ASSESSING THE USE OF EXFILTRATION PERVIOUS PAVEMENTS AS A BEST MANAGEMENT PRACTICE FOR STORMWATER MANAGEMENT FOR LUSAKA URBAN

By
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A dissertation submitted to the University of Zambia in partial fulfillment of the requirements for the award of the degree of Master of Science in integrated water resources management.

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DECLARATION

I, Naphtallie Banda solemnly declare that the dissertation is my own work and that it has never been previously submitted for a degree at this University or other higher institution of learning.

Signed:……………………………..

Date:………………………………...

CERTIFICATE OF APPROVAL

This dissertation by Naphtallie Banda has been approved as fulfilling the requirements for the award of the Degree of Master of Science in Integrated Water Resource Management by the University of Zambia.

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ABSTRACT

Stormwater management is being justified as a fundamental line of consideration in achieving sustainable urban development. Lusaka urban experiences impacts ensuing from developments in form of urban floods. This study was undertaken in Lusaka urban to assess the use of a full exfiltration pervious pavement system as a best management practice for stormwater management. Based on the ICPI guidelines, the study involved a feasibility assessment to select areas supporting full exfiltration pervious pavements, construction of pervious pavements (PICP) in 3 sites, conducting infiltration tests on the constructed pavement systems and monitoring of water infiltrating below the pavement systems succeeding storm events for the study period. A t-test was used to compare significant differences and regression analysis was used for determining relationships.

Key observations are that the central eastern part of the study area has soil physical characteristics supporting full exfiltration pavement systems under which the sites were selected. Infiltration rates on the installed pavement systems with 5mm spacers ranged from 774cm/hr. to 823cm/hr. The average depth of water estimated to have been contributed to the immediate unsaturated zone below the pavement systems through infiltration during each observed rainfall events ranged from 140mm to 211.4mm in 1100mm depth of soil. The study concluded that full exfiltration pervious pavement systems as a best management practice can be integrated with drainage networks for Lusaka urban to reduce floods ensuing from developments. The system will mimic natural environments which allow infiltration of stormwater to potentially contribute to groundwater.

Key words: Stormwater, Best management practices, Pervious pavement, Exfiltration

DEDICATION

I dedicate this work to my family. It was never intended to slip out nor lose out on many moments unshared as energies were devoted to this work. My time spent undertaking the study was occupied with your interest at heart.

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LIST OF ACRONYMS

ASTM	American Society for Testing Material
BMP	Best Management Practice
CGP	Concrete Grid Pavers
EPA	Environmental Protection Agency
HDPE	High Density Polyethylene
ICPI	Interlocking Concrete Pavement Institute
LCC	Lusaka City Council
LULC	Land Use Land Cover
LWSC	Lusaka Water and Sewerage Company
MASL	Meters above Sea Level
MLGH	Ministry Local Government and Housing
N	Nitrogen
P	Phosphorous
PICP	Pervious Interlocking Concrete Pavers
ZMD	Zambia Meteorological Department

CHAPTER ONE: INTRODUCTION

This chapter presents the background of the study, statement of the problem, purpose of study, general objective, specific objectives, research questions, the significance of the study, organization of dissertation and description of the study area.

1.1 Background

1.1.1 Urban Landscape

The wake of urbanization is a notable feature attributed to in African cities that have significantly developed with a rise in services provisions. In some cases, this development has marginally been influenced by the state regarding the role it plays in developing a city (Wragg and Lim, 2014). Lusaka is one of the most developing cities in the Sub-Sahara. Urban environments present more impervious surfaces which in turn heighten landscape change altering natural environments. Many developments are undertaken to provide settlements, commercial structures and industries. Impervious surfaces release entirely all the rainfall which falls on them as runoff. These surfaces include rooftops, driveways, sidewalks, streets, parking lots and facilities not designed to be pervious. Unsustainable use of impervious surfaces in any urban development create continuous impervious surfaces. Continuous surfaces alter the natural landscape thereby having an influence on the transfers, storage and output of water in the hydrologic processes (EPA, 2010). A scenario is forced in which urban areas have hydrologic characteristics different from the natural pattern. The response to this alteration is reduced replenishment of the water table, increased volumes of poor quality storm water runoff with peak rates creating floods in urban areas (MLID, 2004). This phenomenon is escalated by unsustainable methods of urban development which are liable to affecting the condition of the environment (Bean et al., 2004b).

1.1.2 Lusaka Urban Landscape

Lusaka urban agriculture and open land has changed to mostly impervious because of structures being built in many areas owing to its generally flat relief thus creating an urban environment (UN Habitat 2007). The city has been categorized to have the highest country's urban population increase of up to 32% in 10 years (Census, 2010). Lusaka urban has always been at risk from large volumes of storm water that end up as urban floods and are directly related to urban landscape change (World Bank, 2002).

1.1.3 Stormwater Scenarios and Lusaka Urban Landscape Change

Stormwater challenges have flourished especially in developing cities. As the urban grows and impervious surfaces continue to increase exponentially, municipalities have not fully expanded. They have continued to depend on the same aging and undersized stormwater systems though rehabilitations may take place, overhauling the whole system is a long term undertaking beyond reach. Stormwater runoff can transport pollutants as much as 90% found on the impervious surfaces in form of oil and hydro-carbons directly into the water systems by the first half inches of the rains (EPA, 2010). Hence, storm water management is essential and requires sound land use planning and management by urban planners (Parkinson and Mark, 2005). The management of rainfall and the expected storm water flows is paramount for healthy cities (UN Habitat, 1991). The physical planning unit under the Ministry of Local Government and Housing (MLGH) is in charge of authorizing building plans in Lusaka urban. The unit has the mandated to provide standards to the general public regarding structural designs, urban developmental aspects in achieving urban aesthetics and models of development. The authority requires that all designs for structures show drainage networks meant for stormwater management. This is the highly emphasized storm water management strategy for the urban. This system allows water from impervious surface to be directed into drainages leading to streams and receiving waters. It has a single function of draining all the storm water with reduced retention and evapotranspiration functions of the soil and vegetation (NRC, 2008). Further, the capacity of the drainage networks is compromised in a situation where the municipality has a poorly managed solid waste management system. Lusaka municipal council is currently under equipped to efficiently manage solid waste amidst a growing population generating quantities of waste increasingly. Poor stormwater management has continued to contribute to poor sanitation problems in Lusaka urban (ADBG, 2015).

As urban landscapes transform, it is important to prioritise environmentally sensitive stormwater management strategies to deal with the changing urban hydrologic characteristics by using Best Management Practices (BMPs) (Caltrans, 2014). This is paramount especially in a water sensitive urban such as Lusaka which has about 60% of its water source as ground water (130,000m^3/day) (MCC, 2011). An imbalance between the rates of withdrawal of groundwater to recharge can be easily created by this situation (NPDES, 2012). As a BMP for storm water management, permeable surfaces can be used in most structural surfaces alongside drainage networks compared to using a single functional stormwater system alongside conventional impermeable surfaces. Permeable surfaces are in various forms, all for the purpose of infiltrating and temporally storing of stormwater whilst serving as structural surfaces. These include pervious asphalt, concrete and pavers. Other BMP's involve the use of dry wells, vegetated swales, detention basins, sand or oil interceptors, catch basins, large scale control gullies and water harvesting for non-portable uses.

1.2 Problem Statement

Lusaka urban has always been at risk from large volumes of storm water which end up as urban floods and are directly related to urban landscape change which has increased impervious surfaces (World Bank, 2002., Simwanda, 2015). Increased impervious surfaces reduce ground water contribution and increase surface runoff (Phiri and Nyirenda, 2015). The storm water management strategy being employed by the local authority over-relies on drainage networks (UN Habitat, 2007). Some parts of the urban lack drainages and this contributes to urban flooding (LSP, 2015). Drainage system's capacity has been easily compromised with expanding impervious surfaces and has a single function of draining out all the stormwater with reduced replenishment of water through infiltration to replace the abstracted ground water. Rainwater harvesting measures have not been taken to be very important in Lusaka urban which is supposed to be the case of relevance (Gronwall et al., 2010). Regulations have not been enforced to limit as to how much area should remain pervious in the face of outsized construction of impervious surfaces by developers. The local authority has not promoted the use of pervious pavements as the urban landscape is changing (Phiri and Nyirenda, 2015).

Sustainable urban developments should mimic natural systems to reduce their possible impacts. This existing scenario entails large scale pavement retrofitting projects in future which will be a must and costly venture.

1.3 Purpose of Study

The study intends to find out the possibilities of integrating BMP's by using pervious pavements alongside drainage networks as a stormwater management strategy for Lusaka urban. This is to promote developments that allow re-introduction of water into the environment. The local authority has hugely depended on one stormwater strategy and been reluctant about integrating BMPs even as the urban is expanding. Despite widespread consensus regarding the need to construct sewers, the city has been reluctant to shoulder investment costs, which may be difficult to recover (ZESMF, 2015)

Urban development has created negative impacts though expected to perform nearly as the natural environment. When a municipality does not use BMP's and remain using traditional methods, all stormwater problems and costs end up being shouldered by the developers, business houses and residents because they will have to manage floods generated at their facility as well as other streets and communities (EPA, 2010). Pervious pavements can temporarily store, infiltrate and control runoff peak rates of stormwater to reduce impacts of urban development (PSBMPM, 2006). Further, the system can reduce the energy of stormwater to transport solid waste found on the surface of the structure to the drainage network. This does increase the performance of the drainage networks and reduces loads of solid waste transported to the receiving waters. The impervious pavements can easily be retrofitted with pervious pavements and give an opportunity to reduce drainage items. Their use in retrofitting would not require resettling of people and are socially acceptable. They can promote sustainable urban development which is cardinal to watershed health and sustainability of ecological functions (USRMS, 2007).

1.4 Objectives

1.4.1 General Objective

To assess the use of full exfiltration pervious pavements as a best management practice for stormwater management for Lusaka urban

1.4.1.1 Specific Objectives

- To determine the infiltration rate of the pervious pavements (PICP) on the 3 sites of Lusaka urban.
- To estimate contribution of water to the immediate zone when pervious pavements are employed on the 3 sites of Lusaka urban.
- To determine the storm water-pervious pavers relationship for Lusaka urban

1.4.1.2 Research Questions

- What is the infiltration rate of the pervious pavement system in the 3 sites?
- What is the estimated contribution of water to the immediate zone when the pervious pavement is used on Lusaka urban landscape on the 3 sites?
- What is the stormwater-pervious pavement relationship for Lusaka urban landscape?

1.5 Significance of the Study

The study promotes environmental governance in urban planning through stepping up regulations for active participation in water resource and environmental management. The priority of the municipality will be to ensure that all developments mimic natural environments by ensuring that the construction of impervious pavements is controlled as well as integrating BMP's in the stormwater management strategies. This will reduce urban floods, reduce transport of waste to drainages and receiving waters. Substantial amounts of stormwater will be retained to the environment to support ecological processes and to add to ground water. By enhancing monitoring, the developers will be adopting environmentally sensitive strategies and coming up with stormwater management plans for their developments which should fit or not work against the municipality's strategy. When pervious pavements are integrated with the drainage networks, impacts resulting from alterations of hydrological characteristics in the urban will be reduced, promoting sustainable urban development and healthy cities. The study adds to information on disaster risk reduction for disasters that can occur by not regulating the use of impervious pavers in new developments.

1.6 Organization of Study

The dissertation is organized in seven chapters. Chapter one presents the background of the study, Chapter two presents the literature review, Chapter three describes the characteristics of the study area, Chapter four provides the methodology used in the study, Chapter five gives the findings of the study, Chapter six gives the discussion and Chapter seven gives the recommendations and conclusion.

1.7 Conclusion

The chapter presented the background of the study, statement of the problem, purpose of study, general objective, specific objectives, research questions, the significance of the study and organization of the study.

CHAPTER TWO: LITERATURE REVIEW

This chapter presents the reviewed literature on best management practices, stormwater management, and the role of local authority in stormwater management, landuse land-cover change for Lusaka urban, water governance, groundwater development, groundwater recharge, and vulnerability of the Lusaka aquifer, waste management and soil depth above basement.

2.1 Best Management Practices

Best management practices (BMPs) in stormwater management are activities, facilities, measures, or procedures that are used to manage volume, rate and water quality of storm water runoff (USRMS, 2007). Municipalities identify and require best management practices for regulation, planning and water quality control. These technologies and various land management practices are used in combination at development sites to attain maximum benefits to the stormwater management drainage system. BMP's are divided into structural and nonstructural practices. Structural BMP's capture runoff and use gravitational settling of pollutants through a porous medium for pollution reduction and infiltration of water. These structures include dry detentions ponds, wet (retention) ponds, infiltration trenches and pervious and porous pavements. The structural BMP's work along with nonstructural BMP's which include efficient site planning by authorities with public awareness to stop non-point water pollution to use natural techniques such as stormwater wetlands, bio-retention wetland which promotes pollutant removal as well as infiltration of water (Smith, 2006)

The authorities assess BMP's to be employed on individual basis in their cities by considering various factors existing on the site that can support their use. Each BMP should be able to reduce impact of developments through runoff reduction, pollutants reduction, sediments reduction, peak flow detention, and recharge ground water (Bean et al, 2004).

2.2 Stormwater Management

The stormwater management strategy employed in Lusaka urban in mainly comprised of drainage networks. The drainage networks drain out stormwater to receiving streams and rivers. The main drains in the study area are Bombay drainage system covering an area of about 35.85km^2. It consists of the two drainage subsystems that join towards the north-end of the system namely the Bombay drainage basin and Lumumba drainage basin. The whole system has a total of 166 sub-catchments defined by tertiary drainage networks discharging into primary or secondary drainage systems to control stormwater discharge through the City Centre and drains into the Ngwerere stream (MCC, 2013). The drainage system's capacity has been compromised due to the undersized drains, blockage by solid waste, siltation from lack of maintenance, and low velocities in unlined drainages. The impervious area for Lusaka urban has increased. Increased impervious surface areas are a primary source of stormwater runoff (MLID, 2004). The urban is consequently experiencing impacts potentially due to developments that are increasing impervious surfaces. The storm water management strategy currently being employed in Lusaka urban over-relies on drainage networks and experiences floods in most parts of the city (UN Habitat, 2007). In line with this scenario, Lusaka urban has always experienced large volumes of storm water that ends up as urban floods. (World Bank, 2002). Over-reliance on drain lines with increased impervious surfaces affects hydrologic processes by reducing the replenishment through infiltration of the abstracted ground water, induces high peak rates of urban floods and pollution of receiving streams. Over a long period of time this affects ecological processes and ground water resources (MLID, 2004).

The aggregate reservoir stone base for the pervious pavement offers infiltration and partial treatment of stormwater pollution. The infiltration of rainfall assists in maintaining the water balance in soil, streams, and groundwater which are the main stages of the water cycle. In highly polluted stormwater, the system can be connected to a treating pond for final treatment. These pavements are also cost effective in new development where local regulation limit total amount of impervious cover. They can also be cost effective in already established urban areas expanding parking lots but don't have ponds for detaining stormwater (Smith, 2006).

Urban agriculture in Lusaka has waned over the years because land for agriculture is now being given away to residential development (LCC&ECZ, 2009). Environmental protection is employed in remedying impact from development, but more than that should be in relation to yielding more benefits from the natural environment (Smith, 2006). Lusaka is experiencing problems related to urban development in the aspect of unplanned urbanization and inadequate waste management. Governance in this respect has become handicapped with less resource mobilization in record keeping of landuse and master planning. (UN Habitat, 2007). An increase in intensity of urban development in short space of time comes along with it various problems especially with less technical and social structures initiating degrading of urban and sub-urban watershed by storm-water runoff through a variety of mechanisms including frequent channel-eroding flows and nonpoint pollutants originating in wash-off from developed impervious surfaces (McGarity, 2010). The intentions of responsible authorities should be toward maintaining natural drainage and treatment systems or by limiting flows to the drainage system especially if they are working near capacity (Smith, 2006).

2.2.1 Types of Pervious Pavements

Table 1: Properties of different pervious pavements

Properties	**Pervious Concrete**	**Porous Asphalt**	**Permeable Interlocking Concrete Pavers (PICP)**
Full Exfiltration	Infiltrates water into soil subgrade and to a drain (High permeability soil).	Infiltrates water into soil subgrade and to a drain (High permeability soil).	Infiltrates water into soil subgrade (High permeability soil).
Partial Exfiltration	N/A	N/A	Infiltrates part of water into soil subgrade and to a drain (Average permeable soils)
No Exfiltration	N/A	N/A	Directs all the water into underdrain (Very low permeable soil)
Design	Warm-mix asphalt underlain by a choke stone and aggregate base/subbase reservoir	Hydraulic cementing binding system combined with aggregates.	Concrete units that form permeable joints when assembled.

Void Space	Void space 18% to 25%	Void space 15% to 25%	Open paver surface area of 5 to 15%.
Controls	Reduce runoff slowly into drains, longevity, Cooler asphalt temperatures, Reduced demands on other stormwater facilities	Reduce runoff slowly into drains, Reduced demands on other stormwater facilities	Reduce volume by trapping and slowly releasing precipitation into the ground instead of drains, reduce need for other required size of BMPs' Saves money and Effort
Pavement requirement	Design pavers	Design pavers	Use local industry / Designed pavers
Surface Cleaning	Periodic vacuuming. If completely clogged Periodic vacuuming		

(Bruinsma et al., 2017)

2.2.1.1 **Illustration of Pervious Pavements**

Figure 1: Types of pervious pavement systems. (Selbig and Buer, 2018).

2.2.2 Role of Local Authority in Stormwater Management

LCC serves as the planning authority for the urban. Under the legislative framework, through the town and country planning act, they provide effective planning and control of developments in Lusaka. This is through the statutory provincial planning authorities who are serviced by the department of physical planning and housing. The public health Act CAP 291 helps the enforcement of building regulations.

Governance of issues in any city have lapses if there is a weak local government. This is exhibited through inadequate delivery due to poor resources utilization and mobilization. Performance on the part of LCC has been difficult due to resources and thus cannot regulate developments effectively. The authorities who are supposed to be at the helm of development do not have adequate capacity to initiate the attempting of urban environmental problems. They also lack coordination with other authorities like ZEMA to effectively manage the urban environment. Further, central government does not avail resources for environmental management other than donor aid. These resources would help LCC to promote sound environmental management in aspects such as stormwater management (UN Habitat, 2007).

In cities, municipal stormwater management objectives should be intended in preserving natural drainage and treatment systems, and limit flows to the drainage systems more especially when they usually work at near capacity. Modeling of stormwater using simple methods such as Rational Method, NRCS TR-55, as well as sophisticated models such as HEC and EPA SWMM can give results that can inform drainage design guidelines for specific site development proposals brought to municipalities for approval. As such, when the municipalities make site designs, they will incorporate some design goals such as reducing the generation of additional storm water, capture and treat a specific water quality volume, treat runoff to remove a percent of a pollutant, enhance stream channel protection, and maintain groundwater recharge rates. The use of pervious pavers in stormwater management gives a performance yielding to reach such design goals set by the authorities (Smith, 2006)

Urban health problems have been seen as key for developing healthy cities. It is not a matter of one region, rather a network of regions can share strategies, and formulate policies (UN Habitat, 2011).

2.3 Land Use Land Cover Change for Lusaka Urban

Much of the city's area which was woodland or grassland has been converted to urban notably at a rapid scale. Urban development has mainly been through constructions of upcoming business structures, industrial plants, planned and unplanned or informal residential settlements. Built up area has shown an increase of over three times from 13% to 42.2% over the 20 year period of 1990 to 2010. The landscape has become continuously connected due to built-up areas that have increased. The developments were observed to be more connected due to increased built up areas. Such development is not sustainable and needs intervention to show dispersion as more structures are being built. The more connected the developments are, the more impervious land cover is created reducing the open area that infiltrates stormwater (Simwanda, 2015).

As urban areas expand, the drainage system become overloaded with polluted water and urban floods. The common solution by municipalities has been to upgrade or redesign the systems. This does not add to the solution as it never works on the causes. Solutions should be aimed at reducing stormwater runoff. This can be through water retention, detention and infiltration before leading to the drainage system. This is meant to maintain a balance in the hydrological cycle after developments. The use of pervious pavements is effective in reducing stormwater quantities in urban areas. The design should guarantee necessary infiltration of stormwater and mechanical strength (Marchioni and Becciu, 2015).

Lusaka urban growth has increased from 4% to 35% in spatial coverage by 2014 from the year 1986. More land has been converted from cropland to building increasing the impervious surface with the western side of the urban being prominent due to uprising industries and settlements for the working class who prefer to be in locations near their work places. The extent of infrastructure development has created impervious surfaces which reduce the infiltration of water important for ecological processes and biogeochemical cycles. This also has increased volumes, duration and intensity of surface runoff. (Phiri and Nyirenda, 2015).

Lusaka City has undergone rapid urban expansion amongst other cities in the Sub-Sahara Africa. Even though this is a present day case, the city's original plan was not intended for expansion to capital status. The initial area was 2.6km^2 and increased to 18km^2 in 1931. In 1961 to present, the urban has increased to 375km^2. A first formal urban master plan was completed in 1975 and reviewed in 1999. In 2000, an integrated development plan (IDP) to provide a framework to guide urban development in Lusaka up to 2020 was never approved, with only parts of it adopted, developments in the urban of over 60% have been done under informal land delivery. The impact of this system of development promotes constructions in stormwater buffer zones without any mitigation steps to compensate the altered environment. This has greatly reduced ecosystem diversity and many of the areas being prone to flooding in the rainy season (Gulf Ingenieure, 2013).

Efforts have been made to make Lusaka urban achieve more formal developments. A comprehensive development plan was commissioned in 2009 under JICA which included sub-programs for water supply and sewerage, transport, and environmental improvement for the year 2030 (JICA, 2009).

Landuse change is the most unescapable socioeconomic force driving changes and degradation of ecosystems. Urban development is one of the activities that has hugely changed landscapes. Such change has an impact on important ecosystem processes and services which can have a range of consequences from short term to long term. The changing landscape and their effects are influenced by government policies. Urban sprawl along with other human activities have substantially altered and fragmented the landscape and this affects local and regional climate by changing the energy balance on the surface. Further, soil degradation associated with construction reduces the quality of land resources (UN Water, 2013).

2.4 Water Governance

Water management in Zambia has undergone reforms that have led to new institutional framework which is shaped according to several principles to govern water resources.

The key principle in these reforms include separation of water resources management from water supply and sanitation. Water resource management is under the Department of Water Resources Development and Water Supply and Sanitation is under the Local Authority. This is in effect meant to make water supply and sanitation functions brought closer to the customers through the separation of policy making and service provision. The local authority jurisdiction has been in peri-urban areas and most of these are in the outskirts of the municipality and cities. Most of the peri-urban areas are characterized by a high number of unplanned structures, non-existence of basic services such as water supply, stormwater drainage, sewerage and solid waste disposal. Most of these unplanned areas have been established in reserved service lanes. This has made it difficult for service providers although commercialization in water supply has brought about upgrade of system to satisfy levels at various stages. Lusaka has 33-peri urban areas which account for 60% of the City's population (Nwasco, 2016).

In Zambia, the water sector has recognized that water resource management and development should be multi-sector, coordinated among various sectors as environment, industry and housing. In this regards, the sector has set up water sector advisory groups. Following water sector advisory groups formulation, the sector has been undergoing reforms guided by the nation water policy of 2000 which is a revision of the 1994 policy. The guiding principle being integrated water resource management. The governance systems for the development, management and use of water resources is still under developed. Some of the pressures on water include poor resource management, regulation and enforcement of legislation mechanisms, lack of an integrated approach to water resource management and lack of regulation to protect groundwater. Government investments in water related issues represent less than one percent of total government expenditure and are allocated principally to water supply and sanitation and river development. There is always insufficient funds to enforce legislation (UN Water, 2013).

The local authority having the mandate to plan can recommend for adoption of integrated development plans, local area plans and any other prepared by the local authority. The authority is responsible to monitor the implementation and enforcement of the integrated development plans in accordance with the planning act. The planning authority may amend or update integrated development plans for the purpose of protecting areas of ecological significance or mitigate effects of natural disasters or for the upgrading of settlements. The integrated plan shall serve as a basis on which the local authority's capital and operational budgets shall be drawn up and approved (Parliament of Zambia, Act No.3 of 2015).

2.5 Groundwater Development

The City has originally depended on groundwater from the Lusaka dolomite south of the city as a source of water supply. From 1950s when the city was given capital status, the aquifer has been explored and exploited. Private drilling activities date from the 1950s on private residential plots, smallholdings and industrial sites. In this period, substantial groundwater abstraction level of 43,000m^3/day was obtaining on boreholes constructed on the Lusaka dolomite. Boreholes were characterized by high yields, low drawdown, main intersection depth to the water ranging from 15m to 39m and an average depth of 53m. The aquifer has exhibited characteristics of being responsive to over abstraction.

A presence of faults, fractures, channels and over abstraction can affect the aquifers in terms of depletion and migration of pollutants. Groundwater development in the area has in most cases not been explorative but rather by demand. As such, groundwater development has usually just consisted of geophysical investigations based on geological structures and maps (Mpamba. 2008).

2.5.1 Groundwater Recharge

Recharge of groundwater by rainfall vary widely from 8% to 35% of the annual rainfall for the Lusaka plateau. The amount of withdraw is not to exceed the annual rainfall of 822mm for the area. The effective surface area for recharge for Lusaka plateau yields $45.44 \times 10^6 m^3 year^{-1}$ in relation to the annual rainfall amounts received in the area. Estimation of groundwater abstraction and aquifer storage for the area for 1879 boreholes of $50.265 \times 10^6 m^3$ $year^{-1}$ to $65.385 \times 10^6 m^3$ $year^{-1}$ is more than the estimated rainfall recharge for the area. The value might not include groundwater abstraction from boreholes privately drilled and are not on the records of the responsible authorities. The abstracted quantity might be sustained by groundwater storage (Mpamba, 2008).

Infiltration of urban runoff to recharge groundwater is a sound recommendation for urban environments. After consistent monitoring, there is minimal evidence that infiltration has negative impacts on ground water. In most instances, stormwater dilutes the concentration of contaminants which can build up in the soil and migrate to groundwater. During the process of infiltration following a rainfall event, environmentally harmful contaminants are intercepted and efficiently stopped from reaching groundwater. This stormwater management practice improves surface water quality and increases quantities of water being contributed to recharge groundwater (Dallman and Spongberg, 2012).

Recharge of groundwater in urban areas can occur by contribution of water through leaky pipes which can improve aquifer systems. In such scenarios, abstraction becomes less problematic. It will be less affected by pumping of water from private wells and the public utility. This is also viable when the urban area depends on surface water and supplements with groundwater, but recharge will need to be checked by regular evaluation of developments and rainwater harvesting. In rapidly rising urban areas, temporary over exploitation of aquifers does promote economic activities for the dwellers in a short run, but to sustain such strategies, there is a need for development legislation and control based on understanding groundwater systems applied even at individual levels (Gronwall et al., 2010).

2.5.2 Vulnerability of the Lusaka Aquifer

Lusaka city is built on the main aquifer held by marbles described as the Lusaka dolomite. The Lusaka dolomite is said to have a high groundwater potential, though it is evident that high and low yielding boreholes do exist on the Cheta formation as well. This suggests uniform fracturing in all aquifers and karstification of carbonates on Lusaka plateau (Mpamba, 2008).

A vulnerability map for Lusaka City planning confirms the aquifer being shallow but productive with karst features. This characteristic exposes it to contamination from activities being undertaken on the surface due to insufficient protective layer and a shallow groundwater table.

Concentrations of nitrates as well as other anthropogenic inputs to groundwater are largely unknown but likely to be greatest in the urban and agricultural areas. Transport of these pollutants in the aquifers is potentially greatest via fractures in the crystalline bedrocks and karstic limestone formations. Groundwater is also potentially vulnerable to pollution in these areas, particularly where water tables are shallow (Norrgren et al., 2000).

Poor management of solid waste and storm water drainage, and the generally flat terrain further compound the problem of contaminating groundwater in sites which have been illegally become waste disposal sites within communities of Lusaka. Despite widespread consensus regarding the need to construct sewers, the city has been reluctant to shoulder investment costs, which may be difficult to recover (ZESMF, 2015).

Soil moisture storage has a physically important role in the hydrological cycle, and it has a vital influence on the amount of rainfall which becomes runoff and groundwater recharge. Limited data suggest that Zambian groundwater has generally very low concentrations of dissolved constituents (total dissolved solids concentrations typically less than 200 mg/l; MacDonald and Partners, 1990). Given the geology of the region, the principal groundwater-quality problems are likely to be pollution problems associated with metal mining (BGS, 2001).

Water infiltrating through permeable pavements is likely to cause a rise in NO_3-N and a fall in TKN due to the effect of oxidation occurring within the pavement subbase with little change in phosphorous concentrations. Pavements also exhibit lowest concentrations of heavy metal, oils, grease and bacteria likely due to adsorption of filtering by the open graded aggregates. As such, they demonstrate lower total pollution loadings (James and Shahin, 1998).

The metasediments which dominate in the central part and underlay the Lusaka, are composed, from bottom to top of Matero Quartzite, Ridgeway Schist and Lusaka Dolomite. These are grouped in the Lusaka Formation, prevalently composed of dolomitic marbles. From a structural point of view many fracture joints, shears and thrust faults occur especially on the schist-dolomite contact, representing highly permeable areas in which surface water easily reaches the water table. Locally upon these ancient rocks alluvial sediments have been deposited. Furthermore all these rocks are covered with a more or less thick cover of soils, mainly composed of iron-oxide oliths in a clayey matrix on dolomitic lithologies and sandy sediments on schists, gneisses and granites (Waele and Follesa, 2003).

2.5.3 Waste Management

Lusaka's population produces about 1,100,000 kg/day of waste material for a yearly production of 400,000 tons. Unplanned townships lack the primary services which include waste management. Liquid waste is not collected and are dumped in open channels or left in pit latrines without any waterproofing. The same can be told for solid urban waste which is dumped in a haphazard way in the open spaces between the houses or is sometimes locally collected and brought in illegal waste dumps. (Waele and Follesa, 2003)

Lusaka has a crisis of sanitation which in-turn has claimed many lives during outbreaks of communicable diseases such as cholera, dysentery, typhoid. This has also compromised the environmental soundness of the urban. About 90 percent of the resident living in the peri-urban rely on unimproved pit latrines and 10% to 15 % use sewers and septic tanks. This possess a threat of contaminating ground water which has been the case with residents who depend on shallow wells as a source of water for household use. The contamination is through fissures in the underlying rock (ADB, 2015)

2.5.4 Water Table

Information on the seasonal groundwater fluctuations and effects of abstraction for the study area is managed using monthly recording of levels in production and open wells. This information is not prioritized for contribution to resource assessment. Most information is mainly used for statistics and not for spatial analysis (Mpamba, 2008). The karst terrain that exists on Lusaka urban makes the groundwater levels to be very shallow. The terrain has underground channels or conduits which can allow pollutants without filtration. This is common in low income settlements of Lusaka urban. Most of these parts are prone to experiencing contamination of water especially in wet season with oral-feacal transmission making it risky for consumption. This compromises water quality in the urban with very sub-standard sanitation and hygiene practices in most of these parts. To reduce groundwater contamination, there is need to define groundwater protection areas and zone them while implementing good practices in those very areas (Gronwall et al., 2010).

2.6 Soil Depth above Basement

Surface drainage is almost exclusively present on the crystalline lithologies or schists, while on the dolomitic marbles water tends to disappear randomly underground along fractured zones habitually close to the contact. Surface karst on the dolomitic marble is hidden by a layer of laterite soil which can attain a thickness of a couple of meters. These laterites are extensively exploited by local people. In the places where this cover has been excavated, a well karstified surface is exposed. Extensive rounded Karren fields, sculpted on the boundary between laterite and carbonatic rock are clearly visible and go down up to 4 to5 meters from the surface. In the absence of the filtering laterite cover these exposed rounded Karren fields constitute places in which surface drainage water easily infiltrates and reaches the subterranean aquifer. Some deep drill holes have demonstrated that the dolomitic marbles of the Lusaka Formation are fractured and karstified up to a depth of at least 100 m, constituting the most important aquifer of central Zambia (Nyambe and Maseka, 2000).

2.7 Conclusion

This chapter has given the literature which was reviewed on best management practices, stormwater management, and role of local authority in stormwater management, landuse land cover change for Lusaka urban, water governance, groundwater development, groundwater recharge, and vulnerability of the Lusaka aquifer, waste management and soil depth above basement.

CHAPTER THREE: DESCRIPTION OF THE STUDY AREA

The chapter presents the location of the study area, climate, topography, geology, soils, and drainage.

3.1 Location

Lusaka is located in the south central of Zambia at 15° 25’ S and 28° 17’ E. on the Central African Plateau. The elevation of the plateau ranges between 1200m and 1300m above sea level (See Figure 2).

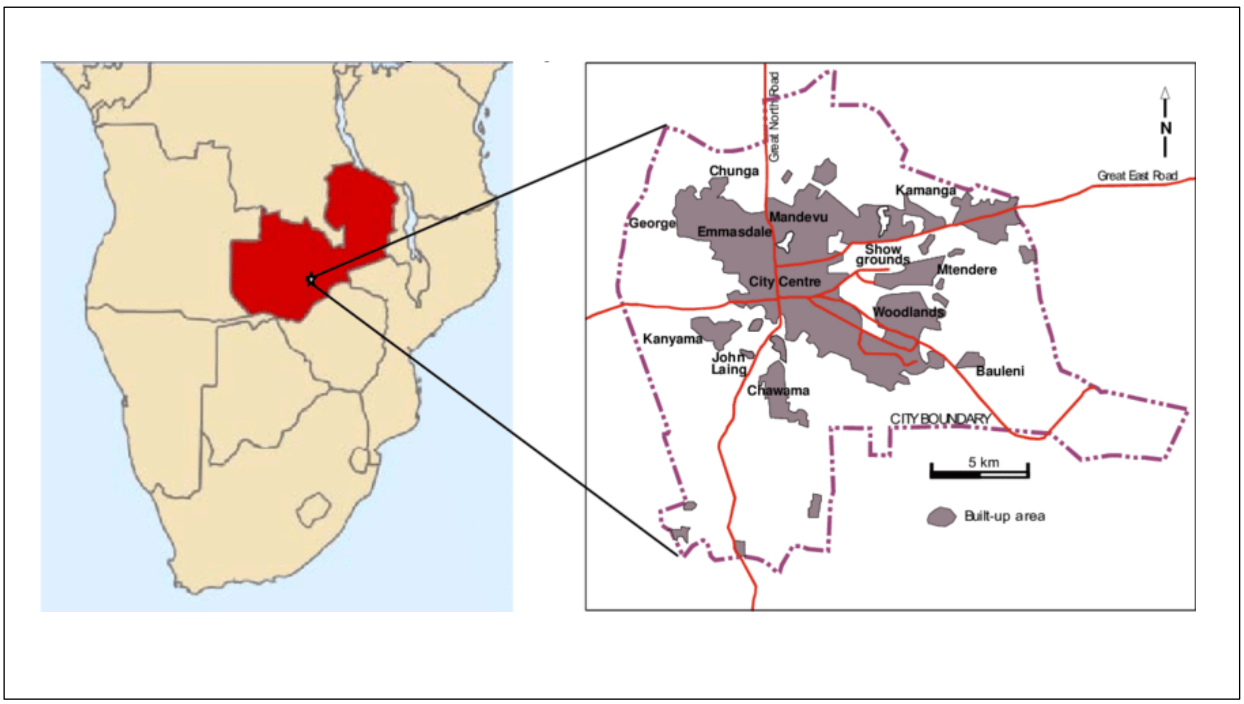

Figure 2: Map of Lusaka built-up area constituting the urban [Source: Gronwall et al., 2010]

3.2 Climate

The urban lies in ecological zone II of the 3 zones that characterize the country's rainfall pattern. The climate of Lusaka has four seasons, namely winter beginning from June to August, summer from September to October, rainy season from November to March and post rainy season from April to May. The annual rainfall received in this zone ranges from 800mm to 1000mm. Most of the rainfall annually is concentrated in the rainy season from November to March. The remainder falls in October and April. The 30 year average annual rainfall for Lusaka is 820mm. Rainfall is usually in intense storms with thunder and lightning. Heavier rain thunder storms are mostly restricted in areal extent and duration traveling on easterly winds. The lowest and highest temperatures vary between 8.4^{O}C and 31.0^{O}C and are recorded in July and October respectively. Day light hours are shortest in June and the longest day light hours are in December. The average evapotranspiration for the area ranges from 500-750mm. The average annual wind speed is 1.8m/s (ZMD).

3.3 Topography

The area is overlain by topped hills in the northern part characterized as quartzite horizons. Flat formations are characterized by dolomite and limestone while schist and quartzites dominate the mostly broken hilly part. Older quartzites form extensive ridges several hundred feet high. Schist and dolomite boundaries are indicated by steep downward slopes from schist to dolomite. The area exhibits a flat terrain as it is part of the Central African plateau. The general elevation gradient within the plateau is about 0.14 % outwardly.

3.4 Geology

Lusaka is a plateau formed from tectonic events which would have resulted in an uplift. The tectonic events can be said to have been a recumbe folding accompanied by faulting and thrusting (Simpson el al., 1963, Drysdall and Smith 1960). The Lusaka plateau comprises of Cheta, Dolomite and Chunga formations. The foremost rocks comprise gneisses and quartzites of the Chunga Formations, schists and quarzites of the Cheta formations, dominated by thick and extensive sequences of limestones and dolomitic limestones. The limestones and the dolomitic limestones are metamorphosed and have been suggested to be called marble and dolomitic marbles for the purpose of distinguishing them from the various carbonate rocks (Nkhuwa, 1996). The Cheta and Lusaka Dolomite belong to the Katanga Super group, while the Chunga Formations creates up the Basement Complex. Carbonates occupy an area of about 470km^2 in the study area, while the schist and quartzite occupies an area of about 221km^2 (Mpamba, 2008). The area underwent a late shear foliation which has largely destroyed all structures to earlier folding and usually postdates the granitization of the gneisses. This shear foliation has been refolded and chances are that the young Katanga has been folded twice with the first phase producing tight recumbent shear folds. The parallel sided outcrop of the Lusaka Dolomite south and west of Lusaka is believed to be downfaulted, and its base may be a thrust plane. This formation is unlike any lower member of the succession and, in the north, is apparently unconformable. Gabbroic plugs marginally affected by regional metamorphism intrude the Cheta Formation, but not the Lusaka Dolomite. A small, probably intrusive, granite boss intrudes the Cheta and Chunga metasediments north-west of Lusaka (Gulf Ingenieure, 2013).

3.5 Hydrogeology

Lusaka city is built on the main aquifer held by marbles described as the Lusaka dolomite. Other subordinate aquifers are constituted within marbles that are of Cheta Formation located to the south and north of main aquifer. Some minor aquifers have also developed in schists and quartzites of cheta and chunga formation and within alluvial deposits. All the aquifers have different potential for groundwater while the Lusaka dolomite is said to have the highest groundwater potential among them because of the developed karstic system (Mpamba, 2008). Outcrops are visible within the study area and are of the Cheta Formation (schists and quartzites), Chunga Formation (schists and quartzite) and Lusaka Dolomite (marbles and dolomites) belonging to the Katanga Super group a single geological sequence that occupies the northern and central parts of Zambia. These are all aquifers each with a different potential (Figure 3).

The flat morphology of the Lusaka plateau is the result of intense weathering of the outcropping lithologies resulting in flat schist and carbonate plains with rounded quartzite hills, forming an immense erosion plateau known as the Gondwana and Africa surface. The Lusaka plateau forms a watershed between the Chunga River, which ends up in the Mwembeshi River to the West, and many smaller rivers which end up into the Chongwe to the Northwest and Kafue Rivers to the South (Waele and Follesa, 2003).

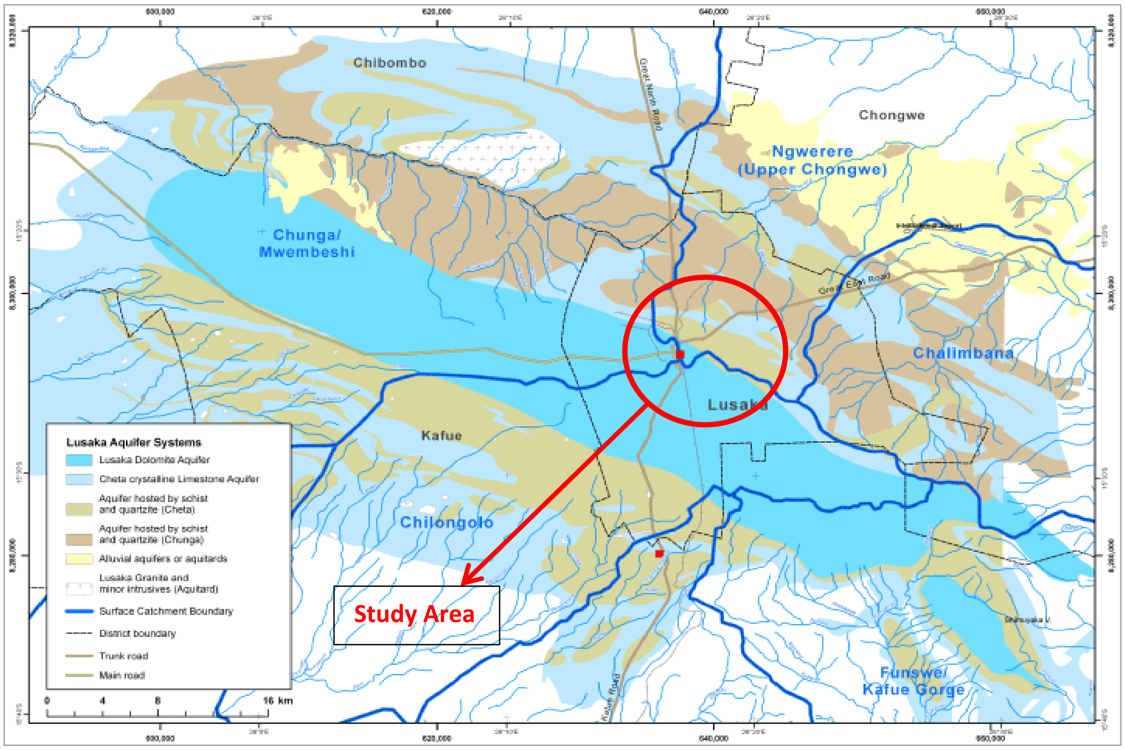

Figure 3: Aquifer systems for Lusaka. [Source*:* Baumle and Kang'omba, 2009]

3.6 Soils

There are four soil groups found in the study area. Orthic-plinthic ACRISOLS-These are well drained to moderately well drained, very deep, brownish yellow to pale brown, friable, fine loamy to clayey soils, having a clear clay increase with depth and thick sandy loamy sand topsoil. Chromic-hapllc LUXISOLS-These are well drained to moderately well drained, deep, strong brown, friable, moderately deep to very deep, yellowish red to strong brown, friable fine loamy to clayey soils having a clear clay increase with depth. Orthic-eutric LEPTISOLS-Moderately well drained to imperfectly drained, shallow, dark brown to yellow brown, coarse to fine loamy soils. Niti-luvic PHAEOZEMS –These are well drained, very deep, dark reddish, friable, shiny, fine clays, soils with a humic topsoil (MA, 1991)

3.7 Drainage

Lusaka urban is placed on the plateau being part of the Central African Mid tertiary peneplain. This occurs at an elevation of 1260m above mean sea level (amsl). The urban is drained by the three river basins, Chongwe, Chunga-Mwembeshi, and Kafue river basins (See Figure 4). The urban does not flourish with streams. The carbonate rock underlain the urban exhibits itself with sinkholes, permeable laterite and epikarst, thus rarely have streams (Mpamba, 2008).

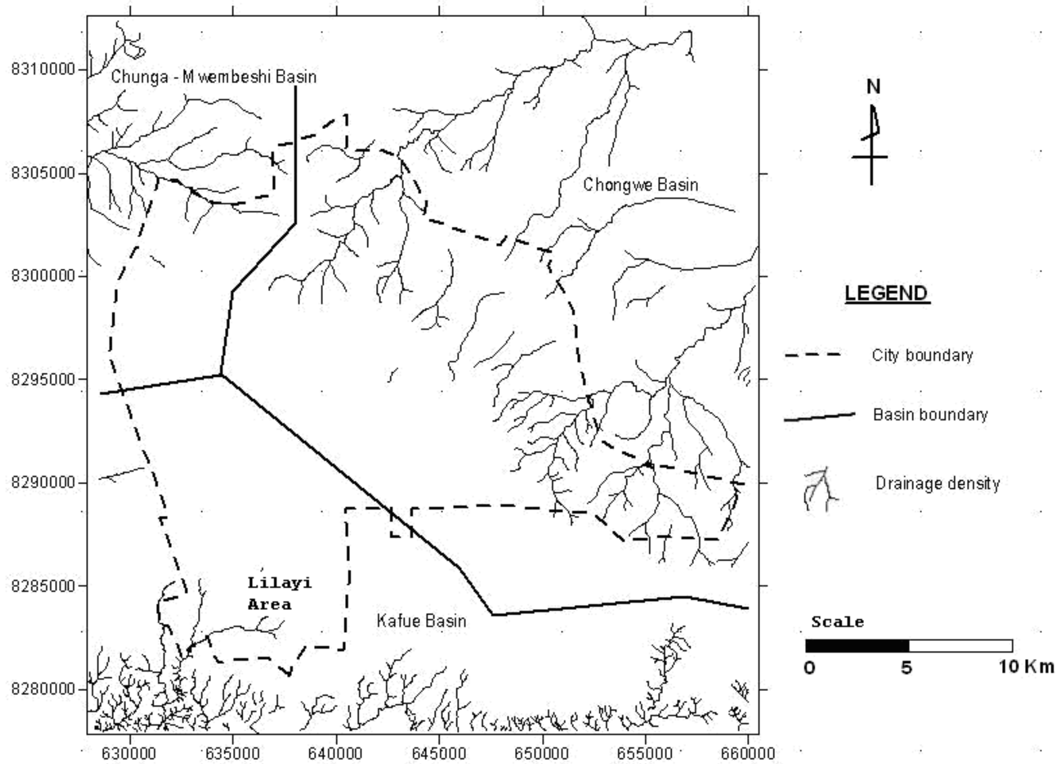

Figure 4: The 3 river basins draining Lusaka urban. [Source: Mpamba, 2008, page 20]

3.8 Conclusion

The chapter described the study area. It presented the location, climate, topography, geology, hydrogeology, soils and drainage of the study area.

CHAPTER FOUR: MATERIALS AND METHODS

This chapter presents the feasibility analysis, full-exfiltration system design, desktop assessment, rainfall and traffic data, soil subgrade sampling, determination of depth, construction of reservoir, installation of pavers, environmental requirements, stormwater monitoring, determination of infiltration on pavement system and stormwater pervious pavement relationship.

4.1 Full Exfiltration Pavement System Design

A design for full exfiltration pervious pavement system reservoir of stone base was done using the feasibility formula given in the ICPI guide book (Smith, 2006).

4.1.1 Feasibility Analysis

Following the steps indicated in the guide book, this criterion involved checking for rock outcrops, soil texture using hand texture, proximity to utilities, slope and hot spots land uses. If an area showed potential, further test included soil infiltration using the field test double ring infiltrometer, porosity using in-situ sampling, bulk density, and minimum depth to water table using reference data provided by the Water Resources Management Authority..

4.1.1.1 Potential experimental sites were purposively selected from the Nine (9) (CBD, CBD 1, Nipa, Luangwa, ZESCO, Chibelo, UNZA, SOS and Mkandawire) authorised areas for undertaking the feasibility assessment (See Figure 5). These sites were areas reserved for developments and road expansions. Areas with already established impervious surfaces were not authorised because retrofitting on existing impervious area was not allowed. To this effect, only 3 - (ZESCO, Chibelo and UNZA) sites were used. These areas were extending, showed potential while also considering minimal initial financial implications in enhancing approach adoption targeted for low cost area developers. Each plot was covering 24m^2 area. The sites installed with a pervious pavement system did not have an impervious area contributing runoff exceeding it 5 times, making sure that the impervious area will not increase cover draining into the pavement. In this respect, the plots for the study were banded with 6'' (15.24cm) concrete blocks not to allow excess runoff from the extensive surrounding areas. The area's water table in all the sites was not greater than 0.6m and had sufficient depth required to filter pollutants. At least over 30m was maintained between the pavement system and water supply wells, streams and wetlands. The slope was less than 5% and plots were set at greater than 1m away from building foundations. Porosity and bulk density did not influence the incorporation of drain pipes to sustain the system's infiltration potential of stormwater in the sited areas.

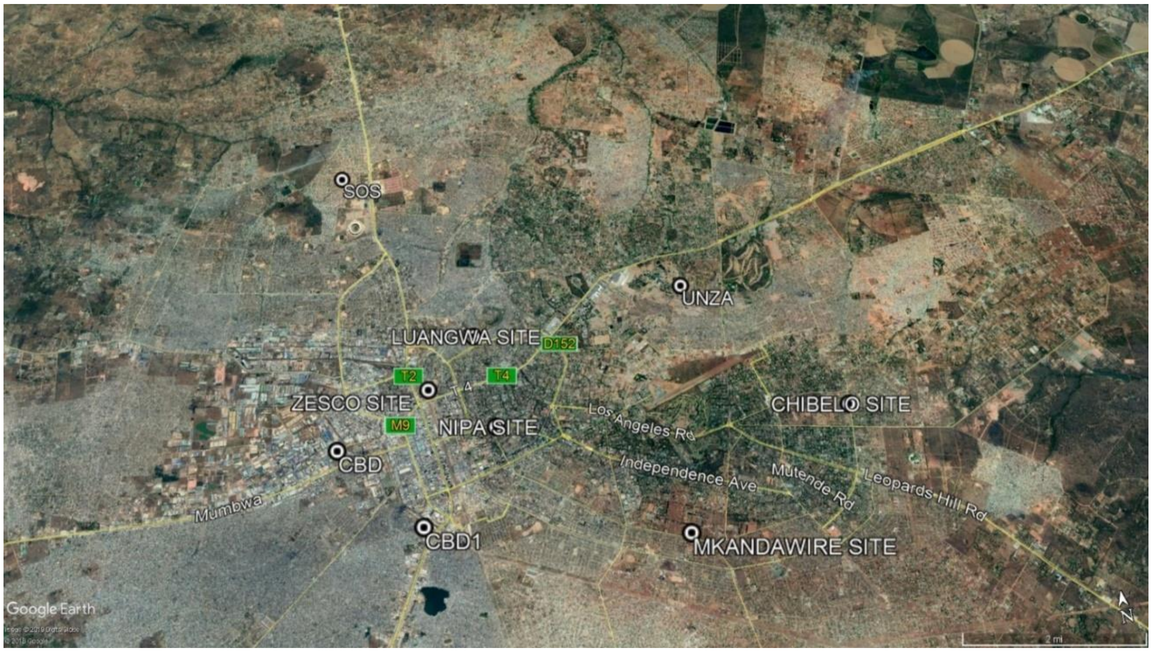

Figure 5: Lusaka urban sites assessed from which experimental sites were selected [Source: Google image, 2013]

4.1.2 Desktop Assessment

A preliminary assessment was conducted prior to the hydrological design. The assessment involved consideration of the following factors:

4.1.2.1 *Underlying geology and soil maps*

This involved carefully analysing the geology of the study area using documented information, soil maps and physical tests and site visits to check the areas potential of supporting full exfiltration pervious pavements. The criteria was to exclude all areas and their peripherals which exhibited any outcrop as this would not provide sufficient soil depth. Soil pits were excavated up to 2m in areas which indicated sufficient soil depth to support infiltration activities. Sites which exhibited such potential were selected for setting up the experiments.

4.1.2.2 *Verifying history of fill soil or previous disturbance or compaction*

The surrounding areas for the selected sites were observed critically to check for possible interaction of activities that would relate to what exist on the sites. Some sites were found to have inorganic debris associated to overtime anthropogenic activities in soil pits.

4.1.2.3 *Review of topographical maps and identifying drainage patterns*

Topographical maps for the study area were analysed. The area is a plateau and is relatively flat in most parts. This was considered not a hindrance to the construction of the pavement system which require generally flat areas.

4.1.2.4 *Identifying streams, wetlands, wells and structures*

There are a number of streams, wetlands, wells and built structures in the study area. The urban is undergoing rapid development, thus structures are being belt in all the areas owing to the fact that it is relatively flat. The experimental sites were not sited near any stream, well, wetland or any structure.

4.1.2.5 *Absence of storm water hotspots*

The experimental sites were isolated from any structure and were away from any stormwater hotspots.

4.1.2.6 *Identifying current and future land uses draining onto the site*

The experimental sites were offered for the period of the experiment and will not continue to remain for further tests.

4.1.3 Rainfall and Traffic Data

4.1.3.1 *The total area and percent of impervious surface draining on the pavement*

The plots for the experiment were sited on areas isolated from any drainage network or impervious areas. In this view, the system was independent of the surrounding environment. Each 6mx4m plot had a system which comprised of an impervious and a pervious area. A 2mx4m area was pervious while 4mx4m was impervious. The impervious area generated flow draining on the pervious area. The plot was banded not to allow runoff from the surrounding areas. This would have added to the impervious area draining on the pavement system as well as runoff with constituents from other areas beyond the limits which the pavement could degrade.

4.1.3.2 *The design storm*

The design storm with return period for the area is 123mm, 5year return period as supplied by the local authority (ZMD).

The volume of runoff to be captured and exfiltrated using the design storm is given as:

Runoff Volume = AP m^3. (Equation 1)

Where:

A is Runoff (mm) contributing area to the pervious pavement.

P is rainfall (mm) expected from rainfall (storm design).

4.1.3.3 *The estimated vehicular traffic loads expressed as 18,000 kip (80 KN) equivalent single axle loads (ESALs) over the design life of the pavement with a number of life years.*

This factor was not considered in this study. If any was designing a pavement system that would allow traffic, they need to put into consideration that factor.

4.2 Soil Subgrade Sampling

The soil subgrade was analysed for soil depth and soil infiltration. Compaction test is a requirement if the pavement is being designed for vehicular traffic. In this case, the pavement system did not include vehicular traffic, thus only infiltration and other physical parameters were done on the soil subgrade.

Test pits were excavated up to 2m on each site to check the bottom for any bed rock or impeding layer. More pits should be excavated if there are outcrops within the area. In this case, the potential sites had no outcrops. Each site was tested for surface infiltration before constructions using the double ring infiltrometer - ASTM D 3385 standard for infiltration rate in field soils. A constant head method was used in determining the basic infiltration rate (IR) required in the design. The determined value of the infiltration rate is used as an input (**f**) in the reservoir layer design. Other tests included, soil texture, bulk density and porosity.

4.3 Determination of Depth

In determining the total depth of the reservoir, the following is recommended:

- Bedding layer of aggregates size No. 8 should not exceed 50mm thickness.
- Base layer aggregates size No. 57 should be 100mm in thickness.
- Subbase layer of aggregates size No. 2 varies depending on the calculated required depth in the design.

The following equations were used in the design based on the ICPI handbook:

The design volume of water to be stored in the pavement base (Vw) is given by:-

Vw = ∆Qc Ac + PAp – fTAp. (Equation 2)

The volume of the stone base and subbase can also be defined in terms of its geometry as:

Vp = Vw/Vr = dpAp. (Equation 3)

Where:

dp = the depth (mm) of the stone base (including subbase).

Ap = the permeable pavement surface area (m^2).

Vr = the stone base and subbase void ratio (typically 0.4).

Qc = Runoff volume (m^3).

Ac = Contributing area (m^2).

P = Precipitation (mm).

f = Infiltration (cm/hr.) (Soil).

T= Filling time generally 2-hours duration where the flow into the pavement exceeds the flow out of the pavement. Thus, duration of 2-hours is used for T.

Setting the previous two equations equal will result in the following relationship:

$$dpApVr = \Delta QcAc + PAp - fTAp$$

The surface area of the permeable pavement (**Ap**) and the depth of the base (**dp**) can be defined in the following forms from the above equation:

$$Ap = \frac{\Delta Qc\ Ac}{Vr\ dp - P + fT} \quad \text{(Equation 4)}$$

$$dp = \frac{\Delta Qc\ R + P - fT}{Vr} \quad \text{(Equation 5)}$$

Where:
R = equal to the ratio of the contributing area and the permeable pavement area (**Ac/Ap**).

Maximum allowable depth d_{max} of the base by feasibility formula:

$$d_{max} = f \times T/Vr$$

Where **dp** must be less than or equal to d_{max} and at least 0.6m above seasonal high ground water table. If **dp** does not meet this criteria, the surface area of the permeable pavement must be increased or a smaller design must be selected.

4.4 Construction of Reservoir

Sites numbering 3 were constructed with a pervious pavement system. The sites were at Unza (behind school of mines) as site 1, ZESCO central business area (Adjacent to the Kabwe round about fly over bridge) as site 2, and Chibelo (Malata area adjacent to Lake Road) as site 3.

The materials for the bedding, base and subbase courses that make up the storage reservoir were sourced from a quarrying company in Lusaka. The aggregates are being harvested from a hard and durable rock. The aggregate sizes for the layers were bedding course (ASTM No.8 aggregates), base course (ASTM No.57 aggregates) and subbase course (ASTM No.2 aggregates). The materials underwent a sieve analysis for grading requirement (Table 1). The quarrying firms around the area do not supply some aggregate sizes expected in the design due to consumer preferences and type of use in the construction industry. The curve for the aggregate percentage was not lying in the expected grading requirement. A void space percentage was determined for each layer of aggregates to estimate volume of stormwater storage in relation to the required void ratio when the recommended aggregates sizes are used.

Table 2: The grading requirement for the aggregate layers required in making up a reservoir.

Grading requirement for ASTM No.8 bedding and joint filler	**SIEVE SIZE(mm)and(in)**	**PERCENT PASSING**
	12.5mm (1/2in)	100
	9.5mm (3/8in)	85 to 100
	4.75mm (No.4)	10 to 30
	2.36mm (No.8)	0 to 10
	1.16mm (No. 16)	0 to 5
Grading requirement for ASTM No. 57 base	**SIEVE SIZE(mm)and(in)**	**PERCENT PASSING**

	37.5mm (11/2in)	100
	25mm (1in)	95 to 100
	12.5mm (1/2in)	25 to 60
	4.75mm (No.4)	0 to 10
	2.36mm (No. 8)	0 to 5
Grading requirement for ASTM No. 2 subbase	**SIEVE SIZE(mm)and(in)**	**PERCENT PASSING**
	75mm (3in)	100
	63mm (21/2in)	90 to 100
	50mm (2in)	35 to 70
	37.5mm (11/2)	0 to 15
	19mm (3/4in)	0 to 5

The total thickness of the pavement is made of the bedding course, base course and the subbase course. The guide gives the standard depth for the bedding and the base course. The subbase is given by the design depth. The recommendations on depths are:

- 80mm-thickness of concrete pavers (depends on type of pavers used).
- 50mm-No. 8 Bedding course.
- 100mm-No. 57 Base course.
- (As per design)-No. 2 Subbase course.

After marking the plot area, the required depth was excavated to the design depth of the reservoir design. The exaction was made to meet the actual depth. If the excavation is slightly more than the required, soil should not be used to compensate the increased volume, rather more aggregates will have to be used to fill up the increased reservoir volume. This is followed by aggregate spreading starting with subbase material and ending with the base material. Each layer of aggregates was evenly compacted using a portable compactor after spreading. The first layer to be spread is aggregates size No.2 for the subbase material. Aggregates size No. 57 forms the base layer and are spread following the aggregates size No. 2. The larger sizes of aggregates create an uneven surface, thus, the bedding course formed by aggregates size No.8 is spread to stabilize and partially choke or close the surfaces of the base. Crushed stone of 1mm to 3mm size was used to fill in the spaces between the pavers.

4.4.1 Installation of Pavers

The Pavers used in the study were sourced from a local firm which supplies to most of the developers in the area. The local industries construct pavers using the ratios 1:4:4 (Industry standards). Paver installation can be done by hand or with mechanical equipment. In this study, installation on top of the stone reservoir was done by hand (See Figure 7). The spacers used in the study are inbuilt on the pavers as designed by the industry. The spacer size was 5mm (See Figure 6) and were filled using the crushed stone of 1mm to 3mm sizes. The filling material was spread and swept clean on top of the pavers and compacted using a hand pushed rammer. The plot was constructed with a 20cm hedge on the boundary to make a closed system and control flow of runoff generated outside the system since it was not retrofitted.

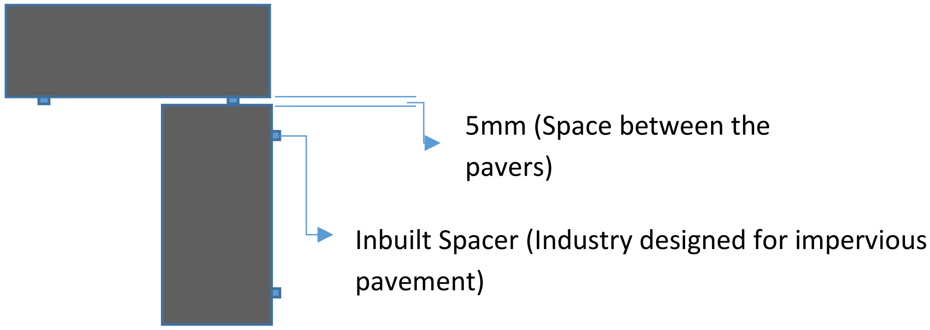

Figure 6: An illustration of the inbuilt spacers on the pavers used in the study.

Figure 7: Installation of pavers after spreading the bedding layer.

4.4.2 Environmental Requirement

The environmental requirement is not to install the pavement system in the rain. This system was installed prior to the rain season. Installation in the rains may allow sediment into the reservoir that can clog the system and reduce the life span. Continued activity on surface of the subbase causes compaction closing up pores that are meant to promote infiltration of stormwater into the soil. Further, when the surface is wet, the sediments will easily find their way in to the aggregates and clog the system.

4.4.3 Installation of Access Tubes

In this study, aluminium access tubes (2.2m in length, 50mm in diameter) were used to serve the purpose of allowing the probe or detector tube for the gauge to access below the pavement system for soil moisture measurement. Aluminium tubes were used to reduce interactions of thermal neutron with heavier elements or high affinity which affect readings compared to other materials. An access tube was installed on the subgrade before spreading aggregates which form the reservoir of the pavement system. A second tube was installed 5m adjacent to the pavement system on the natural environment as a control and for calibration. The tubes extended 40cm above the soil to enable the positioning of the probe shield case on top of the tube. Rubber tops were used to cover the tube tops to avoid water and other materials finding their way into the tube. The tubes were sealed at the bottom by the manufacturer and especially opted for in this experiment to avoid possible entry of water from a shallow water table.

4.4.4 Calibration

The neutron gauge was calibrated to the existing environment on the experimental plots. One site was used for calibration to take into account of any effect on the calibration coefficient which can be resulting from difference in soil materials. Soil materials from different sites can exhibit a change in moisture content with depth (USDA, 2002). The same gauge was used for all the readings during the period of under consideration. Calibration of the neutron gauge was conducted by determining a linear relationships of the two gauge readings in counts per minute (counts min^{-1}) at dry and wet scenarios from a calibration tube and their corresponding gravimetric water content in grams ($g.g^{-1}$). To avoid effects of electronic drift, temperature and other electronic effects, the count value was not used as read in the soil depth, rather, a count ratio (CR) used was defined as:

CR=Count Rate in Soil / Count Rate in Standard $=N/N_s=C.T^{-1}/C_s.T_s^{-1}$.

Where C is the number of counts measured in soil within time T (min), Cs is the number of counts measured in the standard material within time T (min), N is the count rate (cpm) in the soil and Ns is the count rate (cpm) in the standard material.

4.5 Stormwater Monitoring

Storms events numbering 36 were monitored for contribution to the unsaturated zone through infiltration using the neutron gauge (See Figure 8 and 9). Daily moisture readings were done following rain storms for the whole period of the rainfall season in all the sites using access tubes. One access tube was installed on the pavement system. A second tube was installed in the natural environment for control. The moisture data collected during the rainy season was analysed for soil moisture changes in the soil profiles to determine quantities being contributed to the unsaturated zone by the pervious pavement system.

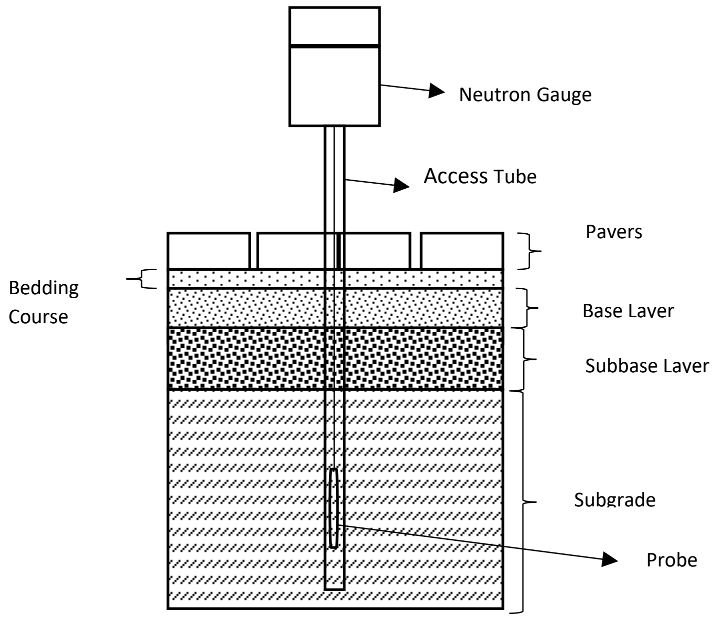

Figure 8: An illustration of a gauge with a probe below the pavement system

Figure 9: The gauge set to take moisture readings on the tube installed on the pavement system.

4.6 Determination of Infiltration on Pavement System

The average infiltration rate (IR) test was done on the installed pavement on the sites to determine the amount of stormwater which can infiltrate the system using the double ring

Figure 10: Installation of a double ring infiltrometer on the pavement system.

infiltrometer. A double ring infiltrometer was used so as to reduce lateral movement of water from the inner ring. The rings were set on the pavement and their base was sealed with plumber's patty to stop the lateral flow of water on the surface of the pavement (See Figure 10). This test was done on all the plots three weeks after installation and readings were taken from the floating ruler in the inner ring until all the water infiltrated. The test was conducted twice on each plot after a month.

4.7 Stormwater-Pervious Pavement Relationship

A regression analysis was used to determine the storm water-pervious pavement relationship for Lusaka urban. After determining contribution of moisture to the unsaturated zone, a regression analysis was used to determine the relationship between the water quantities that can be possibly contributed to the environment and the water quantities infiltrated per depth below the pavement. This will give an indication of possible amounts of water that can be harvested when the system is installed.

4.8 Conclusion

The chapter presented full-exfiltration system design, desktop assessment, rainfall and traffic data, soil subgrade sampling, determination of depth, construction of reservoir, installation of pavers, environmental requirements, stormwater monitoring, determination of infiltration on pavement system, and stormwater pervious pavement relationship.

CHAPTER FIVE: PRESENTATION OF RESULTS

The chapter presents results on the feasibility assessment, infiltration on pervious pavement, contribution to the immediate unsaturated zone and stormwater-pervious pavement relationship.

5.1 Feasibility Assessment

5.1.1 Site Characteristics

The northern and southern parts of the urban exhibited wide areas of rock outcrop due to the dominance of dolomite and schists formations on which the urban lies. The central eastern part of the urban had sufficient soil depth to support construction of full exfiltration pervious pavement. It is underlain by schist and quartzite formation (See Figure 11, 13 and 15).

Figure 11: Central part of the urban supporting the use of pervious pavements [Source-google image 2020]

The soils tested from the 3 sites had loamy sand top soil. They are described as mostly well drained to very deep, highly molted, loamy sand top soils with a high content of clay as depth increased. The soils belong to orthic-plinthic acrisols (Soil Survey department) (See Figure 14). The tested mean surface infiltration from the three sites within the study area was 72 cm/hr. The porosity ranged from 35% to 41% on top soils and reduced as clay increased with depth. The bulk density ranged from 1.35g/cm^3 to 1.76g/cm^3. The bulk density was increasing with depth indicating high clay content which has higher bulk density values.

Figure 12: Wide areas of rock outcrop in the southern and northern parts of the urban

Figure 13: The central part of the urban exhibiting sufficient soil depth to support exfiltration pervious pavements.

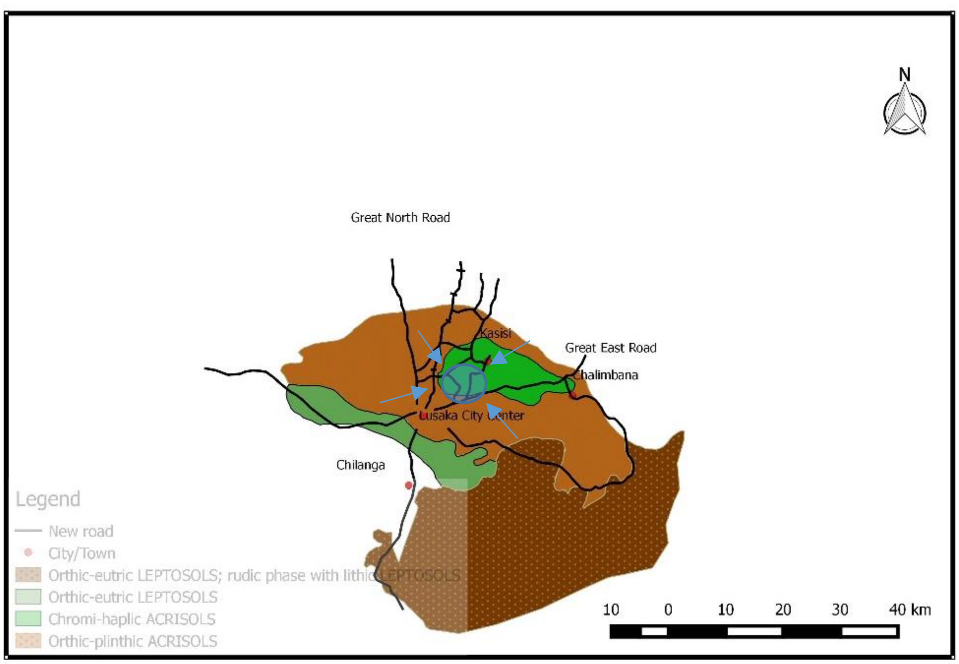

Figure 14: The map shows the soils existing in the study area (After Soil Survey Department-Soil Map).

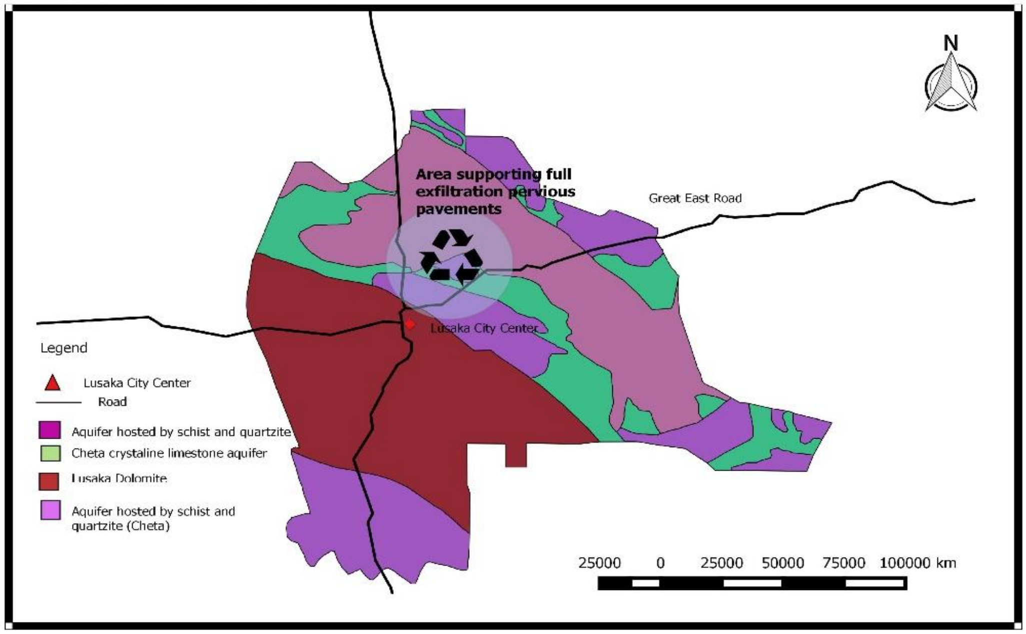

Figure 15: Underlying aquifers below the area supporting full exfiltration pervious pavement (After geological map of Lusaka-Source: Baumle and Kang'omba, 2009)

5.2 Design Depth

The maximum allowable depth by the feasibility formula was determined as 600mm for all the sites using the soil physical parameters which were obtaining as inputs.

5.3 Infiltration on PICP

The mean infiltration rate determined using the double ring infiltrometer on the installed pervious pavement systems with 5mm inbuilt spacers on the experimental sites 1, 2 and 3 was 780cm/hr. (See Figure 16).

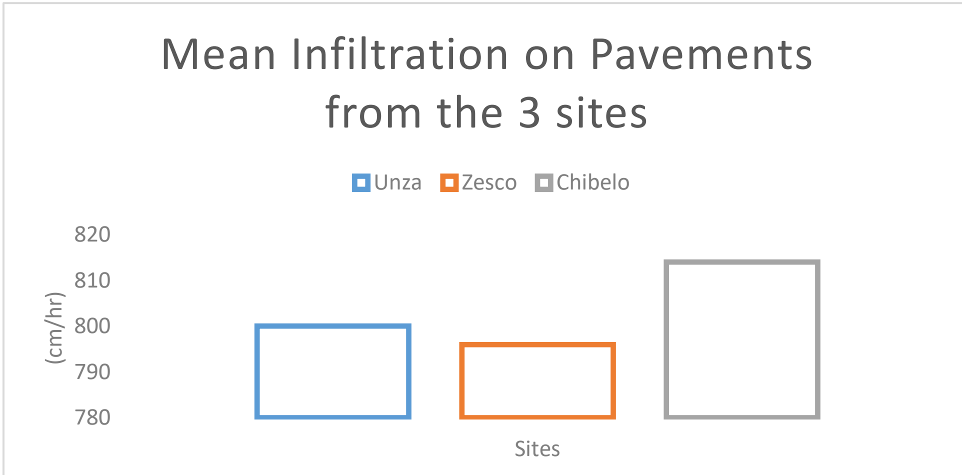

Figure 16: Mean Infiltration on the pavements for the 3 sites. Site 1-Unza, Site 2-Zesco and Site 3-Chibelo.

5.4 Stormwater Contribution

5.4.1 Stormwater Events

The rainfall received on the 3 sites is presented in Figure 17. The amounts received during the 36 stormwater events considered in the study was approximately the same in all the sites. The total amount of rainfall received on the pavements was 391mm over the observed period of the study.

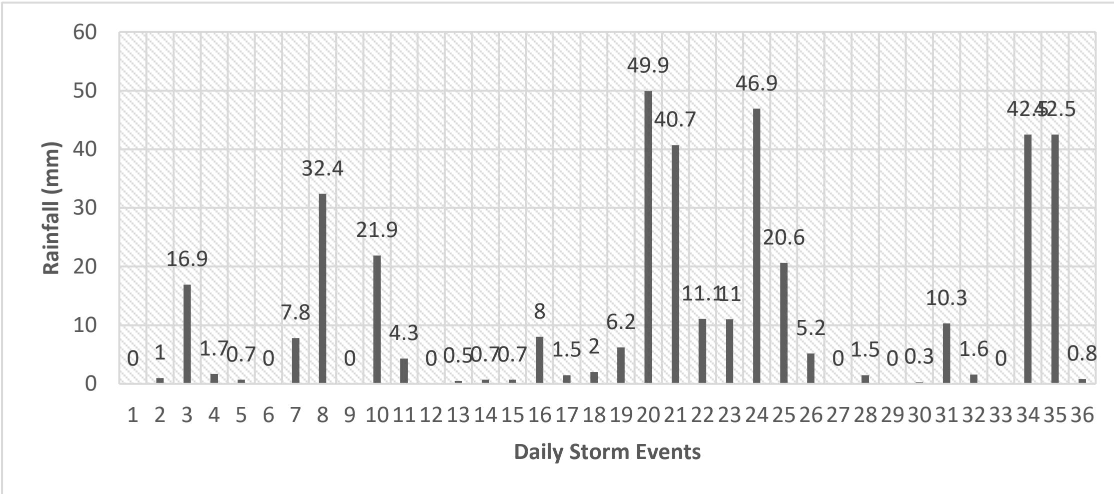

Figure 17: Total amount of rainfall received during the 36 stormwater events

5.4.2 Stormwater Contribution to the Unsaturated Zone

The mean depth of stormwater estimated to have been contributed to the immediate unsaturated zone by infiltration during the observed rainfall events is 140mm in 1100mm depth of soil below the pavement system (See Figure 18). This represents the stormwater which was infiltrated by the pavement adding to quantities available for groundwater recharge and ecological purposes.

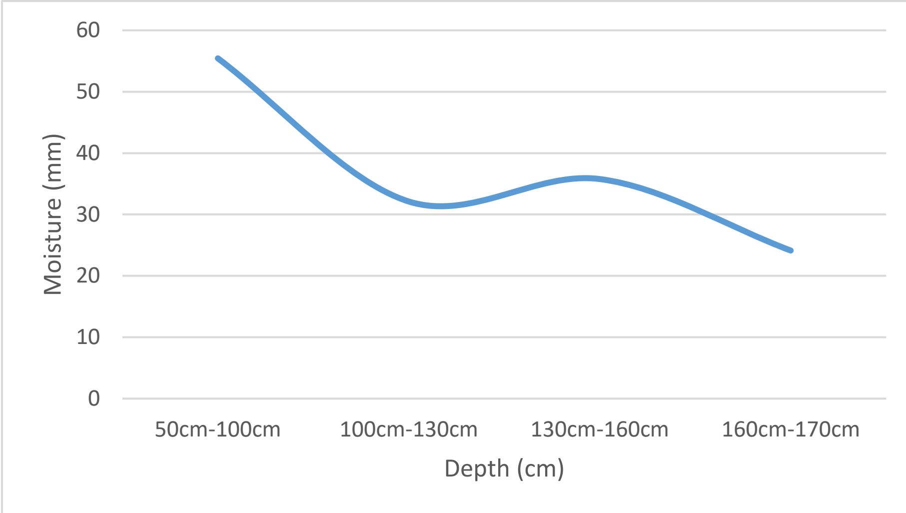

Figure 18: Mean millimeters of water contributed to immediate zone below the pavement system.

The pavements on the 3 different plots received rainfall amounts from the storm events.

The response is shown in Figure 19.

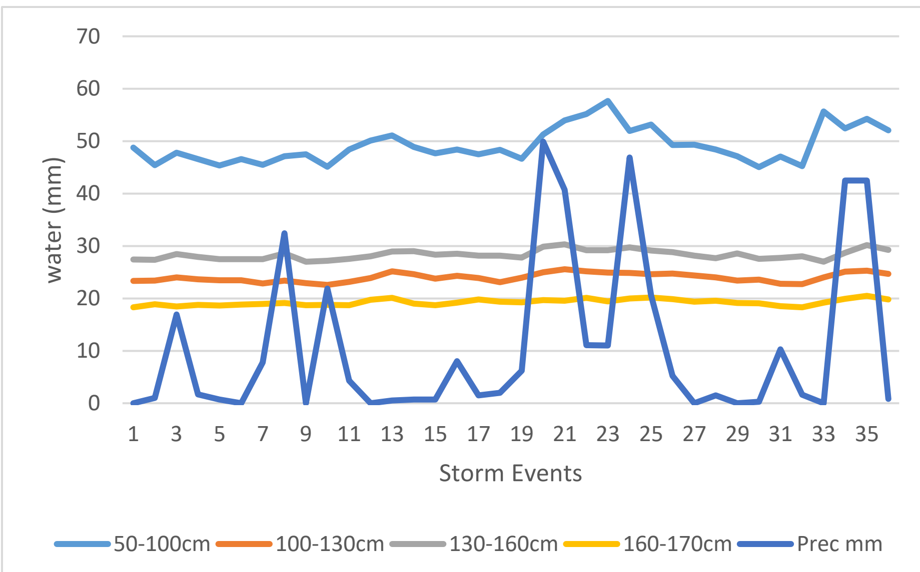

Figure 19: Pavement response to stormwater contribution on site 1

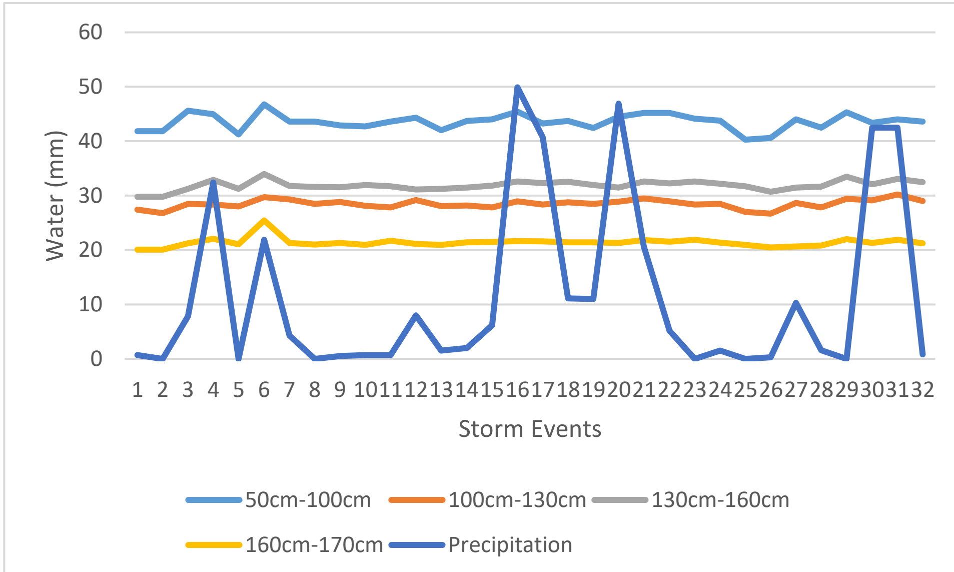

Figure 20: Pavement response to stormwater contribution on site 2.

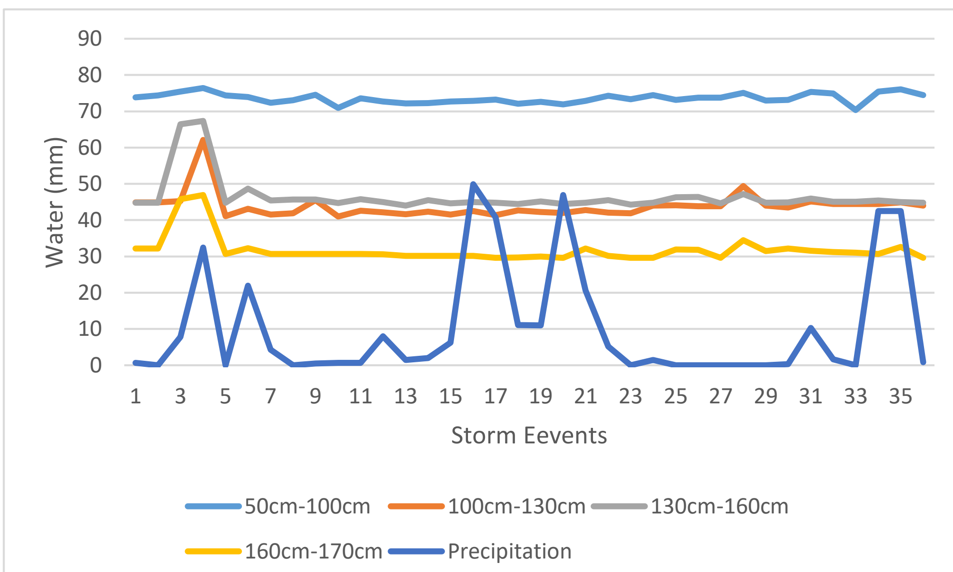

Figure 21: Pavement response to stormwater contribution on site 3.

5.5 Stormwater- Pervious Pavement Relationship

The Figures 22 to 29 below show the stormwater-pervious pavement relationships and the responses of the pavement to stormwater events for Lusaka urban in sites that allow full exfiltration at four different soil depth below the pavement system.

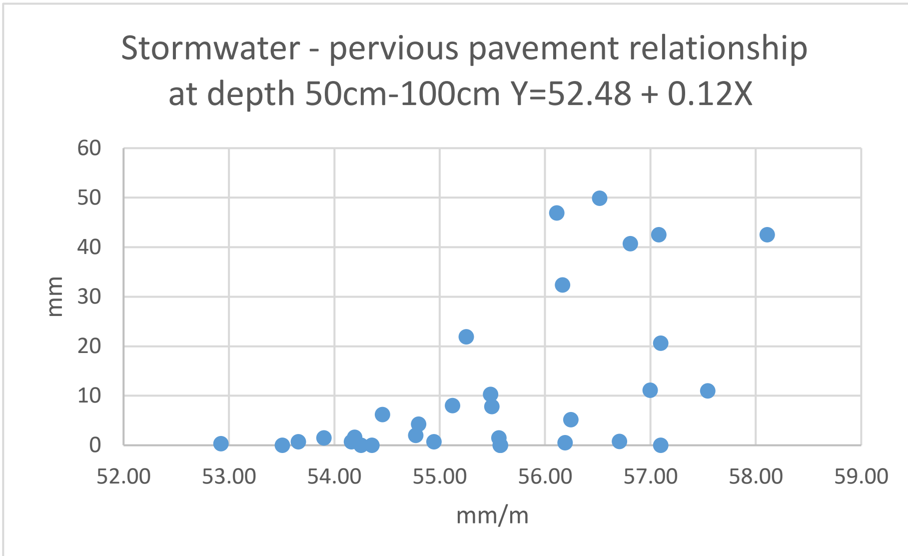

Figure 22: Least squares regression for the Stormwater-pervious pavement relationship at depth 50cm-100cm below the pavement.

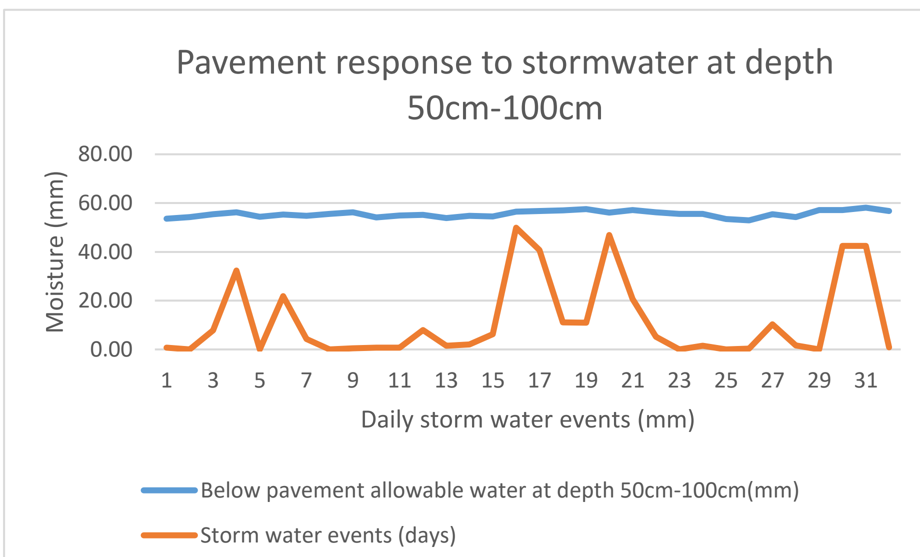

Figure 23: Pavement system response to rainfall events at depth 50cm-100cm below the pavement.

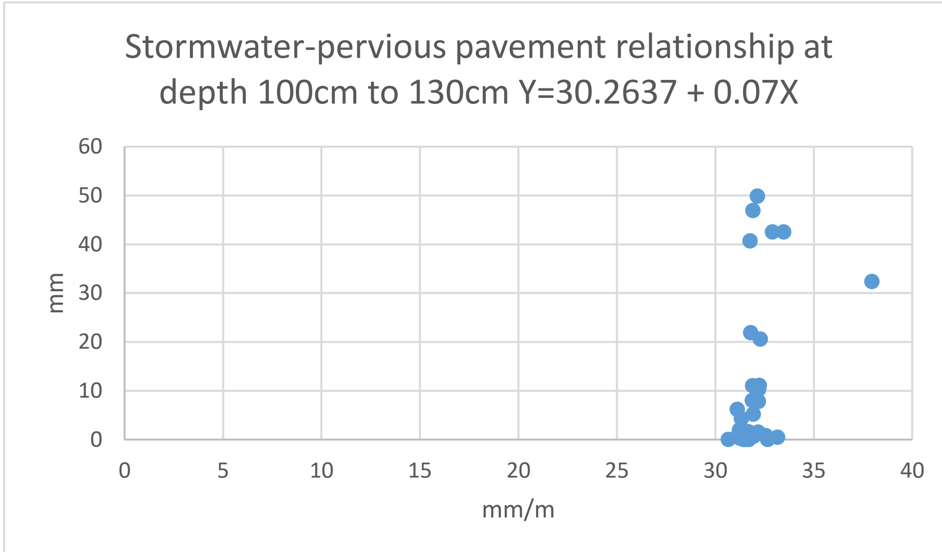

Figure 24: Least squares regression for the Stormwater-pervious pavement relationship at depth 100cm-130cm below the pavement.

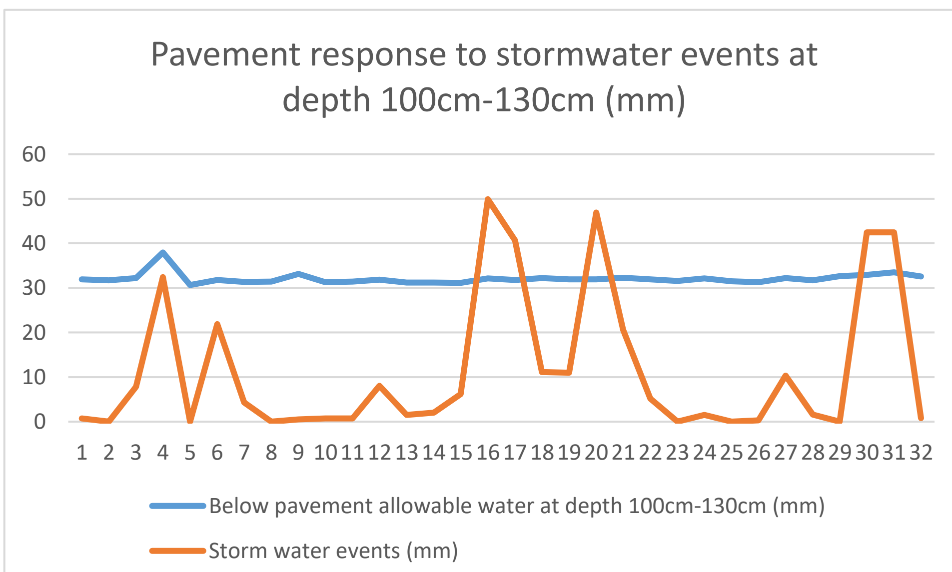

Figure 25: Pavement system response to rainfall events at depth 100cm-130cm below the pavement.

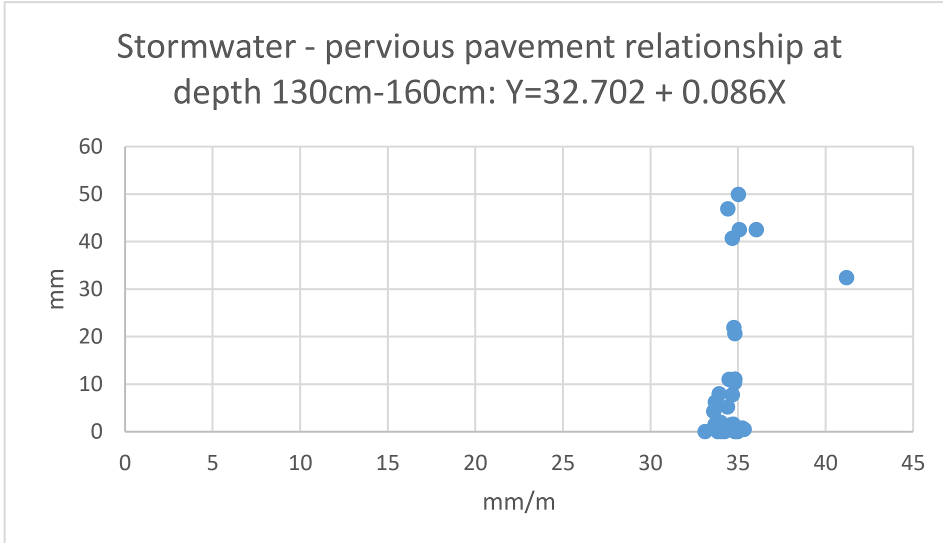

Figure 26: Least squares regression for the Stormwater-pervious pavement relationship at depth 130cm-160cm below the pavement.

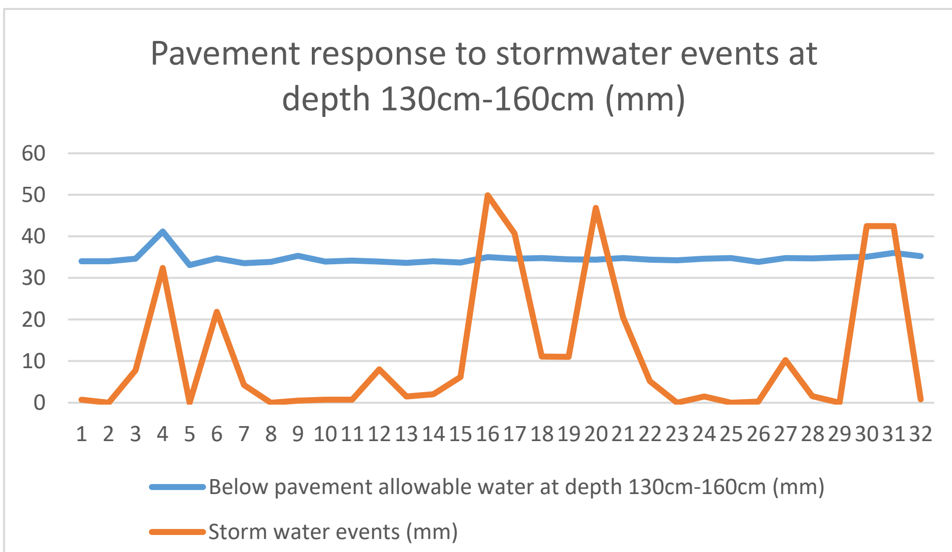

Figure 27: Pavement system response to rainfall events at depth 130cm-160cm below the pavement.

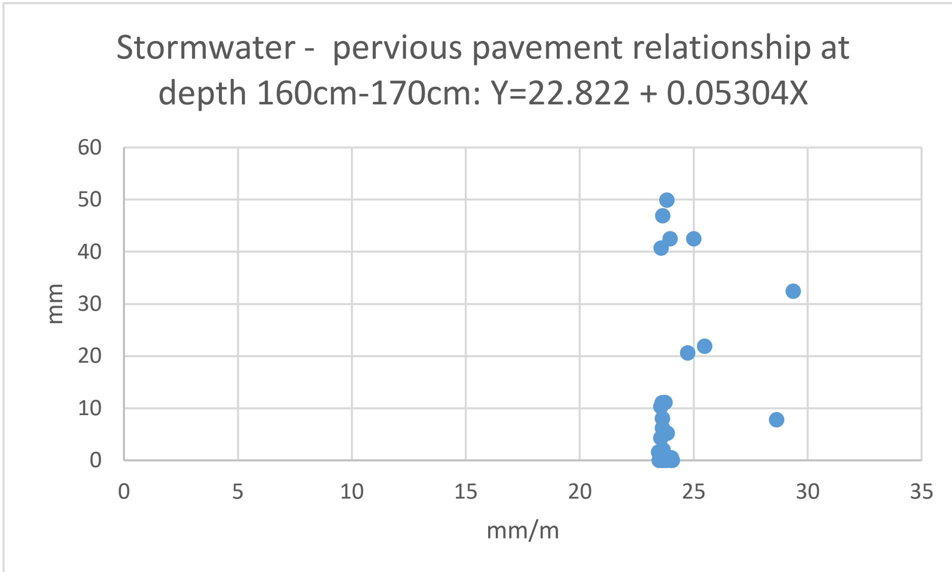

Figure 28: Least squares regression for the stormwater-pervious pavement relationship at depth 160cm-170cm below the pavement.

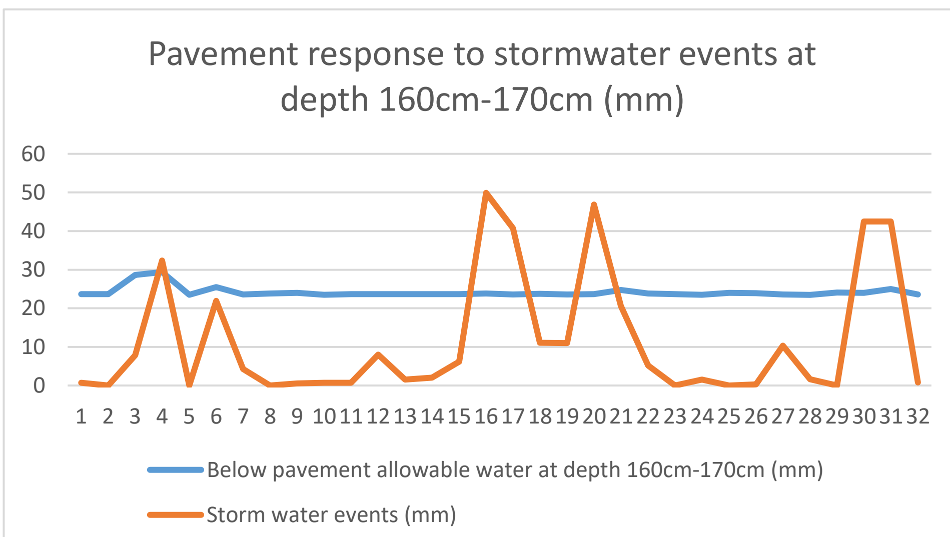

Figure 29: Pavement response to rainfall events at depth 160cm-170cm below the pavement.

5.6 Comparison of Measured Infiltration on Pervious Pavement System

The measured infiltration on the pervious pavement systems using the double ring infiltrometer indicated an infiltration rate which ranged from 774cm/hr. to 823 cm/hr. with a paver spacing of 5mm. An average infiltration rate of 780cm/hr. was estimated for the system (See Figure 16). The t test conducted to determine the significance difference between the infiltration rates from the sites gave a calculated t value less than the tabular value of 3.182 at 3 degrees of freedom at 5% level of significance. The estimated average infiltration was achievable on all the plots by following the stipulated steps of installation of pervious pavements in line with the ICPI handbook for all the sites. Further, infiltration rate on the pavement depended on the soil texture of the subgrade. The soils making up the subgrade in all the sites is homogeneous as such may have influenced the infiltration rate.

5.7 Comparison of Measured Stormwater Contributed to the Unsaturated Zone

The measured stormwater contributed to the unsaturated zone showed a change in moisture content within the depths of 50cm to 100cm, 100cm to 130cm, 130cm to 160cm and 160cm to 170cm. The t test was conducted to check for the significant differences of moisture content within the depths on each site and between the sites. The t test conducted to determine the significant difference in moisture content at 4 different depths on each site gave a calculated t greater than the tabular t of 2.030 at 35 degrees of freedom on all the 3 sites at 5% level of significance. Water present at the depth 50cm to 100cm which is just below the aggregates exhibited a higher moisture content in all the sites. This was followed by depth 130cm to 160cm, 100cm to 130cm and the least being 160cm to 170cm. This behavior can be attributed to stormwater movement from the aggregate reservoir to the immediate depth which leads to groundwater contribution. In all the moisture readings, site 3 recorded higher moisture values due to hydrological characteristics of the area. The area has a history of exhibiting subsurface stream flow. The t test conducted for determining the significance of difference of moisture contents in the 4 depths between sites had the calculated t less than the tabular t of 3.182 at 3 degrees of freedom at 5% level of significance on site 1 and 2. The calculated t was greater than the tabular t when compared with site 3 with a calculated t being greater than the tabular t of 3.182 at 3 degrees of freedom at 5% level of significance. This indicated that there was no significant difference between the sites 1 and 2 while site 3 was significantly different from the two sites. Based on the similar behavior of moisture differences which indicated stormwater contribution to the lower depths, the difference arising with site 3 from 1and 2 may be attributed to contribution of moisture other than stormwater events. Without this contribution, there is no significant difference in the way stormwater moved from the aggregate reservoir to the lower soil depths.

CHAPTER SIX: DISCUSSION

The chapter presents the integration of pervious pavements with drainage networks for Lusaka urban stormwater management, effect of geology on the use of pervious pavement in Lusaka urban and the stormwater pervious pavement relationship.

6.1 Integrating Pervious Pavements with Drainage Networks for Lusaka Urban Stormwater Management.

The full exfiltration pervious pavement system has proved to infiltrate sufficient amounts of stormwater of at least 800cm/hr. with a minimal inbuilt spacing of 5mm on pavers. This quantity of stormwater being infiltrated at this rate is more than the average annual rainfall received in the area ranging from 800mm to 1000mm (MDZ). During the observed storm events, no flooding occurred on the pavement systems demonstrating that it will not flood unless the system gets clogged due to fine material accumulation when not cleaned to free up the spacers. Flood producing rainfall depends on a rainfall intensity which exceeds soil infiltration rates, and thus gives rise to surface runoff (EPA, 2010). This might not have been reached during the observed season as the highest rainfall quantities received was 49.9mm less than the obtained infiltration rate of 72cm/hr. The sites where not installed with rain gauges to estimate on site rainfall amounts per storm event. Data from the central weather station for Lusaka urban was used to represent all the three sites assuming that the rainfall received was evenly distributed in all the experimental sites. This is showed from the way each site responded to storm events with no significant difference. The pervious pavement system can function to substantially reduce stormwater volumes which create urban floods resulting from increased impervious surfaces. The pavements can perform to reduce stormwater volumes while the surface structure is conveniently used as a walk path and parking lot. The water infiltrating below the pervious pavement system will add to the immediate unsaturated zone and finally contribute to groundwater in areas that do not have rock formation impeding infiltration. The use of pervious pavements can also reduce the transportation of solid waste to the drains and receiving waters. Lusaka urban has a challenge of indiscriminate disposal of solid waste by the urban population. The indiscriminately disposed waste gets transported into the drainage network. When the waste accumulates in the drainages and culverts, this causes blockages. Blocked drainages and culverts cause stormwater volumes to collect thus resulting in to urban flooding (Gulf Inginieure, 2013). In such a scenario, storm water runoff has been an agent in transporting solid waste into the drainage networks and receiving waters.

A key factor in using a pervious pavement system is the lifetime design infiltration of the entire plot and the soil subgrade. This is so because it can experience short-term events of water storage and long-term reductions infiltration from partially clogged surfaces. Long term infiltration rates depend on the intensity of use and the level to which the surface has received sediments that might clog the system. The achieved infiltration rate of the pavement during the study was dependent on the spacers, joint material in the spacers, bedding layer and base layers, soil depth and soil texture. The spacers can be increased during design of blocks. A much larger space between the blocks can raise the infiltration rate to achieve a higher efficiency but should be done in accordance with standards as well as achieving the optimal use of the pavement as a surface structure. In this study, pavers used in the common impervious pavements were opted for in the construction to promote what is already accepted and being commonly used. Pervious pavements will have to be installed 1m away from building foundations, away from hotspots and should have sufficient infiltration capacity exhibited by the soil.

6.2 Effect of Geology on the Use of Pervious Pavement in Lusaka Urban

The geology of Lusaka urban renders some parts unsuitable for infiltration activities. The area suitable for infiltration activities lies in the central eastern part of the urban while the northern and southern other parts had a reduced potential. In this respect, full exfiltration pervious pavement system is a possible best management practice able to be integrated with the drainage networks to manage stormwater in this part of the urban. The central eastern part of the urban experiences urban floods due to the built-up structures which have increased the impervious surface (Gulf Ingenieure, 2013). It was observed to be able to support pervious pavement systems because of having sufficient soil depth and does not exhibit outcrops in most of the parts. The northern and southern parts are substantially underlain by schist and dolomite formations respectively with minimal depth of soil to support full exfiltration pervious pavement system but responding to storm events depending on their geological characteristics. Karstic features present sinkholes which allow stormwater to infiltrate through the conduits. Porous formations also allow stormwater to infiltrate alluding the porous characteristic for a certain period of the rain season. The scenario changes as the water table rises after saturation during the season which causes flooding when the area experiences prolonging rains. Prolonged rainfall events on the other hand create flooding scenarios in the northern part (Waele and Follesa, 2003).

In this regard, for any developer installing a pervious pavement system even in the area existing in the region which supports infiltration practices, test pits have to be dug and samples analyzed by qualified personnel to determine physical parameters occurring on their site. Possible outcrops can be checked on the surface to ascertain if formations exist which can impede infiltration. Areas located in the peripherals of the wetlands can be checked for water logging. In such areas, it is recommended to install under drain perforated HDPE pipes below the pervious pavement system. The system will not entirely infiltrate the whole detained quantity of stormwater but infiltrate sufficient stormwater in the early stages of the rainy season. After attaining saturation, the remaining stormwater volume drains to the drainage networks leading to streams. In practice, the system is pretreating, reducing quantity and infiltrating a sufficient quantity of stormwater in to the environment. In areas having karsts formations which exhibit porousness, a lining material can be installed below the pervious pavement system with the perforated pipes. This system is lined to entirely not allow any infiltration of stormwater. The stormwater will not infiltrate beyond the lining material and only drain out through the pipes leading into the drainages. This system can possibly be employed in the southern and southwest parts of the urban to protect the Lusaka aquifer from contamination. The liner can be high HDPE and rubber asphalt which is also recommended in areas that are directly over a solid rock with no loose rock layer above such as the northern part, soils that cause unacceptable behavior when exposed to infiltration or expansive soils, soils which have low permeability and strength, and lower depth (0.6m-0.8m) to the water table as exists in some parts of the urban.

6.3 Stormwater-Pervious Pavement Relationship

Stormwater quantities captured below the pavement system are in relation to the area on each site and create a response that maybe predicted. In this relationship, as the size of the reservoir increases to not greater than 0.6m (Smith, 2006), stormwater quantities are expected to increase depending on the void ratio resulting from the aggregates and infiltration rate of the subgrade. The relationship of stormwater contribution in the subgrade depending on the received rainfall on the pervious pavement systems at depth 50cm to 75cm, 75cm-100cm, 100cm to 130cm, 130cm to 160cm and 160cm to 170cm is depicted in Figures 22, 24, 26 and 28. This relationship can be predicted using the tested linear relationships in Figure 22, 24, 26 and 28. Any developer can use the relationship to estimate the possible obtainable relationship if it lies in the tested area. The response to stormwater events at depth 50cm to 100cm below the pavement system indicates an increased moisture reading higher than other depths. This is followed by the response at depth 130cm to 160cm. This depth occurs after a depth of 100cm to 130cm (See Figures 23, 25, 27 and 29). This behavior can be attributed to stormwater transitioning to other depths which results into contribution to groundwater. There is a decrease in moisture accumulation as the depth increases which can be related to natural drainage affected by impeding soil pans and underlying rocks but creates a distinct relationship, while due to more water accumulation in the immediate zone below the pavement system. During the study, the pavements did not experience flooding scenarios. This is attributed to the fact that the subgrade infiltrated all the stormwater which was seen transitioning from depth to depth. The storm events during the study may not have sufficed estimated events that could cause the subgrade's infiltration rate to be overtaken and cause flooding.

CHAPTER SEVEN: CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

The study concluded that pervious pavement (PICP) systems significantly infiltrate large volumes of water in the reservoir. The systems infiltrate sufficient stormwater using locally manufactured pavers with 5mm inbuilt spacers commonly used in the area for constructing impervious pavements. The system can suffice to infiltrate stormwater which ends up as urban floods emanating from continuous impervious surfaces created by intensified urban development. The system infiltrated stormwater to the immediate zone to transition to ground water. The water presented to the immediate zone below the aggregate reservoir ends up as volumes compensating abstraction. The pavement response to stormwater events can be predicted for planning in stormwater management to enhance sustainable urban development. Drainage networks can be integrated with full exfiltration pervious pavements as a best management practice for stormwater management for Lusaka urban especially in parts which exhibited potential to support infiltration practices. The pervious pavement's surface structure will function as a parking lot, or drive way or walk path while allowing large volumes of stormwater to be collected and infiltrate slowly. This will reduce impacts of developments and mimic natural environments. The surface geology existing on some parts of the urban can influence direct recharge of precipitation to the aquifer for Lusaka urban. It is important that the recharge zones remain protected from settlements. The system aids in sustaining the drainage networks from compromise or near failure. The system will reduce cost in other stormwater management facilities which can be compensated by the use of pervious pavements. In future, this can enhance acquisition of stormwater credits to benefit those who incur costs in establishing runoff reduction strategies on their developments.

7.2 Recommendations

The use of full exfiltration pervious pavement systems as a stormwater management strategy for Lusaka urban can be a Best Management Practice amongst other BMPs depending on characteristics prevailing on the area. Drainage networks can be integrated with full exfiltration pervious pavement systems for stormwater management in Lusaka urban. Test pits have to be dug or site information can be sourced to determine depth of soils above the formation or water table in cases where the system can possibly be installed. A design depth can be provided to the developer depending on the existing site characteristics. The Local authority should deliberately step-up regulations on limiting size of area to be kept pervious and impervious on any development depending on the site characteristics and the environmental needs of the area. Adoption of infiltration practices in stormwater management strategies for developers should be guided in their routines and programmes to foster sustainable methods of urban development. Various stormwater management strategies which involve the reuse of stormwater in the environment or other economic activities can be promoted by the local authority. Further research can be conducted on the possible use of non-exfiltration and partial exfiltration. These systems can suffice in reclaimed wetlands and in areas with dolomite and schist formations. Water governance should be considerably extended to stormwater management in urban areas.

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APPENDICES

APPENDIX I: NEUTRONE GAUGE WATER MONITORING DATA SHEET

Name of Data Collector:…………………………………………………………………………..

Name of Site:…………………………………Tube …………………………….

Location/coordinates:……………………………………………………………….

Date:………………………………………..

Time:……………………..Standard/Shield Count:……………………………...

Depth	Count No.	Counts on PAVEMENT TUBE	Counts on CONTROL TUBE
0-20cm	1		
	2		
	3		
Average			
20cm-50cm			
	1		
	2		
	3		
Average			
50cm-75cm	1		
	2		
	3		
Average			
75cm-100cm	1		
	2		

	3		
Average			
100cm-130cm	1		
	2		
	3		
Average			
130cm-160cm	1		
	2		
	3		
Average			
160cm-170cm	1		
	2		
	3		
Average			