also be interesting to analyse rain water for hydrocarbons in order to compare what hydrocarbons are present in pure rain water compared to the ones found in the water from Segoditshane River.

The fact that the samples had been stored for some time could affect the results. Sample 1, 4 and 7 had been stored for almost two months and sample 2, 5 and 8 for a couple of days.

5.1.4 Total suspended solids and Volatile Suspended Solids

The TSS and VSS results are presented in Table 5.4. The excluded values were negative and since concentrations cannot be negative those values are not presented in the table.

Table 5.4. TSS and VSS values as well as one value from the U.S. Geological Survey (Burton & Pitt, 2002). The gaps in the table mean that the measured value is negative and omitted or in the USGS case that no value was available.

Sample	TSS (mg/l)	VSS (mg/l)
Segoditshane 1		
1	0.025	-
2	0.13	-
Segoditshane 2		
4	0.25	0.05
5	-	-
UB campus		
7	0.65	0.06
Motheo Apartments		
8	0.185	0.08
Other study		
USGS	50	-

The reason for some values being invalid could be human errors like inaccuracy in the measurements or mistakes during weighing. The VSS values are lower than the TSS values which is reasonable since the VSS is a part of the TSS. Compared to the mean concentration of suspended solids in the USGS study, 50 mg/l, the concentrations of total suspended solids in Table 5.4 are much lower. The conditions in the USGS study and in Segoditshane differ which one should have in mind while interpreting the results. The fact that the samples had been stored for some time could affect the results. Sample 1, 4 and 7 had been stored for almost two months and sample 2, 5 and 8 for a couple of days. To remove the suspended solids from the water a dam can be constructed where the particles can settle.

5.1.5 Biochemical Oxygen Demand

The BOD results can be seen in Table 5.5. The stormwater samples taken in January (sample 1, 4 and 7) were stored for two months before analyzed for BOD_5. The exact storing days for the samples before the BOD analysis was made can be seen in Appendix II, Table 9.7. The BOD_5 for a water sample represents the oxygen consumed after five days and since the water had been stored before the measurements started the more accurate value would probably be higher than the values presented in Table 5.5. The samples were stored in a refrigerator, however, and the microbial activity was probably very low at the low storage temperature compared to the temperature at site. The samples taken in March (sample 2 and 4) were analyzed just a few days after the sampling occasion and are hence probably more accurate. The USGS value in the table is from the Stormwater Effects Handbook and is lower than most of the samples except the UB campus sample which is about the same. One must however bear in mind that the conditions and circumstances in USGS and in Segoditshane River are not the same and the results are therefore not fully comparable.

Table 5.5. BOD_5 results. Included is also a BOD result from a stormwater quality study performed by USGS presented in Stormwater Effects Handbook (Burton & Pitt, 2002). Due to errors in the measurements no values for BOD were given for sample 3 and 6.

Sample	BOD_5 (mg/l)
Segoditshane 1	
1	22
2	21
3	-
Segoditshane 2	
4	25
5	60
6	-
UB campus	
7	8
Motheo Apartments	
8	25
Other study	
USGS	7

5.1.6 Chemical Oxygen Demand

The COD values are presented in Table 5.6. As well as for the BOD_5 analyses the samples were stored for some time before the analyses were performed. The exact storing days for the samples before the COD analysis was made can be seen in Appendix II, Table 9.8. The samples taken in January (sample number 1, 4 and 7) were stored for two months, the samples taken in March (sample number 2, 5 and 8) were stored for about a week and the samples taken in April (sample number 3 and 6) were stored for about two days. The storage could affect the results. The samples were stored in a refrigerator, however, and the microbial activity was probably very low at the low storage temperature compared to the temperature at site. Compared by the COD results from the USGS and Bellevue studies the COD results in this report are considerably higher. The difference could be due to errors in the analyses. The COD being higher than the BOD_5 is logical since more organic matter can be degraded chemically than biologically and hence more oxygen is consumed.

Table 5.6. COD results. Included is also a COD results from two stormwater quality studies, one performed by USGS and another one performed in Bellevue, U.S. Both studies are presented in Stormwater Effects Handbook (Burton & Pitt, 2002).

Sample	COD (mg/l)
Segoditshane 1	
1	14784
2	1223
3	2798
Segoditshane 2	
4	3493
5	4172
6	6763
UB campus	
7	4040
Motheo Apartments	
8	5877
Other studies	
USGS	60
Bellevue	46

5.1.7 Microorganisms

The first results from the microbiology analysis were given in the second day of the analysis. The microbiology analysis was performed for only two samples taken during the same day in Segoditshane River. This must be kept in mind when reading the results. The results from the Plate count (PCA) and the Most Probable Number (MPN) methods are shown in Table 5.7. The PCA results are probably more accurate than the MPN index. This is due to that different dilutions were used compared to dilutions needed to read the MPN index table correctly. The MPN results are therefore not further discussed and instead the focus is on the PCA results.

Table 5.7. Plate count and Most Probable Number values. Sample 1A, 1B and 2A, 2B are from Segoditshane site 1 and 2 respectively.

Sample	1A Dilution 1:10	1B Dilution 1:10	2A Dilution 1:10	2B Dilution 1:10
PCA (cfu/ml) (mean)	2270	1940	3900	8230
MPN index per g	0.9	2.3	0.9	2.3

The agar plates with different dilution factor differed significantly in numbers of colonies. The agar plates with lowest dilution, 1:10, were chosen for further counting due to the high number of colonies present, shown in Table 5.7, while the plates with dilution 1:1000 only contained a few colonies which were not enough for counting. A dilution factor in between the two first e.g. 1:100 could perhaps have been used to get more reliable results for the colony counting.

Comparing the plate count results to the standards of bathing water in Sweden and EU, the results from the plate count were more than 200-800 times larger than the limit for good bathing water quality (1000 cfu/100 ml for good standard).

The results from the EMBA plates were given on day three. All the EMBA-plates had green metallic sheen in some amount. The plates streaked with sample S1B and S2B had the most green- metallic sheen, hence the most coliform bacteria of all the plates studied, see Figure 5.8.

Figure 5.8. EMBA plates for sample S2B to the left and S1B to the right taken from the two different sites in Segoditshane River. The green metallic sheen indicates coliform bacteria.

On day four the results from the tubes containing brilliant green bile broth was checked. The Durham tubes contained gas but there was almost no change in colour. The tubes could therefore not be said to have entirely positive results. The plates were found positive for bacteria and *E. coli* was presumed in at least two of the plates due to the bad smell caused by bacteria growth.

After the api 20E test the result of the bacteria species indicated K. ozaenae for S1A and Aeromanas hydrophilia or Salmonella arizonae for S2B. All of those are bacteria which can live in the enteric system of humans and potentially cause diseases in humans. Although the results of which bacteria species were present were connected to uncertainties as regard to performance both in sampling and laboratory analysis. The results still indicate enteric bacteria in the water. Hence from the results, an occurrence of sewage water as contamination in the Segoditshane River cannot be ruled out. Concluding these results, precautions may have to be arranged to prevent sewage water to discharge into the Segoditshane River. It must however be considered that this analysis for fecal bacteria was made for samples taken at only one time and at only two sites along the river. For more reliable results more samples along the river should be taken with repeated and quality assured analyses.

More samples and analyses during a longer period of time would have given more reliable results and this is valid for all different parameters.

5.2 Quantity

The quantity of water in Segoditshane River and in the Segoditshane River catchment has been estimated using rainfall data and information related to the catchment. The results are presented in the following section.

5.2.1 Rain in Segoditshane River catchment

To get an idea of the precipitation in Segoditshane River catchment the rain recorded at two rain gauge stations was analyzed. The two rain gauge stations are Gaborone rain gauge station just outside the catchment and Mogoditshane rain gauge station inside the catchment. Rain data from both rain gauge stations was used to represent the rainfall in Segoditshane catchment. The total precipitation measured per year at Gaborone rain gauge station is presented in Figure 5.9. In the figure it can be seen that there have been large variations in total annual precipitation between 2001 and 2010. During those years the total annual precipitation has varied between approximately 250 and 900 mm.

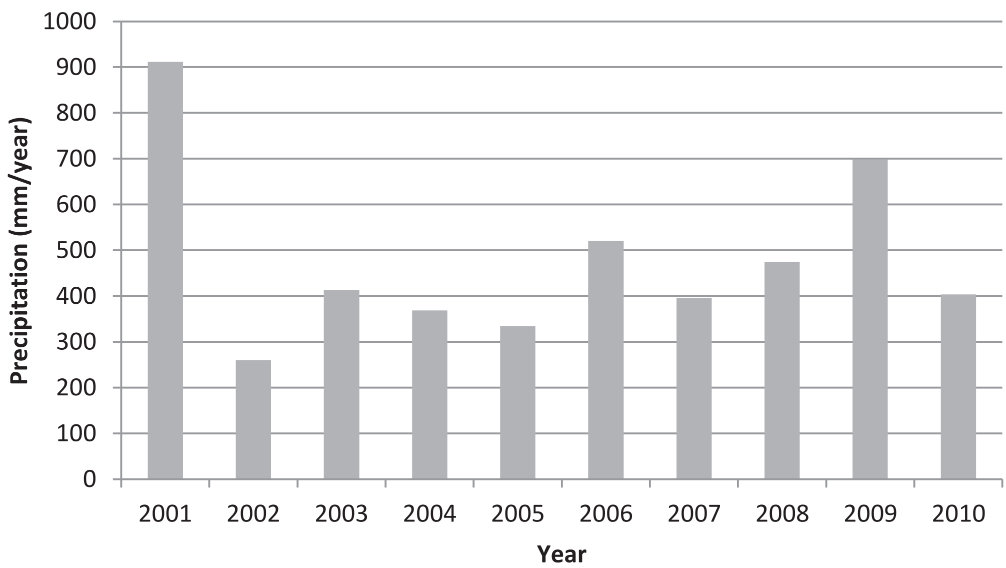

Figure 5.9. Precipitation recorded per year at Gaborone rain gauge station 2001-2010.

To see how the rains have varied over months during the time period between 2001 and 2010 the variations are shown in Figure 5.10. December, January and February are the months with highest precipitation although e.g. November has had large peaks of rain.

Mogoditshane rain gauge station is located inside the Segoditshane River catchment and the precipitation from this station during 2009-2010 is shown in Figure 5.11. Due to short, non-continuous rainfall data-series only two years, 2009 and 2010, could be presented.

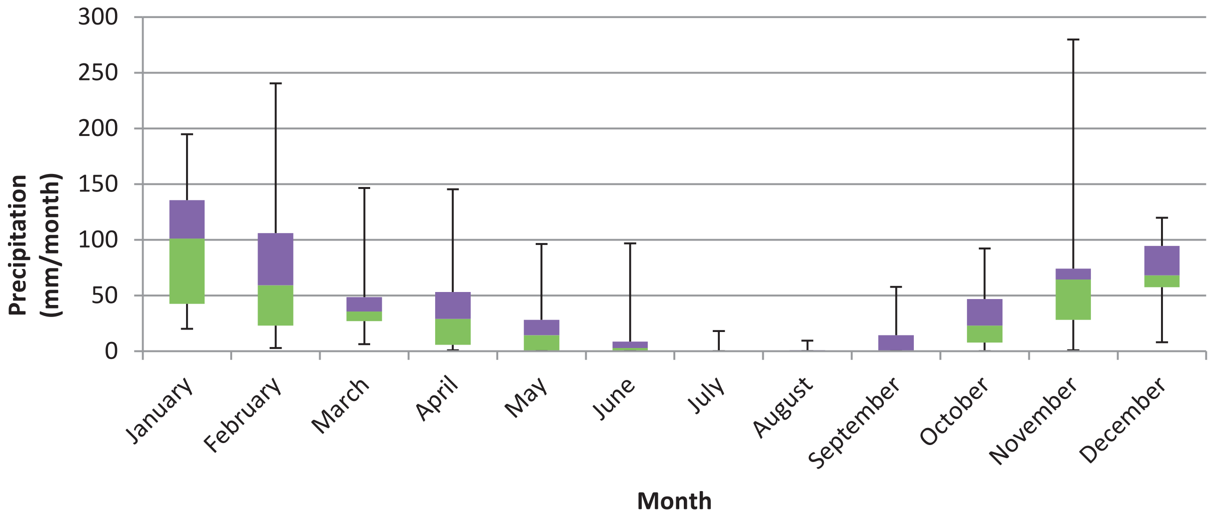

Figure 5.10. Variations of precipitation at the Gaborone rain gauge stations over months 2001-2010. The middle line between the top and the bottom parts of the box represents the median precipitation for each month. The top and bottom of the box represent the 75th and 25th percentile, respectively. The top and the bottom bar represent the maximum and minimum precipitation, respectively.

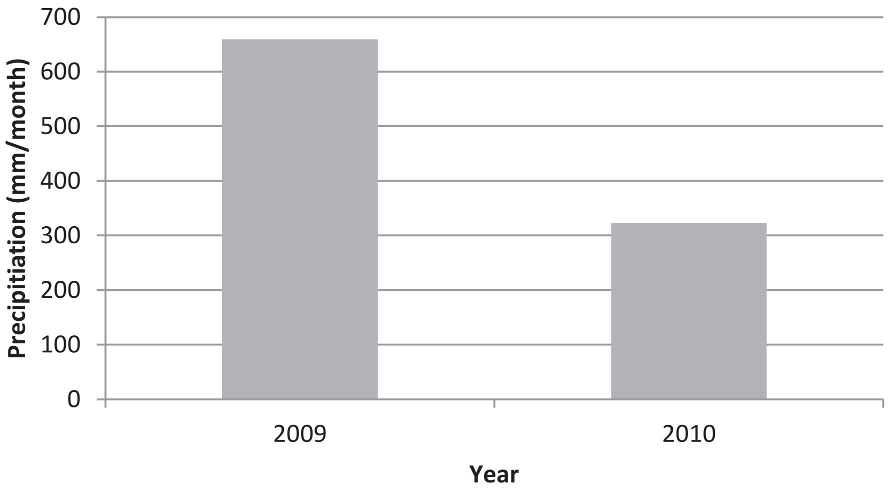

Figure 5.11. Precipitation recorded per year at Mogoditshane rain gauge station 2009-2010.

Comparing the precipitation during 2009 and 2010 from the Gaborone and Mogoditshane rain gauge stations shows that there are similarities between the stations although a somewhat larger precipitation is registered at the Gaborone rain gauge station.

5.2.2 Volumes of water in Segoditshane River catchment

To further analyse the rain data and to get an idea of how much rain that precipitates within the catchment each year the precipitation is multiplied with the area of the urban Segoditshane River catchment, 60 km^2. In Figure 5.12 the total volume of rain precipitated per year in the urban Segoditshane River catchment during ten years from 2001 to 2010 according to rain data from Gaborone rain gauge station can be seen.

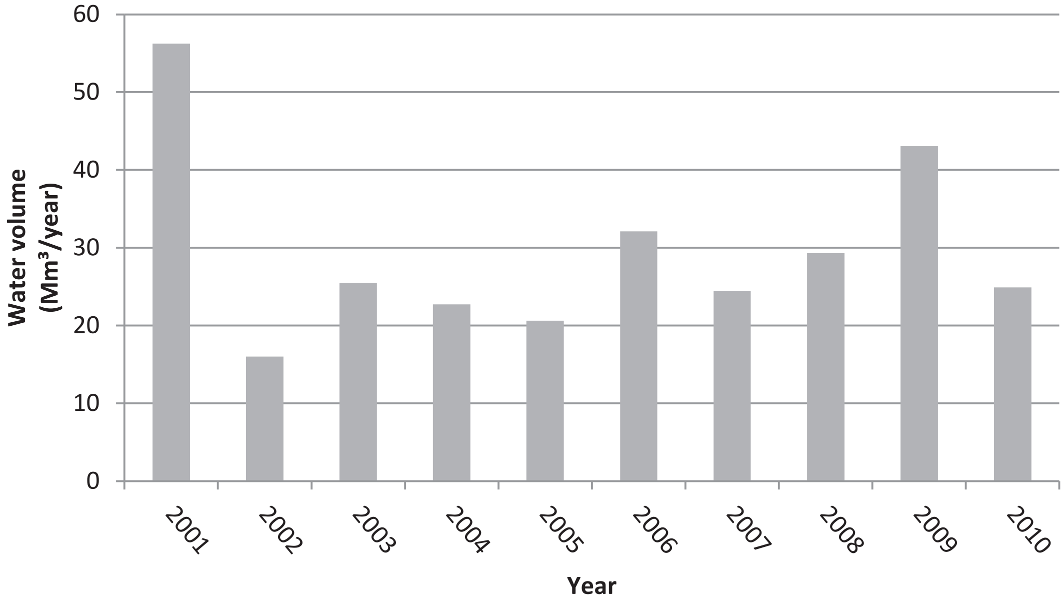

Figure 5.12. Total volume of rain precipitated per year, estimated for the Segoditshane River catchment area and calculated from rain data from Gaborone rain gauge station 2001-2010.

The total volumes of water precipitated in the Segoditshane River catchment according to rain data from Gaborone rain gauge station vary between 15 and 55 Mm^3, see Figure 5.12. Those amounts are considerably higher than the amounts of water possible to collect in Segoditshane River that were calculated in the report "Water from Segoditshane River" from 2010 which was around 5 Mm^3. It is logical that the total amount of rain precipitated is higher than the amount of water possible to collect due to factors like evaporation and infiltration.

How the monthly volumes of rain precipitated have varied over years is shown in Figure 5.13. Since the highest precipitations occurred in December, January and February the largest volumes of precipitation also occur during those months. In June, July and August the precipitation is very low and the water volumes possible to collect are hence also very small. The available amount of water to collect and reuse is therefore very dependent on the monthly rainfalls.

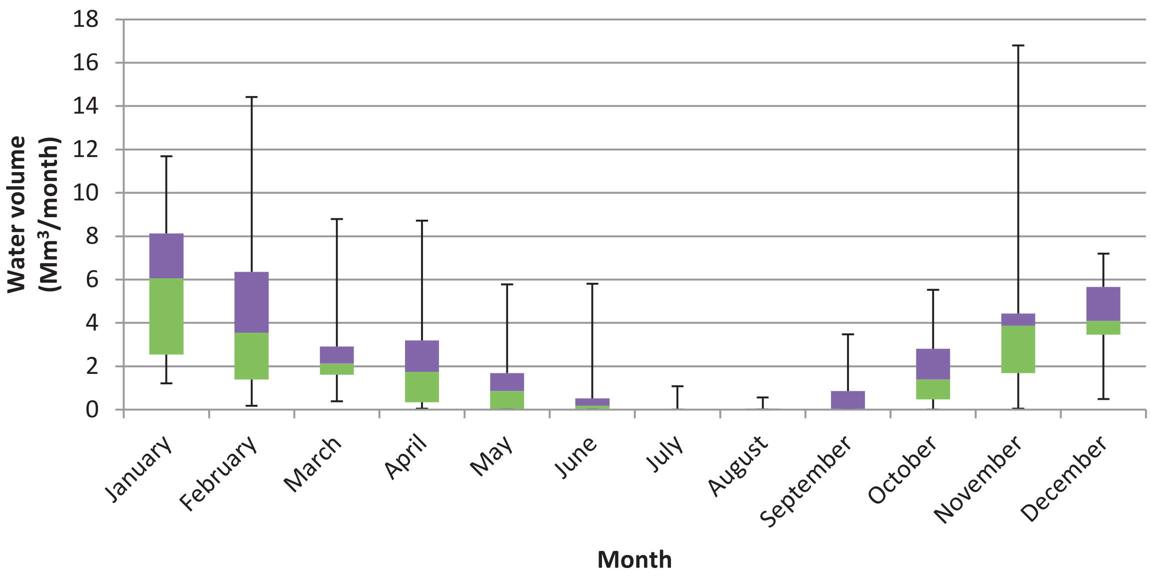

Figure 5.13. Water volume precipitated per month, estimated for the Segoditshane River catchment area, calculated from rain data from Gaborone rain gauge station 2001-2010. The middle line of the box represents the median precipitation for each month. The top and bottom of the box represent the 75th and 25th percentile, respectively. The top and the bottom bar represent the maximum and minimum precipitation, respectively.

In Figure 5.14 the total volume of rain precipitated per year in the urban Segoditshane River catchment, 60 km^2, during two years from 2009 to 2010 according to rain data from Mogoditshane rain gauge station can be seen. From this station only the total rain during two years can be presented due to short non-continuous series of rain data . The highest amount of water, 40 Mm^3, was received in 2009 and the lowest, 20 Mm^3, in 2010.

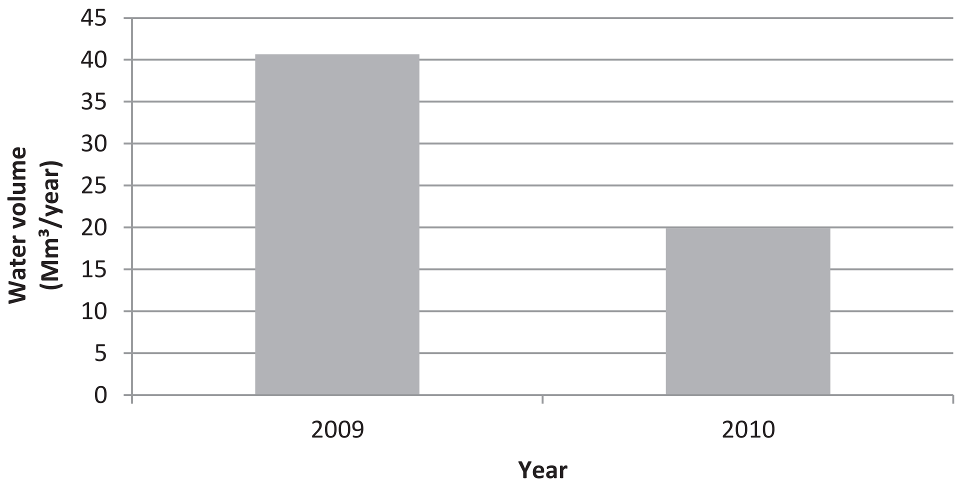

Figure 5.14. Total volume of rain precipitated per year according to rain data from Mogoditshane rain gauge station 2009-2010.

The Gaborone rain gauge station has received slightly more rain than the Mogoditshane rain gauge station. Using rainfall data from Gaborone rain gauge station therefore results in larger water volumes.

5.2.3 Three water volume scenarios for Segoditshane River catchment

In this section the results from the three different scenarios are presented.

Water volume according to Scenario 1 – Roads and gravel areas

Scenario 1 states that the water falling on the larger roads and the gravel areas is all the water that is discharging to Segoditshane River and possible to collect. The variation in volume over each month, according to scenario 1, for the years 2001-2010, is presented in Figure 5.15.

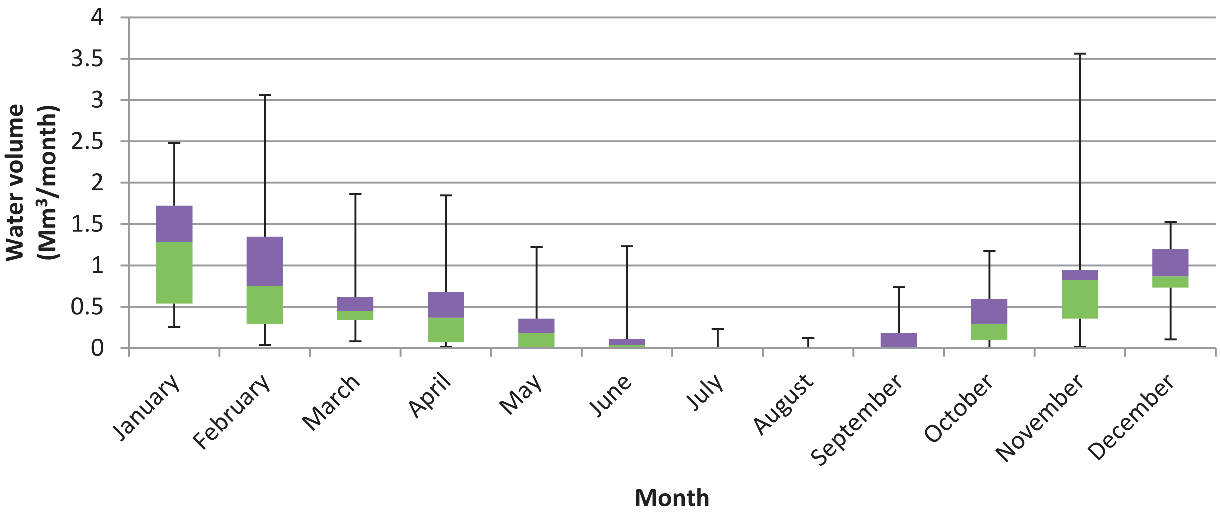

Figure 5.15. Water volume possible to collect from larger roads per month according to Scenario 1 with rain data from Gaborone rain gauge station. 2001-2010 The middle line of the box represents the median precipitation for each month. The top and bottom of the box represent the 75th and 25th percentile, respectively. The top and the bottom bar represent the maximum and minimum precipitation, respectively.

For scenario 1, January is the month with highest monthly average rainfall while the largest rain measured during the ten year period is from November. The months receiving most rain are according to Figure 5.15 November to February which give volumes of water around 1 Mm^3 in average per these month. The months with least rain are July and August. The average value of all the monthly medians for the water volume was calculated to be approximately 0.4 Mm^3. That would correspond to a water volume of 4.8 Mm^3 per year which is 15% of the total water use in Gaborone The quantity calculations are limited due to evaporation not being included. The resulting values of possible water volumes to collect are therefore larger than the amount that would actually be possible to collect.

Water volume according to Scenario 2 - Roofs

Scenario 2 states how much rainwater that can be collected directly from the roof areas in Segoditshane River catchment. Rainwater tanks could be installed close to residential houses in order to collect rainwater and prevent it from infiltrating into the ground. How the water volume varies each month in scenario 2 over the ten years 2001-2010 is presented in Figure 5.16.

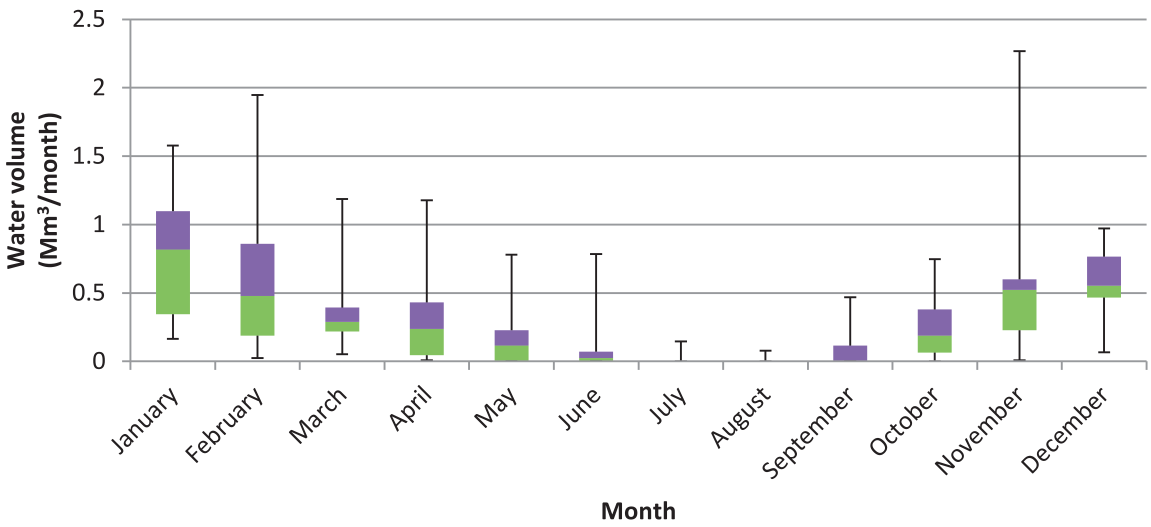

Figure 5.16. Water volume possible to collect from roof areas per month according to Scenario 2 with rain data from Gaborone rain gauge station. The middle line of the box represents the median precipitation for each month. The top and bottom of the box represent the 75th and 25th percentile, respectively. The top and the bottom bar represent the maximum and minimum precipitation, respectively.

For scenario 2 the average volume of water possible to collect from rain falling on roofs is largest in January with approximately 0.8 Mm^3 water per month. After January, the average rain amounts for November, December and February resulted in average monthly rainfalls of 0.5 Mm^3. The water volumes described in scenario 2 can possibly be collected in rainwater tanks close to the residential areas. The average value of all the monthly medians for the water volume was calculated to be approximately 0.3 Mm^3. Annually this value corresponds to a water volume of 3.6 Mm^3 which is 10% of the total water use in Gaborone. The quantity calculations are limited due to evaporation not being included. The resulting values of possible water volumes to collect are therefore larger than the amount that would actually be possible to collect.

Using the same rainfall data over a period of ten years, scenario 1, including larger roads and gravel areas, gives larger water volumes possible to collect than scenario 2 which only includes the roof areas in the city.

Water volume according to Scenario 3 – Roads, roofs and gravel areas

Scenario 3 states which amount of water that could be collected if all the areas of the larger roads, all the roofs and gravel areas were connected and all the water discharged to Segoditshane River and collected in a dam downstream the river. The variation of the volume per month according to scenario 3 over the years 2001-2010 is presented in Figure 5.17.

In scenario 3 where the roof areas are connected to the road and gravel areas larger water volumes can possibly be collected. January was during the ten year period 2001-2010 the month with largest average value, approximately 2 Mm^3. The next month in order of size in volume have average water volume of around 1 Mm^3. The average value of all the monthly medians for the water volume was calculated to be approximately 0.6 Mm^3. Annually this value corresponds to a water volume of 7.2 Mm^3which is 23% of the total annual water use in

Gaborone. The quantity calculations are limited due to evaporation not being included. The resulting values of possible water volumes to collect are therefore larger than the amount that would actually be possible to collect.

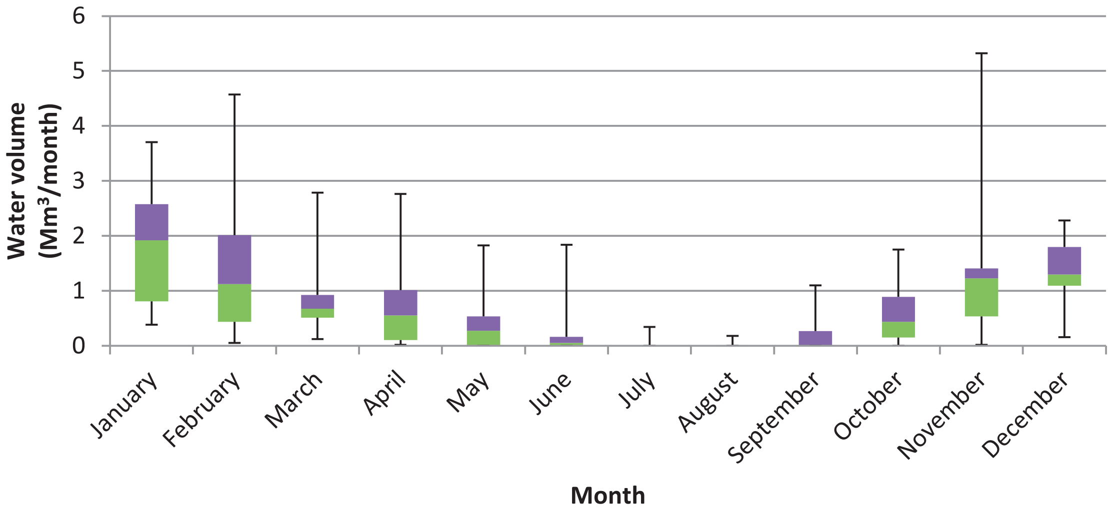

Figure 5.17. Water volume possible to collect from connected roads, roofs and gravel areas per month according to Scenario 3 with rain data from Gaborone rain gauge station. The middle line of the box represents the median precipitation for each month. The top and bottom of the box represent the 75th and 25th percentile, respectively. The top and the bottom bar represent the maximum and minimum precipitation, respectively.

Comparison of scenarios

Comparing the different scenarios, scenario 3 is the scenario which can give the largest possible water volumes to collect using one collection method. However, this scenario may be difficult to create in reality because of the situation in Gaborone today. To connect all the roofs to the stormwater system and channels may be a lot of work.

Another suggestion is to install rainwater tanks close to the residential houses in order to collect the rainwater before it reaches the ground, like in scenario 2. In this way the volume of rainwater falling on roofs may be collected instead of infiltrating into the ground.

Collecting rainwater in tanks like in scenario 2 can be combined with scenario 1 where stormwater from roofs and gravel areas may be collected in a stormwater dam downstream Segoditshane River. One benefit from combining these two scenarios is that the rainwater collected in tanks is probably cleaner than if it had been transported through the stormwater system and collected downstream Segoditshane. The combination of scenario 1 and scenario 2 can however not be assumed to be equal scenario 3. Scenario 2 only takes the house-roof area in the catchment into account but the same area is already considered to be gravel areas in scenario 1. If scenario 1 and 2 were combined it would count for a larger area than the total urban catchment area.

Limitations in the stormwater quantity calculations
When the runoff coefficients used in the different scenarios were calculated the topography of the surface was not considered due to lack of data. The runoff coefficients are therefore rough estimates. The evaporation could also not be included and this was also due to lack of data. To get more reliable results both the topography and the evaporation should also be included. In order to make a computer model over the flow in Segoditshane River flow measurements in the river would have been needed. No flow measurements have been done in the Segoditshane River before, and during the time of the field study the flow was too low to perform flow measurements.

5.3 Discussion based on the aim and research questions

In the following section the quality and quantity parts are discussed based on the aim and research questions for this thesis.

How is the present state of the water quality in Segoditshane River?
The quality of Segoditshane River was examined by analyzing different water quality parameters. High concentrations of some metals; lead, arsenic, cadmium and aluminium were noticed while other metals were relatively low. More analyses and measurements must be performed in order to secure the metal results and find solutions to the problem of high metal concentrations. For the heavy metals found in high concentrations, suitable treatment methods are needed. Although the presence of *E. coli* bacteria was not confirmed in the samples, the EMBA plates showed the green metallic sheen typical for growth of coliform bacteria (Figure 5.8). Indications of other bacteria species which may be pathogenic to humans were detected from the microbial samples. The presence of enteric bacteria indicates possible contamination of sewage water in the river but the bacteria may also origin from faeces from animals. The water temperature was relatively high at all sampling occasions which is favorable for growth of microorganisms. Particularly bacteria capable of infecting humans grow well in temperatures approaching the temperatures of the human body. The water was stagnant at several sampling occasions which also favor microbial growth.

Debris and solid waste are to some extent a problem in Segoditshane River, both for quality reasons and for flow conditions. Solid waste in the stormwater drainage channels is a quality problem and the waste can also cause blockages in the channels, preventing discharge to Segoditshane River. Measurements of collecting the waste as well as preventing the spread of waste in the stormwater drainage channels should preferable be initiated in order to improve the water quality and flow conditions.

Hydrocarbons related to oil and traffic has been found in the water from Segoditshane River. It was not investigated in what amount the different hydrocarbons have been found and therefore it is difficult to say how important these pollutants are to the total water quality in Segoditshane River. However, it is still pollution and for further use of this water a treatment method for these compounds should be found. Since hydrocarbons stick to particles a dam could be a suitable treatment method regarding suspended hydrocarbons. In a dam the flow velocity is reduced and the particles can sediment. In the following section dams will be further discussed regarding collecting systems.

From the present state of the water quality in Segoditshane River, are water quality improvements motivated and how can those improvements be arranged?
Based on the present state of the quality in Segoditshane River, quality improvements are motivated regarding possible inflow of sewage water to the river and high concentrations of

metals but also regarding solids and hydrocarbons. This is especially important if the water is to be reused but also for environmental reasons. Bacteria which may cause e.g. diseases in humans may be present in sewage water and the high temperature would favor the growth of these bacteria. Prevention of leakage of sewage water into the Segoditshane River is important in order to reduce the amount of bacteria in the water. High concentrations of metals are toxic for the environment and could be harmful to humans if the water is to be reused as e.g. drinking water. Hydrocarbons should be regarded since they may cause severe health problems, especially during long-term exposure. Both metals and hydrocarbons attach to particles and therefore treatment of solids is important to reduce the pollution load in the water.

One treatment method that could be used along the river is biological treatment, either bioremediation, phytoremediation or a combination of them. What type of biological treatment that is most suitable regarding the conditions in Segoditshane River need to be investigated thoroughly. Biological treatment, e.g. in the shape of vegetated swales and wetlands, have several advantages like reduction of peak flows and removal of pollutants. However the infiltration rate also increases which is a disadvantage in the case with Segoditshane River where there is a wish of collecting as much water as possible. There are contradictions between collecting as much water as possible with a lower quality and collecting less water but with higher quality where the improved quality is due to the water passing the biological treatment-site. Another aspect that needs to be taken into consideration is that plants and arrangements of the biological treatment can be destroyed during high flows. During the rainy season in Botswana and Gaborone heavy rain can lead to high flows in Segoditshane River and a biological treatment site would then need to be protected. One possible solution could be to construct a site with biological treatment where normal flows run through the site but heavier flows are directed outside the site. In a solution like this all water in Segoditshane River would not be treated in the biological treatment-site at high flows but in order to protect the vegetation it could be a better solution. The flow in Segoditshane river vary and the plant in the biological treatment need to be persistent to the different circumstances like high flow as well as drier periods.

What quantity of stormwater can be expected from Segoditshane River catchment area?

The amounts of water in Segoditshane River usually vary a lot during the year and depend on several factors. The factors include amount of rain falling, rainfall intensity, imperviousness, stormwater drainage connections to the river, evaporation, infiltration etc.

In this project the situation was simplified by excluding rainfall intensities and evaporation due to lack of data. The three different scenarios were used to give an idea of how much water that could possibly be collected, evaporation not included. Today there are many residential houses that are not connected to the stormwater drainage system and the water from roofs instead infiltrate into the ground. By excluding infiltration calculations in this report, the addition of groundwater flow into the Segoditshane River from infiltrated water was also excluded. Due to lack of, or poor maintenance of stormwater drainage systems, some water stays in small ponds where it infiltrates the underlying soil or evaporates. This is also one loss of water which has not been studied in detail in this project.

The most straightforward quantity calculation is to use the best connected impervious areas in the city - the water falling on roads and some amounts on gravel areas that are discharged into the Segoditshane River like in scenario 1. This states that maximum 1.3 Mm^3 can be expected as runoff in Segoditshane River as a median value for January which is usually the rainiest month of the year. This can be compared to the average monthly water consumption in

Gaborone of 2.7 Mm^3. However the amount of 1.3 Mm^3 was calculated for the month receiving most rain and the average monthly amount of runoff into Segoditshane River is lower than this. In the report about Segoditshane from DWA from 2010 it was concluded that 5 Mm^3 can be collected each year which is in the same range as the average annual value for scenario 1, 4.8 Mm^3. However, in the Segoditshane report from DWA all the assumptions and calculations are not totally presented and in order to make a better comparison of the water volumes more information about the different conditions would have been preferred. The water volume of 4.8 Mm^3 corresponds to approximately 15% of the total annual water usage (32 Mm^3) in Gaborone. One must have in mind that evaporation was excluded from the quantity calculations in this project and therefore the water volumes possible to collect presented above will in reality be lower.

The amount of water able to be collected in storage tanks connected to houses was calculated to be 0.8 Mm^3 as a median value for January. The total annual volume of water possible to collect in rainwater tanks would be 3.6 Mm^3. This corresponds to 10% of the total annual water use in Gaborone. These numbers assume that every house has some kind of collection system and that there is no spill, meaning that all runoff goes directly to the storages. This project is focused on the Segoditshane River catchment, thus, there are many parts of Gaborone city which are not included in the quantity calculations for collecting runoff water from roofs. The potential of collecting rainwater from residential house roofs may therefore be considerably higher.

If the runoff from residential house roofs could also be connected to the stormwater system in the city and if the water would be discharged into Segoditshane River it would be possible to get an amount of 1.9 Mm^3 as calculated in Scenario 3 as the median for January. This assumes that no water is hindered by debris or other clogging material in the drainage channels and culverts. The annual average volume of water possible to collect from Segoditshane according to scenario 3 is 7.2 Mm^3 which corresponds to 23% of the total annual water use in Gaborone. This is perhaps the most uncertain quantity result because the present state is very different to the situation described in Scenario 3. Much infrastructural work would probably be needed in order to get Scenario 3 in Segoditshane River catchment.

In what way can the water from Segoditshane River catchment area be collected and reused?

There are several alternatives for how the water from Segoditshane River catchment can be collected. Stephenson suggests in one report from DWA in 2010 that water from Segoditshane can be collected in a dam close to the discharge into Notwane River. This alternative is a good way to collect water close to the city where it can be used. The dam can be connected to the raw-water pipe system and transported to the water treatment plant located close to Gaborone dam.

Another alternative is to let the water from Segoditshane River discharge into Notwane River and then be collected in dams downstream in Notwane River as DWA stated in the report Lower Notwane Dam Pre-Feasibility Study. By leading the water further away there may be some quantity losses by infiltrating and evaporating water but the quality may be improved through reduction in pollution by plants along the river. The transport distance would also be longer if the water from those dams should be used in the city.

As seen in Scenario 2 in the results there is a possibility of water from house roofs to be collected at site close to the houses, so-called rainwater harvesting. The quality of this water is more difficult to control than if all the stormwater would be collected in e.g. a dam where regular controls of the quality could be done. At the same time the rainwater collected from roofs are presumably cleaner than stormwater collected from the ground. The water collected at site may therefore be better to use for purposes not as vulnerable to pollution. The water may not be used as drinking water but for e.g. irrigation in gardens.

6 Conclusion

Depending on the intended use of water from Segoditshane River, different quality improvements of the water are needed. Pollution has been found in the water from Segoditshane including high concentrations of arsenic, lead, cadmium and aluminium. Hydrocarbons related to traffic pollution have also been noticed. The microbiology results showed no indication of *E.coli* but indicated presence of enteric and potentially pathogenic bacteria. This indicates possible sewage contamination in the river but the bacteria may also origin from faeces from animals. In order to reduce the amount of bacteria in the water in Segoditshane River measurements regarding the leakage of sewage into the river are needed.

If the water from Segoditshane River is to be used as drinking water, more proper treatment of the water would be needed than if the intended use for the water would be e.g. irrigation. For Segoditshane River, biological treatment in terms of bioremediation and phytoremediation is one suggestion for removal of metals and hydrocarbons to improve the water quality downstream in the river. The biological treatment can be combined with the use of one or more stormwater dams further downstream where additional compounds can settle and the water can be collected for further use. Depending on the intention of use for the collected stormwater, additional treatment processes may be needed after the dams.

The water from Segoditshane River catchment could preferably be collected in a dam and be used in drinking-water production. A stormwater dam can be used to collect the water volumes from Segoditshane River and trap pollution through settlement. There are two main alternatives where a dam can be constructed. One suggestion is to place the dam just before the outlet to Notwane River. Another suggestion is to construct a dam further downstream in the Notwane River catchment. If the dam is placed close to the city a larger amount of water may be collected without losses through infiltration and evaporation. Constructing the dam further downstream may, on the other hand, favor a better water quality but the water would still need to be pumped back to the city. In the quantity calculations evaporation was not included. Due to the exclusion of evaporation, the actual amounts of water possible to collect according to the different scenarios are less than the water volumes presented below. The amount of water possible to collect in one year from Segoditshane River originating from rain falling on roads and gravel areas is less than 4.8 Mm^3. This water volume corresponds to 15% of the total annual water use in Gaborone.

Another suggestion of how to collect water is to use rainwater harvesting by collecting rainwater in tanks close to residential houses. The water would not hold the same quality as if it was treated in dams and in water treatment plants but could be used for other purposes than for drinking water. The water volume possible to collect in rainwater tanks in one year would be less than 3.6 Mm^3 which corresponds to 10% of the total annual water use in Gaborone. At present state, the water falling on house roofs is not connected to the stormwater drainage system in Gaborone and instead infiltrating into the ground. If connections to the stormwater drainage system were made, water from roofs could also be collected in a dam downstream in Segoditshane River. This corresponds to a total water volume less than 7.2 Mm^3 possible to collect per year, 23% of Gaborone's total water use per year.

To summarize there is a potential worth considering of collecting stormwater in Segoditshane River and rainwater from house roofs in Gaborone in order to reuse the water and hence improve the stressed water situation in Gaborone.

7 Suggestions for future studies

Due to several limitations in this master thesis all aspects needed in order to get a complete picture of the conditions in Segoditshane River, both in terms of water quality and water quantity, could not be included. Suggestions of future studies connected to Segoditshane River are stated in the following section.

Quality
In order to get a more detailed picture of the water quality in Segoditshane River, further and more specific quality analyses should preferably be done. The sampling should be done regularly during an adequate period of time and at several sites along the river. Sediment samples should also preferably be taken and analyzed in order to investigate what type of pollutants that are trapped in the sediment in the river.

Analyses of nutrients were excluded in this thesis due to lack of time and analyzing equipment. If the water quality in Segoditshane River is to be studied in the future a nutrient analysis should preferably be included to get a better overall picture of the water quality in the river.

Treatment methods and collecting systems
Creating a dam in Segoditshane River would probably improve the water quality and also be a storage alternative for collected water. The location of the dam should be investigated thoroughly before constructed. Other suggestions in order to improve the water quality are to construct sites with biological treatment along the river. Specific conditions in terms of e.g. flow, water quality and aim with the project should be carefully regarded before construction. Collaboration between engineers and biologists could contribute to successful designs of open stormwater solutions.

Quantity
During the field study for this master thesis the flow in Segoditshane River was very low and it was not possible to perform any flow measurements. If the water quantity in Segoditshane River is to be studied further in the future flow measurements should preferably be performed periodically. This, in combination with e.g. longer time series of rainfall data and more reliable runoff coefficients, will enable the use of computer models in order to investigate the flow in the river. To get more reliable runoff coefficients factors like e.g. topography should be included in the calculations. Evaporation also need to be included to receive more accurate quantity calculations.

Since the stormwater in Gaborone to a large extent ends up in Segoditshane River a better overview of the stormwater system in the city would be useful when the conditions in the river are studied. A map showing how the stormwater channels are connected would be useful in the future. Maintenance of the stormwater and the stormwater system is also important in order to improve the system as well as the conditions in Segoditshane River.

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9 Appendices

The four appendices contain Hydrocarbon results, Time before BOD and COD analyses, MPN table and Sampling coordinates

9.1 Appendix I – Hydrocarbon results

The complete results from the hydrocarbon analysis performed by a Gas Chromatography Time of Flight Mass Spectrometry, GC TOF MS can be seen in Table 9.1 to Table 9.6. The identified substances corresponded to a standard with 90% similarity. The results only show the presence of the detected compounds and not the concentrations.

Table 9.1. Raw data for Sample 1 from hydrocarbon analysis.

Sample 1
Silicon tetrafluoride
Phthalic anhydride
Diethyl Phthalate
Hexadecen-1-ol, trans-9-
Nonanoic acid
Eicosane
7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione
Phenol, 2,4-bis(1,1-dimethylethyl)-
Nonadecane
Butylated Hydroxytoluene
1,7-di-iso-propylnaphthalene
Hexadecenoic acid, Z-11-
Octadecane
Diisooctyl phthalate
Octadecane, 1-iodo

Table 9.2. Raw data for Sample 2 from hydrocarbon analysis.

Sample 2
1,2-Benzenedicarboxylic acid
7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione
Hexadecen-1-ol, trans-9-
Propane, 1,1'-sulfonylbis-
Benzoic acid
Diethyl Phthalate
Octadecane
Benzothiazole
Pentadecane
Nonadecane
Dibutyl phthalate
Propanoic acid, 2-methyl-, 3-hydroxy-2,4,4-trimethylpentyl ester
Octadecane

Table 9.3. Raw data for Sample 4 from hydrocarbon analysis.

Sample 4
2,4-Dibenzoylpentanedioic acid, dimethyl ester
1,2-Benzenedicarboxylic acid
Diethyl Phthalate
1-Hexadecanol
7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione-
m-Anisic acid, 4-nitrophenyl ester
Benzoic acid, silver(1+) salt
Phenol, 2,4-bis(1,1-dimethylethyl)-
Succinic acid, pentyl propyl ester
Propanoic acid, 2-methyl-, anhydride
Propanoic acid, 2-methyl-, 3-hydroxy-2,4,4-trimethylpentyl ester

Table 9.4. Raw data for Sample 5 from hydrocarbon analysis.

Sample 5
Eicosane, 2-methyl-
Octacosane
Benzothiazole
Propanoic acid, 2-methyl-, anhydride
2-methyloctacosane
Diethyl Phthalate
7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione
Benzoic acid
Heptacosane
Dibutyl phthalate
Acetonitrile
1,2-Benzenedicarboxylic acid
Phenol, 2,4-bis(1,1-dimethylethyl)-
Carbamic acid, N-[1,1-bis(trifluoromethyl)ethyl]-, 4-(1,1,3,3-tetramethylbutyl)phenyl ester
Octadecane

Table 9.5. Raw data for Sample 7 from hydrocarbon analysis.

Sample 7
L-(+)-Threose, aldononitrile, triacetate
Succinic acid, pentyl propyl ester
Acetonitrile
Diethyl Phthalate
1,2-Benzenedicarboxylic acid
11-Hexadecen-1-ol, (Z)-
Dodecanoic acid, 11-amino-, methyl ester
Hexadecen-1-ol, trans-9-
1-Docosene
4-Methylphthalic anhydride
Dibutyl phthalate
1,2,4,5-Tetroxane, 3,3,6,6-tetraphenyl-
7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione
Benzoic acid
Diisooctyl phthalate
1-Hexadecanol
Tetrahydropyran Z-10-dodecenoate

Table 9.6. Raw data for Sample 8 from hydrocarbon analysis

Sample 8
Diethyl Phthalate
1,2-Benzenedicarboxylic acid
7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione
Hexadecen-1-ol, trans-9-
Benzoic acid
Octadecane
Pentadecane
Phenol, 2,4-bis(1,1-dimethylethyl)-
Nonadecane
Propanoic acid, 2-methyl-, anhydride

9.2 Appendix II – Time before BOD and COD analyses

This section presents tables with the number of days the samples were stored before the BOD and COD analyses as well as the TSS and VSS analyses were made.

Table 9.7. Number of days between the sampling date and the date of the BOD analysis.

Sample	Days between sampling and analysis
Segoditshane 1	
1	57
2	1
3	3
Segoditshane 2	
4	57
5	1
6	3
UB campus	
7	5
Motheo Apartments	
8	58

Table 9.8. Number of days between the sampling date and the date of the COD analysis.

Sample	Days between sampling and analysis
Segoditshane 1	
1	64
2	8
3	2
Segoditshane 2	
4	64
5	8
6	2
UB campus	
7	12
Motheo Apartments	
8	65

Table 9.9. Number of days between the sampling date and the date of the TSS and VSS analyses.

Sample	Days between sampling and analysis
Segoditshane 1	
1	42
2	7
Segoditshane 2	
4	42
5	7
UB campus	
7	43
Motheo Apartments	
8	10

9.3 Appendix III – MPN table

This section contains the table for the MPN- Most Probable Number in the microbiology analysis as can be seen in Figure 9.1.

Appendix 1

MPN TABLE:
MPN index and 95% confidence limits for various combinations of positive results when various numbers of tubes are used. (Inocula of 1, 0.1, and 0.01 g)

	3 Tubes per dilution			5 Tubes per dilution		
		95% Confidence limits			95% Confidenc limits	
Combination of positives	MPN index per g	Lower	Upper	MPN index per g	Lower	Upp
0-0-0	<0.3	<0.05	<0.9	<0.2	<0.05	<0.
0-0-1	0.3	<0.05	0.9	0.2	<0.05	0.7
0-1-0	0.3	<0.05	1.3	0.2	<0.05	0.7
0-2-0	—[b]	—	—	0.4	<0.05	1.1
1-0-0	0.4	<0.05	2	0.2	<0.05	0.7
1-0-1	0.7	0.1	2.0	0.4	<0.05	1.1
1-1-0	0.7	0.1	2.3	0.4	<0.05	1.1
1-1-1	1.1	0.3	3.6	0.6	<0.05	1.5
1-2-0	1.1	0.3	3.6	0.6	<0.05	1.5
2-0-0	0.9	0.1	3.6	0.5	<0.05	1.3
2-0-1	1.4	0.3	3.7	0.7	0.1	1.7
2-1-0	1.5	0.3	4.4	0.7	0.1	1.7
2-1-1	2.0	0.7	8.9	0.9	0.2	2.1
2-2-0	2.1	0.4	4.7	0.9	0.2	2.1
2-2-1	2.8	1.0	15	—	—	—
2-3-0	—	—	—	1.2	0.3	2.8
3-0-0	2.3	0.4	12	0.8	0.1	1.9
3-0-1	3.9	0.7	13	1.1	0.2	2.5
3-0-2	6.4	1.5	38	—	—	—
3-1-0	4.3	0.7	21	1.1	0.2	2.5
3-1-1	7.5	1.4	23	1.4	0.4	3.4
3-1-2	12	3	38	—	—	—
3-2-0	9.3	1.5	38	1.4	0.4	3.4
3-2-1	15	3	44	1.7	0.5	4.6
3-2-2	21	3.5	47	—	—	—
3-3-0	24	3.6	130	—	—	—
3-3-1	46	7.1	240	—	—	—
3-3-2	110	15	480	—	—	—
3-3-3	>110	>15	>480	—	—	—

Figure 9.1. MPN-table for microbiology analysis.

9.4 Appendix IV – Sampling coordinates

The coordinates for the sampling sites are presented in Table 9.10.

Table 9.10. Table showing the coordinates for all sample sites.

Sample	Coordinates (WGS84)
Segoditshane 1	
1	-24.637461, 25.921345
2	-24.637461, 25.921345
3	-24.637461, 25.921345
Segoditshane 2	
4	-24.638335, 25.901397
5	-24.638335, 25.901397
6	-24.638335, 25.901397
UB campus	
7	-24.653328, 25.920298
Motheo Apartments	
8	-24.653859, 25.920487

9.5 Appendix V – Microbiology analysis method

The method for the microbiology analysis is presented in Appendix V.

The water collected from Segoditshane River had some colour and smell which indicated that it might contain sewage water. Testing for *Escherichia- coli (E. coli)* bacteria as an indicator of sewage (e.g. fecal contamination) was therefore initiated at department of biological sciences at University of Botswana. The testing for *E. coli* was performed during five days which included several techniques to determine possible *E. coli* presence.

The method for analyzing pathogens is based on the fact that coliform bacteria like *E. coli* are anaerobic, gram-negative, rod-shaped bacteria which ferment lactose with gas fermentation within 48 hours at 35°C.

Day 1

Bottles for sampling were autoclaved and prepared for the sampling in the morning. Diluents were also sterilized using autoclaving. Eosin mehylene blue agar (EMBA) was weighed and prepared for the EMBA plates. The EMBA was boiled and stirred and later autoclaved. The initial purple colour changed to red after the autoclaving. Plate count agar powder was weighed, mixed with distilled water, boiled and autoclaved.

Lactose broth and bromocresol were weighed and mixed with water to prepare for the MPN count. The lactose broth with bromocresol was poured into sample tubes with Durham tubes inside and was set for single and double strength, doubling the amount of bromocresol in the double strength tubes. The Durham tubes containing the broth were then autoclaved for approximately 1.5 hours to sterilize the solutions.

Samples were collected from the river in autoclaved glass bottles and brought directly to the microbiology lab. Samples were taken from site 1 and 2 at Segoditshane River, two samples from each site. For each sample (1A, 1B, 2A, 2B) three double strength sample tubes including small Durham tubes and six single strength sample tubes were assorted.

The samples were diluted to three different dilution rates, 1:10, 1:1000 and 1:100000. The dilution procedure was then repeated for the three remaining samples 1B, 2A and 2B.

From the three different sample dilutions 1 ml was transferred on to duplicate petri dishes. This was repeated for every sample and dilutions. When the plate count agar had cooled down to about 45-50° C after autoclaving, 10-15 ml of plate count agar was poured into every petri dish containing water sample and was gently rotated to mix the agar with the sample.

For each sample and dilution, 1 ml was also transferred into triplicate lactose broth tubes. The 1:10 sample dilution was transferred into the three lactose broth tubes with double strength and the 1:1000 and 1:100000 dilutions were transferred into the single strength tubes. The plates and the tubes were then incubated at 37° C for 24 hours.

Day 2

From the plates the colonies were counted manually. The aerobic mesophilic count was calculated per ml of water using the dilution factors.

The Most Probable Number (MPN) was determined inspecting which tubes were positive. The positive tubes had changed colour from purple to yellow (due to acidification) and produced gas into the small Durham tubes turned upside down inside. From a MPN table in the laboratory manual given at General microbiology at University of Botswana the MPN was then read from the combination of number of positive tubes. The MPN table can be found in Appendix III.

From the most positive tube of lactose broth for each sample a loopful of broth was taken and streaked on an EMBA plate. The EMBA plates were then incubated at 37° C for 24 hours.

Day 3
The EMBA plates were studied for green metallic sheen which is the characteristic for certain gram negative bacteria like *Escherichia coli* on EMBA (Willey *et al.*, 2011).

Some portion of the colony on the plates was transferred into a nutrient agar slant on petri dishes and also in a tube with brilliant green bile broth. This was done for all the four EMBA plates. The brilliant green bile broth was used specifically for indication of growth of coliform bacteria (Willey *et al.*, 2011).

The slants were incubated in 37° C for 24 hours and the lactose broth tubes were incubated at 44.5° C for 24 hours.

Day 4
Two positive plates were chosen for continuous analytical profile index (api 20E) procedure. From the two sample plates gram staining could have been the next step but the api 20E test are seen to be more accurate for deciding the bacteria species and was therefore preferred.

Two api 20E test strips were made for the two chosen agar sample plates. The strips can be seen in. The test is made for investigating what bacteria are present in the sample. Half of the pits in the strip contain enzymes and the other half contains sugars.

A loopful of sample from each plate was mixed into two sample tubes containing 0.85 % physiological saline (NaCl). From each of the two sample tubes sub-samples were then transferred into the enzyme- and sugar pits. Mineral oil was added in the pits labeled AH, LDC, ODC, H2S and URE to create an anaerobic environment. The test strips were incubated in 37° C in 24 h.

Day 5
After incubating in 24 h the reagents were added into the api 20E pits named IDA, IND, VP1 and VP2. The test strips were set to leave 10-15 min. The colour change was then compared to the reading table in the api 20E manual. A combination of numbers was given for each strip. The combination of numbers was then read in the BioMérieux catalogue for api 20 E identification system containing catalogued bacteria species.

9.6 Appendix VI – Populärvetenskaplig sammanfattning

Återanvändning av regnvatten för att förbättra Gaborones vattensituation

Gaborone, liksom större delen av södra Botswana, lider av extrem vattenbrist. Torka och uteblivna regnperioder har gjort att vatten nu måste transporteras långa sträckor för att täcka stadens behov. Den ansträngda vattensituationen talar för att använda alternativa vattenkällor, däribland återanvändning av regnvatten.

Den största delen av regnvattnet i Gaborone rinner ut i Segoditshane, ett vattendraget som rinner genom staden. Vattnet i Segoditshane innehåller höga koncentrationer av vissa tungmetaller, främst kadmium och bly, men också andra metaller som aluminium och arsenik. Det förekommer även kolväten med troligt ursprung från stadens trafik. Mikrobiologiska analyser tyder på att utsläpp av avloppsvatten kan förekomma längs Segoditshane.

Regnvattnet i Gaborone kan samlas upp på olika sätt. Ett sätt är att samla upp regnvatten från hustak i regnvattentankar. Ett annat sätt är att låta regnvattnet från staden rinna ut i Segoditshane och nedströms vattendraget samla upp det i en damm. De olika alternativen har olika för- och nackdelar. Vatten från hustak som samlas upp i regnvattentankar är troligtvis renare än det som runnit en längre sträcka på marken och samlats upp i Segoditshane. Däremot kan det vara lättare att kontrollera kvaliteten på vattnet om det endast samlas upp på ett ställe. En damm kan även förbättra vattenkvaliteten genom sedimentering av partiklar.

Det uppsamlade vattnet kan ha olika användningsområden. Det kan till exempel användas som dricksvatten eller till bevattning av grödor. Beroende på användningsområden för det uppsamlade vattnet, behövs olika typer av rening. Biologisk rening är en reningsmetod där metaller och kolväten tas upp av mikroorganismer och växter. Metoden kan användas längs Segoditshane för att förbättra vattenkvaliteten.

Om allt vatten som faller på hustak i Gaborone under ett år skulle samlas upp, skulle det motsvara högst en tiondel av allt vatten som årligen används i Gaborone. I ett torrt klimat med oregelbundet regn är det bra att ta vara på allt vatten som finns. Varje droppe räknas!

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