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INTEGRATED URBAN DRAINAGE SYSTEM; THE CASE OF AYAT TO MEGENAGNA LIGHT RAIL TRANSIT SYSTEM ROUTE

By

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A thesis submitted to the school of Graduate Studies of Addis Ababa University in partial fulfillment of the requirement for degree of Master of Science in Civil Engineering

Advisor

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Integrated Urban Drainage System; the Case of Ayat to Megenagna Light Rail Transit Route

Master of Science Thesis

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Abstract

Addis Ababa is one of the fastest growing cities in Africa and urbanization is known to increase the amount of runoff generated from the urban catchment. Due to urbanization and lack of proper design and management, the cities transport infrastructure has experienced frequent flooding. The application of Integrated Sustainable Urban Drainage System (SUDS) is a recent trend in developed countries (like the UK) for flood mitigation with added benefit of amenity and water quality. The aim of this study was to assess SUDS applicability in solving the existing drainage problem and minimizing the flood risk associated to transport infrastructure.

In this study Ayat to Megenagna section of the Addis Ababa Light Railway Transit (LRT) line was chosen as a study area. Areas along the route with drainage problems have been identified and catchment was delineated. IDF curves were developed and rational method was used to estimate the existing runoff. Rooftop rainwater harvesting and rain gardens were proposed to solve the drainage problem. A tool that uses daily rainfall records of 30 years is developed in Microsoft Excel to quantify the amount of runoff reduction that can be achieved by using SUDS. The tool calculates the percentage of runoff that can be intercepted using a given storage capacity of rainwater harvesting system for a given daily non potable water demand. The tool is developed in such a way that allows modelling of different demand and storage size scenario.

The result is presented in terms of a typical 90 square meters' parcel found in the study area of which 89% is covered with roof area and 11% with rain garden. For daily non potable water demand of 257 liters it is found that the optimum storage tank capacity is 1500 liters. Using a tank of 1500 liters' storage capacity, the percent reduction in runoff that can be achieved is found to be 51% of runoff generated from rainfall of 2cm or less depth. This shows that considerable runoff reduction can be achieved using rainwater harvesting and rainwater gardening. These study shows that integrated sustainable drainage systems can be used to protect transport infrastructure along Ayat to Megenagna route and the author recommends further detailed study and implementation.

Keywords: Integrated Sustainable Drainage System, Source Control, Runoff Reduction Tool, Rainwater Harvesting, Light Railway, Addis Ababa

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Acronyms and Abbreviations

AA LRT	Addis Ababa Light Rail Transit
AACRA	Addis Ababa City Road Authority
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
BMP	Best Management Program
BIOECODS	Bio-Ecological Drainage System
CIRIA	Construction Industry Research and Information Association (UK)
CSA	Central Statistical Agency (Ethiopia)
DEFRA	Department for Environment Flood and Rural Affairs (USA)
DEM	Digital Elevation Model
ERA	Ethiopian Road Authority
ERC	Ethiopian Railway Corporation
GDEM	Global Digital Elevation Model
GOF	Goodness of Fit
IDF	Intensity Duration Frequency
IUDS	Integrated Urban Drainage System
LID	Low Impact Development
NASA	National Aeronautics and Space Administration (USA)
RWH	Rainwater Harvesting
SUDS	Sustainable Urban Drainage System
UDFCD	Urban Drainage and Flood Control District (USA)
UN HABITAT	United Nations Human Settlements Program
US EPA	United States Environmental Protection Agency
WSUD	Water Sensitive Urban Design

1. Introduction

1.1. Background

Cities are where human beings pursue fulfillment of basic needs and where they obtain essential public goods. In cities most of the time various products and services can be found abundantly. Cities are also where ambitions, aspirations and other intangible aspects of life are realized, providing contentment and happiness and increasing the prospects of individual and collective well-being. That is why more than half of the world population is now living in urban areas, urbanization and migration to urban areas having their fair share.

In the last quarter of 2011, the world population reached the seven billion mark (UN HABITAT, 2013). It took only 12 years to add one billion to the six billion population. It took 123 years to double from one to two billion. These numbers highlight the extent to which the world population has increasingly come to live in urban areas since more than half of this population is living in urban areas.

The fascinating fact in the urbanization trend of the world, as stated by the United Nation’s State of the World’s Cities 2012/2013 report, is the fact that in 2025 Africa’s urban population will outgrow Europe’s and Latin America’s urban population. In 2025, the aggregate urban populations of Africa, Europe, Latin America and the Caribbean are expected to reach 642 million, 566 million and 560 million, respectively (UN HABITAT, 2013).

Urbanization is accompanied by two major changes. The first change is the urban centers tend to concentrate people, enterprises, infrastructures and public institutions. The second change is the large scale urban spatial expansion as cities and towns swell and grow outward in order to accommodate population increases. These changes alter the natural landscape, land uses and land cover.

Infrastructure is the physical structures needed for society to operate. It is described as the foundation for economic productivity and human wellbeing because it provides the energy and water resources that society needs to function, and enable people, information and goods to move efficiently and safely. Hence the growth of a city or an urban center is greatly synonymous with the growth of its infrastructure.

As the amount of infrastructure grows it comes with a consequence to natural hydrological makeup of the urban area. Before the increase of built up percentage, greater amount of rain water used to percolate through the earth surface and join the ground water or be used by the plants. Increase in the built up areas will alter the hydrological makeup by blocking natural streams or\and by reducing the water absorption capacity of the surface. This will result in the demand for a manmade drainage infrastructure in order to deal with the water that ‘lost its way by human action’.

History of human society and its ancient civilization show that urban drainage systems were constructed with great care from early beginning. Historical accounts show that the objectives of the systems were to collect rainwater, prevent flooding, and convey wastes. By 21st century human civilization has learned from its experience that building large drainage infrastructure only won't solve drainage problem of urban areas. Hence the concept of Integrated Sustainable Urban Drainage System is born.

Integrated sustainable urban drainage usually means different things for different people. In this study the definition of United Kingdom Department of Environment, Food and Rural Affairs is adopted. Accordingly integrated urban drainage is defined as management of the risk arising from drainage and flooding in urban areas (encapsulating surface water management planning) through a portfolio of approaches (Balmforth, et al., 2009). Managing the risk that arise from drainage and flooding in urban areas is a complex task and integrated urban drainage recognizes this complexity. Integrated urban drainage delivers full suite of techniques, adaptation and resilience measures that integrate in a sustainable manner to manage the urban flood risk through the coordinated approach from different stakeholders. Among the techniques promoted by integrated urban drainage system are the implementation of sustainable urban drainage system, rainwater harvesting and reuse, improving water management and environmental protection while contributing to biodiversity and amenity objectives are the few.

Addis Ababa is one of the rapidly urbanizing cities of the world. Its geographic location in the center of Ethiopia, combined with lack of development policies in other urban centers have given the capital the majority of social and economic infrastructure in the country. As a result, it has been a melting pot to hundreds of thousands of people, coming from all corners of the country in search of better employment opportunities and services. Because of rapid population growth Addis Ababa, one of the fast growing cites in Africa, is facing critical challenges. Among the challenges of the city are high rate of unemployment as well as housing and transportation shortage.

Infrastructure developments that solve the problem and realize the cities path to be a megacity are currently underway. This urbanization process will increase the impermeable surfaces and become major flood risk unless proper drainage design and mitigation measures are taken.

Service life of infrastructure can be highly reduced by improper drainage system. It can be seen from rainy season which lasts from July to September that the highways are covered by surface water. This water accelerates the deterioration rate of the roads and results in economic loss. The flooding of the highways is the result of improper drainage system of the roads and poor integration of road and urban storm water drainage network (Ewnetu, 2013).

The new Addis Ababa Light Railway Transit System (AA LRT) project is part of the cities urbanization process that is intended to solve the transportation problem of the capital. The project will add another variable to the existing drainage network. This results in the need for an integrated drainage system, as an alternative design strategy to the conventional method, in order to protect the newly built LRT system and areas affected by it.

1.2.Problem Definition

Storm drainage systems of a city are ideally aimed to handle peak flow resulting from rainfall of return period equal or greater to their design year. Drainage system of a road or railway are expected to function smoothly in handling flow along or across their alignment. Unfortunately, it is almost usual to observe flooding of drainage system of Addis Ababa after every rainfall.

The inconvenience to the road users and threat to the local community added to the economic damage of infrastructure that can be caused by it, flooding is a critical challenge that is intensified by urbanization. Conventionally this problem is being addressed by designing and building drainage infrastructure of larger dimensions to convey flood downstream, if it is being addressed at all. The conventional philosophy of designing large drainage systems is problematic in two regards. First the parameters involved in the design are subject to continuous change because of the rapid urbanization the city is going through. Second conveying large amount of flow by large drainage infrastructure possess greater threat at downstream population, even if it protects the immediate infrastructure it is built to protect.

Using a wider range of methods instead of just building a barrier or a conveyance would assure a more resilient and dependable flood control solution. This thesis aims to propose an integrated urban drainage system as a solution to flood risk associated to the Addis Ababa Light Rail Transit System as well as the road network. Integrated drainage system would address the risk of flooding to the LRT through multiple solutions that address the risk from its source using sustainable mechanisms. The LRT is located on the already problematic road and this study will show how integrated drainage system could be used to protect both the road and railway infrastructure as well as the community by addressing existing challenges of the road and the new ones created by the LRT.

1.3.Objective

1.3.1. General Objective

The general objective of this research is to assess the applicability of integrated sustainable drainage system in solving the existing drainage problem and minimizing flood risk to the railway infrastructure along the Ayat to Megenagna route.

1.3.2. Specific Objectives

- To identify areas along the route with drainage problem
- To delineate the catchment contributing flows to those identified areas
- To estimate the amount of runoff before designing integrated drainage systems.
- To propose integrated sustainable drainage systems
- To estimate the amount of runoff reduction due to the proposed integrated drainage systems

1.4. Thesis Outline

The thesis is made up of seven chapters. The first chapter introduces the thesis. The second chapter presents knowledge from literatures that are reviewed in a way that explains the theoretical background and the gaps in other works as well as experiences from other countries. The third chapter is all about the study area. It starts with the whole Addis Ababa and goes into detail of Ayat to Megenagna route of the light rail transit system and then to a specific location along the route.

The forth chapter, data and analysis methods, discusses the data used and mentions their source as well as the data screening and comparison made. It also contains the detail analysis methods employed together with justification of methods used. Hydrological results of the catchment prior to design of integrated drainage system are presented in the fifth chapter. The sixth chapter is where integrated urban drainage system is presented as an alternative to conventional hydraulic design. Design tool for efficient rainwater harvesting system is developed and its impact in controlling runoff is shown. The last chapter concludes the work and give recommendation for future work.

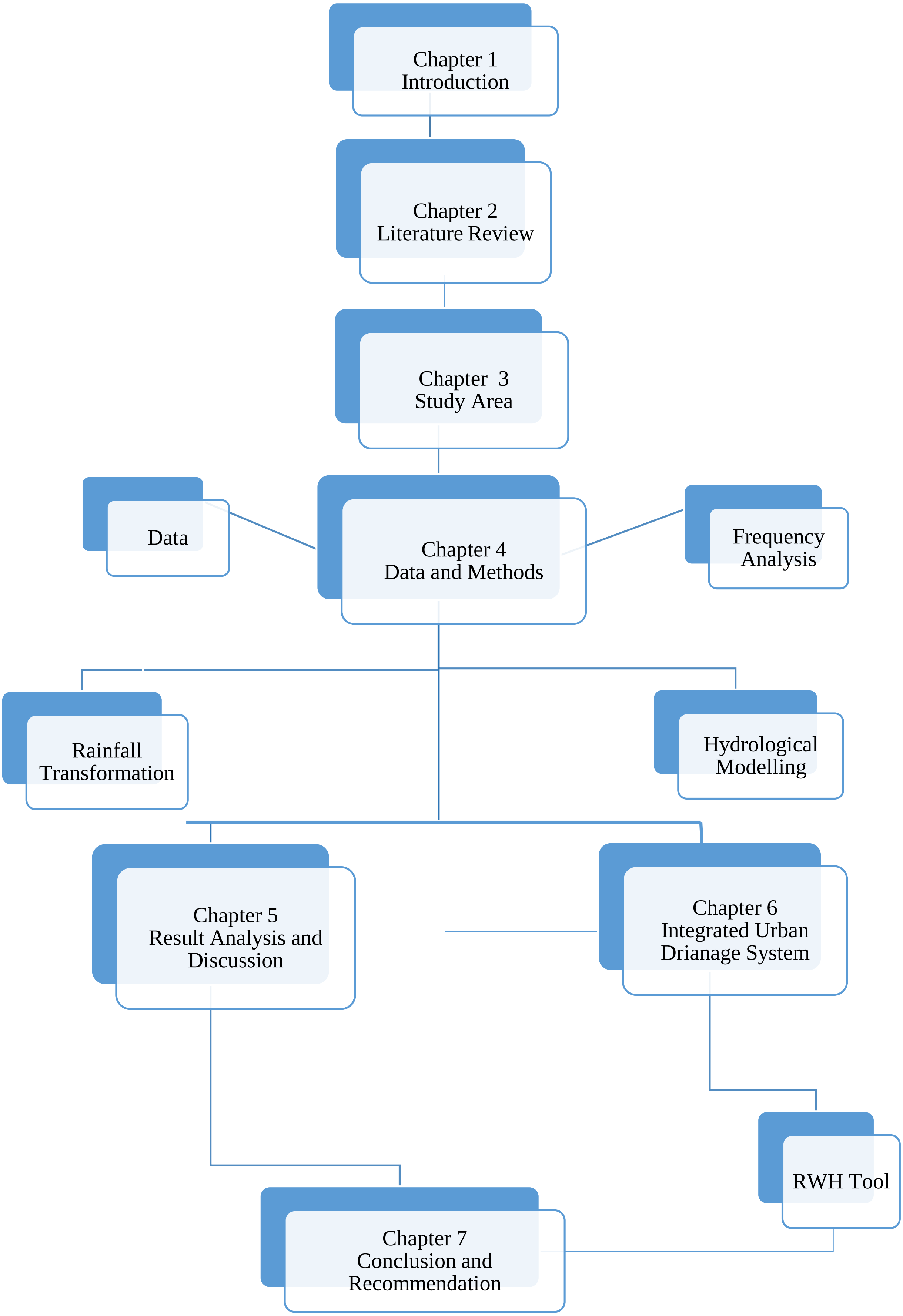


Figure 1: Outline of the thesis

2. Literature Review

This section of the thesis includes three subsections. The first subsection presents review of literatures on drainage problem of Addis Ababa. The second subsection present theoretical backgrounds and how integrated urban drainage system is being used as solution. The last subsection presents the experiences from cities in United States of America, United Kingdom and India.

2.1.Studies on Drainage issues of Addis Ababa

In order to establish the fact that drainage problem exists in the city and to understand the works that are done, literatures are reviewed. The literatures showed no doubt on the existence of drainage problem in the city. The presentation of the problems in the literature are presented either in the form of malfunctioning of specific component of the urban transportation or broader problems on urban drainage systems themselves.

Two studies on drainage problems that exist in Addis Ababa city are reviewed in this sub section. Both studies are performed by post graduate students of Addis Ababa University. The first thesis is titled, "*Study of the Urban Drainage System in Addis Ababa, Yeka Sub city*" (Dagnachew, 2009). The second thesis is titled, "*Investigation on Storm Drainage Problem of Addis Ababa - Case Study at Gotera – Wollo Sefer, Saris - Gotera and Ring Road"* (Desalegn, 2011). The objectives, methods and results of both these are presented in brief with their shortcomings.

i. Study of Urban Drainage System in Addis Ababa, Yeka Sub city

The of objectives of the study are the following.

- To identify the major challenges in urban drainage management system.
- To investigate the impact of Yeka mountain on Yeka sub city.
- To discover the major impacts of the urban storm water drainage system on existing natural water ways.
- To assess the level of integration between road and urban storm water drainage infrastructure.
- To design urban storm water drainage network as an option to sustainably manage the urban storm water drainage system.

The methods employed by the author to attain the above stated objectives is mainly site observation and photographs. The author has used rational method of runoff analysis to show the impact of land use change of Yeka Mountain by varying runoff coefficient. Even though rational method is not the right choice for a large area as that of the Yeka Mountain he has tried to highlight the impact of deforestation on downstream population. Dagnachew have considered only reforestation and deforestation aspects of Yeka Mountain to control the amount of runoff generated. But it is known that the expansion of housing to the area has happened and reforestation seems unlikely solution. A broader source control strategy must be sought for to solve the eminent problem.

The study goes on to discuss nonpoint pollutions to Kebena, Hanku and Jelisa rivers in the study area. Good survey has been made to evaluate the density of storm drainage infrastructure and on average only 3.2 percent of the roads have some sort of drainage infrastructure at the time of the survey i.e. 2009. The author has performed design of trapezoidal, rectangular and circular storm drainage lines that would increase their density. What the study failed to consider is the high urbanization rates that are taking and will take place in the area. The increase in the impervious areas requires more than just building drainage structures that quickly drain off stormwater.

Among the recommendation of the study is reforestation of Yeka Mountain which according to the author will decrease the runoff coefficient from 0.7 to 0.25. Mr. Dagnachew also recommends the proper maintenance of the existing urban drainage networks. Another important recommendation made is the need for sustainable urban drainage system such as rainwater harvesting.

ii. Investigation on Storm Drainage Problem of Addis Ababa - Case Study at Gotera – Wollo Sefer, Saris - Gotera and Ring Road

The author set to work with aim of investigating storm drainage problems, design and construction issues on selected roads in Addis Ababa and provide appropriate solution for problems. Congested traffic due to flooding of roads after small depth of rainfall, erosion of pavements resulting in reduction of service life of road infrastructure and impact of road flooding on nearby population have motivated the author.

In the study condition survey is performed to assess status of drainage system elements such as manholes and their inlets. The data from survey together with original design were used to investigate the construction and maintenance performance. The original hydraulic design is reviewed by the author and a modified design was undertaken. The thesis tries to formulate the idea that good design, construction and maintenance of drainage infrastructures solve the flooding problem completely. That is why the concluding remarks of the author ask for small inlet spacing, higher inlet efficiency and frequent maintenance. Those suggestions made by the study are necessary but not adequate. Other proactive solutions, that aim to handle flood from its creation, as opposed to reactive solutions, that aim to dispose the generated runoff to downstream at any cost, need to be found.

In the remaining section of the literature review what other countries have found as a solution to urban flooding and their experience are presented on a case study basis.

2.2. Urban Drainage Systems

2.2.1. Historical Development of Urban Drainage Systems

History of human society and its ancient civilization show suggest that urban drainage systems were constructed with great care. Furthermore, historical accounts show that the objectives of the systems were to collect rainwater, prevent flooding, and convey wastes. They were able to find the systems that met their objectives after trial-and-error modifications. At the time, planning and design were limited. Few numerical standards existed for urban drainage and engineering calculations were not used during design. Despite the lack of optimization and the use of trial-and-error construction methods, numerous ancient urban drainage systems can be rated very successful. Lewis Mumford summarized the state of ancient urban infrastructure when he stated that ancient sewer systems were an uneconomic combination of refined technical devices and primitive social planning (Burian, 2004).

Urban drainage was firmly established as a vital public works system in the early parts of the twentieth century. Engineers continued to improve design concepts and methods. During the second half of the twentieth century regulatory elements were spread in the United States, Europe, and other locations addressing urban drainage issues. Computer modeling tools advanced the methods used to design and analyze urban drainage systems. Regulations, monitoring, computer modeling, and environmental concerns have altered the perspective of urban drainage from a public health and nuisance flooding concern during the first half of the twentieth century into a public health and nuisance flooding with additional concerns for ecosystem protection and urban sustainability.

Communities worldwide are yet searching for innovative techniques to capture, detain, and use rainwater within the watershed instead of constructing massive drainage structures. Many communities are developing watershed-wide stormwater quality management plans to meet the dual objectives of flood prevention and water quality control. Urban drainage has indeed expanded significantly during the past few decades beyond a technical challenge to drain the urban area rapidly to include the consideration of social, economic, political, environmental, and regulatory factors.

2.2.2. Sustainability in Urban Planning

According to the United Nations, the world’s population has recently become predominantly urban, and the total world urban population is projected to double by 2050. Because of the urbanization trend, the U.N. Habitat has reasoned that “the millennium ecosystem goals will be won or lost in cities!” (UN HABITAT, 2013). This reality has made different disciplines such as civil engineering, urban planning and architecture to focus on developing and testing new theories, strategies, and best practices to enhance the sustainability of cities. To tackle economic, social and environmental sustainability in an integrated way experts from design and planning disciplines are demanded to engage in interdisciplinary practice with economists, social scientists, biologists and other engineers. Beyond sustainability research and practice also engages the stakeholders and decision makers, in a genuine and meaningful manner, throughout a continuous, interactive, and iterative process of urban planning and design. (Tress, et al., 2005)

Unlike the historical drainage systems that would aim to collect and dispose of water as quickly as possible which have an adverse effect on the receiving infrastructure nowadays an alternative approach is being utilized. This alternative approach aims to reduce the volume of water discharged to the receiving body of water. It will do so by encouraging the infiltration of water into the ground, and by providing water storage within the drainage system to attenuate the peak discharge. Hence downstream receiving infrastructure do not have to cope with a greater volume of flow and a higher peak discharge any more. A number of techniques are available for achieving this which are collectively known as Sustainable Drainage Systems.

The experiment in urban sustainability planning and design is evolving rapidly through theoretical research, innovative urban policies, and pilot or demonstration projects intended to test new approaches at pilot scale. Among these pilot initiatives are Low Impact Development (LID), green urbanism, and ecological urbanism are the prominent ones.

Water is essential for all life because it is the universal solvent that transports and redistributes nutrients and pollutants across entire watersheds. But urbanization itself threatens future water quality and management for urban uses in most cities of the world. Therefore, sustainability of water resources is the central challenge for sustainable urbanism

Urban planning and design can play a key role to preserve, protect, restore and reuse the full spectrum of water uses that cities depend on, including: drinking water provision; wastewater collection, treatment, disposal, and reuse; stormwater management; and innovative, more holistic systems to create a new urban hydrological cycle (Natural Resources Defense Council, 2014).

To achieve sustainability and resilience in cities, urban infrastructure must be reconceived and understood as a means to improve and contribute to sustainability. Arguably, achieving sustainability will depend on significant innovations. In the 21st century, much of the infrastructure of the developed world will be replaced or rebuilt, and even more infrastructure will be needed to service the rapidly expanding cities of the developing world (Nelson, 2004). This can be viewed as an opportunity, the magnitude of global infrastructure development represents an extraordinary opportunity to redirect and reconceive the process of urbanization from one that is inherently destructive to one that is sustainable in specific terms.

Innovative urban planning and design is possible where ambitious goals for multiple aspects of sustainability can be adopted to guide and focus the design process, including: a sustainable urban hydrology model, zero net energy use, a mix of urban uses, inclusion of biodiversity, and providing a healthy environment for people. The planning and design disciplines have developed a significant body of knowledge with respect to sustainable water resources, and more recently have begun to use cities as laboratories to test new practices and thereby promote innovation (Kato & Ahern, 2008).

Urban planning is inherently a strategic process because, rather than employing tactics to respond to urban changes it attempts to understand and proactively manage the elements and forces that causes change (Ahern, 1995) (Sijmons, 1990). By definition planning is proactive, but not all planning is strategic. For urban planning to be strategic, it requires integration of interdisciplinary knowledge to define strategic goals consistent with political expectations, economic factors, and the reality of the existing landscape condition. Strategic urban planning requires a particular blending and integration of knowledge, vision, creativity, and political skills.

2.2.3. Integrated Urban Drainage Systems as Solution

Integrated urban drainage is defined to mean different thing by different people. But every definition includes the fact that integrated urban drainage must recognizes the complexity of managing risk arising from drainage and flooding in urban areas. Furthermore, it utilizes coordinated effort from different stakeholders to deliver full suite of techniques, adaptation and resilience measures that integrate in a sustainable manner to manage flood risk.

According to United Kingdom’s Department for Environment Flood and Rural Affairs (DEFRA) research framework for implementing integrated urban drainage, it is defined as management of the risk arising from drainage and flooding in urban areas through a portfolio of approaches (Balmforth, et al., 2009).

Worldwide number of different countries are working toward integrated drainage, either on its own or as part of a broader approach to managing the water cycle. In United Kingdom the term Sustainable Urban Drainage System (SUDS) is used to mean integrated urban drainage system, as integration of drainage system with the environment ultimately lead to sustainability. In United States integrated drainage is often referred to as Best Management Practices (BMPs), or Low Impact Developments (LIDs). In Australia it is often incorporated in Water Sensitive Urban Design (WSUD), and in New Zealand the term Low Impact Urban Development is used. The following paragraphs will try to discuss integrated drainage systems as defined by United States and United Kingdom together with their components so that suitable ones could be adopted for this thesis.

United States Environmental Protection Agency (EPA) calls the practices for controlling stormwater runoff volume and reducing pollutant loadings to receiving waters as Low Impact Development (LID). According to the agency LID is a site design strategy with a goal of maintaining or replicating the predevelopment hydrologic regime through the use of design techniques to create a functionally equivalent hydrologic landscape (US Environmental Protection Agency, 2000). Hydrologic functions of storage, infiltration, and ground water recharge, as well as the volume and frequency of discharges are maintained through the use of integrated and distributed micro scale stormwater retention and detention areas, reduction of impervious surfaces, and the lengthening of flow paths and runoff time.

The principles of LID are based on controlling stormwater at the source. Those principles focus on conservation of natural features, minimization of impervious surfaces, hydraulic disconnects and disbursement of runoff. LID practices such as bio-retention facilities or rain gardens, grass swales and channels, vegetated rooftops, rain barrels, cisterns, vegetated filter strips and permeable pavements perform both runoff volume reduction and pollutant filtering functions.

Construction Industry Research and Information Association (CIRIA) of United Kingdom uses the term Sustainable Urban Drainage System (SUDS) to refer to drainage methods that can mitigate adverse effects of urban stormwater runoff on the environment. According to CIRIA SUDS mitigate storm runoff effects through the following ways (CIRIA, 2007).

- reducing runoff rates by attenuation
- reducing excess runoff volumes that result from urbanization
- encouraging natural groundwater recharge
- reducing pollutant concentrations in stormwater, and protecting the quality of the receiving water body
- acting as a buffer for accidental spills by preventing direct discharge of high concentrations of contaminants to the receiving water body
- contributing to the enhanced amenity and aesthetic value of developed areas
- providing habitats in urban areas and opportunities for biodiversity enhancement

Sustainable drainage uses both landscaped features and harder engineering (CIRIA, 2010). Landscaped features include green roofs, and more natural features such as ponds, wetlands and shallow vegetated channels called swales. Harder engineered SUDS components, such as permeable paving, and soak-away can be used and often are incorporated into high density developments.

The introduction of Sustainable Urban Drainage Systems (SUDS) is seen as a means to redress the balance and manage surface water runoff within the urban environment in a fashion that minimizes the impacts of development on the quality and quantity of runoff, whilst maximizing amenity and biodiversity opportunities. The three-way urban drainage triangle is illustrated in Figure 2.

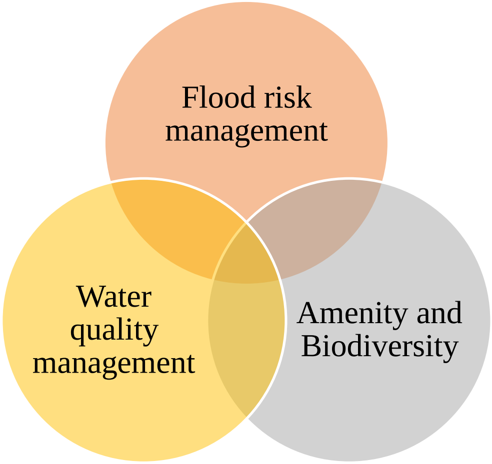


Figure 2: The SUDS Triangle (Adopted from CIRIA, 2010)

Different SUDS alternatives, their description, use, place of application and state of their benefit for flood risk, water quality and amenity purpose is summarized in the flowing table.

Table 1: Components of SUDS (Adopted from CIRIA, 2010)

	Description	Use	Where to apply	Decrease quantity	Increase quality	Amenity and biodiversity benefits
Green roofs	Covering roof of building with vegetation	To control runoff close to source.	Private on piece of land (Source Control)	Good	Medium	Good
Soakaways	Excavation or trench that can be filled with filter material. Allows water to soak away into the ground	To store runoff, filter out pollutants and recharge groundwater	Private (SC) Also next to roads. Can be easily retrofitted	Good	Good	Low
Rainwater harvesting	System to collect water from impermeable surfaces for use in non-potable water situations	Reduce the amount of potable water use	Private (SC)	Good	Medium	Medium
Permeable pavements	Surface that allow water to soak into the ground or a gravel filled base.	Water is stored in the base and released gradually. Can be used in permeable and impermeable ground conditions	Private (SC), car parks and some roads.	Good	Good	Low

	Description	Use	Where to apply	Decrease quantity	Increase quality	Amenity and biodiversity benefits
Geocellular / Modular systems	Modular plastic system that can be used to create below ground infiltration or storage	Can both store and allow infiltration of water.	Driveways, car parks, next to roads.	Good	Low	Low
Channels and rills	Open landscaped channels which can be vegetated, used to convey water from one SuDS component to another.	Used to convey water and can provide some storage	In small land, in open space	Medium	Good	Good
Bio-retention	Depressions backfilled with a sand/soil mixture and planted with vegetation. Water enters through a vegetated surface and then trickles via a filter layer entering a perforated pipe at the bottom before being carefully transported downstream.	To store water and release it gradually. Some water quality improvement is provided by a filter layer.	Private (SC), in open space, next to roads and parking.	Good	Good	Good
Infiltration trench	Stone filled trenches that allow water to soak into the ground, as close to where the rain lands as possible.	To control the amount of runoff and provide storage. Needs permeable ground condition	Open space next to roads and car parks.	Good	Good	Good
Filter strips	A vegetated area of gently sloping ground designed to drain water evenly off impermeable areas and filter out silt and other material.	To filter out pollutants especially sediment, before runoff entering another SuDS component or watercourse	Open space, next to road and car parks	Medium	Good	Medium
Filter drain	They are gravel filled trenches with a pipe with small holes installed in the bottom	The gravel slows the flow by storing water and releasing it gradually. Requires periodic maintenance	In open space, next to roads and car parks	Good	Medium	Low
Swales	Shallow vegetated swales that can run parallel to hard surfaces, allowing runoff to trickle down the side slopes and into the base of the component.	To treat and attenuate runoff.	In open space, next to roads and car parks	Good	Good	Good

	Description	Use	Where to apply	Decrease quantity	Increase quality	Amenity and biodiversity benefits
Trench troughs	Open landscaped channels which can be vegetated, over filter medium and under-drained. Used to convey, attenuate and improve water quality.	Used to convey water. Will provide some storage and attenuation.	In open space.	Good	Good	Good
Detention basin	Shallow vegetated depressions to control the amount and rate of runoff and some water quality improvement.	To store water during large storms, and release it gradually.	In open space	Medium	Good	Medium
Wetland	Retention ponds with more emergent aquatic vegetation and a smaller open water area.	The wetlands store water and release it slowly. Sediment removal also takes place through settlement and biological treatment occurs	In open space, next to roads and car parks	Good	Good	Good
Retention ponds	Artificial ponds with an open water area and marginal wetland around the edge.	Ponds store water and release it slowly, allowing sediment to settle and biological treatment.	In open space	Good	Good	Good

2.3.Experiences

2.3.1. Experience from United States

Urbanization and the related increase in imperviousness is not challenge unique to Addis Ababa. Increase in imperviousness and the resulting increase in stormwater runoff is a challenge every city has to face. In this subsection case studies of different cities in United States of America is reviewed. Integrated drainage systems or Low Impact Development (LID), as they are called in USA, used for runoff reduction and other benefits are briefly presented.

i. Canal Park, Washington DC

The first LID project that will be discussed is located in the capital of USA, Washington DC. Canal Park, Washington DC project transformed a once empty lots that were not used for any purpose other than car parking into something that create a public amenity and enhances the community by providing environmental benefits. The site is developed to serve as both a park and a neighborhood stormwater retention area to capture, treat, and use runoff collected onsite and from adjacent residential and commercial properties (U.S. EPA, 2014).

The land where Canal Park area is located is owned by federal government, this shows similar setting to our country where all land is owned by government. The development though is made by public and non-profit private entities partnership. The area of the site is 1.2 hectare and the drainage area it serves is 1.6 hectares. The constructed green infrastructures are rain gardens (on 700 square meter), tree planters, permeable pavers, rainwater harvesting and a green roof. These LID features are sized to retain at least 3 cm of rainfall from a 24-hour storm on site. Rainwater harvested from adjacent parcels are directed to the park’s stormwater features in addition to the surface rainfall already captured on the site and from adjacent streets.

The annual benefits of Canal Park LID are as follows;

- Capture 10,800 cubic meter of stormwater runoff through the rain garden/rainwater harvesting system and tree planters
- Infiltrate 3,200 cubic meter of stormwater directly into the ground through tree pits and permeable pavers
- Use 5,700 cubic meter of stormwater runoff for irrigation, bathroom facilities, and outdoor amenities such as the ice skating rink and interactive fountains
- Meet 66% of the park’s non-potable water demand
- Avoid the cost of treating and delivering 5,700 cubic meter of potable water
- Reduce the amount of stormwater by up to 8,900 cubic meter annually from entering downstream drainage infrastructure.

ii. Sun Valley Watershed, California

Encompassing communities of Sun Valley and North Hollywood, the Sun Valley watershed is located in the San Fernando Valley about 22 kilometers northwest of downtown Los Angeles. The watershed is approximately 11.4 square kilometers (U.S. EPA, 2013).

Sun Valley watershed is good illustration of how green infrastructure can be used to reduce localized flooding. Before the application of green infrastructure, the area has been faced with the need to solve its frequent flooding problems. During rainfall events, stormwater flows are conveyed along street surfaces, and water collects at several of the major intersections in the area, similar to the problem of Addis Ababa. In addition to flooding problems, reduced groundwater availability of groundwater supplies has occurred due to reduced infiltration and recharge.

To alleviate the area's flooding problem LA Department of Public Works compared two alternative solutions i.e. constructing a system of storm drains or constructing a series of LID oriented solutions. LID alternatives are chosen for implementation because of three reasons. The first, LID alternatives offer multipurpose approach to stormwater management that is responsive to the need to integrate flood control, stormwater pollution reduction and water supply efforts. Second they address additional community issues, such as lack of recreational resources, wildlife habitat, and aesthetic amenities in the watershed. The third reason is that LID oriented solutions yield a much higher benefit to cost ratio over their lifespan.

The types of LID solutions are focused on infiltration, water conservation, stormwater reuse and subsurface conveyance systems and site specific BMPs such as mulching (covering the earth with decaying leaves or bark) and tree planting. These LID solutions reduced stormwater runoff by 50 percent.

2.3.2. Experience from United Kingdom

As presented in the previous sub section urbanization and the related increase in imperviousness is not challenge unique to Addis Ababa. Increase in imperviousness and the resulting increase in stormwater runoff is a challenge every city has to face. In this subsection case study of a city in United Kingdom is reviewed. Integrated drainage systems or Sustainable Urban Drainage Systems (SUDS), as they are called in UK, used for runoff reduction and other benefits are briefly presented.

i. Norwood, Lambeth, London

Chatsworth Way and Ardlui Road are found in the residential area of Norwood. They were at high risk of flooding prior to implementation of SUDS. The two roads fall within a critical drainage area as identified by Lambeth authorities.

The main SUDS used are rain gardens. A site suitable design was used for the rain garden which allows above and below ground storage, using materials which are readily available.

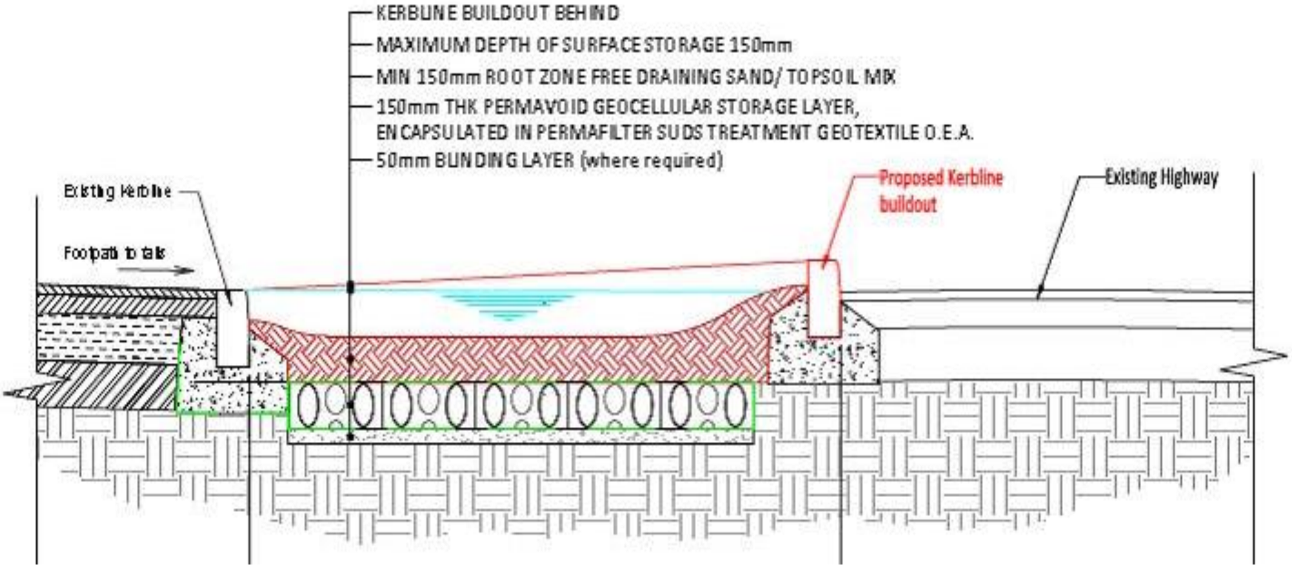


Figure 3: Rain garden with underground storage used in Norwood

(Wilson & Pennington, 2014)

The benefits of installing the rain garden manifested themselves shortly after their construction. On Ardlui Road with medium infiltration for a hundred year return period rainfall event the application of rain garden has resulted in 4 percent reduction in runoff which is the worst case compared to Chatsworth Way. On the other hand Chatsworth Way runoff have reduced 16 percent for the same return period rainfall event which is the best case (Wilson & Pennington, 2014).

2.3.3. Experience from Malaysia

In previous two subsections experiences from United States and United Kingdom were presented. In this subsection experience from pilot projects undertaken in Malaysia is presented.

i. Bio-ecological Drainage System at Universiti Sains Malaysia

Universiti Sains Malaysia (USM) Engineering Campus has taken a series of measures to reduce runoff rates, runoff volumes and pollutant loads by implementing a source control approach for stormwater management (GHANI, et al., 2008).

The sustainable solution includes a series of components namely ecological swale, on-line underground storage, and dry ponds as part of the Bio-ecological drainage systems that contribute to the treatment of the stormwater before it leaves the campus. This system was designed to combine infiltration, delayed flow, storage and purification as pre-treatment of stormwater before discharging to constructed wetlands. In addition to source controls; these measures include integrating large-scale landscapes into the development as a major element of the stormwater management system. The detention pond provides the function of a stormwater detention, solids settling, and biological treatment. Finally, wetlands provide both stormwater detention and biological treatment prior to the runoff entering the recreational pond. All of these benefits help to ensure that the final discharge from a sustainable urban drainage system will not pollute rivers, nor create flooding downstream.

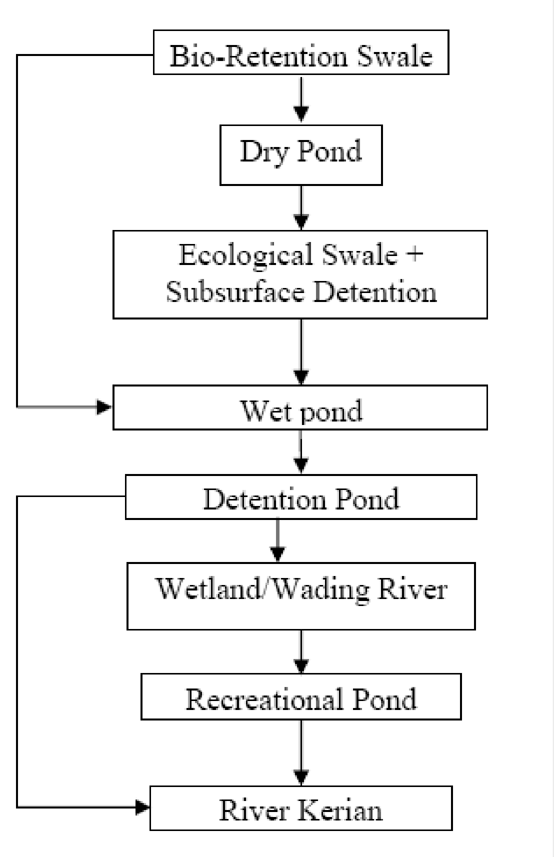


Figure 4: Schematic diagram of BIOECODS

The dry swales are designed for 10-year flood with a slope of 1 in 1000. The wet pond is designed for 10-year flood and detention pond 50-year flood. The wetland purifies stormwater for up to 2-year flood. The results on peak flow attenuation and stormwater treatment throughout the system are given in the following figure.

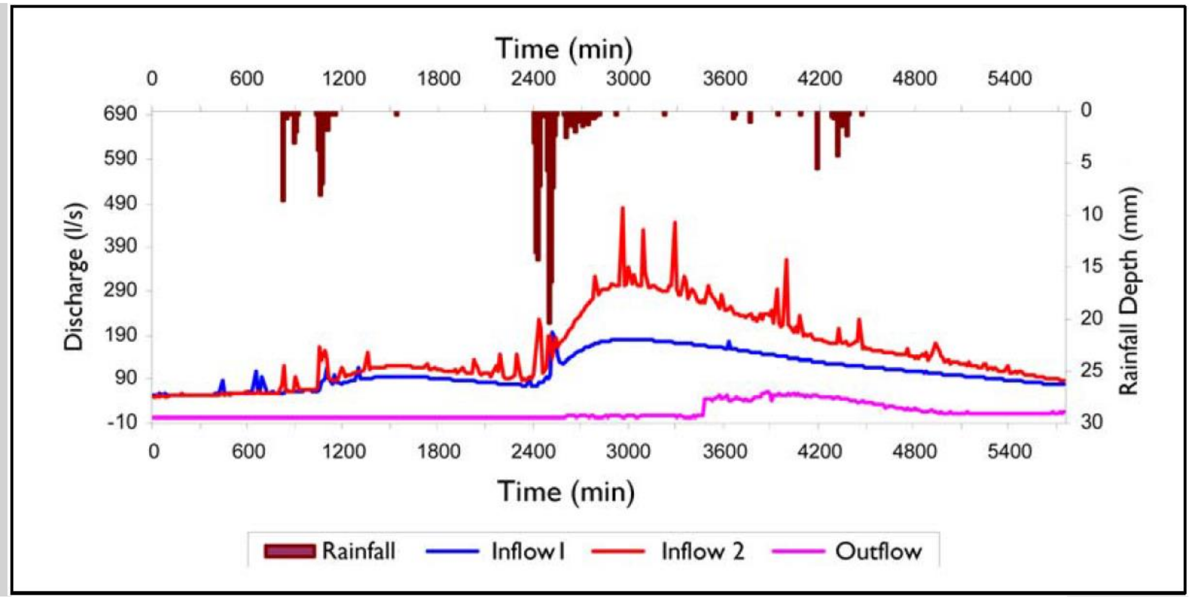


Figure 5: Peak flow attenuation during a 100-year event (21st - 24th July 2007)

3. Study Area

3.1. Addis Ababa

Established in 1886 by Emperor Minilik II, Addis Ababa is one of the oldest and largest cities in Africa (UN-HABITAT, 2008). Being the capital of a non-colonized country in Africa, Addis Ababa has been playing a historic role in hosting the regional organizations such as the Organization of African Unity / African Union, and the Economic Commission for Africa, which contributed to the decolonization of African countries, and later bringing Africa together.

Addis Ababa is one of the rapidly urbanizing cities of the world. Its geographic location in the center of Ethiopia, combined with lack of development policies in other urban centers have given the capital the majority of social and economic infrastructure in the country. As a result, it has been a melting pot to hundreds of thousands of people, coming from all corners of the country in search of better employment opportunities and services. Because of its rapid population growth Addis Ababa, one of the fast growing cites in Africa, is facing critical challenges. Among the challenges of the city are high rate of unemployment as well as housing and transportation shortage.

The new Addis Ababa Light Rail Transit system project is part of the cities urbanization process that is intended to solve the transportation problem of the capital. The fact that the project is located in Addis Ababa is the reason of choosing the city as study area. The project will add another variable to the existing drainage network. This results in the need for an integrated drainage system, as an alternative strategy to the conventional design, in order to protect the newly built LRT system and areas affected by it.

Figure 6: The nearly complete AA LRT System (photo taken on June, 2015)

3.1.1. Location

Addis Ababa is located at the center of Ethiopia between latitude of $8^0 50' 11''$ - $9^0 05' 29''$North and longitude of $38^0 39' 40''$ - $38^0 54' 57''$East on Universal Transverse Mercator projection. The capital lies at the foot of Mount Entoto which is 3400 meters above sea level and extends south wards to its lowest point near to 2000 meters above sea level around Akaki i.e. south most edge of the city.

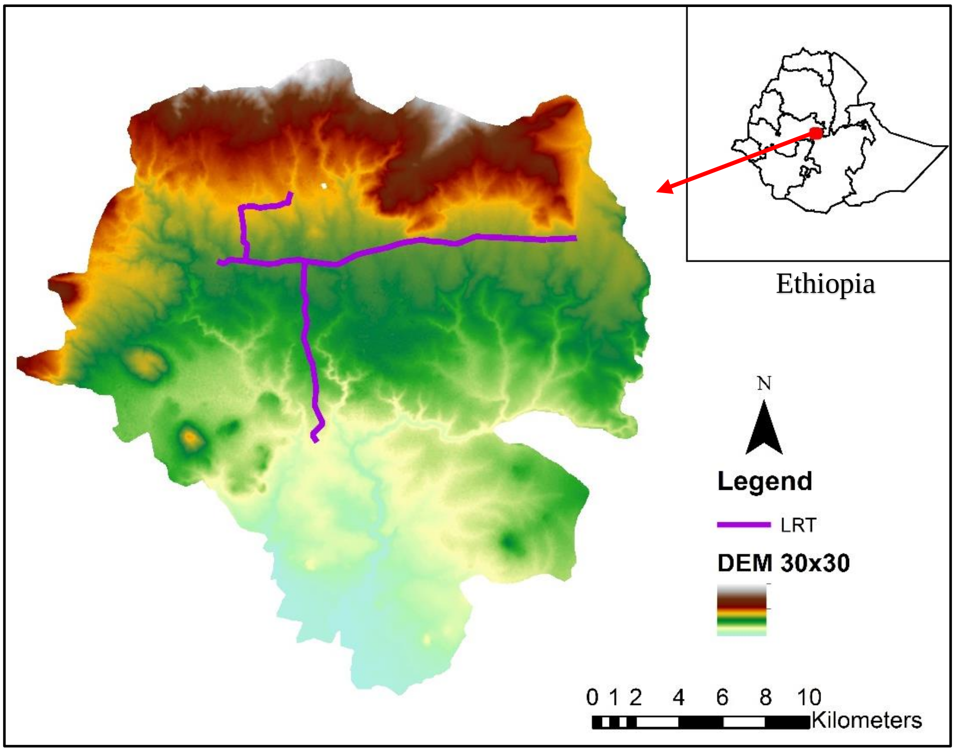


Figure 7: Location Map of Addis Ababa and LRT

3.1.2. Climate

Because Addis Ababa is located around the equator its temperature stays nearly constant month to month with no more than 10 ^{0}C change and a temperate climate due to its high-altitude location in the subtropics. The average minimum and maximum temperature of each month is presented in the following graph. The graph is generated from the raw data obtained from Ethiopian Meteorological Agency.

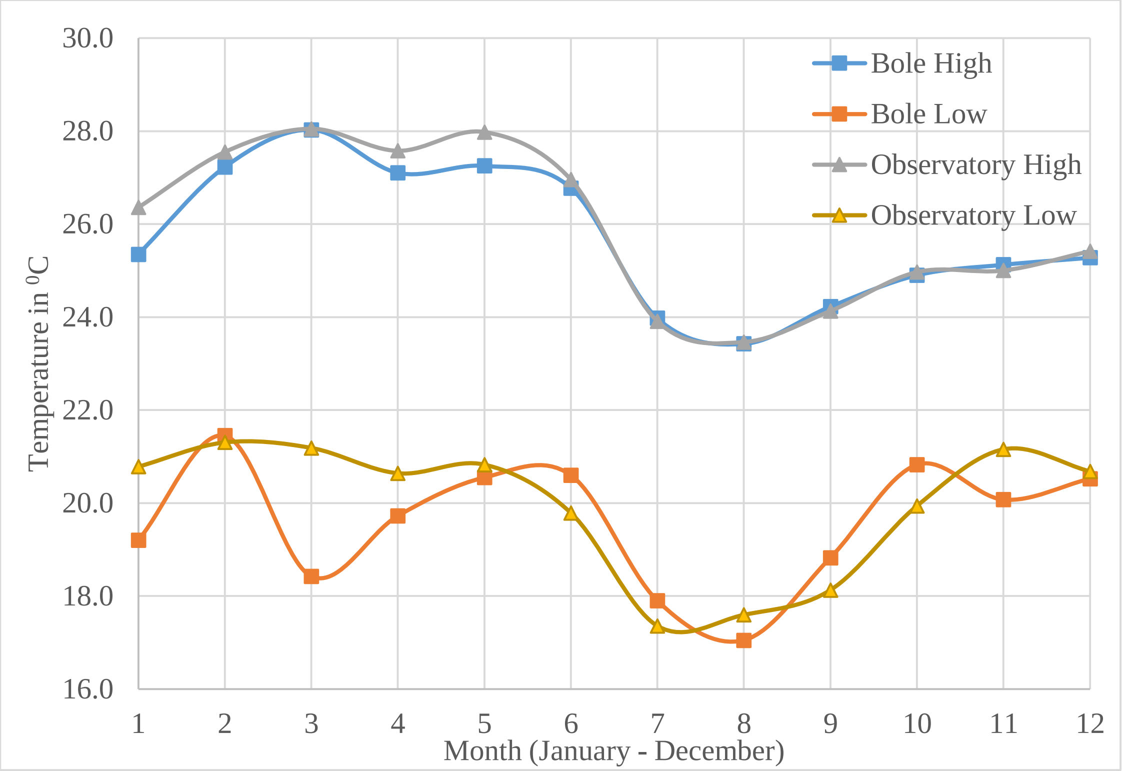


Figure 8: Average High and Low Temperature of Bole and Observatory Gauging Stations

Addis Ababa has a pronounced rainfall peak during the summer season locally known as Kiremt which is from June to September. It also exhibits a considerable amount of rainfall during February to May locally known as Belg, Bega being between October and January with minimum rainfall record. Daily rainfall

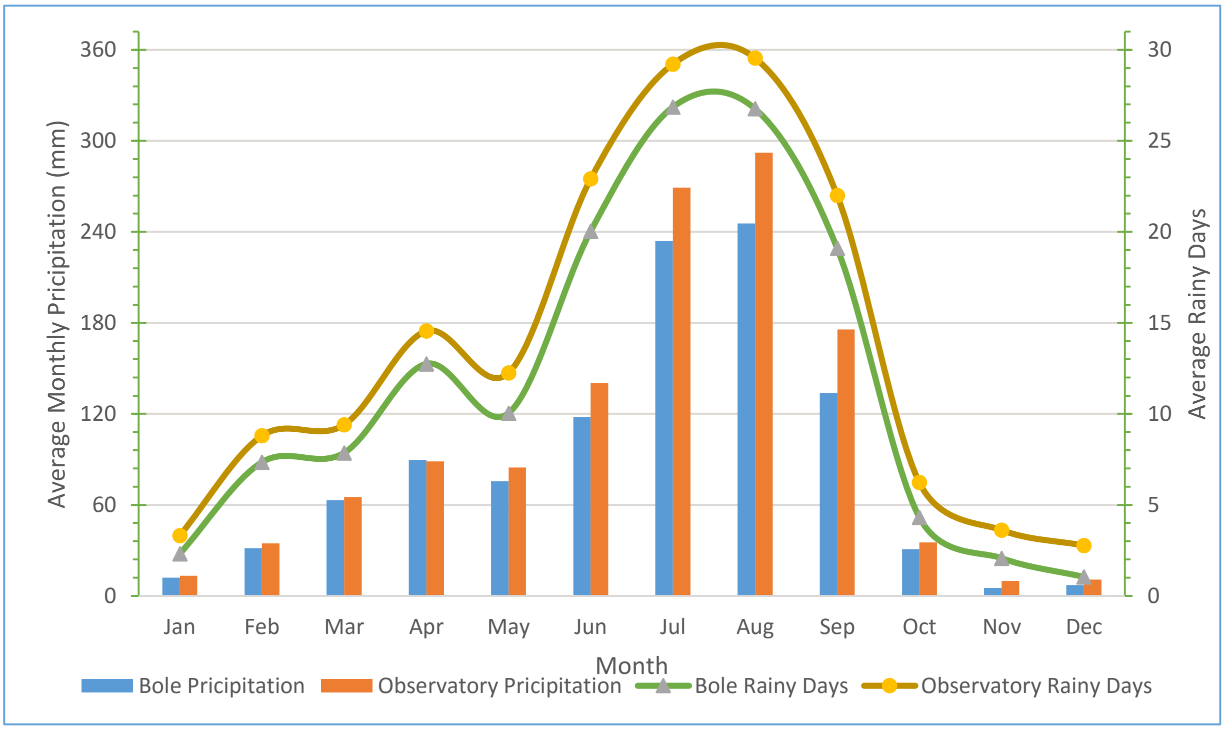


Figure 9: Average monthly rainfall depth and rainy days of Bole and Observatory Stations

records of stations in Addis Ababa as obtained from National Metrological Agency depict that the rainfall distribution is bimodal in nature.

3.1.3. Demography

Population projection of Ethiopia for all regions at woreda level from 2014 – 2017 has been done by Central Statistical Agency (CSA, 2013). The population distribution of Addis Ababa for all ten sub cities on 2015 is as shown in Table 2 below. Ayat to Megenagna LRT route is located in Yeka sub city and as it can be seen from the table that Yeka is the second most populated sub city in Addis Ababa. Furthermore, Yeka sub city is the fourth least in regard of population density. This shows as there is high probability for further urbanization of the sub city which have implication on future hydrological set up.

Sub City	Population	Area (km^2)	Density	Density Rank
Adis Ketema	305,058	7.408	41,180	1
Akaki Kaliti	216,538	118.080	1,834	10
Lideta	240,989	9.175	26,266	2
Arada	252,705	9.914	25,490	3
Kirkos	264,337	30.184	8,758	4
Gulele	319,712	120.610	2,651	9
Bole	369,189	120.610	3,061	8
Nefas Silk Lafto	377,892	68.301	5,533	6
Yeka	414,212	87.444	4,737	7
Kolfe Keraniyo	512,369	61.251	8,365	5
Total Population	**3,273,001**			

Table 2: Population and Population Density of Addis Ababa by Sub City

3.1.4. Land Use and Land Cover

Addis Ababa have land use ranges from agricultural to high density commercial areas. The land use and land cover of the city have evolved as forest and agricultural lands are built up. Figure 10 below shows the current land use of Addis Ababa. Areas in dark are highly urbanized areas whereas lighter areas are crop land, forest, green areas or areas along a river. Historical Land use land cover map of Addis Ababa is also presented in Figure 11 below.

Figure 10: Urbanization Map of Addis Ababa City in 2015

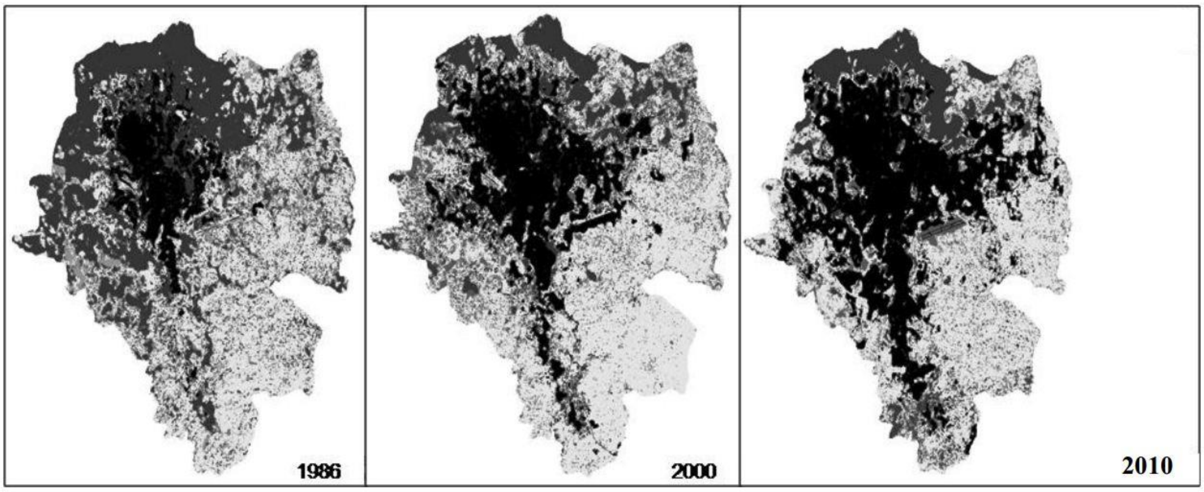


Figure 11: Urbanization Maps of Addis Ababa City in 1986, 2000 and 2010
(Source: (Kasa, et al., 2013))

3.2.Ayat to Megenagna Light Railway Transit System Route

The Addis Ababa Light Railway Transit (LRT) is a two phase project of total 74km. The phase I of the project which involves the construction of 34.25km electrified, standard gauge and dual track rail line traversing the city from east to west and from north to south is currently underway. The design capacity of the LRT is 80,000 passengers per hour.

The east to west line is from Torhailoch to Ayat and it passes through Mexico square, Meskel square and Megenagna. The total length of the line is 17.35km of which 13.3km is at subgrade and the rest is elevated section. The east to west line have a total of 22 stations, 18 at grade and 6 at elevated stations at average interval of 0.813km.

The north to south line starts from Menelik II square and ends at Kaliti. It passes through Mercato market, Meskel square and Saris. The total length of the line is 16.9km of which 11.6km is at subgrade and the rest is elevated section. There are also 22 stations on this line too. From the 22 stations, 7 are elevated station and 5 are common with the east to west line. The north to south line and the east to west lines share a common track of 2.7km.

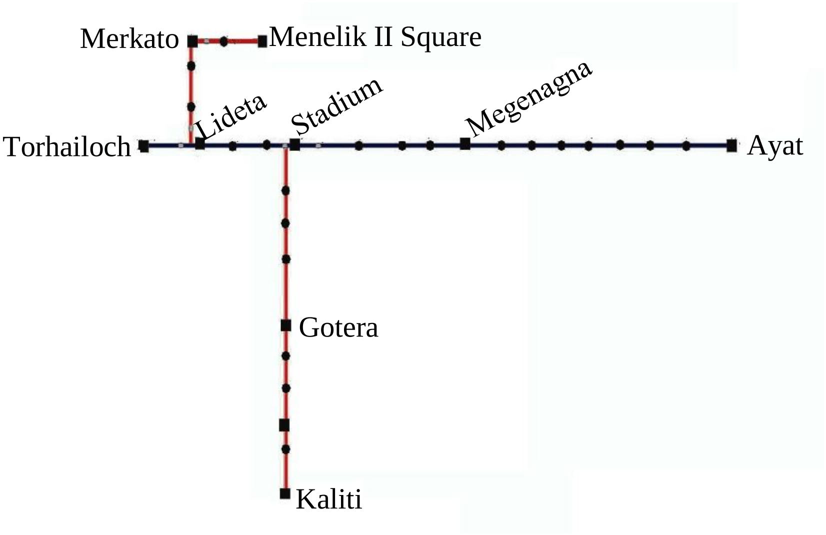


Figure 12: Phase I of Addis Ababa LRT System Project

The route selected for this study is section of the East to West LRT route and it starts from Ayat and ends at Megenagna (refer to map shown below). The Ayat to Megenagna LRT route is 8.2km in length and it is crossed by river streams flowing from upper Yeka Mountain to downstream low laying area

Figure 13: Map of Ayat to Megenagna LRT Route

3.2.1. Locations of Prevalent Flooding

As mentioned in the previous section the route selected for this study is the Ayat to Megenagna LRT route which is 8.2km in length. In order to meet the objective of this research by implying integrated drainage system that would considerably mitigate flood risk, focusing to a more localized sub basin is essential. In order to select a study focus area assessment of the Ayat to Megenagna line have been made, information from inhabitants of the area is informally collected and prevalent flooding areas have been identified. Those areas are presented below.

i. At Entrance to the Ayat LRT Depot

Pier of an access bridge to the Ayat depot is constructed on an existing road drainage channel. This will greatly alter the hydraulics of the area as the road drainage channel is already functioning at its peak as it receives storm drainage from feeder road from upstream neighborhood as shown on Figure 14 and Figure 15 below. At the time of the site visit performed on the 4/1/2015 no alternative drainage system has been provided by the contractor. The design of new drainage system at this location requires thorough investigation and the author believes this area is potential flood risk area.

Figure 14: Pier of Access Bridge constructed on side drainage ditch

Figure 15: Drainage ditch from feeder road connected to main road

ii. At CMC Roundabout

Roundabout generally need great deal of care in designing drainage, this is mostly because of their geometric arrangement. What makes the CMC roundabout different is the fact that it is crossed by the newly built Light Rail Transit system. Furthermore, it is located at the drainage stream crossing point of the local catchment including Yeka Mountain. Due to the high slope from the hills towards the roundabout, the damage that might be caused by the flow is obvious.

Figure 16: Areal Image of CMC Roundabout

Figure 17: Plants got enough water and soil to grow on ballast around CMC roundabout

During the rainy season the roundabout is affected by frequent flooding. Because the LRT network crosses the roundabout at grade, flooding of the road possess greater flood risk to it. As it has been observed by site visits, flooding of the crossing have resulted in ballast fouling. Hence this area needs investigation and design of appropriate drainage mechanism. Furthermore, to tackle the problem from its source a catchment wide study should be done to protect the valuable infrastructure. A design strategy for using integrated sustainable drainage system is presented for study focus area along the route, which can be implemented to this location too to minimize flooding.

iii. Around Beshale hotel

This location is a good illustration of how the LRT system is being affected by water draining into the ballast. Due to improper drainage system provision the water that drains in to the system together with sediment load from the upstream have created a comfortable situation for plant growth. To solve the problem immediately a drainage infrastructure is required, and to minimize the problem the flow should be controlled from its source

Figure 18: Ballast contamination and plant growth in front of Beshale hotel

iv. At Megenagna Roundabout

At Megenagna roundabout the LRT crosses below the existing road from South to North at cut section by dropping its elevation while nearing the roundabout from East. The rainfall that drops in the vicinity have nowhere to go except to follow the grade downward only to be trapped under the roundabout. This water have resulted in destabilization of the existing structures by scouring the foundation (Ewnetu, 2014). Even though structural measures have been taken to protect the bridge structures the flooding risk still persists for the LRT network. Hence a wide catchment based study is required to control the water from its source.

Figure 19: Flood risk at Megenagna Roundabout

3.2.2. Selection of Study Focus Areas

Different areas which are affected by floods on the Ayat to Megenagna railway route along with drainage problems are briefly discussed in the previous sections. The areas discussed are potential flood risk areas and can well be used to illustrate how integrated drainage system could alleviate the flood risk. Due to time and resource limitations, focusing on specific location and illustrating how integrated drainage system

Figure 20: Surface flow pattern around Beshale Hotel

could be used is found to be the best way forward for this study. Hence the drainage problem around Beshale Hotel is used as an illustration case. There is no specific reason why this area is chosen over other areas where drainage problem exists.

4. Data and Methods

4.1.Data

4.1.1. Rainfall Data

The first data required for this thesis is rainfall data. Rainfall data for Addis Ababa city can be obtained from two locations, namely Addis Ababa Observatory Station and Bole International Airport Station. Because Bole International Airport Station is closer to the study area, rainfall data collected from this station is used in the study. The data includes the record of daily rainfall precipitation throughout the year ranging from 1954 to 2014 GC for 61 consecutive years. These rainfall data are records of rainfall depth in a 24hr duration.

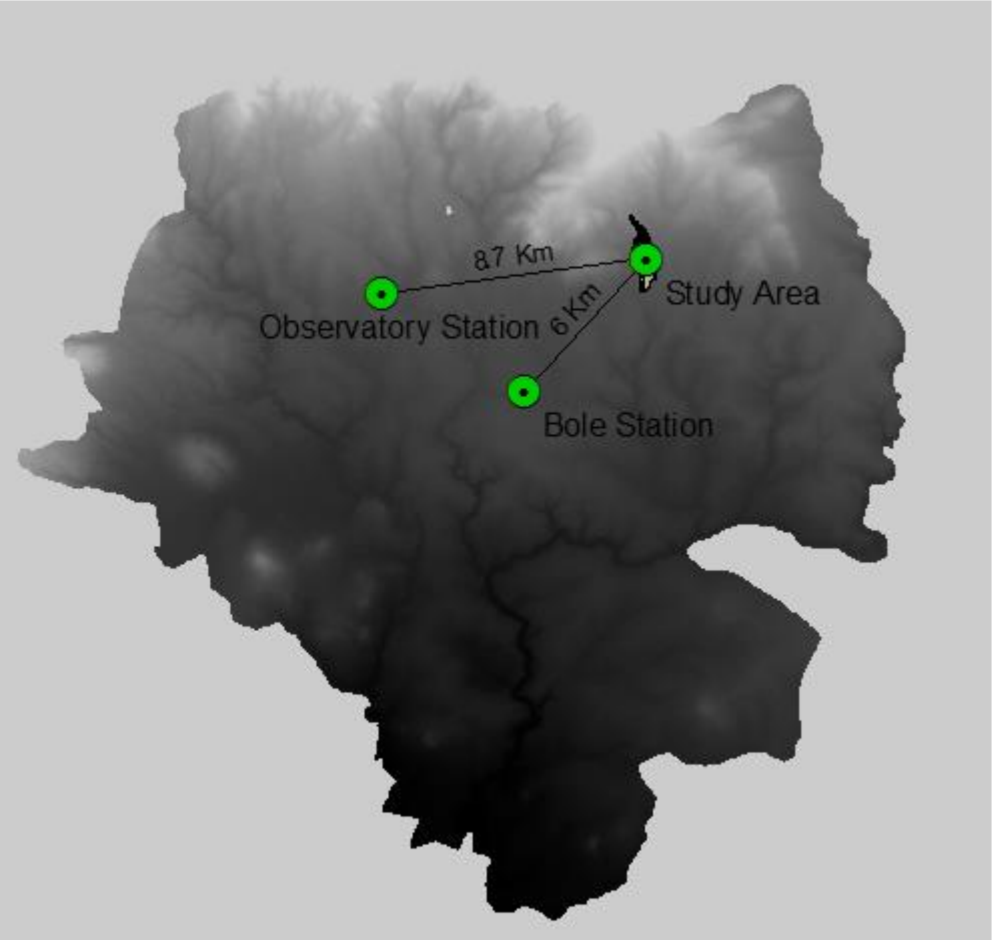


Figure 21: Location of rainfall gauge stations relative to study area

The rainfall data obtained is used to develop IDF curves so that the equation can be used in rational method. For a specific time of concentration, duration of rainfall is assumed the same and its intensity is estimated from the developed IDF curve. The methods employed to develop the IDF curve and the assumptions made are presented in detail in the next chapter.

4.1.2. Elevation Data

Topography of the study area is important since the analysis that are to be done are primarily elevation based. Accuracies of elevation maps may vary greatly. More accurate results are obtained by project specific surveying. Project specific surveying may include satellite imagery or field surveying. Because elevation of the whole catchment is required for this project area, obtaining project specific elevation map is not possible. Rather global elevation maps from satellite imagery are readily available in a raster and digital elevation format. There are different providers of digital elevation models both open source and commercial.

Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) is one kind of elevation data. ASTER GDEM was developed jointly by Ministry of Economy, Trade and Industry of Japan and the United States National Aeronautics and Space Administration (NASA). Second version of the elevation data with 30 by 30 meter resolution released in 2011 is openly available on different web sites including https://earthdata.nasa.gov. It is the source of elevation data for this thesis.

4.1.3. Land Use Land Cover Data

The third type of data required is the land use land cover of the study area. The land use land cover data will be an essential input for the calculation of rational method runoff coefficient determination. The runoff coefficient of a surface is dependent on the land use and land cover of the area. The map is obtained from Addis Ababa and Surrounding Oromia Master Plan Office. The overview map of the study area is shown on Figure 22 below. The map is geo-referenced in ArcMap and every location in the map will have known land use value, this will help in developing a look up table for calculating runoff coefficient.

4.1.4. Soil Type Data

Another type of data required is the soil type of the study area. It is an essential input for the calculation of runoff coefficient. The runoff coefficient of a surface will vary with soil type of the area, because some kind of soil absorb more water than the other. For this study soil type is of no use in determining the runoff coefficient because the study area is urban. Rather it is taken in consideration when proposing an integrated sustainable drainage system. The overview of the map is shown on Figure 23 below it is obtained from Addis Ababa and Surrounding Oromia Master Plan Office. The map is geo-referenced in ArcMap and every location in the map will have known soil type value.

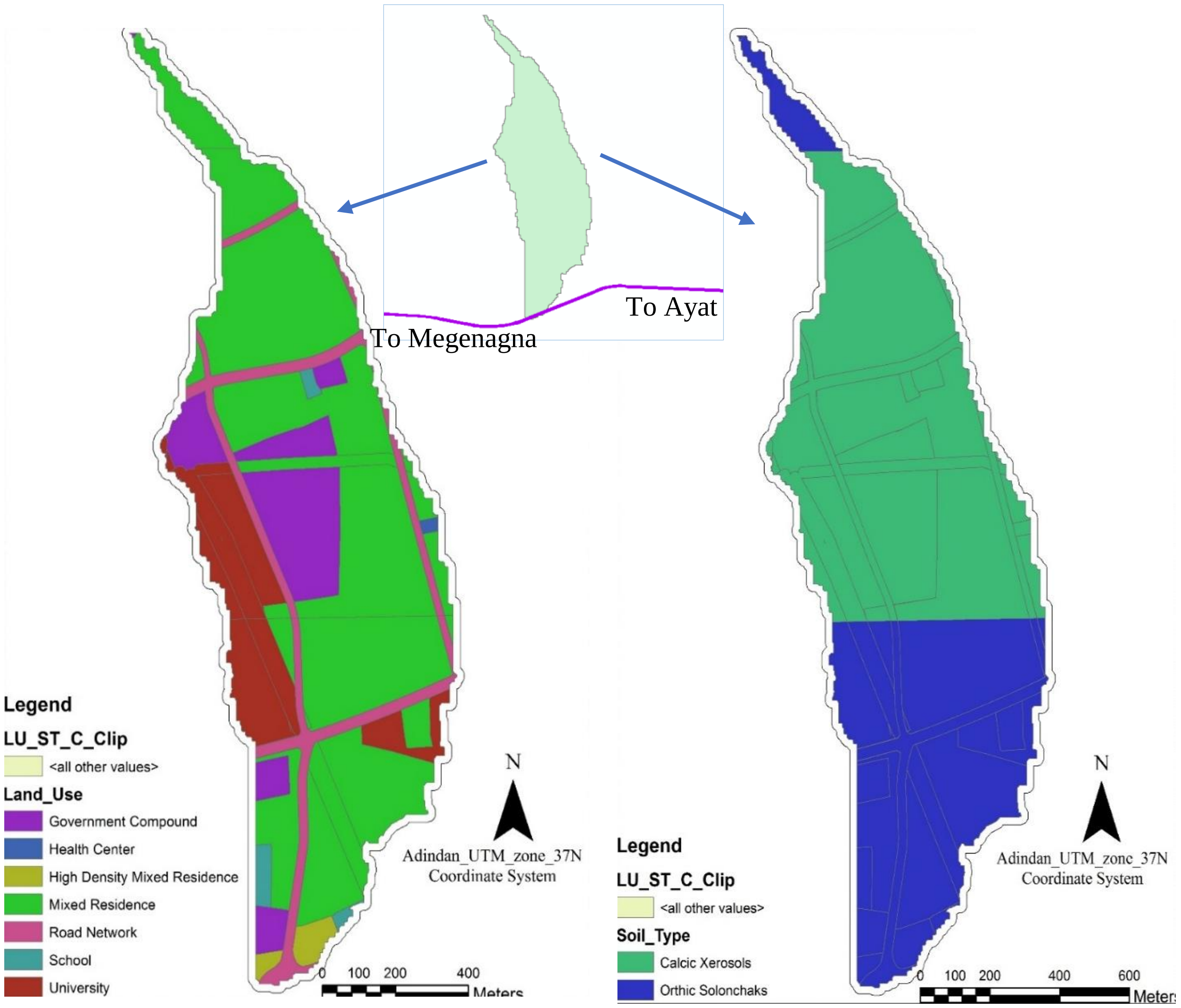


Figure 22: Land Use Map of Study Area

Figure 23: Soil Type Map of Study Area

4.2.Rainfall Frequency Analysis

The objective of frequency analysis of hydrologic data is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions (Chow, et al., 1988). Since rainfall data of previous years are available for the project area, the design rainfall can be determined by frequency analysis. Furthermore, the IDF curve can be developed using the frequency analysis.

The historical rainfall data available is a 24hr duration rainfall hence an appropriate IDF reduction method need to be used to obtain rainfall intensities of shorter duration. The IDF reduction method suggested in Ethiopian Road Authority Drainage Design Manual 2013 is used in this research.

Any probability distribution can be used as the model but the reliability of the distribution is checked by the goodness of fit tests. Gumbel and Log Pearson Type III methods are used as suggested by Ethiopian Drainage Design Manual (ERA, 2013) and their goodness of fit is analyzed in the next section.

The limitations of these statistical methods lie on the assumption that are made in using them. First rainfall is assumed not to be affected by climatic trends. While the may be true in the last century, now in the 21st century the relation between climate change and rainfall intensity is becoming more apparent. Second annual maximum series are considered as sample of random and independent events (The Hydrology Subcomittee, 1981). Historical data are used to drive sample, then the sample is used to estimate a population which will be used in making projections of the magnitude and frequency of rainfall (Chow, et al., 1988). Hence, for reliable estimates for extreme hydrological event, long term data series is required.

i. **Gumbel: -** Also known as Extreme Value Distribution Type I or double-exponential distribution of extreme values. It is based on the assumption that the cumulative frequency distribution of the largest values of samples drawn from a large population can be described by the following equation:

$$F(X) = e^{-e^{\alpha(X-\beta)}} \; where \; \alpha \; and \; \beta$$

The methods employed in Ms. Excel are as follows

- Annual extreme values are obtained using =max(∀) function, where ∀ represents all record of 24 hour daily rainfall obtained from Ethiopian Meteorological Agency as mentioned in data section.
- Average of yearly maximum rainfall data is obtained using =average () function
- Standard deviation of the data set is obtained using =stdev () function
- The constant α of the data set is calculated using $\alpha = Stdev(\,) * \sqrt{\frac{6}{\pi}}$
- The constant u of the data set is calculated using $u = \; average(\,) - 0.5772\alpha$
- Using equations $y_T = -\ln\left[\ln\left(\frac{T}{T-1}\right)\right]$ and $X_T = u + \alpha y_T$ where y is reduced variant, T is return period and X is rainfall the result is tabulated for different return period

ii. **Log Pearson Type III: -** is a three-parameter gamma distribution with a logarithmic transform of the variable. Mean, standard deviation, and coefficient of skew are the three necessary parameters that are necessary to describe the distribution.

The methods employed in excel are as follows

- The logarithms of annual maximum values are calculated
- The average (=average ()), standard deviation (=stdev ( )) and standardized skew (=skew ( )) of the data set are obtained using the respective excel functions.
- Coefficient k to be used in calculating K_T is obtained as ${Skew(\,)}/{6}$

- Coefficient z to be used in calculating K_T is obtained using excels $=Normsinv\left(\frac{1}{T}\right)$ function where T is the desired return period.
- Coefficient K_T is calculated as

$$K_T = z + (z^2 - 1)k + \frac{1}{3}(z^3 - 6z)k^2 - (z^2 - 1)k^3 + zk^4 + \frac{1}{3}k^5$$

- Y_T is calculated using $Y_T = average(\,) + K_T * stdev(\,)$
- Magnitude of precipitation with a return period of T, X_T, is obtained by transforming Y_T.

$$X_T = 10^{Y_T}$$

4.2.1. Goodness of Fit Test

The goodness of fit (GOF) tests measure the compatibility of a random sample with a theoretical probability distribution function. These tests show how well the selected distribution fits to data. There are three most commonly used GOF tests. These tests are the Anderson-Darling, the Kolmogorov-Smirnov, and the Chi-Squared tests. In all three tests a parameter or statistic unique to each method is calculated for the required distribution types and these distributions are ranked based on their parameter values.

Kolmogorov-Smirnov Test

This test is used to decide if a sample comes from a hypothesized continuous distribution. It is based on the empirical cumulative distribution function (ECDF). Assume that we have a random sample $x_1, \ldots, x_n$ from some continuous distribution with CDF F(x). The empirical CDF is denoted by

$$F_n(x) = \frac{1}{n} \cdot \left[\text{Number of observations} \le x\right]$$

The Kolmogorov-Smirnov statistic (D) is based on the largest vertical difference between $F(x)$ and $F_n(x)$. It is defined as

$$D_n = \sup_x |F_n(x) - F(x)|$$

When comparing different distribution lower statistics means better fit.

Anderson-Darling Test

The Anderson-Darling procedure is a general test to compare the fit of an observed cumulative distribution function to an expected cumulative distribution function. This test gives more weight to the tails than the Kolmogorov-Smirnov test.

The Anderson-Darling statistic (A^2) is defined as

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\cdot[\ln F(X_i) + \ln(1 - F(X_{n-i+1}))]$$

The hypothesis regarding the distributional form is rejected at the chosen significance level (alpha) if the test statistic, A^2, is greater than the critical value obtained from a table. When comparing different distribution lower statistics means better fit.

Chi-Squared Test

The Chi-Squared test is used to determine if a sample comes from a population with a specific distribution. This test is applied to binned data, so the value of the test statistic depends on how the data is binned. Although there is no optimal choice for the number of bins (k), there are several formulas which can be used to calculate this number based on the sample size (N). For example, EasyFit employs the following empirical formula: $k = 1 + \log_2 N$

The data can be grouped into intervals of *equal probability* or *equal width*. The first approach is generally more acceptable since it handles peaked data much better. The Chi-Squared statistic is defined as,

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

where O_i is the observed frequency for bin i, and E_i is the expected frequency for bin i calculated by

$$E_i = F(x_2) - F(x_1)$$

where F is the CDF of the probability distribution being tested, and x_1, x_2 are the limits for bin i. When comparing different distribution lower statistics means better fit.

EasyFit 5.6 Professional software is used for testing goodness of the recommended Log Pearson-III and Gumbel Methods. Log Pearson-III method have proved to be good fit in all the three tests compared to the Gumbel's Method.

Distribution	*Kolmogorov-Smirnov*		*Anderson-Darling*		*Chi-Squared*	
	Statistic	Rank	Statistic	Rank	Statistic	Rank
Log-Pearson 3	0.07575	1	0.23723	1	1.9898	1
Gumbel	0.08057	2	0.2599	2	2.8508	2

Table 3: Goodness of Fit of Log-Pearson III and Gumbel Methods

As shown on Table 3 the statistics for both methods are calculated and the ranking is given. Accordingly, the Log-Pearson III is chosen for further frequency analysis.

4.2.2. Design rainfall of shorter duration

The rainfall depths obtained from gauging station are of 24hr duration depth. Design and analysis of drainage structures require rainfall intensity duration relationship of shorter duration. Because rainfall data of shorter duration is unavailable appropriate IDF derivation for shorter duration is required. Ethiopian Road Authority Drainage Design Manual of 2013 suggests the following equation.

$$R_{Rt} = \frac{t}{24}\frac{(b+24)^n}{(b+t)^n}$$

Where:

R_{Rt} = Rainfall depth ratio R_t: R_{24}

R_t = Rainfall depth in a given duration t

R_{24} = 24hr rainfall depth

Coefficients b = 0.3 and n = 0.78 - 1.09

The methods employed to develop IDF curve for the shorter duration events using the above equations are as follows.

- Using the trend line equation obtained from Log Pearson type III method of frequency analysis, i.e. $y = 11.414\ln(x) + 38.795$ where y is 24-hour rainfall depth (R_{24}) of a return period x under consideration, R_{24} is calculated for 2, 5, 10, 25, 50 and 100 year return period.
- Rearranging the above equation gives

$$R_t = \frac{t}{24}\frac{(b+24)^n}{(b+t)^n} * R_{24}$$

Intensity (mm/hr) $I_t = \frac{R_t}{t}$. Substituting in the above equation gives

$$I_t = \frac{R_{24}}{24}\frac{(b+24)^n}{(b+t)^n}.$$

- Using b = 0.3 and n = 0.92 as suggested by ERA manual results are tabulated for rainfall durations 10, 20, 30 … 180 minutes.
- The resulting table is graphed for each return period.

In order to incorporate into software and automate the estimation of runoff representation of intensity duration frequency relationship with an equation is required. A polynomial equation sixth degree have proved to be a good representation of the resulting IDF curves. For instance, the coefficient of determination, R^2, of a 25 year return period for duration less than 180 minutes is 0.9999. Hence the polynomial equation can be used to represent the IDF curve of 25 year return period to obtain rainfall intensity for a given duration, provided that the duration is below 3 hours. Equations obtained representing IDF curves for different return period are presented in the results section.

4.3.Hydrological Modeling Using ArcGIS ArcHydro Tools

4.3.1. Watershed and Stream Network Delineation

Every hydrological modelling starts from delineating streams and watersheds, and obtaining watershed properties such as area, slope, flow length, flow direction, stream network, etc. Traditionally this was being done manually by using contour maps. Now the time have changed and the availability of digital elevation models (DEM) and computer programs have made it possible to perform automated analysis.

ArcHydro tool of ArcGIS is utilized in this research for Hydrological Modelling. The strong mathematical capability and its compatibility with vast Hydrological Modelling software is the main reason for choosing ArcGIS.

Since one of the objective of this research is to put forward strategies for design and analysis of drainage structures, tools that ease repetitive process are developed. Because of these tools standard processes that are crucial for hydrological modelling but are similar for different projects do not have to be time consuming. One of such tool is the terrain pre-processor. It is called terrain pre-processor because it is the primary step that will be used as input for many other hydrological modelling tools.

The steps in terrain pre-processing are to Import raw data, make raw DEM depression less, Determine Flow Direction, Compute Flow Accumulation grid, Define Stream, Segmentation of Steam, Catchment Grid Delineation, Catchment Polygon Processing and Drainage Line Processing.

The above nine steps despite their great importance for hydrological and hydraulic analysis are computer intensive and require little input from the user. The user only needs to provide the raw digital elevation model at the beginning and the required number of cells or area threshold for stream definition. Hence the whole step can be done at once by creating a model with two parameters i.e. Raw DEM and the area in square kilometer. For this thesis a model is developed which asks for the two parameters and perform the terrain processing. The model is developed in Model Builder of ArcGIS application. The results of the processing are put in the same directory with the input Raw DEM. The model looks as follows.

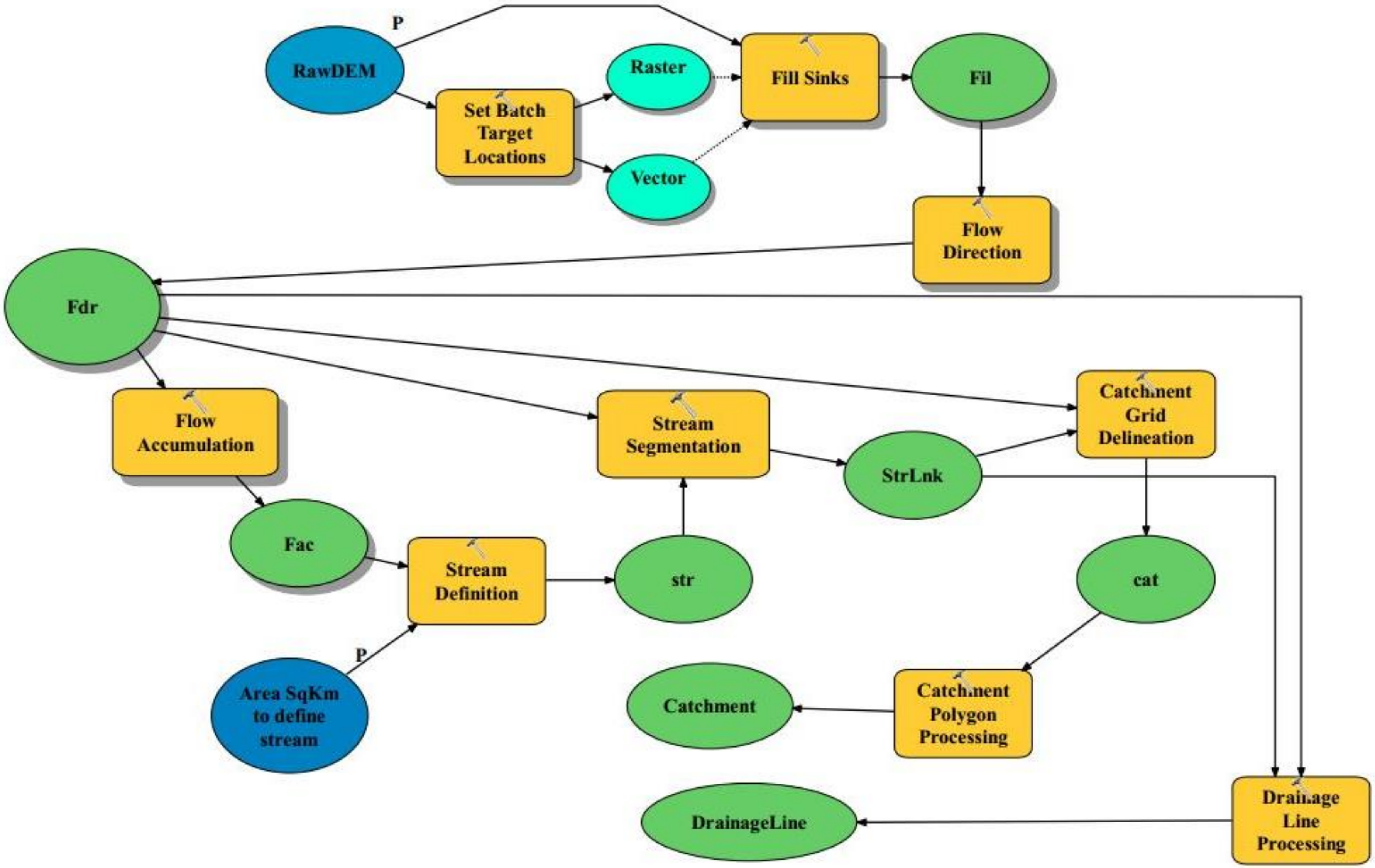


Figure 24: Custom ArcGIS Model for Terrain Preprocessing

4.3.2. Catchment Delineation for Study Area

In the previous sub section, the methods employed to determine the overall watershed make up as well as the flow directions have been detailed. The flow directions and the drainage lines obtained show the major and minor streams according to the definition made for streams.

In order to focus into specific area, the local catchment draining to the specific point must be obtained. This is simple task as all the parameters required to delineate sub watershed i.e. flow direction grid, steam grid, catchment and ad-joint catchment are already generated by the model developed in the previous section. All that need to be done in order to get the local catchment is to select the specific point using the ArcHydro extension tool of the ArcGIS and the result will be displayed automatically.

4.3.3. Stream Network Verification

After the drainage lines of the project area are determined by running the terrain processor model they have to be verified against existing natural steams. The verification is required because there may be some inconsistencies between the actual streams and streams obtained from terrain processing due to inaccuracy of digital elevation model data. If vector data of natural streams were available, the DEM would be made to agree with the streams to make the result more accurate. Because of the unavailability of stream network vector data accuracy is achieved by overlaying topographic map and land use map of the area and comparing them. This method is acceptable by different literatures under circumstances. Greater similarity between analysis result and existing stream is achieved by altering the *minimum area to define stream* parameter of the model.

4.4.Rainfall – Runoff Transformation using Rational Method

Runoff estimation can be performed by either statistical methods or deterministic methods. Statistical methods are based on historical gauging records to estimate the probability of occurrence of a given event. Runoff from a given site may be subject to changes by urbanization and drainage improvements, statistical methods have no parameter to account for these changes and that is their limitation. Unlike statistical methods deterministic methods are based on a cause-effect consideration of the rainfall-runoff processes. Rational method is one of deterministic methods.

The idea behind the rational method is that for a spatially and temporally uniform rainfall intensity (i) which continues indefinitely, the runoff at the outlet of a catchment will increase until the time of concentration ($t_{c)}$, when the whole catchment is contributing flows to the outlet. This takes the assumption that peak runoff doesn’t result from more intense rainfall of shorter duration. The peak runoff is given by the following expression:

$$Q_p = 0.278\ C\ i\ A$$

Where Q_p = peak runoff in m^3/s
C = runoff coefficient
i = rainfall intensity in mm/hr
A = catchment area in km^2

4.4.1. Runoff Coefficient C Determination

The runoff coefficient is the most important variable in the rational method of rainfall to runoff transformation. The study area constitutes different land use types ranging from university play ground to high density residential parcels. A weightage method is employed to obtain the representative runoff coefficient i.e. the individual areas multiplied by their specific runoff coefficient and their values added together and divided by the cumulative area. The following table is used to assign runoff coefficient to study area.

Type of Drainage Area	**Runoff Coefficient C**
Business: Downtown areas	0.7-0.95
Neighborhood areas	0.5-0.7
Residential: Single-family	0.3-0.5
Residential: Multi units, detached	0.4-0.6
Residential: Multi units, attached	0.6-0.75
Suburban	0.25-0.4
Residential (0.5 hectares lots or more)	0.3-0.45
Apartment dwelling areas	0.5-0.7
Industrial: Light areas	0.5-0.8
Industrial: Heavy areas	0.6-0.9
Parks, cemeteries	0.1-0.25
Playgrounds	0.2-0.4
Railroad yard areas	0.2-0.4
Unimproved areas	0.1-0.3

Table 4: Runoff Coefficient for Use in Rational Method
(ERA, 2013)

4.4.2. Time of Concentration Tc Determination

The time of concentration is the time required for runoff to flow from the most remote point of the basin to the location being analyzed. In Rational Method time of concentration is used to determine the rainfall duration which will result in maximum runoff. The duration is then combined with rainfall intensity duration frequency (IDF) relation of the area developed in previous section of this thesis. The required design rainfall intensity is then established from IDF curve for the required frequency.

Manning’s equation can be used for road and railway side drainages as well as cross drainages because the channel cross section is defined and known. But Manning’s equation is not used to calculate time of concentration for sub basins.

Flow path from the upstream sub basin to the outlet is well defined because of the volume of the water, hence the equation developed by United States Soil Conservation Service as suggested by literature is used.

$$T_c = \left(\frac{0.87L^2}{1000S_{av}}\right)^{0.385}$$

Where T_c is time of concentration (hours), L is hydraulic length of catchments measured along flow path from the catchment boundary to point where flood needs to be determined (km) and S_{av} is average slope in (m/m)

Depending on the morphology of the catchment not all areas might be contributing to the peak flow. Because of this time of concentration is not necessarily the time taken to flow along the longest flow path.

The method of obtaining the combination of time of concentration and the contributing area in that time duration is calculating the contributing area by incrementing the time of concentration by some time step. In this thesis an alternative method that fulfils the same goals have been implemented.

The longest flow path is incrementally truncated from the upstream most point to the downstream. The contributing area to the furthest point on the truncated flow path is calculated. This process of truncating flow path and calculating the contributing area to the tip of the flow path is performed repeatedly. The reasoning and an assumption behind this is, when the flow length is shortened the area contributing to the outlet of the catchment will reduce. The amount that the area contributing to the outlet reduces is equal to the amount of the area draining to the upstream most point of the shortened flow length.

When the longest flow path is shortened even though the contributing area reduces, the rainfall intensity will increase. The challenge is then to find the optimum condition that will result in maximum runoff at the outlet. This is done by iterative process using wide range of tools in ArcGIS and Microsoft Excel. The Microsoft Excel tables are presented in the Appendices section.

5. Result Analysis and Discussion

In this chapter the results obtained from the analysis methodologies detailed in previous chapter will be presented in order of their appearance. Furthermore, short discussion as to what the results mean will be presented together with the results.

It should be noted that results presented in this chapter are before the application of the integrated drainage system. Some results like the IDF Curve won't be affected but others will be affected by the application of integrated drainage system. The proposed integrated drainage systems and the effects that they will have on the catchment in different aspects including the runoff reduction will be presented in the next chapter. Here results are presented so that comparison will be made after the application of the integrated drainage system.

5.1. Intensity – Duration – Frequency Curves

The resulting IDF curve from steps shown in section 4.2.2 is as follows. The IDF curve is developed from 24-hour rainfall data of 61 years i.e. 1954 to 2014, obtained from Ethiopian Meteorological Agency rainfall gauge located around Bole, Addis Ababa. Appropriate reduction equation as depicted in the methodology section have been applied.

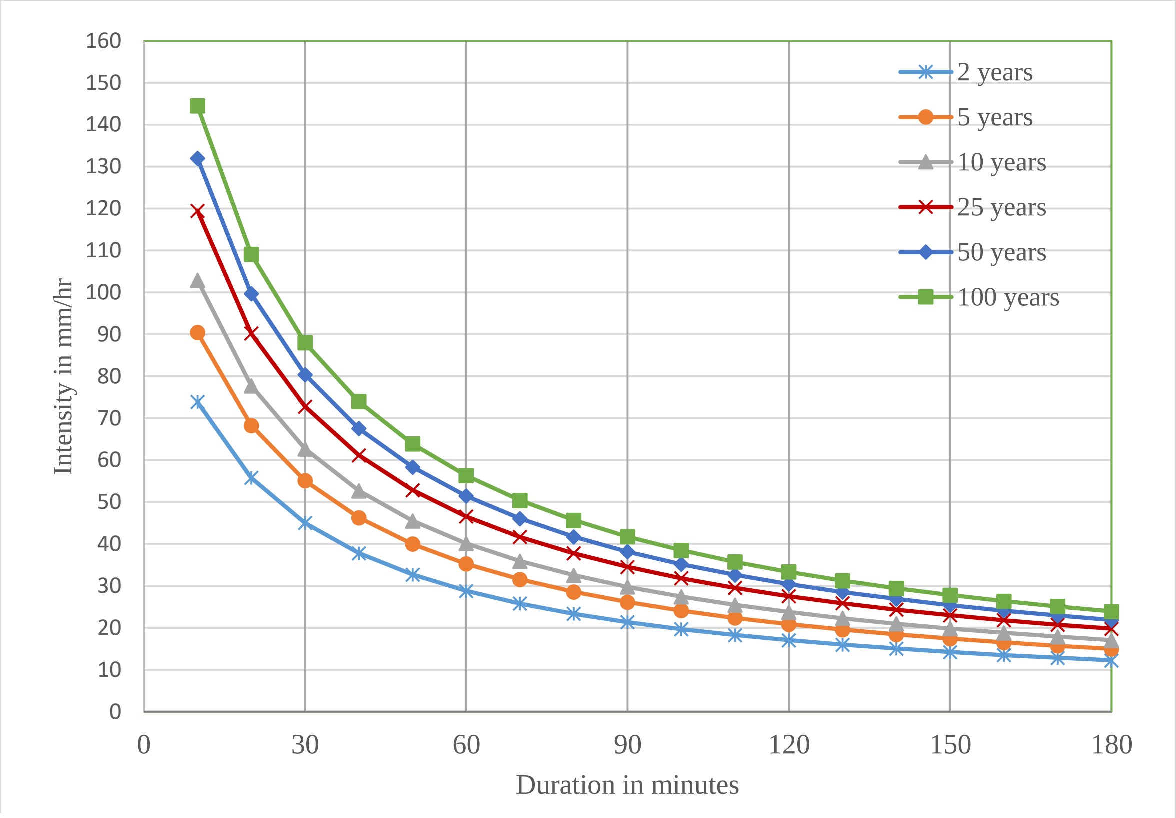


Figure 25: IDF Curve for Addis Ababa from Bole Airport Data

It is important to mention that IDF curve of Addis Ababa from Bole rainfall gauging station have previously been developed. Addis Ababa City Road Authority have presented an IDF Curve for Addis Ababa on its

Drainage Design Manual (AACRA, 2003). Unfortunately, date ranges of the data used by the authority is not mentioned, because the release year of the manual is January, 2003 it is clear that latest record they had was 2002 or earlier. Even though data ranges of this analysis and the authorities are not the same, the IDF curve developed by AACRA is presented here for comparison.

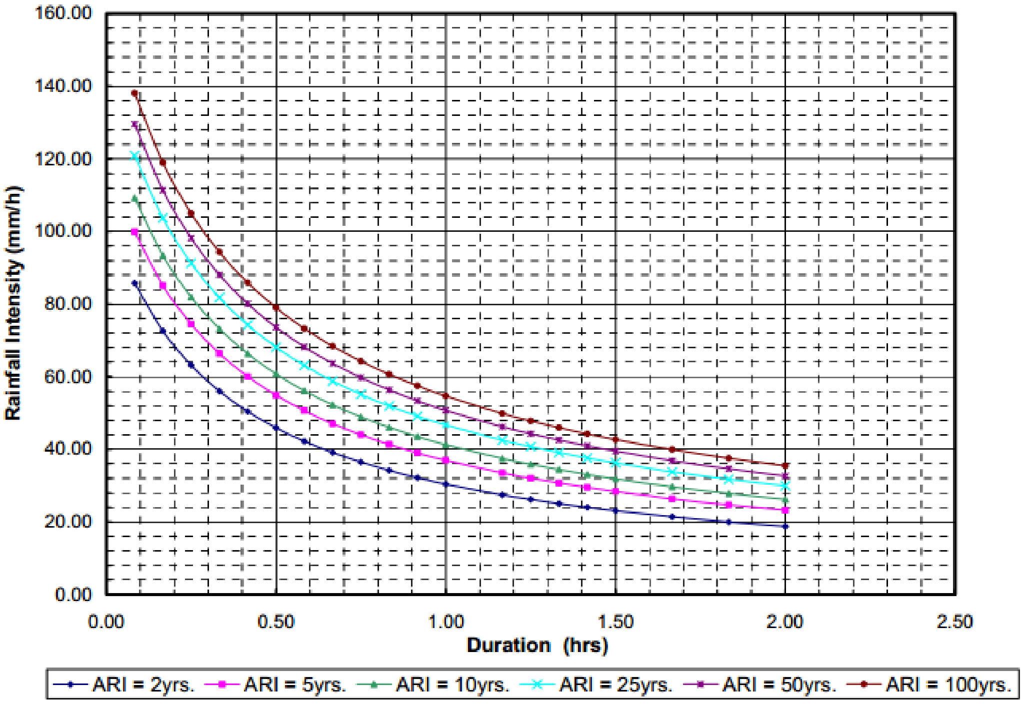


Figure 26: IDF Curve of Addis Ababa (AACRA, 2003)

The following table compares the IDF curves from self-analysis and AACRA.

Table 5: Comparison of IDF curve results with IDF from AACRA

D (min)	**15**		**30**		**60**		**90**		**120**	
ARI (Yrs)	Self	AACRA	Self	AACRA	Self	AACRA	Self	AACRA	Self	AACRA
2	63.95	64.00	44.89	45.00	28.87	31.00	21.34	23.50	16.95	17.50
5	78.28	75.00	54.94	56.00	35.33	36.00	26.12	28.00	20.74	22.50
10	89.11	82.00	62.54	60.00	40.22	41.00	29.73	32.00	23.61	26.00
25	100.43	92.00	72.59	68.00	46.68	47.00	34.51	36.00	27.41	30.00
50	102.16	97.00	80.19	73.00	51.57	51.00	38.12	40.00	30.28	32.00
100	117.10	106.50	87.80	80.00	56.46	55.00	41.74	43.00	33.15	35.00

It can be seen from the two graphs and the above table the IDF curve of Addis Ababa have changed. The data range used are different for the analysis made for this thesis and that of the road authority manual. This may have caused the changes.

5.2.Stream network and catchment delineation

Terrain processing have resulted in flow direction and flow accumulation grids. And stream networks are obtained based *area to define stream* parameter that specifies how fine the network should be. Those flow streams cross the Ayat to Megenagna route at certain locations. The specific location at left of Beshale Hotel shown in the following figure is of great interest to this thesis. The point is taken and catchment is delineated for it. The result is shown in the following figure. The blue lines indicate streams and the black line shows the catchment.

Because this is urban area the stream network and catchment delineation have multiple limitations. The first limitation is the accuracy of elevation data used for modelling. The accuracy of DEM used is not good enough to correctly represent the complex urban terrain. The second limitation is in urban environment like this, runoff flows not only on surface but it also flows through manmade drainage structures such as roadside ditches. Therefore, unless built structures are incorporated in high accuracy DEM, stream networks will lack accuracy.

With the limitations in mind the catchment delineation can be taken as worst case scenario. All runoff generated from the catchment will not flow towards the outlet because of the limitations mentioned above. If the runoff generated from catchment is reduced using integrated sustainable drainage system, then the runoff that flow to the outlet point will also reduce.

The land use composition of the catchment is shown in the following table. The fact that the majority of the catchment is of mixed residences land use type, i.e. almost 55%, makes the catchment for source control type of integrated drainage system.

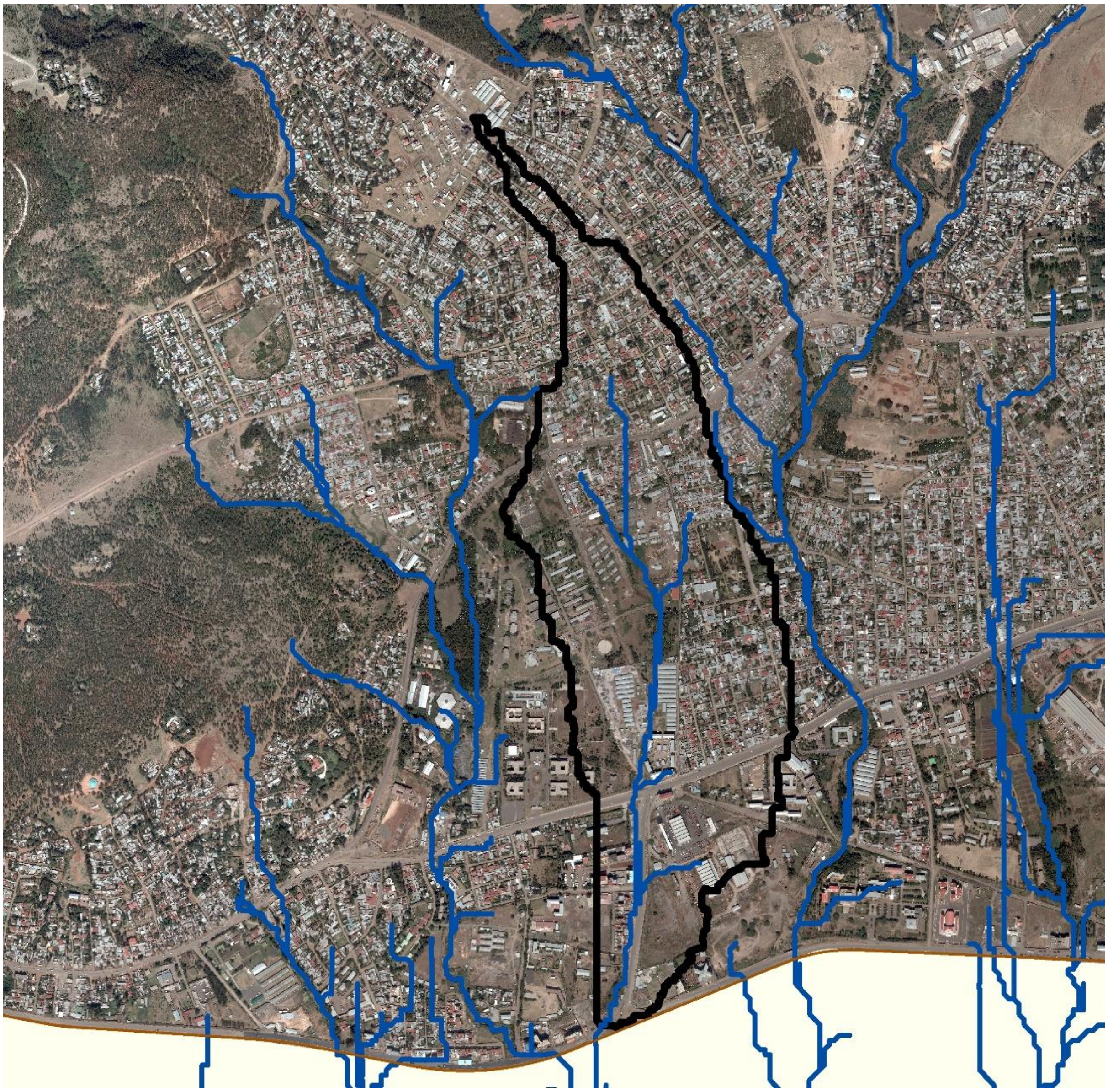


Figure 27: Study area catchment and outlet

Land Use	Area (m^2)	Percentage	Runoff Coefficient C
Mixed Residences	549,142.34	54.9%	0.65
Government Compounds	131,379.96	13.1%	0.5
University	127,364.42	12.7%	0.55
Asphalt Roads	93,145.50	9.3%	0.9
Cobble stone Roads	72,451.37	7.2%	0.7
High Density Mixed	13,645.03	1.4%	0.7
School	11,778.80	1.2%	0.75
Health Center	1,714.66	0.2%	0.6
Total =	**1,000,622.08**		
		Representative C =	**0.65**

Table 6: Land use composition of study area

5.3. Results of Rainfall Transformation

To estimate the amount of runoff generated from the catchment area shown in Figure 27 above rational methods is used. As mentioned in the methodology section an alternative procedure is used to obtain the optimum contributing area that will result in small time of concentration so that the rainfall intensity is at maximum.

As it can be seen from Figure 28 and Figure 29 below the runoff gradually increases when less catchment area is considered because the increase in time of concentration will result in higher rainfall intensity that will out balance the reduction in area. This happens until the flow length of 1.55 km, beyond this point further reduction in the contributing area resulted in the reduction of the runoff. Accordingly, the peak runoff for each return period is shown on Table 7 below.

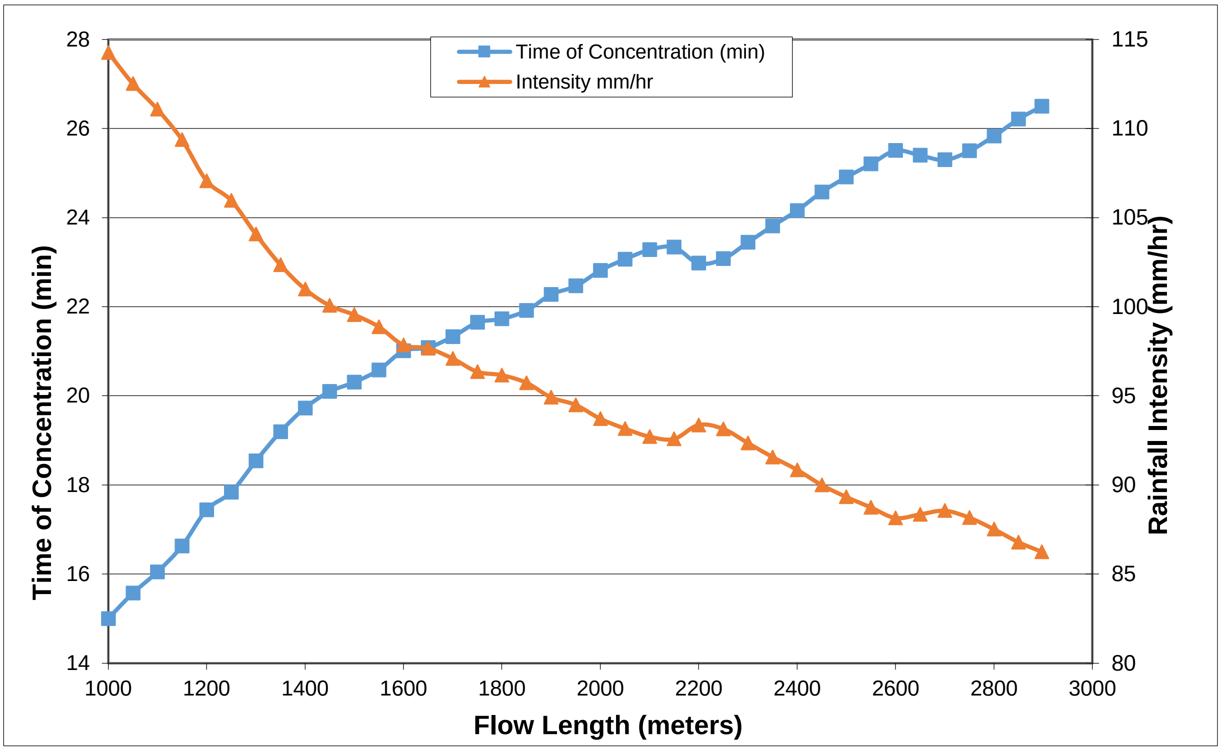


Figure 28: Result of reduction in flow length on time of concentration and intensity

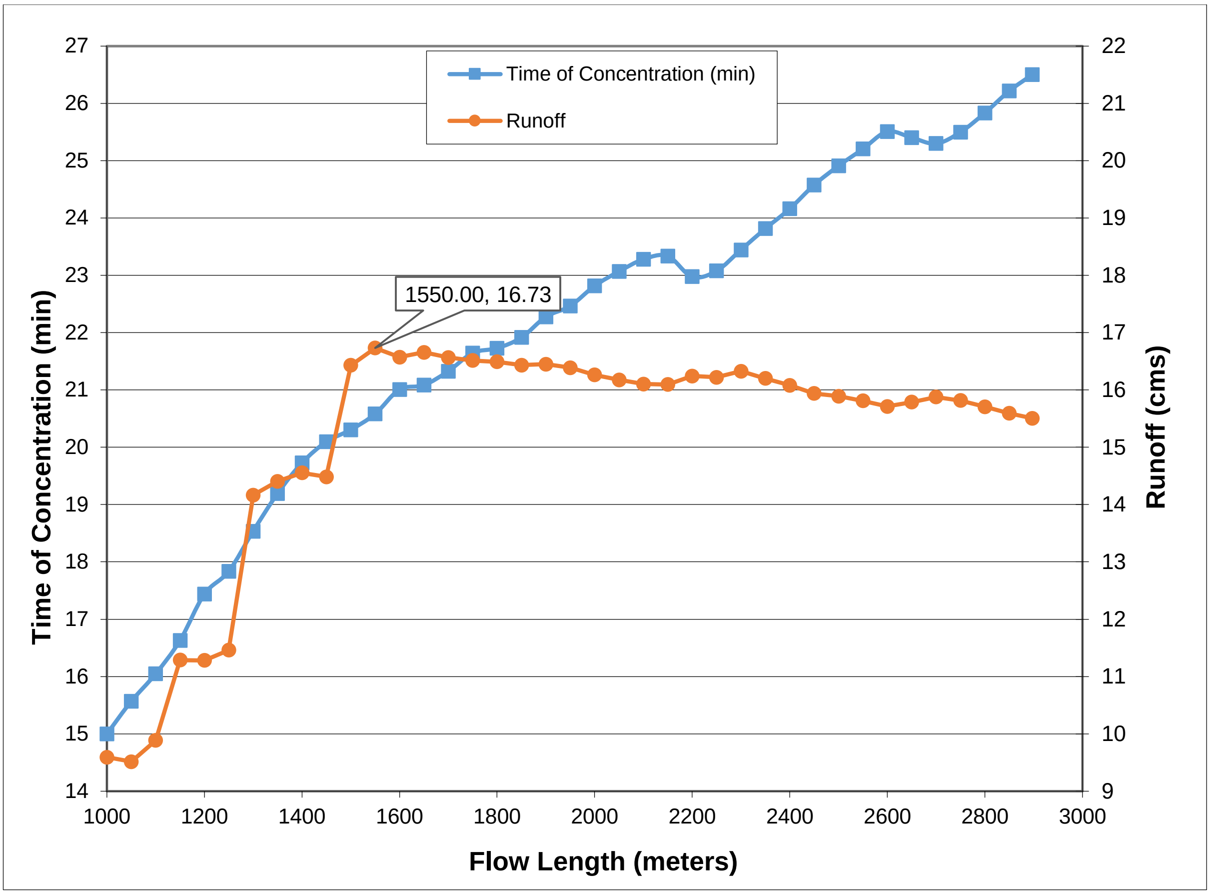


Figure 29: Result of reduction in flow length on time of concentration and runoff

Table 7: Peak runoff results

Return Period in years	Peak Runoff in m^3/s
5	11.5
10	13.0
25	15.1
50	16.7
100	18.3

6. Design of Integrated Drainage Systems

After the amount of runoff from catchment have been estimated the conventional way forward is to design a drainage structure that will accommodate the design runoff and transmit it to downstream of the structure to be protected. But integrated drainage system does not intend to do that. Integrated drainage system aims to control the runoff volume and rate either at the source by reducing impervious surfaces or through conservation of natural features that attenuate the flood peak. In addition to controlling the volume of runoff, integrated drainage systems enhance sustainability through improved quality of runoff water and amenity as well as aesthetic value.

This section of the thesis focuses on illustrating how integrated urban drainage system (IUDS) can be used to minimize runoff from the delineated catchment in order to protect railway infrastructure from flood risk. Even though different IUDS components exist with varying degree of suitability to specific sites, some components require more involvement from policy makers, society and designers. Because of the limited level of awareness, sophisticated IUDS components such as permeable pavements and detention basins are not currently feasible in our country. Two measures are evaluated in this thesis and their role in reducing quantity and rate of runoff discussed. These IUDS measures are rainfall harvesting and rain garden. After the implementation of rainwater harvesting and rain gardens at the appropriate locations, the effect of the solution on reducing runoff will be evaluated in the following section.

6.1.Rainwater Harvesting and Rain Garden Tool

Rainwater harvesting (RWH) is the collection and accumulation of rainwater for reuse, rather than allowing it to run off. Rooftop RWH systems collect runoff from rooftops and convey it to a tank where the water is available for uses that do not depend on potable water. It is suitable for all building types ranging from residential to commercial and industrial and can be retrofitted to existing buildings or integrated into new building designs.

RWH can simultaneously provide stormwater attenuation and runoff volume reduction, whilst contributing to water efficiency and availability. The runoff volume reduction and attenuation is the primary concern of this thesis. The amount of runoff that is reduced form flowing to downstream drainage pathway and reaching the outlet of the sub catchment depend on harvested rainwater demand and storage capacity of RWH system.

In sizing a storage tank several factors must be considered, among which are the following.

- Rainfall amount
- Roof catchment area
- Available space
- Water consumption (household size and needs)
- Intended use of the harvested water (potable, non-potable, irrigation)

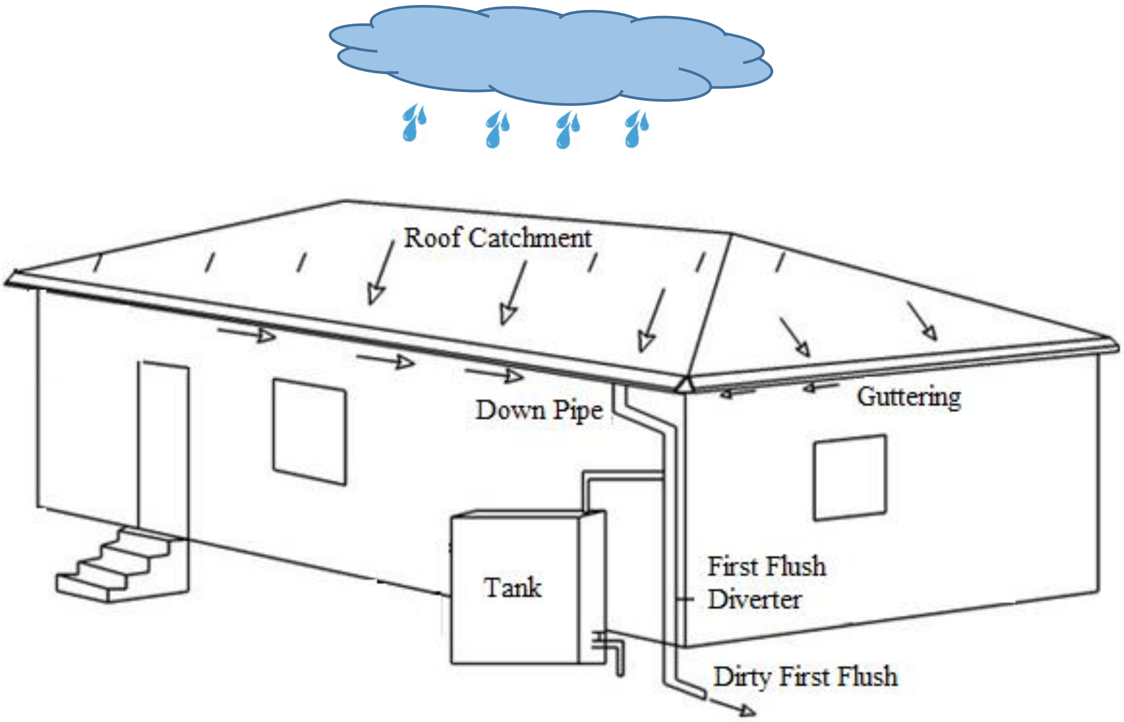


Figure 30: Residential rooftop rainwater harvesting

To protect Ayat to Megenagna railway infrastructure at the outlet of the sub catchment this thesis aims to show the role of source control integrated drainage system, one of which is RWH. As mentioned in the above paragraphs RWH plays great role of runoff volume reduction and attenuation but quantifying amount of reduction that can be attained require analysis.

A rigorous modelling and experiment on residential and commercial plots in cities in US performed by Richard McCuen and his colleagues at University of Maryland (Gilroy & McCuen, 2009). Accordingly, the reduction of volume of runoff on residential plots is found to be 46 percent. Of course the efficiency of the RWH system and the percentage reduction in runoff that can result from using them depend on intensity of rainfall and size of storage tank. Therefore, the reduction that can be obtained is site specific.

To come up with the efficient tank size and optimum runoff reduction that can be achieved by rainwater harvesting system, different countries have developed decision support tools specific to their use (U.S. EPA, 2013b); (UDFCD, 2010); (Kim & Han, 2008); (Basinger, et al., 2010); (Forasté & Hirschman, 2010).

By using ideas from the above mentioned literatures and tools, an excel spreadsheet is developed that will show the impact of using rooftop RWH on the runoff reduction. The developed spreadsheet will show the benefits with regard to reducing runoff volume for specific storage tank size. The optimum tank size is the smallest size that can attain greater percent reduction of runoff while fulfilling the non-potable water demand of the household.

In addition to non-potable water demand, climatic behavior of rainfall is important factor that determines the efficiency of RWH system. The intensity of rainfall and the number of rainy days in a given year influence the availability of harvested water. In order to take this in design of RWH system a time series analysis of precipitation data is incorporated in the spreadsheet tool. A 30 year daily precipitation data of Addis Ababa Bole Airport gauging station is used to evaluate the performance of a hypothetical storm water harvesting system with varying storage capacity. The assumption is that rainfall characteristics will remain uniform and changes that may result from climate change can be accounted by certain percentage.

Other than historical rainfall data the spreadsheet tool takes daily demand, roof area and runoff coefficient, efficiency of RWH system first flush percentage. The daily demands considered in the spreadsheet tool are toilet flushing, indoor floor clearing, laundry and irrigation or gardening. The tool can also accommodate the amount of daily water that can be diverted to secondary stormwater management systems.

The analysis can be performed based on a given parcel in the catchment or based on a given neighborhood block. The input parameters other than historical rainfall data mentioned above are specific to the selected area. Once the analysis is performed on a representative area of the catchment the results can be extrapolated to the whole catchment. The sample block in the study area is shown in the following figure.

Figure 31: Sample block of mixed residence land use in the study area

The spreadsheet is devised in a way that allows the alteration of all the input parameters, hence the roof area can be altered at any time and results can be viewed.

The following paragraphs discuss how the spreadsheet is developed and how it works. Only brief explanations of the steps are made here, details can be viewed from the MS Excel file presented along with this document.

The sheets in the spreadsheet tool are of three categories i.e. sheets were variable input data can be entered, sheets containing equations and algorithms and sheets on which results are displayed. The first sheet is named “Input” and contains all the input parameters. The formulas in other sheets directly refer to cells in this sheet and changes made here will automatically change the output.

The second sheet and third sheets are named “*Time Series I*” and *“Time Series II”*. In *Time Series I* sheet 30 years daily rainfall data record from January 1, 1981 to December 31, 2010 is listed down. Runoff that is generated from the roof area on each day is calculated, after accounting for evapotranspiration and RWH System efficiency by giving a percent reduction value specified in the *Input* sheet. The demand is also presented in a column for each day in the time series by accounting for any seasonal variation that may exist as defined in the *Input* sheet. Different storage size alternatives are presented on top row of the sheet and the amount of storage available each day is calculated. Furthermore, the following parameters are determined for each day in the times series.

- Whether the day under simulation received rain or not
- Whether the amount of rainfall is below or above 2 centimeter
- Whether the hypothetical storage system overflows or not, system will overflow when capacity is exceeded by runoff from roof and demand of that day is not enough to drawdown the storage sufficiently.
- The amount of runoff that exceeds the storage capacity of the system and overflows to downstream drainage system on each day separately for storms of less than and greater than 2 cm
- The volume of overflow is summed for all days compared with the original runoff from roof tops that could have joined downstream drainage network. Then the percentage of runoff reduction is calculated for every scenario of storage capacity alternatives ranging from 200 liters to 10,000 liters.
- Whether system is available for drown dawn and demand is present for the day under simulation.
- Whether storage system is dry or not and
- The amount of demand volume that is met form RWH and its percentage

Other two sheets present overflow frequency, dry frequency, percent demand met and percent runoff volume reduction results for storm of depth less than or equal to 2 cm and greater than 2 cm. Sample tables of the tool are presented in the appendix section. Further details can be acquired from the viewing the spreadsheet tool in Microsoft Excel presented with this document.

Since the contents of the spreadsheet are presented, now what follows is viewing result for specific input and interpretation which will be presented next. The ultimate goal of the spreadsheet is determining the optimum size of storage system that will result in higher percent runoff reduction.

Consider the following input. The area of the parcel is 100 square meters; the size of the household is 5 people. 80 square meter is covered with roof and a 10 square meter garden exists in the compound. Assume the demand of rainwater for irrigating the garden per day is 50 liters/day i.e. 5mm depth of water per day. Also assume 150 liters/day and 57 liters/day demand for floor cleaning as well as toilet flushing and laundry. The input sheet will look like the following.

First flush percentage =	5%
Roof Area (sq. m) =	80
Roof Efficiency (C) =	0.95
How many people will use the building?	5
Rain Garden or Irrigation Area (sq. m) =	10
Centimeters of irrigation required per week =	3.5
Total daily gardening demand (liters) Auto Calculated =	***50***
Day of the year at which gardening starts (1-365) =	1
Day of the year at which gardening ends (2-366) =	366
Daily cleaning and toilet flushing demand (liters) =	150
Daily Laundry demand (liters) =	57
Daily additional use demand (liters) =	0
Day of the year at which additional use starts (1-365) =	1
Day of the year at which additional use ends (2-366) =	366
Daily diversion to d/s runoff reduction system (liters) =	0
Day of the year at which diversion starts (1-365) =	1
Day of the year at which diversion ends (2-366) =	366

Table 8: Input sheet of RWH system design spreadsheet

When the input is placed the following results will automatically be displayed. The first chart shown below is the plot of storage size versus the percentage reduction in runoff achieved for storm events of 2 cm and below. As it can be seen, when the storage size increases the percentage of runoff reduction also increases.

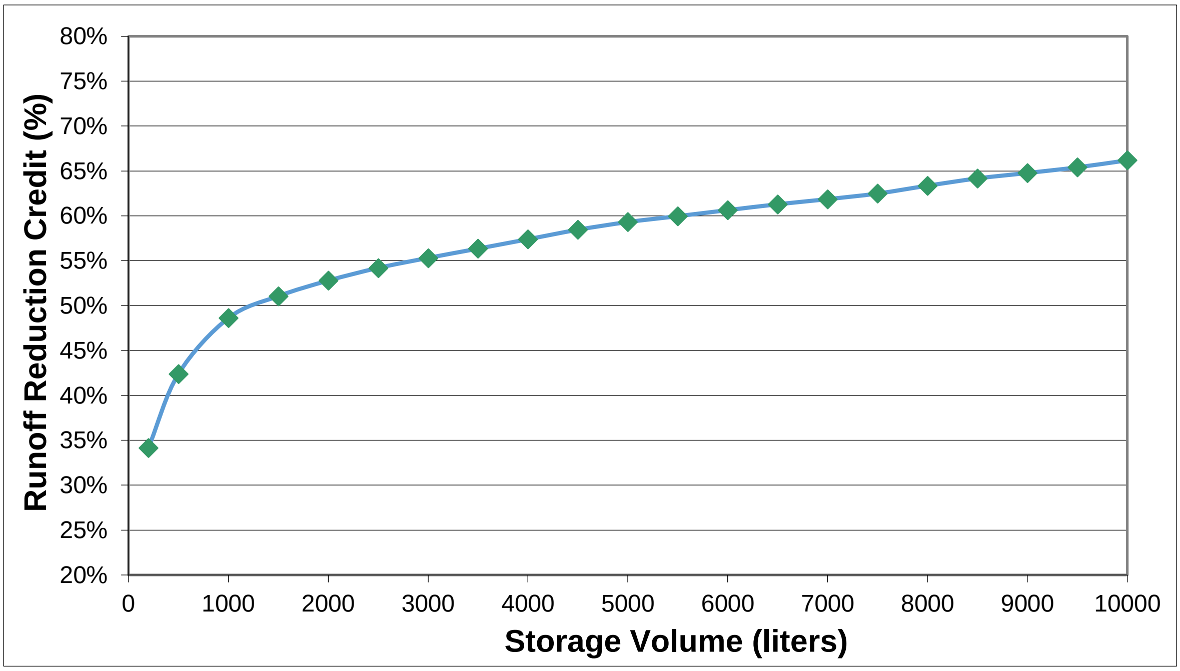


Figure 32: Runoff Reduction Volume Credit Chart

The above chart doesn’t show the optimum size of storage system. The following plot will show the percent of overflow together with percent runoff volume reduction against storage volume. As it can be seen from Figure 33, when storage size increase the runoff reduction volume credit also increases and the frequency of overflow decreases. For the first increases of storage size the rate of change in runoff reduction and overflow frequency is very high. But after a while additional credit obtained by increasing storage size starts diminishing as both curves becomes flatter. Hence the optimum storage size is the shaded area shown on Figure 33 below where a small increase in the storage size result higher runoff volume reduction increase and overflow frequency decrease.

Accordingly for the simulated input scenario the result shows that using a 1500 liters storage tank a runoff reduction of 51% can be achieved. Let us see the implication of this to the whole study area. As shown in chapter 5 of this thesis, land use type of 54.9% of the study area is mixed use. Assuming that 80% of the household in the study area will apply the proposed rainwater harvesting together with raingarden the runoff reduction that can be achieved is a multiplication of 80%, 54.9% and 51% which is 22.4%. This means the cumulative runoff coefficient which was 0.65 before the application of the IUDS solutions would be 77.6% of 0.65 which is equal to 0.5. Furthermore assuming proportionality of rainfall and landuse distribution when area of the study area is truncated, the rainfall discharge will also reduce by 22.4% because the runoff coefficient is reduced by the same amount.

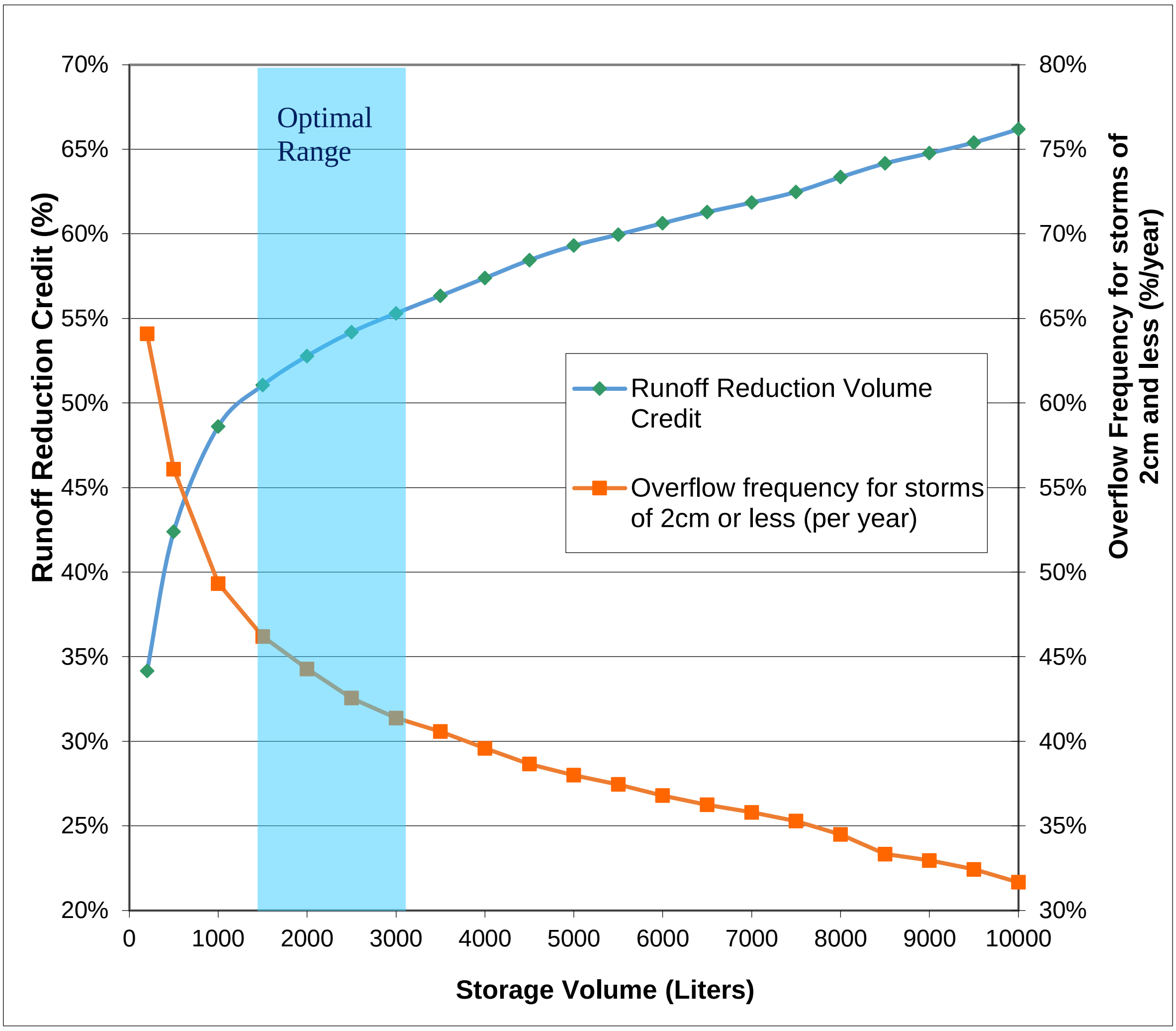


Figure 33: Runoff Reduction Credit Chart and Overflow Frequency

7. Conclusion and Recommendation

7.1. Conclusion

The new Addis Ababa Light Railway Transit System shares the same alignment with the existing road network. The existing road networks are known to have storm drainage problems. Hence LRT is under threat from flooding. General objective of this thesis has been to look for sustainable solutions and assess their applicability.

Ayat to Megenagna route is selected as study area and locations along the route with drainage problem are identified by site visit. The identified locations are at entrance to Ayat LRT depot, at CMC roundabout, around Beshale hotel and at Megenagna roundabout. Location around Beshale hotel is chosen as illustration case and modelling is performed.

Taking into consideration the data limitations, catchment delineation and runoff estimation for the location around Beshale hotel is taken as worst case scenario to indicate the existing condition before the application of integrated sustainable drainage system.

Rainwater harvesting (RWH) is found to be a good integrated sustainable drainage system together with rain garden because of residential nature of the catchment. To estimate the optimum amount of runoff reduction that can be achieved by RWH and to determine the minimum capacity of storage system, a spreadsheet tool is developed.

The spreadsheet tool developed is based daily time series data. It takes daily household harvested water demand and gives the amount of annual runoff reduction percentage for a given storage size of a system. The results in runoff reduction that can be achieved by using rainwater harvesting alone or together with other source control solutions is presented in chapter 6.

Therefore, RWH have proved to be good sustainable solution to reduce the amount of runoff reaching railway infrastructure at outlet of the catchment while reducing the utilization of potable water for non-potable use.

With regard to accomplishment of the thesis, all the specific objectives have been met. Areas along Ayat Megenagna route with drainage problem are identified, catchment delineation, hydrological modelling and estimation of runoff for specific location around Beshale hotel have been performed, rainwater harvesting together with other sustainable solution have been proposed and a tool that estimates the amount of runoff reduction achieved have been developed.

7.2. Recommendation

This thesis has tried to show how integrated sustainable drainage system could be used to reduce the volume runoff that is generated from a given catchment. While utmost care is taken to make the work error free, data limitation has forced the author to model an urban catchment with low resolution DEM data. It is recommended to use more accurate elevation models be used when they become available.

Because the integrated drainage system solution discussed are source control solutions they require participation of different party. The supporting policy that enhance the use of source control solutions should be set forth by the governing body. In addition to placing the policies, an awareness creation campaigns will be required so that every household understands the benefit of using rainwater for non-potable demands.

For future work the author recommends the study of benefits of other integrated urban drainage system solutions such as green roofs, swales and wet lands in runoff reduction to protect infrastructure in the study area. There are school and university playgrounds in the study area which can serve as excellent resource in reducing runoff from the catchment. Future works shall address the design and analysis of this solutions in protecting the LRT infrastructure. Another recommendation for future work is the modification of the RWH Tool to handle industrial rainwater harvesting benefits which will be somehow different from the residential rainwater harvesting benefits.

References

AACRA, 2003. *Drainage Design Manual.* 1st ed. Addis Ababa: Addis Ababa City Road Authority.

Ahern, J., 1995. Greenways as a Planning Strategy. *Landscape and Urban Planning,* p. 131–155.

Balmforth, D., Digman, C., Butler, D. & Shaffer, P., 2009. *Research Framework – The implementation of Integrated Urban Drainage,* Bristol: Environmental Agency.

Basinger, M., Montalto, F. & Lall, U., 2010. A rainwater harvesting system reliability model based on nonparametric stochastic rainfall generator. *Journal of Hydrology,* pp. 105-118.

Burian, S. J., 2004. *Historical Perspectives of Urban Drainage.* s.l.:University of Arkansas.

Chow, V. T., Maidment, D. R. & Mays, L. W., 1988. *Applied Hydrology.* 1st ed. New York: McGraw Hill.

CIRIA, 2007. *The SuDS Manual.* London: Construction Industry Research and Information Association .

CIRIA, 2010. *Planning for SuDS; making it happen.* London: Construction Industry Research and Informatino Association.

CSA, 2013. *Population Projection of Ethiopia for All Regions At Wereda Level from 2014 – 2017,* Addis Ababa: Central Statistical Agency.

Dagnachew, A. B., 2009. *Study of the Urban Drianage System in Addis Ababa (Master's Thesis).* Addis Ababa: AAiT.

Desalegn, G., 2011. *Investigation On Storm Drainage Problem of Addis Ababa (Master's Thesis).* Addis Ababa: AAiT.

ERA, 2013. *Drainage Design Manual.* Addis Ababa: Ethiopian Road Authority.

Ewnetu, M., 2013. Addis Ababa Light Rail Transit System Flood Risk Issues and Recommendations. *Ethiopian Reporter,* 23 March.

Ewnetu, M., 2014. *Addis Ababa Light Railway Transit System Phase I Infrastructure Inventory Report,* Addis Ababa: Unpublished.

Forasté, J. A. & Hirschman, D., 2010. *A Methodology for using Rainwater Harvesting as a Stormwater Management BMP.* San Francisco, American Society of Civil Engineers, pp. 31-44.

GHANI, A. A., ZAKARIA, N., CHANG, C. & AINAN, A., 2008. *Sustainable Urban Drainage System (SUDS) – Malaysian Experiences.* Edinburgh, ICUD.

Gilroy, K. & McCuen, R., 2009. Spatio-Temporal Effects of Low Impact Development Practices. *Journal of Hydrology,* 367(4), pp. 228-236.

Kasa, L. et al., 2013. Impact of Urbanization of Addis Ababa City on Peri-Urban Environment and Livelihoods. *Proceeding of the Tenth International Conference on Ethiopian Economy,* II(1).

Kato, S. & Ahern, J., 2008. Learning by doing: Adaptive planning as a strategy to address. *Environment and Planning 51(4),* p. 543–559.

Kim, Y. & Han, M., 2008. Rainwater storage tank as a remedy for a local urban flood control. *Water Science & Technology Vol. 8,* pp. 31-36.

Natural Resources Defense Council, 2014. *Urban stormwater solutions: These case studies show new ways cities, developers and others are reducing stormwater pollution.* [Online] Available at: http://www.nrdc.org/water/pollution/nstorm.asp

Nelson, A. C., 2004. *Toward a New Metropolis: the Opportunity to Rebuild America.* Washington, DC: Brookings Institute.

Sijmons, D., 1990. Regional Planning as a Strategy. *Landscape and Urban Planning.* , 18(1), p. 265–273.

The Hydrology Subcomittee, 1981. *Guidelines for determining flood flow frequency Bulletin 17B,* Reston, Virginia: U.S. Interagency Advisory Committee on Water Data.

Tress, B., G. Tress & Fry, G., 2005. Integrative studies on rural landscapes: Policy expectations and research practices. *Landscape and Urban Planning 70,* pp. 177-191.

U.S. EPA, 2013b. *Rainwater Harvesting: Conservation, Credit, Codes, and Cost Literature Review and Case Studies.* United States Environmental Protection Agency: EPA.

U.S. EPA, 2013. *Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs,* Washington, DC: U.S. Environmental Protection Agency.

U.S. EPA, 2014. *United States Environmental Protection Agency.* [Online] Available at: http://water.epa.gov/polwaste/green/upload/lid_canal_park_dc.pdf

UDFCD, 2010. *Urban Storm Drainage Criteria Manual: Volume 3, Stormwater Best Management Practices.* Colorado: Urban Drainage and Flood Control District.

UN HABITAT, 2013. *State of the World Cities 2012/2013,* New York: United Nations Human Settlements Programme (UN-Habitat).

UN-HABITAT, 2008. *Addis Ababa Urban Profile,* Nairobi, Kenya: United Nations Human Settlements Programme.

US Environmental Protection Agency, 2000. *Low Impact Development: A Literature Review,* Washington DC: EPA Office of Water.

Wilson, S. & Pennington, P., 2014. *Norwood greening streets, residential retrofit, Lambeth, London.* [Online]
Available at: http://www.susdrain.org/case-studies

Appendices

I. Frequency Analysis and IDF Development

Year	Precipitation (X)	Log10X
1954	57	1.756
1955	28	1.447
1956	48.4	1.685
1957	51.3	1.710
1958	41.3	1.616
1959	44.3	1.646
1960	23.5	1.371
1961	35	1.544
1962	51.8	1.714
1963	56.7	1.754
1964	44	1.643
1965	39.5	1.597
1966	32.4	1.511
1967	42.8	1.631
1968	62	1.792
1969	78.5	1.895
1970	67.5	1.829
1971	41.1	1.614
1972	40	1.602
1973	57	1.756

Year	Precipitation (X)	Log10X		Year	Precipitation (X)	Log10X
1974	34.2	1.534		1994	38.2	1.582
1975	32	1.505		1995	64.7	1.811
1976	40.2	1.604		1996	52	1.716
1977	64.8	1.812		1997	37.3	1.572
1978	51.6	1.713		1998	60.1	1.779
1979	39.6	1.598		1999	37.8	1.577
1980	41	1.613		2000	47	1.672
1981	58	1.763		2001	32.4	1.511
1982	48.5	1.686		2002	28.6	1.456
1983	44.5	1.648		2003	34.6	1.539
1984	82.9	1.919		2004	37.4	1.573
1985	36.8	1.566		2005	44.5	1.648
1986	98.1	1.992		2006	61.7	1.790
1987	53	1.724		2007	35.7	1.553
1988	35.8	1.554		2008	37.2	1.571
1989	48.4	1.685		2009	51.2	1.709
1990	37	1.568		2010	54.4	1.736
1991	59.6	1.775		2011	36.9	1.567
1992	44.3	1.646		2012	64.7	1.811
1993	40.6	1.609		2013	42.6	1.629

Gumbel Method

Xbar = 47.20
Sx = 13.921
a = 10.854
u = 40.935

Return Period	y	xT
5	1.49994	57.216
10	2.250367	65.361
25	3.198534	75.653
50	3.901939	83.288
100	4.600149	90.866

Log Pearson Method

Ybar = 1.6571
Sy = 0.11988
Cs = 0.4000
k = 0.0667

Return Period (T)	1/T	z	kt	yT	xT
5	0.2	-0.842	-0.842	1.758	57
10	0.1	-1.282	-1.282	1.811	65
25	0.04	-1.751	-1.751	1.867	74
50	0.02	-2.054	-2.055	1.903	80
100	0.01	-2.326	-2.328	1.936	86

Table 9: Yearly Extreme Series and Frequency Analysis Calculations

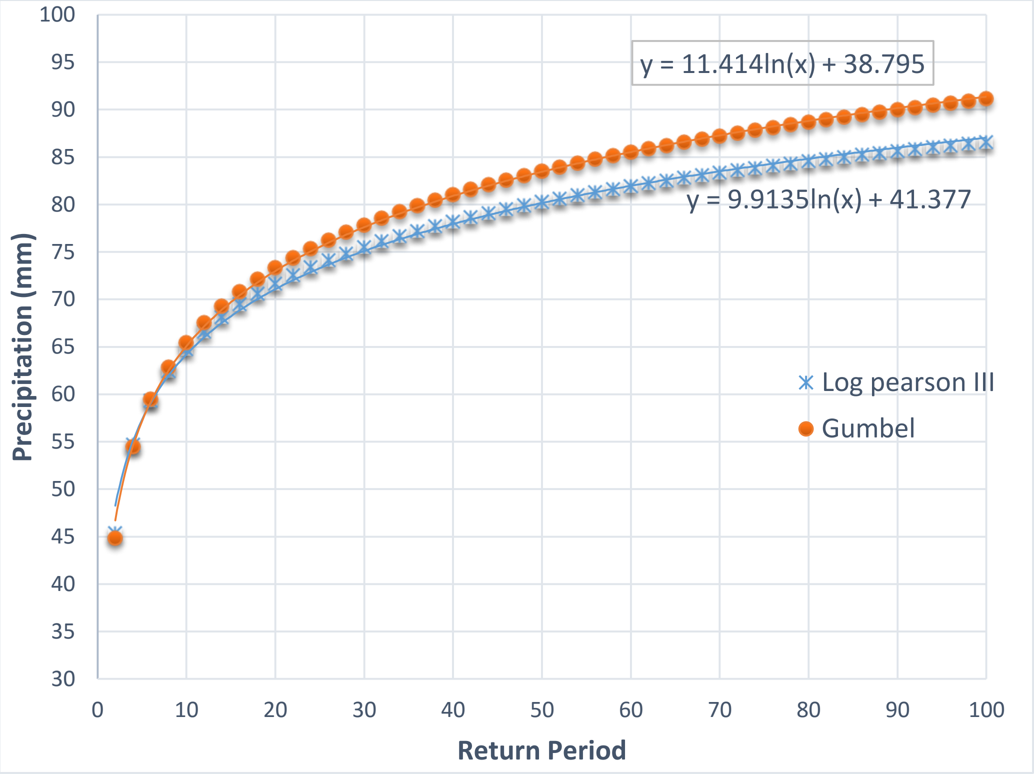


Figure 34: Plot of Frequency Analysis Results

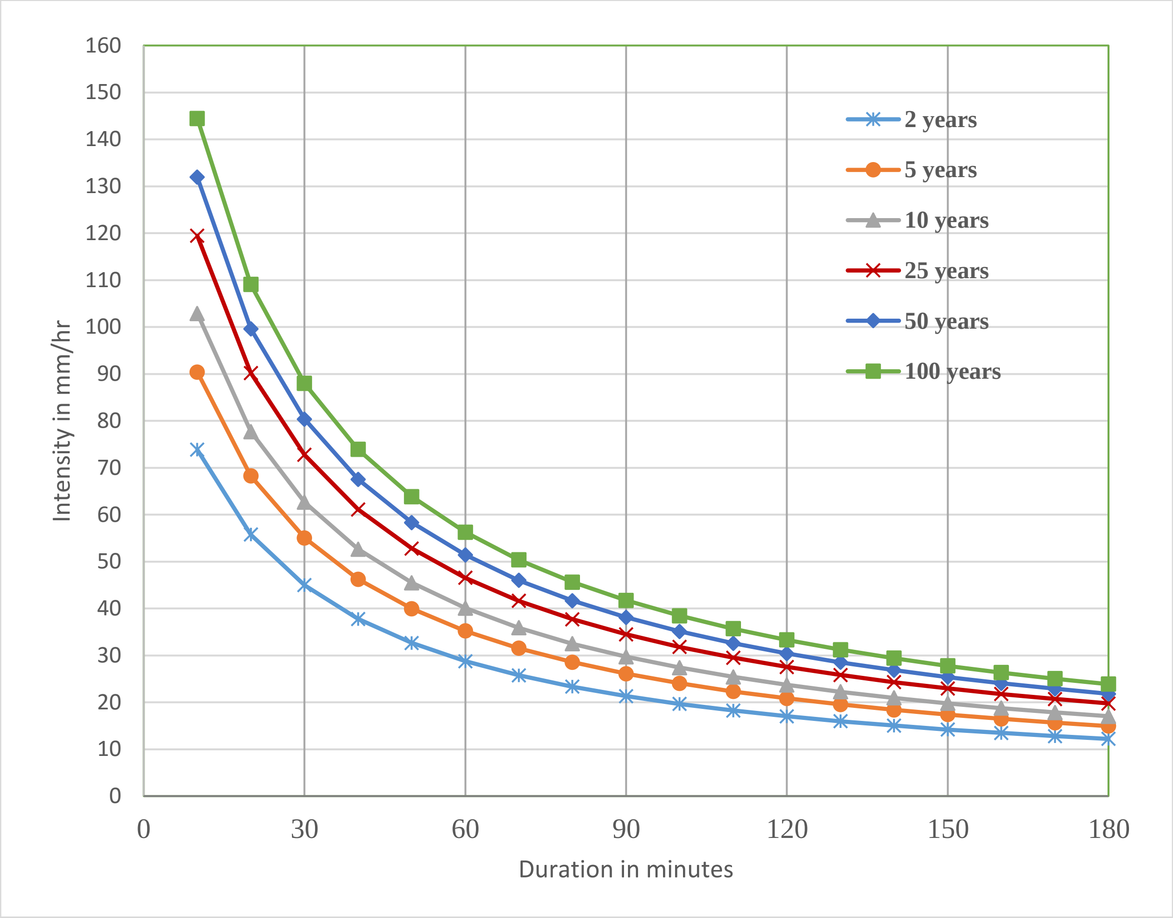
Rainfall of shorter duration using log-pearson

n = 0.92 b = 0.3

$$R_t = \frac{t}{24}\frac{(b+24)^n}{(b+t)^n} * R_{24}$$

Duration(t)	T =	2	5	10	25	50	100
	R_{24} =	47	57	65	76	83	91
10		74	90	103	119	132	144
20		56	68	78	90	100	109
30		45	55	63	73	80	88
40		38	46	53	61	68	74
50		33	40	45	53	58	64
60		29	35	40	47	51	56
70		26	32	36	42	46	50
80		23	29	33	38	42	46
90		21	26	30	35	38	42
100		20	24	27	32	35	38
110		18	22	25	30	33	36
120		17	21	24	28	30	33
130		16	20	22	26	29	31
140		15	18	21	24	27	29
150		14	17	20	23	25	28
160		13	16	19	22	24	26
170		13	16	18	21	23	25
180		12	15	17	20	22	24

Table 10: Calculations of rainfall of shorter duration



Representing in equation, polynomial of degree six

y = c6*x^6 + c5*x^5 + c4*x^4+ c3*x^3+ c2*x^2+ c1*x + b where x is the duration in minutes ranging up to 180 minutes and y is the precipitation in mm.

	2 years	**5 years**	**10 years**	**25 years**	**50 years**	**100 years**
c6	3.54096E-11	4.33E-11	4.93E-11	5.73E-11	6.33E-11	6.93E-11
c5	-2.3592E-08	-2.9E-08	-3.3E-08	-3.8E-08	-4.2E-08	-4.6E-08
c4	6.3592E-06	7.78E-06	8.86E-06	1.03E-05	1.14E-05	1.24E-05
c3	-0.00089528	-0.0011	-0.00125	-0.00145	-0.0016	-0.00175
c2	0.071482463	0.087489	0.099597	0.115604	0.127712	0.13982
c1	-3.36444494	-4.11781	-4.68771	-5.44108	-6.01098	-6.58088
b	101.0547097	123.6829	140.8004	163.4286	180.5462	197.6637

Table 11: Equations representing the IDF Curves

II. Runoff Estimations

Full Length	0.1L	0.85L	El at 10%	El at 85%	Slp1085	Tc (min)	I mm/hr	indvl area	Cum. area	contributing area	Runoff
2897	290	2462	2378	2511	0.061	26	86			1000622	15.51
2850	285	2423	2378	2508	0.061	26	87	580	580	1000042	15.59
2800	280	2380	2378	2506	0.061	26	88	1032	1612	999010	15.71
2750	275	2338	2378	2503	0.061	25	88	440	2052	998570	15.82
2700	270	2295	2377	2498	0.060	25	89	588	2640	997982	15.88
2650	265	2253	2377	2490	0.057	25	88	3320	5960	994662	15.79
2600	260	2210	2377	2483	0.054	26	88	2392	8352	992270	15.71
2550	255	2168	2377	2480	0.054	25	89	568	8920	991702	15.81
2500	250	2125	2377	2477	0.053	25	89	1432	10352	990270	15.89
2450	245	2083	2377	2474	0.053	25	90	4484	14836	985786	15.94
2400	240	2040	2376	2472	0.053	24	91	512	15348	985274	16.08
2350	235	1998	2376	2469	0.053	24	92	480	15828	984794	16.20
2300	230	1955	2376	2467	0.053	23	92	756	16584	984038	16.33
2250	225	1913	2375	2464	0.053	23	93	14748	31332	969290	16.22
2200	220	1870	2375	2459	0.051	23	93	928	32260	968362	16.24
2150	215	1828	2375	2450	0.047	23	93	732	32992	967630	16.09
2100	210	1785	2375	2445	0.045	23	93	732	33724	966898	16.10
2050	205	1743	2375	2442	0.044	23	93	540	34264	966358	16.17
2000	200	1700	2375	2439	0.043	23	94	528	34792	965830	16.26
1950	195	1658	2374	2436	0.042	22	94	476	35268	965354	16.39
1900	190	1615	2374	2433	0.041	22	95	636	35904	964718	16.45
1850	185	1573	2373	2430	0.041	22	96	9368	45272	955350	16.43
1800	180	1530	2373	2426	0.039	22	96	828	46100	954522	16.49
1750	175	1488	2373	2422	0.038	22	96	564	46664	953958	16.51
1700	170	1445	2373	2420	0.037	21	97	4236	50900	949722	16.57
1650	165	1403	2373	2417	0.036	21	98	480	51380	949242	16.66
1600	160	1360	2372	2413	0.034	21	98	6600	57980	942642	16.57
1550	155	1318	2372	2411	0.034	21	99	804	58784	941838	16.73
1500	150	1275	2372	2409	0.033	20	100	23252	82036	918586	16.43
1450	145	1233	2372	2406	0.031	20	100	112928	194964	805658	14.48
1400	140	1190	2372	2404	0.031	20	101	3428	198392	802230	14.55
1350	135	1148	2372	2403	0.031	19	102	18764	217156	783466	14.41
1300	130	1105	2372	2402	0.031	19	104	25808	242964	757658	14.17
1250	125	1063	2371	2401	0.032	18	106	155568	398532	602090	11.46
1200	120	1020	2371	2399	0.031	17	107	15544	414076	586546	11.28
1150	115	978	2371	2399	0.032	17	109	12124	426200	574422	11.29
1100	110	935	2370	2397	0.032	16	111	79008	505208	495414	9.89
1050	105	893	2370	2395	0.032	16	113	24684	529892	470730	9.52
1000	100	850	2370	2394	0.032	15	114	3384	533276	467346	9.59

Table 12: Rational method runoff estimation calculations

III. Rainwater Harvesting Tool Sample Tables

Permanent storage (Liter)					200	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	…	10000
Low water cutoff					10	25	50	75	100	125	150	175	200	225	250	…	500
Storage capacity before overflow					200	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	…	10000
	Day of week	Ppt (cm)	PPT - FF	VR from R	Start Yield for each size												
					10	25	50	75	100	125	150	175	200	225	250	…	500
1-Mar-81	7	0	0	0	10	25	50	75	100	125	150	175	200	225	250	…	500
2-Mar-81	1	0.12	0.11	87	10	25	50	75	100	125	150	175	200	225	250	…	500
3-Mar-81	2	0.64	0.61	462	200	230	255	280	305	330	355	380	405	430	455	…	705
4-Mar-81	3	5.33	5.06	3848	200	500	1000	1500	2000	2500	3000	3500	4000	4021	4046	…	4296
5-Mar-81	4	4.83	4.59	3487	200	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	…	7526
6-Mar-81	5	0.69	0.66	498	200	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	…	7767
7-Mar-81	6	0	0	0	10	243	743	1243	1743	2243	2743	3243	3743	4243	4743	…	7510
8-Mar-81	7	0	0	0	10	25	486	986	1486	1986	2486	2986	3486	3986	4486	…	7253
9-Mar-81	1	0	0	0	10	25	229	729	1229	1729	2229	2729	3229	3729	4229	…	6996
10-Mar-81	2	0	0	0	10	25	50	471	971	1471	1971	2471	2971	3471	3971	…	6739
11-Mar-81	3	0	0	0	10	25	50	214	714	1214	1714	2214	2714	3214	3714	…	6481
12-Mar-81	4	0	0	0	10	25	50	75	457	957	1457	1957	2457	2957	3457	…	6224
13-Mar-81	5	0.45	0.43	325	200	93	118	143	525	1025	1525	2025	2525	3025	3525	…	6292
14-Mar-81	6	0	0	0	10	25	50	75	268	768	1268	1768	2268	2768	3268	…	6035
15-Mar-81	7	0.12	0.11	87	10	25	50	75	100	597	1097	1597	2097	2597	3097	…	5864
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮
31-Dec-10	5	0	0	0	10	25	50	75	100	125	150	175	200	225	250	…	500

Table 13: Rainwater Harvesting Tool sample table

	Day in simulation	Daily Demand	Water for toilet demand	Irrigation demand	Laundry demand	Other demand	2ndry Practice demand	Is there demand?	Is Precip. > 2cm?	Is precipitation =< 2cm and different from zero
1-Mar-81	60	257	150	50	57	0	0	1	0	0
2-Mar-81	61	257	150	50	57	0	0	1	0	1
3-Mar-81	62	257	150	50	57	0	0	1	0	1
4-Mar-81	63	257	150	50	57	0	0	1	1	0
5-Mar-81	64	257	150	50	57	0	0	1	1	0
6-Mar-81	65	257	150	50	57	0	0	1	0	1
7-Mar-81	66	257	150	50	57	0	0	1	0	0
8-Mar-81	67	257	150	50	57	0	0	1	0	0
9-Mar-81	68	257	150	50	57	0	0	1	0	0
10-Mar-81	69	257	150	50	57	0	0	1	0	0
11-Mar-81	70	257	150	50	57	0	0	1	0	0
12-Mar-81	71	257	150	50	57	0	0	1	0	0
13-Mar-81	72	257	150	50	57	0	0	1	0	1
14-Mar-81	73	257	150	50	57	0	0	1	0	0
15-Mar-81	74	257	150	50	57	0	0	1	0	1
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
31-Dec-10	10957	207	150	0	57	0	0	1	0	0

Table 14: Rainwater Harvesting Tool sample table

	200	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	…	10000
# Days	2336	2044	1798	1684	1614	1551	1508	1479	1443	1409	1385	…	1154
	(Total days of overflow due to storm of 2cm or less)/(total number of events <=2cm)												
Percentage	64.1%	56.1%	49.3%	46.2%	44.3%	42.6%	41.4%	40.6%	39.6%	38.7%	38.0%	…	31.7%
	Tank overflow # of days: if ppt is less than or equal to 2cm, then does tank overflow? Yes = 1, No =0												
1-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
2-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
3-Mar-81	1	0	0	0	0	0	0	0	0	0	0	…	0
4-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
5-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
6-Mar-81	1	1	1	1	1	1	1	1	1	1	1	…	0
7-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
8-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
9-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
10-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
11-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
12-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
13-Mar-81	1	0	0	0	0	0	0	0	0	0	0	…	0
14-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
15-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…	⋮
31-Dec-10	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 15: Rainwater Harvesting Tool sample table

	200	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	…	10000
	1,003,447	877,951	783,243	745,985	719,602	698,105	681,132	665,338	649,384	633,246	620,185	…	515,403
	66%	58%	51%	49%	47%	46%	45%	44%	43%	42%	41%	…	34%
	If tank overflows for a storm of <= 2cm, how much volume does it overflow? Ignore all storms > 2cm												
1-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
2-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
3-Mar-81	144	0	0	0	0	0	0	0	0	0	0	…	0
4-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
5-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
6-Mar-81	370	370	370	370	370	370	370	370	370	370	370	…	0
7-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
8-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
9-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
10-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
11-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
12-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
13-Mar-81	6	0	0	0	0	0	0	0	0	0	0	…	0
14-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
15-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
. . .													
31-Dec-10	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 16: Rainwater Harvesting Tool sample table

	200	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	…	10000
Total =	520,572	646,068	740,776	778,035	804,418	825,914	842,887	858,681	874,636	890,773	903,835	…	1,008,616
RR %	34%	42%	49%	51%	53%	54%	55%	56%	57%	58%	59%	…	66%
	Runoff Reduction												
1-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
2-Mar-81	87	87	87	87	87	87	87	87	87	87	87	…	87
3-Mar-81	319	462	462	462	462	462	462	462	462	462	462	…	462
4-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
5-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
6-Mar-81	129	129	129	129	129	129	129	129	129	129	129	…	498
7-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
8-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
9-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
10-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
11-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
12-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
13-Mar-81	319	325	325	325	325	325	325	325	325	325	325	…	325
14-Mar-81	0	0	0	0	0	0	0	0	0	0	0	…	0
15-Mar-81	87	87	87	87	87	87	87	87	87	87	87	…	86.64
. . .													
31-Dec-10	0	0	0	0	0	0	0	0	0	0	0	…	0

Table 17: Rainwater Harvesting Tool sample table