ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

Sustainable Urban Drainage Options for Mekelle City

A thesis submitted and presented to the school of graduate studies of Addis Ababa University in partial fulfillment of the degree of Masters of Science In Civil Engineering (Major in Water supply and Environmental Engineering)

By

Teamir Abraha

Advisor

Dr. Ing. Geremew Sahilu

Addis Ababa University, Ethiopia

March 2018

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Approval by Board of

Dr. Ing. Geremew Sahilu	------------------
(Advisor)	Signature
Dr. Agizew Nugussie	-----------------
Chairman (Graduate committee)	Signature
Dr. Fiseha Behulu	------------------
(Internal Examiner)	Signature
Dr. Yilma Seleshi	------------------
(External Examiner)	Signature

Declaration

I declare that this thesis, which I submit to School of Graduate Studies of Addis Ababa University in partial fulfilment of the requirement of degree of Master of Science in Civil Engineering, is my own personal effort. The thesis has not submitted previously, in whole or in part, to qualify for any other academic award. Furthermore, I took reasonable care to ensure that the work is original, and, to the best of my knowledge, does not breach copyright law, and has not been taken from other sources except where such work has been cited and acknowledged within the text.

Teamir Abraha Tekelehaimanot

March 2018

Acknowledgement

Foremost, I would like to thank the almighty God for his overwhelming blessing, help and protection until this day of accomplishment.

It has been a great opportunity to pursue my Master's degree in the Addis Ababa institute of technology and I acknowledge Mekelle University to which Offers me the chance.

I would like to express my deep gratitude to my advisor, Dr. Ing. Geremew Sahilu for his great guidance, ideas and time, reviewing and giving comments for this paper and all the necessities to develop my work effectively.

In the period of doing my thesis, I have also received significant supports and nice welcome while collection of necessary data from, National meteorological agency (NMA), Ministry of water and Electricity (MOWE), Addis Ababa and Mekelle offices and Mekelle city administration. I admire fulfillment of their responsibility and keep to do so for the following researchers.

Last, I thank all who are not listed here, but take part in for this successful study.

Teamir A.

Table of Contents

Declaration iii

Acknowledgement I

Table of Contents II

Abstract VIII

Acronyms and Abbreviations X

Chapter one 1

1. Introduction 1

1.1 General background 1

1.2 Statement of the Problem 2

1.3 Significance of the research 3

1.4 Objective of the study 3

1.4.1 Main objective of the study 3

1.4.2 Specific objectives of the study 3

1.5 Scope and Limitation of the Thesis 4

1.6 Outline of the Thesis 4

Chapter Two 5

2. Literature review 5

2.1 Necessity for managing storm runoff 5

2.2 Sustainable Urban Drainage Systems (SUDS) solutions 6

2.2.1 The concept of sustainable urban drainage systems 7

2.2.2 Delivering Multiple Benefits through the components of SuDS 8

2.2.3 How SuDS works (The SuDS management train) and Where to use it 11

2.3 Policy, Issues related to Drainage system in Ethiopia 14

2.4 Sustainable development and Sustainability transitions in urban water management 14

2.4.1 Sustainable development 14

2.4.2 Sustainability transitions in urban water management 15

2.5 Existing decision support tools (DST) for storm water management 16

2.6. Selected Previous Researches 21

2.6.1 An Integrated Decision Support Approach to the Selection of Sustainable Urban . 21

Drainage System (SuDS) 21

2.6.2 Assessment of stormwater management options using Multiple Attribute Decision-
.... 22

Making 22
2.6.3 Rainfall–Runoff Simulations to Assess the Potential of SuDS in Highly Urbanized catchments 22
Chapter three 24
3. Materials and Methodology 24
3.1 Description of Mekelle city/study area 24
3.1.1 Geographic Location 24
3.1.2 Rainfall 25
3.1.3 Temperature 26
3.1.4 Land use, land cover and soil type 26
3.2 Existing Drainage system & Flood History of Mekelle city 28
3.2.1 Natural Drainage 28
3.2.2 Existing Storm Water Drainage System 29
3.2.3 Historical flood events 30
3.3 Data types and source of collection 32
3.4 Methodology 34
3.4.1 Data processing and quality checking 35
3.5 Rainfall Frequency Analysis 35
3.5.1 Identifying best fit distribution functions 36
3.5.2 Goodness of Fit Test (GOF) 40
3.5.3 Design Rainfall of Shorter Durations 42
3.5.4 IDF Curve Development 45
3.6 Hydrologic Modelling using ArcGIS 46
3.6.1 General (flow chart) 46
3.6.2 Watershed delineation 47
3.6.3 Catchment Delineation for Study Area 48
3.7 Rainfall – Runoff Transformation 49
3.7.1 Runoff Coefficient (C) Determination 50
3.7.2 Time of Concentration Tc Determination 51
3.8 Modelling using EPA Storm Water Management Model (EPA SWMM5.1) 53
3.8.1 Stormwater system layout 54
3.8.2 Subcatchment parameterization 56

3.8.3 An urban stormwater DSS to select suitable SuDS 57
3.9 The Analytic Hierarchy Process (AHP) 58
3.9.1 Identifying the factors influencing the BMP (Alternatives/Actions) Selection 59
Process 59
Chapter four 68
4. Result and Discussion 68
4.1 General decision hierarchy Result 68
4.1.1 Results of PWC of Main criteria with respect to Objectives 69
4.1.2 PWC of Alternatives (actions) with respect to Sub-criteria 73
4.1.3 Sensitivity analysis 79
4.2 SWMM simulation Results 81
4.2.1 System links and Nodes 82
4.2.2 Subcatchments simulated result 84
4.3 Feasible Locations for the Implementation of Sustainable Drainage Systems (SuDS) 86
4.4 Sensitivity analysis results 92
Chapter five 94
5. Conclusion and Recommendation 94
5.2. Recommendation 96
Reference 97

List of Tables

Table 1: The hierarchy of treatment stages within the management train 12
Table 2: Review of existing Decision Support Tools to support stormwater management.......... 20
Table 3: Land use category their spatial domination within the study area (in %) 28
Table 4: Characteristics of existing urban drainage infrastructures in Mekelle city 30
Table 5: Sources of hydrometric/meteorological information and other relevant data 33
Table 6: Results of different fitting parameters of selected distributions 42
Table 7: GOF Results of selected distribution functions 42
Table 8: 24-hr Rainfall duration for frequency analysis at selected return periods 43
Table 9: Design rainfall computation using R_t: R_{24} (ratio method) 45
Table 10: Runoff Coefficient for Use in Rational Method, (ERA, 2013) 50
Table 11: Preliminary Site Analysis for BMP's technical constraints 59
Table 12: selected set of Alternatives for AHP Method of decision-making 60
Table 13: Scale of relative importance 61
Table 14: BMP comparison matrix (criterion "one"). 62
Table 15: PWC of Sub-criteria or Indicators with respect to Main-criteria 63
Table 16: Priority Vector Extraction, Method 1 64
Table 17: Priority Vector Extraction, Method 2 64
Table 18: Normalized Column Values and Resulting Row Sums 65
Table 19: Random Indices 66
Table 20: Parameters used in SWMM Modeling and their allowable range 92

List of Figures

Figure 1: Concept of SuDS and its diversified solutions Adapted from.. 8
Figure 2: Rainwater harvesting systems 8
Figure 3: Pervious pavements.. 9
Figure 4: Bioretention systems 9
Figure 5: Vegetation Swales along gorges and roads 10
Figure 6: Infiltration trenches along roads, Adopted from (Woods, 2015) 10
Figure 7: SUDS management train, Adapted from an original illustration (Martin P, 2001) 12
Figure 8: Mekelle city with its sub-cities, (Andrea Castro, 2009)... 24
Figure 9: Rainfall series of several recorded years of Mekelle city 25
Figure 10: Temperature (^{0}C) series of several recorded years of Mekelle city 26
Figure 11**:** land use cover of Mekelle from 1985 to 2010, Source (Tahir, 2013)......................... 27
Figure 12: Main Rivers that cross the city, Elala and Aynalem River 29
Figure 13: Existing urban drainage system map of Mekelle city 30
Figure 14: some of areas causing flood due to inadequate urban drainage on Adi-haki sub road 31
Figure 15: flowchart for methodology, (source: own analysis).. 34
Figure 16: Probability density function for different Distributions... 40
Figure 17: Frequency analysis graph 44
Figure 18: IDF-Curve representing Mekelle city using GEV-I 46
Figure 19**:** General flow chart for watershed delineation and stream identification 47
Figure 20: watersheds that overlay with in the city boundary zone and the study area 48
Figure 21: delineated catchments for study area... 49
Figure 22: Drainage density map for study area (left) and location of Drainage-Density in 54
Figure 23: selected 50-sub catchment Over-laid with stormwater drainage network 55
Figure 24: Hierarchy organization of criteria/objectives 61
Figure 25: Structure for decision hierarchy of goal, main criteria and sub- criteria (Indicators) . 68
Figure 26: Results of the Comparison Matrix for Main Criteria Group, demonstrating the 69
Figure 27: PWC of technical criterion Group.. 70
Figure 28: PWC of indicators of Environmental criteria Group.. 71
Figure 29: PWC of Social and community benefits criteria group.. 72

Figure 30: PWC of life cycle costs and long-term affordability in Economic criteria Group...... 73
Figure 31: PWC alternative with respect to the 11 indicator.. 75
Figure 32: Overall sum weightage of indicators... 79
Figure 33: Sensitivity Analysis with respect to weighting of,Technical criteria, Environmental 80
Figure 34: Structure of the SWMM model and arrows present flow direction in the conduits.... 81
Figure 35: Total simulated inflow of outfalls (O-fall 1-6), (01/01/2015-22/12/2016)................ 83
Figure 36: Total simulated inflow of outfalls (O-fall 7&8) , (01/01/2015-22/12/2016) 83
Figure 37: water elevation Profile for within affected nodes and final outfall............................. 83
Figure 38: Max. Depth in selected nodes (A) & Capacity at selected links (B)............................... 84
Figure 39: System runoff and precipitation graph in Subcatchments - S80 (A) and S81 (B)......... 85
Figure 40: Sub-catch results in moderate runoff rate but high in S80 &S81................................ 86
Figure 41: Feasible identification on slope classes (a) and Road buffer and natural streams (b) ... 87
Figure 42: Feasible areas location for the main types of SuDS (a) values of peak runoff (b)......... 88
Figure 43: Layout of SuDS allocation with in S80&S81 89
Figure 44: Maximum depth (a), Capacity at selected links after SuDS implemented (b)................ 90
Figure 45: System runoff and precipitation after SuDS applied in S80 (A) & S81 (B).................. 91
Figure 46: Sensitivity Analysis of Variable Parameters... 93

Abstract

Flood generation became a common incident in Mekelle because of low vegetation cover and the vastly spreading land cover that accompanies development also results in less water being available for infiltration into the ground. Moreover, the increasingly constructing impervious structures facilitate more flood to be produce and overloading the conventional system of drainage in the city. Therefore, the existing flooding impacts on the conventional system studied and parameterized with help of Geographical information system (GIS) application.

The paper also presents a diverse stormwater management technique that potentially could be implement in a case study area and evaluate their sustainability using Analytical Hierarchy Process (AHP) decision support tool. Five alternatives for stormwater management in the selected site evaluated according to 4 main criteria and 11 sub criteria using an Analytical Hierarchy Process type called MCDA model. The model, which applies quantitative scoring and experts invited to conduct the scoring and weighting elements of the method. Again, SWMM tool is applied to compute the rainfall-runoff simulations with in Subcatchments located in the city of Mekelle (Northern Ethiopia).Finally, comparisons takes place between different Hydrologic and hydraulic parameters produced by a design storm before and after installing SWMM-LID control components.

The result showed that the best sustainable stormwater management solution after analysis of the Multi Criteria Analysis weightage tends to Rain garden (A_2), and infiltration trench (A_3) with overall aggregate weight of 0.489 and 0.232 respectively which employs main criteria such as technical, Environmental impact, social impact, and economic impact. Following weightage for the best management types a moderate-weight to Bio-cells (A_1) scoring 0.190, 0.18 to Vegetation swale (A_5) and finally lowest priority of 0.166 to Permeable pavement (A_4). With installing of LID-controls that displace equal amount of area covered by impermeable ground, runoff on affected Subcatchments S80 & S81, high imperviousness, with initial flow rates of 3.16m^3/s and 3.34 m^3/s respectively reduced and controlled. As recommendation, some relevant LID-components are allocated considering the suitability criteria of construction of different site in Mekelle city.

Key Words: *SuDS, Geographical Information system, Analytical Hierarchy System (AHP), Multi-Criteria Decision Approach (MCDA), Rainfall-Runoff simulation, SWMM-LID Controls*

Acronyms and Abbreviations

An	Alternative
AHP	Analytical Hierarchy Process
BC	Bioretention Cell
BMP	Best Management Practices
CDF	Continuous distribution function
DD	Drainage density
DEM	Digital elevation model
DSS	Decision support system
DST	Decision Support tool
ECDF	Empirical cumulative distribution function
EMA	Ethiopian Mapping Authority
EPA	Environmental Protection Agency
ERA	Ethiopian Road Authority
GEV-I	Gumbel Extreme Value Type 1
GOF	Goodness of Fit
GR	Green Roof
HSG	Hydrologic soil group
IDF	Intensity Duration Flow curve
IT	Infiltration Trench
LID	Low Impact Development
MCA	Multi criteria analysis
MCDA	Multi Criteria Decision Aid

NMA	National Meteorological agency
PP	Permeable Pavement
PWC	Pairwise Comparison
QC	Quality control
SuDS	Sustainable urban drainage system
SUDSLOC	SUDS selection and location tool
SUWM	Sustainable urban water management
SWITCH	Sustainable Water Management in the City of the Future
SWMM	Storm Water Management Model
TOPSIS	Technique for the Order of Prioritization by Similarity to Ideal Solution
VS	Vegetation Swale
WSUD	Water sensitive urban design
WMO	World Meteorological Organization

Chapter one

1. Introduction

1.1 General background

As human settlements grew bigger, they quickly began influencing the natural hydrological processes. Ditches dug, fields were under-drained, streams straightened and rivers embanked in order to quickly take water from the land to the sea. At this time, many watercourses running through our towns and cities encased in large pipes beneath the ground are now no longer visible. In doing so, the natural water cycle has significantly disrupted landscapes and wildlife habitats have destroyed and because once permeable land is now impermeable, groundwater recharge is severely restricted (Graham, 2012).

As the process of urbanization accelerates, drains become increasingly overloaded and unable to cope with heavy rainfall. SuDS seek to manage rainfall in a way similar to natural processes, by using the landscape to control the flow and volume of surface water, prevent or reduce pollution downstream of development and promote recharging of groundwater. Natural vegetation, including trees, in SuDS helps to attenuate flows, trap silts and pollutants, promotes infiltration and be robust enough to prevent erosion. It also enhances evapotranspiration and reduces the heat island effect.

The conventional drainage system is mainly a single-objective oriented design with its focus on water quantity control. Today's drainage solutions also highlight the need to embrace more deliberately the other important aspects in urban water management, such as runoff quality, visual amenity, recreational value, ecological protection and multiple water uses (Zhou, 2014).

The change from conventional piped drainage to SuDS has driven by a realization of the shortcomings of traditional methods of collecting and conveying runoff away from developed land. Urban water infrastructure provision and management constitutes a "wicked" problem, which is complex, having no clear obvious solutions with a variety of stakeholders having different interests and attitudes. Urban water management sits within a highly demanding decision on environment where optimal planning pre-supposes a synthesis of complex, heterogeneous information and data of varied spatial and temporal resolution but which must focus on site-specific implementation (Bryan Ellis, 2011).

Major cities of developing countries mainly suffer from the localized problem of flooding and water pollution due to presence of inefficient, unscientific and weakly maintained drainage system. Traditionally surface water that occurs due to rainfall or other activities in a built-up area been removed using underground-fabricated pipe systems, which designed and constructed to prevent local flooding by flushing the water away immediately. These drainage systems are designed for specific flow rate of water and thus they are unable capture the fluctuations due to change in the volume the water. As a result, pollutants from urban areas washed into rivers or the groundwater. (Sharma, 2008).

1.2 Statement of the Problem

Proper urban drainage management is a core to safe discharge flood generated within an urban center or from external sources in to final receiving systems (natural water ways/rivers) or encourage on-site infiltration. With urbanization, it is true that flood hazard increases because imperviousness (roofing, transportation ways, and parking lots) increases which reduces the infiltration capacity of the land.

Similarly, flood occurrence became a common incident in Mekelle because of deforestation and the increase in impermeable areas that accompanies development also results in less water being available for infiltration into the ground. Specifically, impervious structures & problems on provision of urban drainage facilities parallel with road construction were the main cause for flooding scenarios occurred at similar locations. In general, urban drainage management in the city had concentrated only on conventional management.

Because of the old structures and the poorly designed drainage lines, sediments and solid waste bring more complexity to this situation, which brings in excess of the drainage structures capacity, overtops the road embankment and makes the road to function improperly due to erosion and ponding in many parts of the city.

Generally, conventional drainage systems are unable to control moderate to high runoff quantity. Community facilities and landscaping potential been ignored completely while constructing these drainages. Using only conventional system guards the groundwater to no longer recharge since runoff not trapped adequately. It strongly affects the water problem in city like Mekelle which yet dependent upon the groundwater and as a result the drainage system becomes unstable since.so it's such among many reasons that the system need a new approach to drainage that keeps water on site longer, prevents pollution and allows storage and use of the water.

1.3 Significance of the research

The study offers a decision support tool that enables comparison of multi criteria components and the conceivable emphasis on the application for stormwater management, an approach to manage rainfall runoff via development that replicates natural drainage along with the policy and technological interventions that yet not applied on the ground of this country. Yield of this study shares the possible criteria, methodology used and keys from the findings with participants like stakeholders, designers and governmental institutions who make general guidance and design standards.

1.4 Objective of the study

1.4.1 Main objective of the study

This study mainly aims to apply a decision support approach that compares, weigh, analyze SuDS components and select the suitable management type for the case study area.

1.4.2 Specific objectives of the study

The following are specific objectives of the study:

- Model the application of chosen SuDS types in a selected existing case study area to see the difference in stormwater quantity before and after Implementation.

- To establish a set of sustainable criteria and indicator (sub-criteria) for selecting sustainable urban drainage system types.
- To identify areas most prone to flooding problems and reasons for flooding.
- To quantify the amount of runoff and find suitable integrated drainage system component that control the quantity and rate of run-off.

1.5 Scope and Limitation of the Thesis

This thesis originally intended to model and analyze both stormwater quantity and quality within the existing system of study area and find the possible outputs from using integrated system to mitigate the problems analyzed. However, due to none existing stormwater quality data at all, become challenging scenario to indicate the existing quality condition. So, the scope the paper lean towards modeling only the stormwater quantity and implications of SuDS in stormwater quantity management.

1.6 Outline of the Thesis

This thesis is compiled in five Chapters. Chapter one contains the introduction and background, Chapter two contains Literature review of information regarding storm water management and flooding, as well as guidelines in the field, some hydraulic theory, description of the current drainage system, description of different sustainable options and similar previous studies who apply such systems. Chapter three presents materials, methodologies and general description of the study area, Rainfall frequency analysis, delineation of study area, modeling of drainage utility using stormwater management model(SWMM) and a description of the analytical hierarchy process(AHP) and Multi criteria analysis tool with their detail methods of analyzation of priority. In Chapter four, the obtained results from the simulations are presented and discussed, both the Multi criteria analysis (MCA) priorities of SuDS types and simulated existing drainage system runoff and the network results. Later the results using SWMM modelling of existed system are compared with implementation of SuDS components and discuss the output. Chapter five and six discusses the conclusion of the overall results spring from this research and recommend if any unclear situations to inform next researchers or stakeholders. Finally, chapter seven presents the references used for buildup of this research.

Chapter Two

2. Literature review

As literature, review assists in knowledge and information digging on background study of any topic, this review consists of a series of subtopics, which provide suitable information on storm water management, historical background of existing drainage system and SuDS situation. In addition flooding history, review of SuDS solutions and experiences from developed world, policy and issues on drainage system particularly in Ethiopia and related previous studies on SuDS to feed the objective of this paper are also covered.

2.1 Necessity for managing storm runoff

"When rain falls on a natural landscape, it soaks into the ground (infiltration), evaporates, is taken up by plants (evapotranspiration) and some of it eventually finds its way into streams and rivers. These stages of the water cycle can be impended when land is altered by development in urban areas, there tends to be less permeable ground available for infiltration and less vegetation for evapotranspiration. When rain falls on impermeable surface, much more turns into surface water runoff, which can cause flooding, pollution of natural water ways and erosion problems**"**. (Woods, 2015).

According to results of (WPP, 2015) In July 2015, world population reached 7.3 billion has added one billion people since 2003 and according to the medium projection variant, it is still expected to reach 8.5 billion in 2030, 9.7 billion in 2050 and 11.2 billion in 2100". As per the projection, such increases are expected to occur mainly in Africa, which has high fertility, growth of concentration of population towards cities through local migration (rural to urban). In combination of the impacts of rapid population growth (Association, 2002) originally states and (Iwona Wagner, 2008) develop the reasoning of world's water resources, endangered by the ultimate growth of population, expansion of infrastructures, rooted as consequences while peoples seek for better living standard which initiates migration and potential domination of urban over rural settlements. This makes even harder to the governmental authorities to manage and fulfill the demand of the population residing in cities.

As responsible agents failed to do so, Simultaneous constraints enclose the harmony of nature and enforce a complex negative change in environment. Similarly (Damien Tedoldi, 2016) used, the Source of drinking water (surface and ground water) and receiving streams as examples, are facing adverse pollution impacts in which ubiquitous urban-sourced contaminants are transported within Stormwater and soil.

Consideration of stormwater management as root plan will enable as to balance demand in case of frequent climate changes resulting shortage of water and viral situations. Accordingly, Mekelle city, rainy season is characterized to be erratic, unreliable and unevenly distributed throughout the year is, forwarding with easily rising water demand due to high expansion rate and growing population. This will increase pressure on the existing water supplies (currently altering from ground water to surface water sources) and has reduced wildlife habitats of the green spaces and watercourses of the town, which is classified as determinant factor on the local ecosystem.

Necessity of stormwater management doesn't only define or reflect the importance of drainage system, broadly indicates a multiple benefit from well-managed Stormwater to the ecosystem, and withstands poor or chocked drainage systems and rapid runoff as such conditions are unable to overcome incidents such as damaging and disruptive flooding result from local heavy rains.

2.2 Sustainable Urban Drainage Systems (SUDS) solutions

Despite the traditional approaches of stormwater management, Sustainable urban drainage systems are stealing focus and recommended in number of researches and publications, as their techniques contribute positive output while addressing the mitigation measures for environmental pressure, flooding, pollution and climate change adaptation. Implementation of SuDS is increasingly accepted in many parts of the world within the same conceptualization but varies in techniques followed and scientific names of the system. (Frank Warwick, 2013)

Depending on in which country you are looking to, the ways of stormwater management system have different name such as Sustainable Urban Drainage Systems (SuDS) in United Kingdom, Low Impact Development – (LID) in United States, Best Management Practice – (BMP) Canada and United States as well, and Water Sensitive Urban Design (WSUD) in Australia. But this technique basically plays an equally important role of integrated way of taking care of storm water.

2.2.1 The concept of sustainable urban drainage systems

The potential of runoff generated from rainfall is conditionally controlled by the natural principles of water cycle as it travels through the landscape. Passing through natural routes such as infiltration, evaporation, evapotranspiration and storage, the runoff calms down and possible losses of water from the natural basin occurs (Graham, 2012).

Likewise, (Graham, 2012) clarifies the concept as **“**SuDS seek to manage rainfall in a way similar to natural process by using the landscape to control the flow and volume of surface water. As the urbanization follows an increase in hard surfaces where the water is unable to infiltrate, it prevent pollution downstream of development and stimulate recharging of groundwater. Alongside the natural way of treatment (Julie and John, 2010), site selection techniques followed by the best management practices are suited with a sequence of technological interventions. This all ensures efficient and sustainable Surface water drainage through application of drainage components and structures with multi-objective outputs.

As per (Woods Ballard, 2015), the leading and famous initiative to promote SuDS system in UK, proved the concept of SuDS follow principles wherein the objective of each individual methodologies used to handle the stormwater runoff is to have an optimized benefit. Subsequently (Ciara, 2012) elucidates that a successful SuDS system needs assurances of three functions or objectives: thus each should control water quantity, improve water quality, and provide amenity (and biodiversity) benefits or as shown in the figure below.

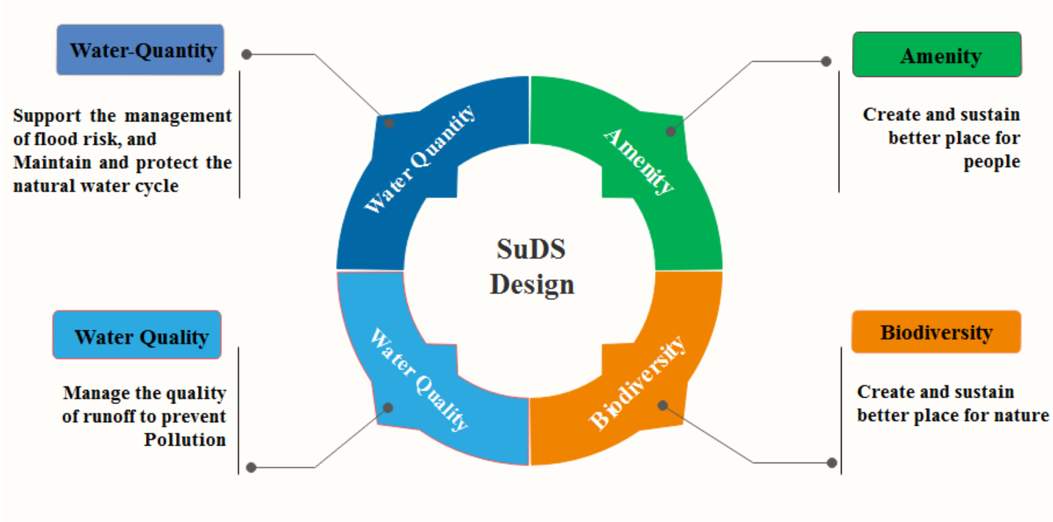


Figure 1: Concept of SuDS and its diversified solutions Adapted from

2.2.2 Delivering Multiple Benefits through the components of SuDS

Different case studies show, Benefits to be achieved through the components of SuDS has proven an advantages gained from multidirectional views with respecting the above four objectives. Some examples of SuDS are illustrated on the figures below. Which are adopted from (LID:BMP, 2014).

Figure 2: Rainwater harvesting systems

Green roofs, where a planted soil layer is constructed on a roof to create a living surface, can reduce surface runoff.

Figure 3: Pervious pavements

Figure 4: Bioretention systems

The above figures which are adopted from *(water, 2009)* and *(UDFCD, 2010)* are Bioretention systems which collect runoff, allowing it to pond temporary on the surface before filtering through vegetation and underlying soils.

Figure 5: Vegetation Swales along gorges and roads

As described in figure-5 Adopted from *(SWITCH, 2010)*, those are types Detention basins, ponds and wetlands that slow the flow of water, store and treat runoff while draining it through the site and encouraging biodiversity.

Figure 6: Infiltration trenches along roads, Adopted from *(Woods, 2015)*

Designing SuDS to deliver more than just surface water management is not difficult or costly but it does depend on early consideration at the master planning stage, creativity, consultation and partnership. Done properly, they can deliver benefits for the whole community in terms of biodiversity, climate regulation, regeneration, learning, health, recreation and play. Those local authorities leading the way in linking the requirement for SuDS to meet the objectives of wider social and environmental policy have understood this to be a cost effective way of delivering sustainable, resilient communities in urban areas (Graham, 2012).

Every components of SuDS are responsible of integrating the system, while the combination of each components could drain a wide variety of Land use/land cover (e.g. residential, commercial or industrial zones, car parks, roads and highways (Stormwater Management (SWMM) manual, 1993). Furthermore, SuDS can provide the following benefits (Woods, 2015)**.**

- Protecting people and property from increased flood risk resulting from the development.
- Protecting the quality of groundwater and surface water from polluted runoff from the development.
- Protecting natural flow regimes (and thus the morphology and associated ecology) in rivers, lakes and streams.
- Supporting local natural habitats and associated ecosystem by encouraging greater biodiversity.
- Improving soil moisture and replenishing depleted groundwater levels.
- Providing society with a valuable supply of water
- Creating attractive places where people want to live work and play through the integration of water and green spaces with the built environment.
- Improving people's understanding of how runoff from their development is being managed and used the benefits of more sustainable approaches.
- Supporting the creation of developments that are abler to cope up with changes in climate.
- Delivering cost-effective infrastructure that uses fewer natural resources and has a smaller whole-life carbon footprint than conventional drainage.

2.2.3 How SuDS works (The SuDS management train) and Where to use it

The management train is the fundamental principle underpinning all SuDS design. It comprises a series of stages in a journey starting when rain falls onto a roof or other hard surface and then flows to its destination, normally a wetland, stream, river or aquifer. SuDS seek to mimic natural hydrological processes in order to reduce pollution, flow rates and volumes.

As rainfall flows from hard surfaces, it carries with it silt particles, organic debris and pollution. The most important component of this run-off is silt to which pollutants adhere. The management train aims to use enough treatment stages to clean run-off and improve water quality as it moves downstream. (Graham, 2012).

SuDS are considered as a design and planning issue and consist of a number of management techniques as seen on the Figure below. Strategies include prevention, source control, site control and regional control of stormwater, and reducing pollution-entering watercourses.

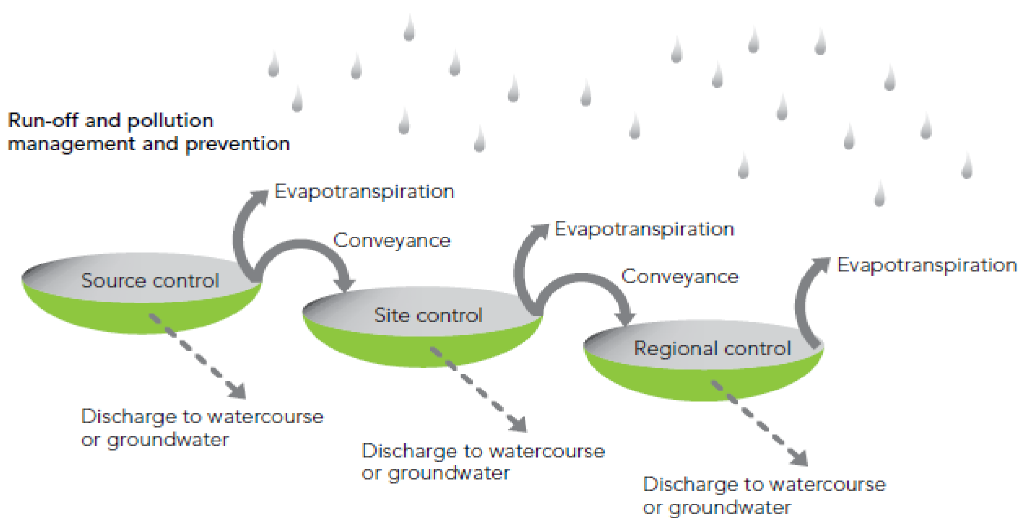


Figure 7: SUDS management train, *Adapted from an original illustration (Martin P, 2001)*

Table 1: The hierarchy of treatment stages within the management train

Prevention	Site housekeeping measures including removal of soil and other detritus from hard-surfaces to reduce impact on water quality downstream. Use design to prevent polluted run-off from entering system. Scale: individual buildings
Source Control	Controlling rainfall at or very close to source by using e.g. Permeable paving, green roofs, rain garden and filter strips. Incorporates rain-harvesting features such as water butts. scale: individual buildings
Site Control	Controlled runoff received from source control feature in detention and retention basin, swales or other surface features. Scale: small residential or commercial developments.

Regional Control	Controlling and storing the cleanest runoff received from the site. Scale: large housing developments, multiple sites which can be targeted for larger ‘community scale’ SuDS feature such as wetland or a group of wetlands. This is the final treatment stage where there is any discharge via a controlled outfall to a stream or river; there should not be any negative impacts on water quality. Ideally, the discharge should improve stream water quality.
Conveyance Features	Move water between the different treatment stages. This should be done using the above ground features such as swales and channels to maximize wild life and people benefits.

Most documents advice that the site area for SuDS are characterized in terms of the potential for infiltration, but little specific guidance or test results were given on sites with very low infiltration capacity and high groundwater levels.

SuDS can be used anywhere. SuDS may apply for new developments and redevelopments, and be retrofitted into existing developments. SuDS can even use in the smallest spaces. Good SuDS design maximizes the use of the available space by delivering efficient drainage together with other functions to help meet the objectives of the site.

For example:

- Pervious pavements can be used for parking
- Rain gardens can be incorporated into traffic calming measures
- Detention basins can be also having recreational uses
- Trees and green roofs can also help to regulate building temperatures

Most of the site pose challenges of one sort or another, but the range of SuDS components and solutions available means that, with the time engagement of the right expertise, effective SuDS schemes can deliver for all developments. This includes high-density developments sites, steeply sloping sites, flat sites, sites with high groundwater levels, and sites within floodplains, contaminated land sites, site with low infiltration capacity and site with unstable soils.

2.3 Policy, Issues related to Drainage system in Ethiopia

- The overall policy goal is to improve and enhance the health, safety and quality of life of the urban and hinterland population and enhance the environment on a sustainable basis.
- Storm water is a component of the total water resources of an area, should not be casually discarded, but rather feasible, and should be used to replenish that resource. In many instances, storm water problems signal either misuse of a resource or unwise land activity.
- Development of stormwater drainage system is not possible in isolation from other infrastructure and environmental sectors. Coordination is necessary between different departments, government and other stakeholders and planning should take cognizance of processes such as integration.
- Storm water drainage planning, design and management activities should ensure the participation of the people and other stakeholders at all levels.
- Environmental considerations such as soil erosion and sedimentation must also be taken in to account (FUPCoB, 2008).

2.4 Sustainable development and Sustainability transitions in urban water management

2.4.1 Sustainable development

The concept of sustainable development is broad and classified. However, noticeably defined as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" by (Future, 1987&2005) .Improved quality of life is possible and suitable, if consideration of environmental conservations are taken under similar circumstances. Such management approaches point out the concept of sustainable urban development, which is a Multi-objective task, aim at balancing and integrating the needs of man versus the nature.

However, as per (World Commision on Environment and Development, 1987) explains, Development in infrastructures in most developing cities (third world countries) follow the wrong concept of development and turns into uncontrolled physical expansion in which space for natural landscape, agricultural, parking and recreational areas are occupied. Therefore, it becomes both difficult and expensive to re-create open space and brings serious implications for the urban environment and economy.

As part of the implementation of the Integrated Development Plan, (Chi Zhang, 2017) describe, “Urban drainage systems are an increasingly important part of urban infrastructure that conveys stormwater and wastewater away from urban areas and contributes to the general well-being of the urban population”. But then again most cities in the developing world have urban water infrastructure deficits and the ones already exist is characterized by an ageing infrastructure, poorly maintained, un-efficient and worsening of natural habitat. Henceforward, as illustrated on (Chi Zhang, 2017), drainage system to be implement should go parallel with sustainable development plans and effective as it offer the compulsory level of service. Moreover, the sustainable system entails adaptation responses in order to deal with the negative effects of present and future unexpected, critical and extreme events that could occur at different periods.

2.4.2 Sustainability transitions in urban water management

Along with (UNDP, 2000), “Technological progress and innovation assisted by scientific researchers are all important ways to facilitate transitions to sustainable development”.

Difficulties which holds back towards sustainable development are Accordingly exemplified by (Bank, 2015) that “ a greater concentration of people, assets, and infrastructure in urban areas, an increasingly complex range of shocks and stresses can put in jeopardy human wellbeing and hard-won development gains”. In addition, (SDSN, 2014).generally argue that poverty, conflict, economic status are the key negatively driven factors in Horn of Africa countries and regions, are vulnerable to challenges such as natural hazards, disease and severely affected by climate and other environmental changes. Therefore, are unable to accomplish goals of transitions towards sustainable development by themselves and are ought to practice resilience.

In terms of sustainability transitions challenge in urban water management, it is important to understand that the points of departure and drivers for potential shifts towards SUWM naturally differ between cities in the developed world and those in the developing world. While cities in the developed world such as Copenhagen have relatively fully developed conventional water service systems, they are increasingly confronted with decaying infrastructure, questions about path dependence, and the choices to be made about the development of appropriate infrastructure in the face of climatic and socio-economic uncertainties**.** These cities face the challenge of retrofitting existing water infrastructure systems and the built environment in general into more sustainable configurations (Mguni, 2015).

As such, these cities face the sustainability transitions challenge of leapfrogging over the technological path dependencies confronting the water sectors of developed cities and instead develop more sustainable configurations of urban water systems simultaneously addressing basic access to water supply and drainage (Mguni, 2015).

Expectantly, today's arrangement and management schemes in infrastructures such as drainage system are to be replace and modified under Sustainable way of guidance into the future. Yet, (Orman, 2013) describes, the sustainable way of guidance needs a scarification of inspection, maintenance and replacement of existing infrastructure. Besides as (Bank, 2015), Master plans developed for future urban sub-surface drainage systems should built/retrofit the system to be friendly with environment. In such actions, efficient and guaranteed level of service could be achieved.

2.5 Existing decision support tools (DST) for storm water management

In this section, a review is made of existing DSTs to assist stormwater management. These tools do not (only) evaluate hydraulic performance of infrastructures, they also include additional information and/or procedures to support decision-making. In summary, they estimate and/or compare costs, benefits and disadvantages of different stormwater options. In fact, most of the reviewed tools include some of the SuDS advantages described in the previous section.

In Table 2, the review of existing DSTs is summarize and evaluated according to the following capabilities: Analysis of the infrastructure hydraulic performance for runoff quantity and quality management. Some tools include urban runoff estimations and analyze quantitatively or qualitatively how the stormwater infrastructures modify stormwater quality.

Decision framework to compare advantages and disadvantages of different stormwater strategies. In general, Multi Criteria Analysis is usually used to compare different decision criteria. These techniques generally include the use of weighted and scored matrices, and hence require the establishment of measurable criteria, whether qualitative or quantitative, to assess the extent to which objectives may be fulfilled. Some authors (A. Benzerra, 2012) and (J.Chow, 2013) have already used these techniques to compare stormwater management options.

This list of capabilities has been selected according to the expected costs, benefits advantages and disadvantages of stormwater strategies that should be considered for a sustainable and energy efficient stormwater management.

The North Carolina State University Rainwater harvesting model (NCSU, 2009), is a simple tool focused on cost and benefits of rainwater harvesting systems. This model uses rainfall data and anticipated usage to establish cisterns inputs and outputs.

The Water Environment Research Federation BMP and LID Whole Life Cost Model (WERF, 2009) is a series of spreadsheets, each of which is specific to one SuDS technique. It provides detailed analysis of capital costs, maintenance and whole life costs for a number of common SuDS techniques. Costs are derived by inputting specific details including design and maintenance hydraulic design.

Center for Neighborhood Technology Green Values (CNT, 2009), is an online tool for comparing the performance, costs, and benefits of two infrastructures scenarios: SuDS development and conventional stormwater practices. The user has to introduce rainfall and drainage area data, while the tool estimates costs and benefits of drainage infrastructures based on data from similar projects.

The COFAS Tool (C.Peters, 2010), is a DST which allows comparison of a range of stormwater strategies through a Multi Criteria Analysis framework. This framework assesses the flexibility of the different options compared. The user can choose decision criteria, but, for each option, decision criteria data (costs, water quality, runoff production, etc.) should be introduce.

Key Performance Indicators (KPI) developed by (J.Chow, 2013) is not a tool but a methodology to compare stormwater strategies, including sustainable designs benefits, with a Multi Criteria decision framework. Nevertheless, it includes procedures to quantify most of the SuDS benefits, like energy savings, rainwater-harvesting benefits, reduction of carbon emissions, etc. This methodology could be included within software are to be used by regional and municipal entities for decision-making.

SuDS for Roads (SEPA, 2013), is a spreadsheet that can be used to estimate whole life costing and whole life carbon emissions of drainage infrastructures. These results used as part of the stormwater selection criteria to provide evidence to support the appropriate selection of SuDS in roads.

SUSTAIN model (EPA, 2013), is a software model that provides process-based simulation of flow and pollutant behavior for a wide range of structural SuDS. It focused on stormwater water quality processes, although it also provides data to estimate drainage infrastructures costs.

UKSuDS (wallingford, 2013), is a group of tools to advise developers with choosing suitable SuDS components, assessing the water quality treatment effectiveness and obtaining indicative costs of these infrastructures. These tools are based on United Kingdom data and they provide independent results, but there is not a global framework to compare different drainage strategies with their results.

Water Sensitive Urban Design in Sydney (WSUD, 2015), developed a Decision Support Matrix to compare different options for stormwater projects. This matrix is a Multi Criteria Analysis implemented in a spreadsheet that compares infrastructures costs with water quality, water quantity, and environmental, social and institutional benefits. This matrix should be populated by the user with data from hydraulic and water quality models.

Construction Industry Research and Information Association developed a spreadsheet called BeST (CIARA, 20154), that provides a structured approach to economically evaluate a wide range of social and ecosystem services provided by drainage infrastructures. All these benefits are used to compare different drainage scenarios in a period. It also lists potential stakeholders to be taken into account when each expected benefit is evaluated.

Finally, New York City developed the online tool Co-Benefits Calculator (NYC, 2015), for stormwater evaluation and planning purposes. This calculator tool identifies co-benefits associated with each type of SuDS and calculates environmental, social, and economic costs and benefits. It was developed based on monitoring data from different SuDS in New York.

As it can be observed in Table 2, there is a wide diversity of DSTs for stormwater management, from tools that only address the estimation of construction and maintenance costs

Table 2: Review of existing Decision Support Tools to support stormwater management.

	NCSU	WERF	CNT	Peters et. al	Chow et al	SEPA	US-EPA	HR Hallingford	WSUD	CIARA	NYC
	2009	2009	2009	2010	2013	2013	2013b	2013	2015	2015	2015
	Analysis of stormwater infrastructure										
Estimation of runoff production	x	x	√	X	√	x	√	√	x	√	√
Estimates rainwater harvesting	√	x	x	X	√	x	x	√	x	√	x
Analyses of stormwater quality	x	x	x	X	√	x	√	√	x	√	√
Analyses of ecosystem service	x	x	√	X	√	x	x	x	x	√	√
	Cost and Benefit estimation										
Estimates O&M costs	√	√	√	X	√	√	√	√	x	x	√
Estimates stormwater pumping & treatment cost	x	x	√	X	√	x	x	x	x	√	√
Estimates rainwater harvesting Benefits	√	x	x	X	√	x	x	x	x	√	x
Estimates flood protection benefits	x	x	x	X	√	x	x	x	x	√	x
Estimates benefits of building insulation improvement	x	x	x	X	x	x	x	x	√	√	x
	Energy consumption and emission estimations										
Estimates Energy consumption and emission during operation and maintenance	x	x	x	X	x	√	x	x	x	x	√
Estimates Energy consumption of stormwater pumping an treatment	x	x	x	√	x	x	x	x	x	√	x
Estimates energy saving during rainwater harvesting	x	x	x	X	x	x	x	x	x	x	x
Estimates energy saving of building insulation improvement	x	x	x	X	x	x	x	x	√	√	x

2.6. Selected Previous Researches

2.6.1 An Integrated Decision Support Approach to the Selection of Sustainable Urban Drainage System (SuDS)

This study mainly concentrates on the characterization and weightage of different SuDS alternatives within their specific sites. Here (Bryan Ellis, An Integrated Decision support Approach to the selection of Sustainable Urban Drainage systems (SuDS), 2011), The decision-making process for the selection of Sustainable Drainage Systems (SUDS) for stormwater runoff management involves a variety of stakeholders within public and private sectors holding differing powers and opinions regarding the significance they attribute to differing control factors such as environmental, social, legal and economic criteria.

The study outlines the web-based multi-criteria analysis (MCA) approach with in The DSS, essentially a screening tool that can be applied by planners and developers on a catchment scale incorporated into the SUDSLOC model developed within the SWITCH Stormwater Management theme. The Multi criteria analysis (MCA) forms the core basis of the adaptive decision support system (DSS) to the SWITCH SUDSLOC selector tool, which intended to support stakeholder negotiation. The development of mutually acceptable sustainable solutions to the problem of control and treatment of urban surface water drainage. The MCA matrix methodology for the DSS and the SUDSLOC model are outlined and some of the advantages and limitations of the integrated modelling approaches are demonstrated.

They conclude, the increasing complexity and competitiveness of environmental decision-making renders decision support a difficult exercise. Despite the popularity of DSS approaches, the ultimate success of DSS development is still uncertain and can undoubtedly be unsuccessful when applied to unstructured problems having a variable quality, wide range of criteria and alternatives or “data warehouse”.

2.6.2 Assessment of stormwater management options using Multiple Attribute Decision-Making

This research is studied by (Nivedita G, 2016), which addresses the problem of selecting the most sustainable stormwater management alternative in developing countries in a dense urban context.

Firstly, suitable Low Impact Development (LID) stormwater management measures for dense urban areas in developing countries were identify based on critical review of literature. Alternatives been formulated as varying percentages (degree of adoption) of these suitable measures to manage the stormwater sustainably. Further, a novel decision making framework is developed which generates the hierarchy for selection of the most sustainable stormwater management alternative.

Four main criteria (technical, economic, environmental and social) comprising three quantitative and eight qualitative indicators have used to evaluate seven alternatives. The regional and local societal priorities are captured through criteria-weightings and are translated into a decision-making methodology. Experts' opinions have been included using Analytical Hierarchy Process (AHP). One of the most widely used Multiple Attribute Decision-Making (MADM) method, TOPSIS is used to rank the alternatives and to identify the most sustainable alternatives. Various scenarios to represent different stakeholders' perspectives have been articulated. Alternative with medium level of cost implication and satisfactory level of performance chosen by the decision-making method in most of the scenarios. The proposed decision making approach can be used for selecting sustainable stormwater management options in densely populated areas of developing countries.

2.6.3 Rainfall–Runoff Simulations to Assess the Potential of SuDS in Highly Urbanized catchments

This paper studied by (Daniel Jato-Espino, 2016), shows the potential benefits of installing different types of SuDS in preventing flooding in comparison with the common urban drainage strategies consisting of sewer networks of manholes and pipes. The impact of these systems on urban water was studied using Geographic Information Systems (GIS), which are useful tools when both delineating catchments and parameterizing the elements that define a stormwater drainage system. Taking these GIS-based data as inputs, a series of rainfall–runoff simulations were run in a real catchment located in the city of Donostia (Northern Spain) using stormwater computer models, in order to compare the flow rates and depths produced by a design storm before and after installing SuDS.

The proposed methodology overcomes the lack of precision found in former GIS-based stormwater approaches when dealing with the modeling of highly urbanized catchments, while the results demonstrated the usefulness of these systems in reducing the volume of water generated after a rainfall event and their ability to prevent localized flooding and surcharges along the sewer network.

Two different SuDS, two extensive green roofs (GR1 and GR2) and a porous asphalt pervious pavement structure (PPS) were included in the model to assess their storm attenuation capability. To test the influence of these systems to prevent flooding, three simulations were run, including each of the SuDS proposed. The aim at this point was to compare the behavior of the nodes and pipes with and without SuDS installed.

The inclusion of these systems resulted in an important reduction in total inflow generated in their respective nodes, even in the case of GR1, which showed the worst performance in terms of avoiding floods and surcharges.

Chapter three

3. Materials and Methodology

3.1 Description of Mekelle city/study area

3.1.1 Geographic Location

Mekelle, the regional capital city of the Tigray region, is located in the northern Ethiopia high lands at 780 km north of Addis Ababa. Geographically it is located between $33^0$20'30''to $13^0$36'52" latitude and $39^0$25'30" to $39^0$38'33" Longitude. It lies in an altitudinal range of 2150-2270 meter asl. The city is bounded in the north and east by hills while in the south and west it consists of relatively flat topography. The eastern ridge known as Choemea is the highest pick of the city. The city is rapidly expanding toward north, North West, and Western direction. (MUBECO, 2016).

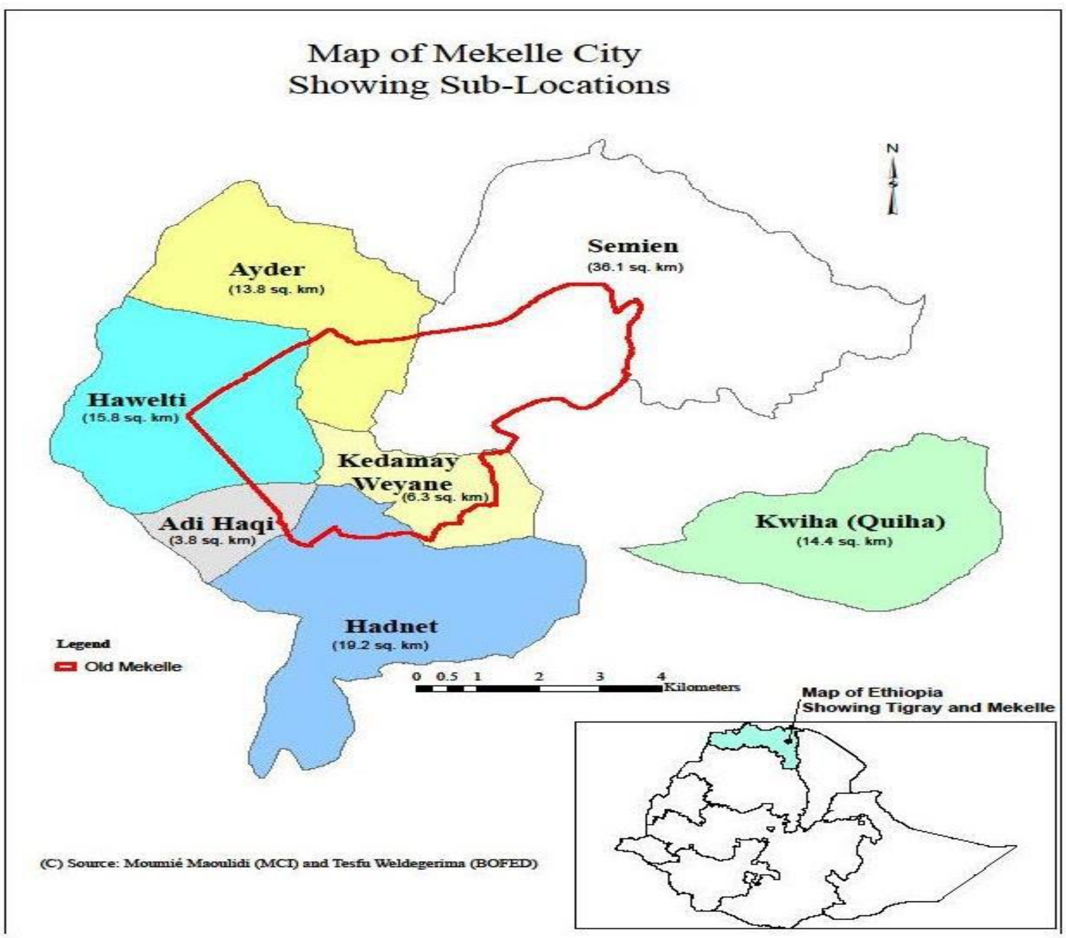


Figure 8: Mekelle city with its sub-cities, *(Andrea Castro, 2009)*

The landform of Mekelle area, characterized by flat and rolling mountain topography. The hilly terrain is situated at the northern and eastern fringe of the city, extends further to the east where limestone and dolerite bedrocks are exposed. Moreover, the geomorphology and geologic condition are important constraints and limiting factors in the future development and expansion of Mekelle City.

3.1.2 Rainfall

In view of the fact that Mekelle is found to the North of the Equator, its summer (rainy season) occurs by the months of June, July and August and characterized to be erratic, unreliable and unevenly distributed throughout the year. (Ephrem G.G, 2013).

From the analysis of metrological data records observed by several stations nearest to the study area, it has a total annual average rainfall of 575.9 mm/year. The amount of rainfall varies from year to year and within months of the year in the study area.

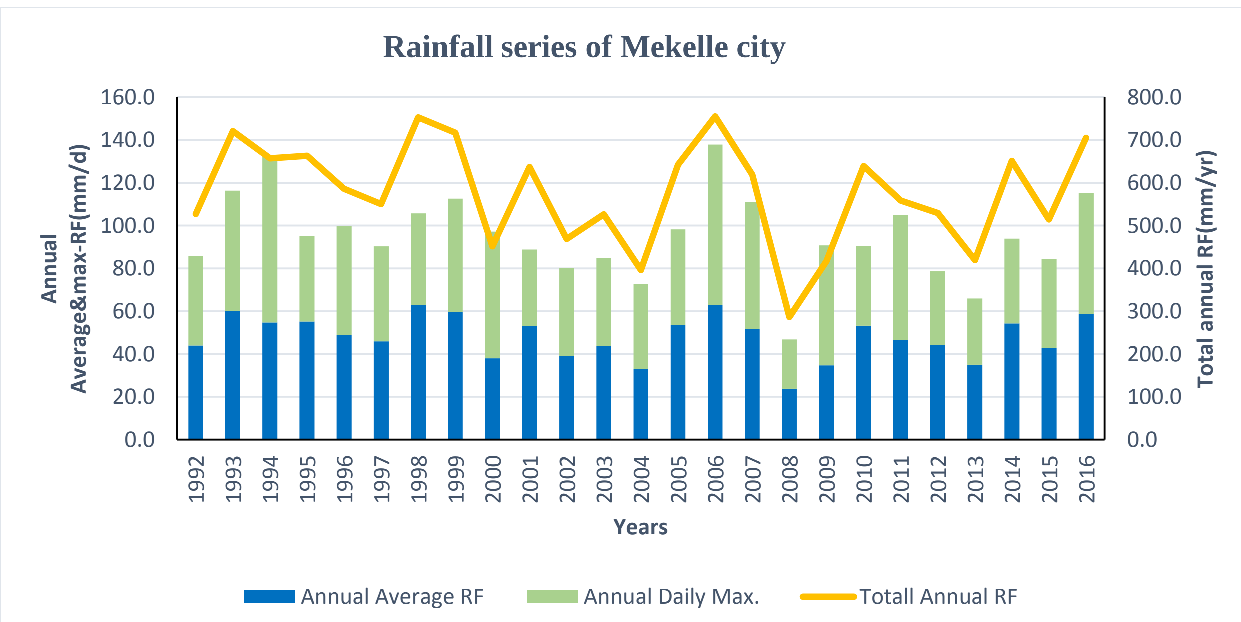


Figure 9: Rainfall series of several recorded years of Mekelle city

3.1.3 Temperature

Temperature determines the suitability of a site for settlement and development of various infrastructures, especially for the water cycle characterization. From the historical temperature records, the average maximum and minimum temperature of the area are determined. Accordingly, the area has an annual average maximum temperature of 27.6^{0}C and annual average minimum temperature of 11.52^{0}C. There is monthly variation in temperature. May and June are the hottest months with a monthly mean maximum temperature of 30.2^{0}C and 29.8^{0}C respectively, and monthly mean minimum temperature of 14.2^{0}C and 13.5^{0}C. December and January are the coldest months with a mean monthly maximum temperature of 25.4^{0}C and 26.6^{0}C and monthly mean minimum temperature of 8.6^{0}C and 8.3^{0}C respectively.

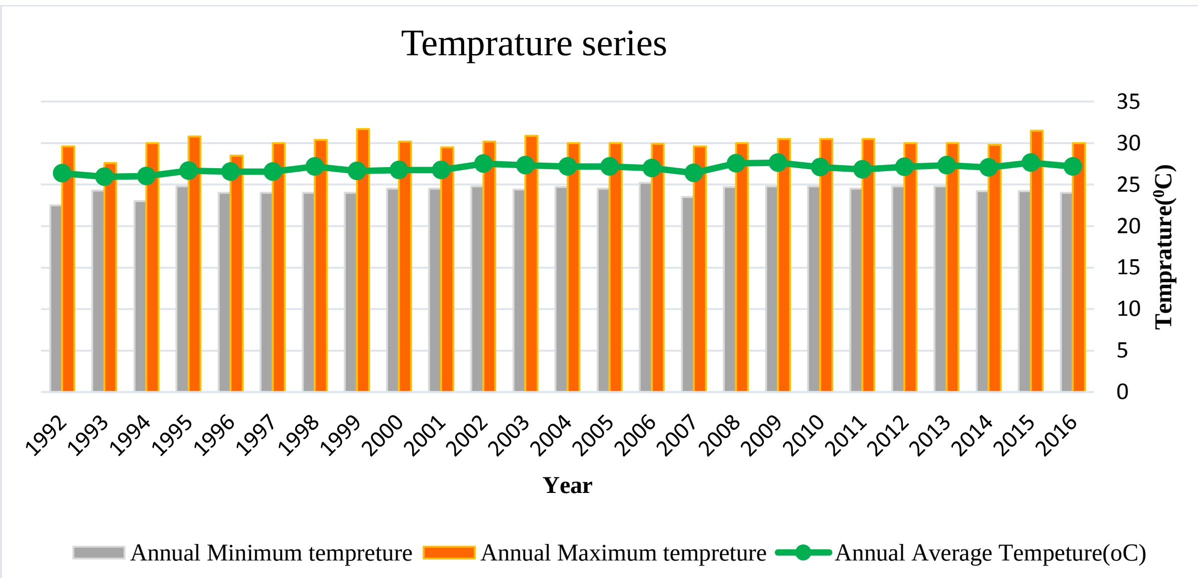


Figure 10: Temperature (^{0}C) series of several recorded years of Mekelle city

3.1.4 Land use, land cover and soil type

Mekelle city, generally well planned except for small sections at the foot of the escarpments where the houses are highly clustered and with narrow streets. In the eastern part there is a natural boundary sharply ending the periphery of the town.

The city stretches from the northern cliff around Messebo to the Debry area around south and extends from Quiha at the East to MayEmeri to the West. The Endayesus hills on the east side and the sharp cliffs and steep slopes of the Messebo escarpment have surrounded the larger part of the city. Quiha is bounded by natural and manmade boundaries in south by Alula Aba Nega International Airport East by a cliff and North by steep slope Aynalem is one small village to the south of the city disconnected from these two settlements by vast agricultural land, airport and military camps. The city is disconnected by vast Agricultural land, escarpment, mountains terrain, military camp, long travel distance, and airport, which restricts smooth, easy and direct access as well as movement from the center of city to the other side. Besides, from physical pint of view, it also hampers future development potential of the city in north, east and south direction. (MUBECO, 2016)

The town is presently rapidly expanding towards the North, Northwest and west. The layout of utility services in Mekelle generally follows the town plan. The land use pattern outside Mekelle is mainly dominate by farmlands, grazing areas, residential villages and protected areas for soil and water conservation.

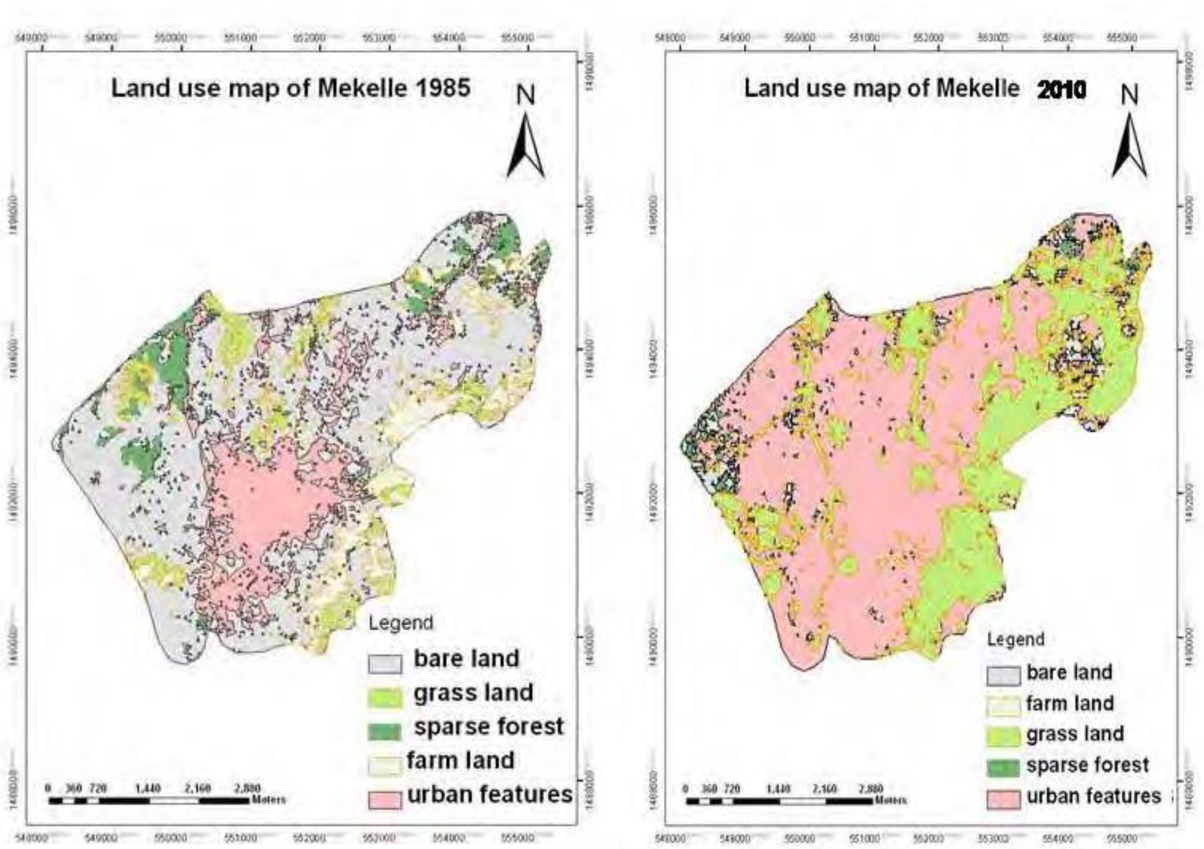


Figure 11**:** land use cover of Mekelle from 1985 to 2010, Source *(Tahir, 2013)*

According to *(Adminstration, 2016)*, the land use of study area is about 2393.5ha, accessed using the Arc-GIS enables to withdraw a collection of all land-use types (table 3) in which mixed type of use (40.17%) is spatially dominant and Manufacturing & storage (0.90%) type of land use covers less space than all.

Table 3: Land use category their spatial domination within the study area (in %)

Land use category	Land cover(ha)	%Total Area
Commerce & Business	264.14	11.04
Green Area	573.35	24.0
Social & Municipal Service	224.70	9.39
Existing Manufacturing & storage	21.50	0.90
Road, Transportation, Utilities & Infrastructure	248.61	10.4
Administration	25.78	1.08
Existing Mixed use	961.38	40.17
Pure residence	73.43	3.07
Total	2392.91	100.0

(Source: Mekelle city administration)

3.2 Existing Drainage system & Flood History of Mekelle city

3.2.1 Natural Drainage

The drainage system of a catchment area controlled by several factors including geology, structure and topography. In terms of its drainage condition, the city is part of Tekeze basin where the tributaries join Geba River then to Tekeze River. The catchment is characterize by flow from places of high elevation toward the area with flat topography. Elala and Aynalem Rivers are the perennial streams and major tributaries of the Giba River. The Elala River drains the central plain whereas Aynalem River drain the south of the potential zone. There are many tributaries feed both the rivers with substantial amount of water during rainy season. These rivers are seasonal where the peak discharge attained during summer. (MUBECO, 2014)

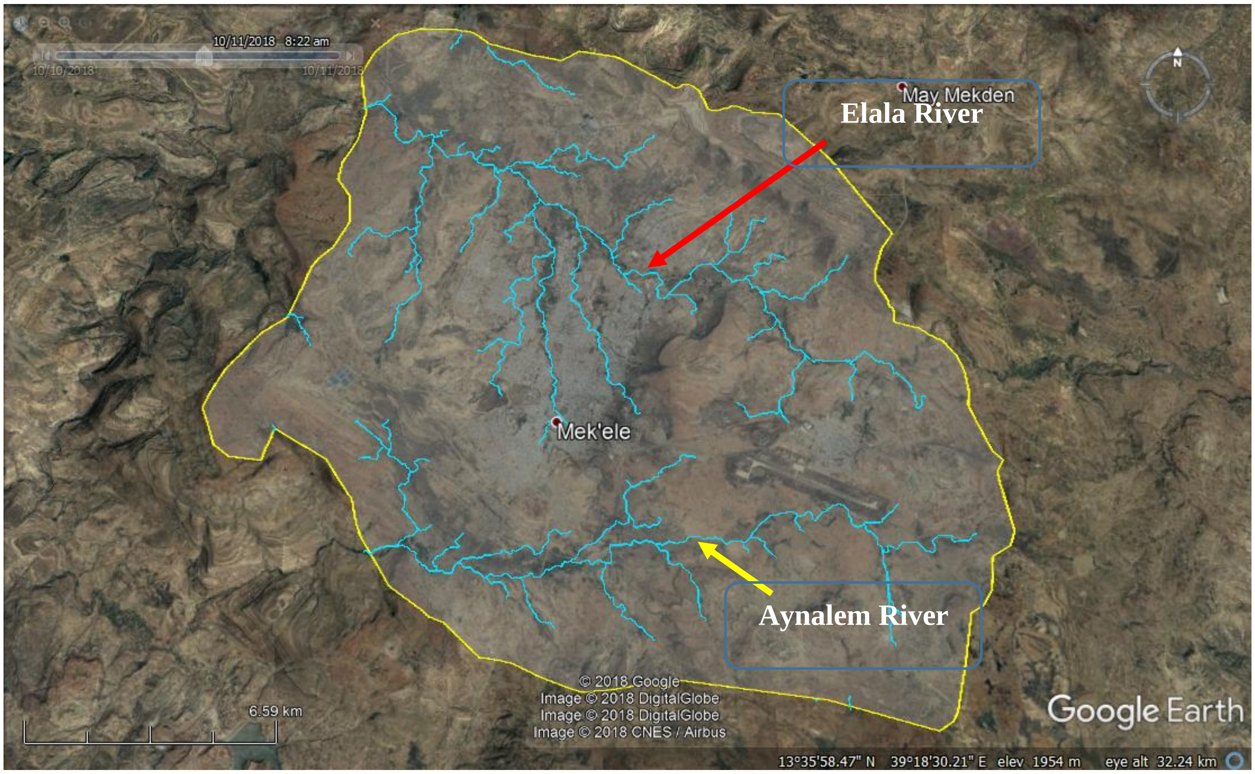


Figure 12: Main Rivers that cross the city, Elala and Aynalem River

The two rivers (Elala and Aynalem), facilitate the surface drainage system of the city that contributes to small-scale irrigation in its environs with significant positive implication. The tributaries feed both rivers with substantial amount of discharge during rainy season signifies the risk of flood to the nearby settlements during these periods and the vulnerability of soil erosion and land degradation on the built-up area. Allocating space for protective land uses in the plan preparation is considered.

3.2.2 Existing Storm Water Drainage System

Several studies state different views of urban drainage system within the city (MUBECO, 2014). Field survey for the inspection of stormwater drainage lines shown yet some changes has made but a lot has to be accomplish for the future. The table below of the study reviewed from Mekelle university report indicates, the Trend of storm water drainage lines development in Mekelle city and Concrete pipe drain is the dominant type of infrastructure showing constant increment of use while other categories of conveyances are applicable in subways.

Table 4: Characteristics of existing urban drainage infrastructures in Mekelle city

Years	Closed Pipe	Open Drain			Sub total
	Concrete Pipe drain	Masonry Channel drain	Stone tile drain	Concrete lined	
2009	15.53 km	2.66 km	3.2 km	6.66 km	28km
2010	15.53 km	2.66 km	3.2 km	6.66 km	28km
2011	18.55 km	5.97 km	3.94 km	5.53 km	33.99km
2012	36.28 km	5.96 km	3.94 km	5.53 km	51.71km
2013	38.55 km	9.87 km	3.94 km	5.53 km	57.89km

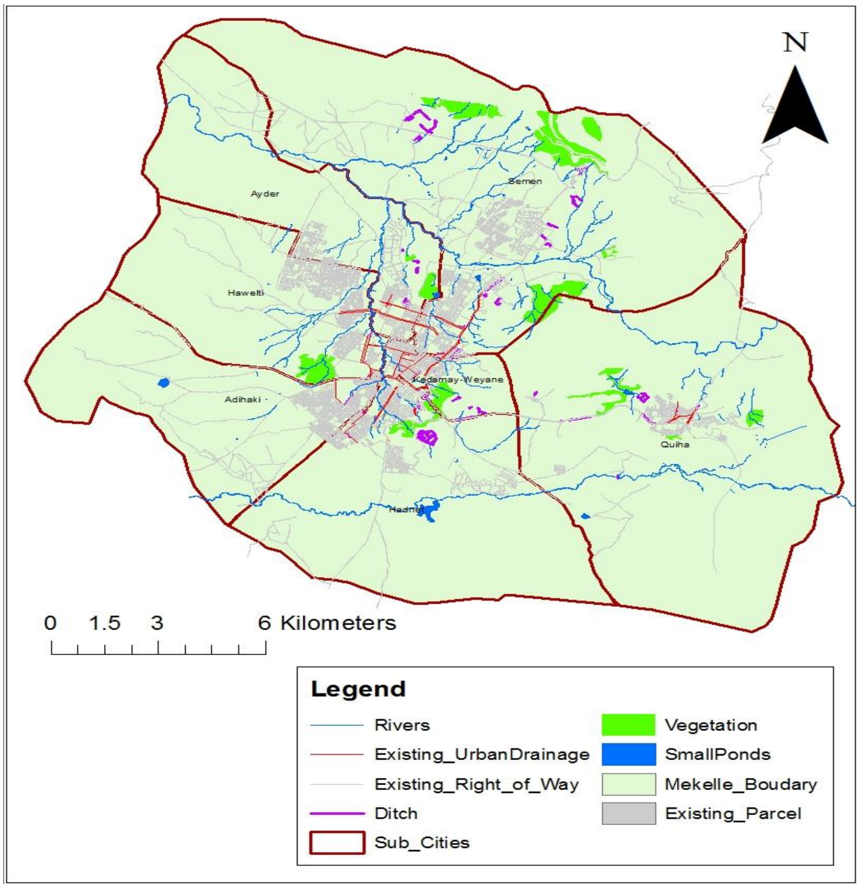


Figure 13: Existing urban drainage system map of Mekelle city

(Source: own)

3.2.3 Historical flood events

Due to urbanization, the hydrology or the natural cycle of water is disrupted and altered. Urbanization has removed the vegetation that intercepts, slows and returns rainfall to the air through evaporation and transpiration. Grading has flattened hilly terrain and filled in natural depressions that slow and provide temporary storage for rainfall.

Figure 14: some of areas causing flood due to inadequate urban drainage on Adi-haki sub road (Left) and Road in Adishumdhun Area (Right), (source: *(Adminstration, 2016)*)

Rainfall that once infiltrated into the ground now runs off the surface. The addition of buildings, roadways, parking lots and other surfaces that are impervious to rainfall has further reduced infiltration and increased runoff. Due to this effect, some of the main streets of the city have inadequate drainage facility and some of the area are-

- Road in Daero Area, found with in kedamay weyane sub-city
- Almost most sub-ways of kebelle 16 and romanat square area, inside kedamay weyane sub-city
- Adihaki market areas, found with in kedamay weyane sub-city
- Cobbled stone Road in Adihawsi Area, found with in Hawelti sub-city

Along with the flooding, when viewed from the point of view of actual and potential coverage of the problem (of affected and affecting areas, communities, activities etc.), water pollution may come to forefront in Mekelle city. In one way or another, most of the wastes that are improperly handled during generation, storage, collection, transportation and disposal, ultimately are arriving at waterways and water bodies in various ways.

The water way flowing through; stadium-Humera hotel, Adi Haqi market area (where it joined by the river coming from upper areas of kebelle 17 condominium houses, Adventist school, and then Adi Haqi open market)), Abiators, and down to Regional Administration Office (Regional Parliament office) covers the largest area of city and carry the highest burden of waste in the city.

As a result, almost all the waterways and water bodies in the city and crossing the city are threaten by these wastes. According to the concerned bodies of the city's environmental agencies, the quality of almost all the waterways in the city is damaged by waste (both liquid and solid) generated in the city (MUBECO, 2016).

Construction of cobblestone in Mekelle city is solving the problem of shortage of road network of the city also increase connectivity during rainy season and reduce dust problems. However, due to lack of provision of appropriate storm drainage facility, cobble stone roads particularly constructed in steep slopes are rather becoming channels of concentrated flooding and damages itself and soundings.

3.3 Data types and source of collection

Hydrological data, classified in hydrometric (Water level, Discharge, Groundwater, and Sediment) and hydro-meteorological data (Rainfall, Evaporation Temperature, Humidity, Wind speed and Sunshine) some of them in which have been dealt with in this collection system.

Monitoring the Hydro-metrological system in Ethiopia usually takes place with the manual process; Automatic gauging system is only applied in Addis Ababa, bole international airport station that is accessed by the National Meteorological agency of Ethiopia (NMA). However, branch offices of the agency are also using manual recording system. Climate Data for this study are collected from National meteorological agency, Mekelle gauging station that governs the 20 stations found at zonal system of the Tigray region. The following data types and source were obtain from different authorities:

Table 5: Sources of hydrometric/meteorological information and other relevant data

No	Type of Data	Details	Source of Data	Data collection frequency	Unit
1	hydrometric	water level, discharge, ground water etc.	N/A	N/A	N/A
2	meteorological data	Precipitation	NMA	Daily	mm
		Climatic Data (T^0, E, Wind speed...)	NMA	Daily	(^{0}C,mm/d, Km/hr.,)
3	Structural Plan files (shape files, A-CAD...)	Land use map	Mekelle city administration	Varies	Varies
		Soil Data	Mekelle city administration	Varies	Varies
		Parcel Map	Mekelle city administration	Varies	Varies
		Existing Urban drainage system layouts	Mekelle city administration	Varies	Varies
		Water bodies, etc.	Ministry of water, irrigation& Energy	Varies	Varies
4	DEM(digital elevation model),30m	Elevation data	USGS, Earth explorer	Varies	Varies

Where, NMA=National meteorological agency and

N/A=Not available

3.4 Methodology

The methodology for this study is based on a variety of spatial data and weather observations, which are utilized through GIS analyses and subsequent stormwater modeling. GIS is applied in order to (i) select appropriate study sites, (ii) delineate and subdivide study catchments, and (iii) parameterize the study subcatchment and related stormwater systems for use in stormwater modeling. Using these parameterizations, SWMM simulation is conducted and their results analyzed to assess the suitability of the stormwater management types.

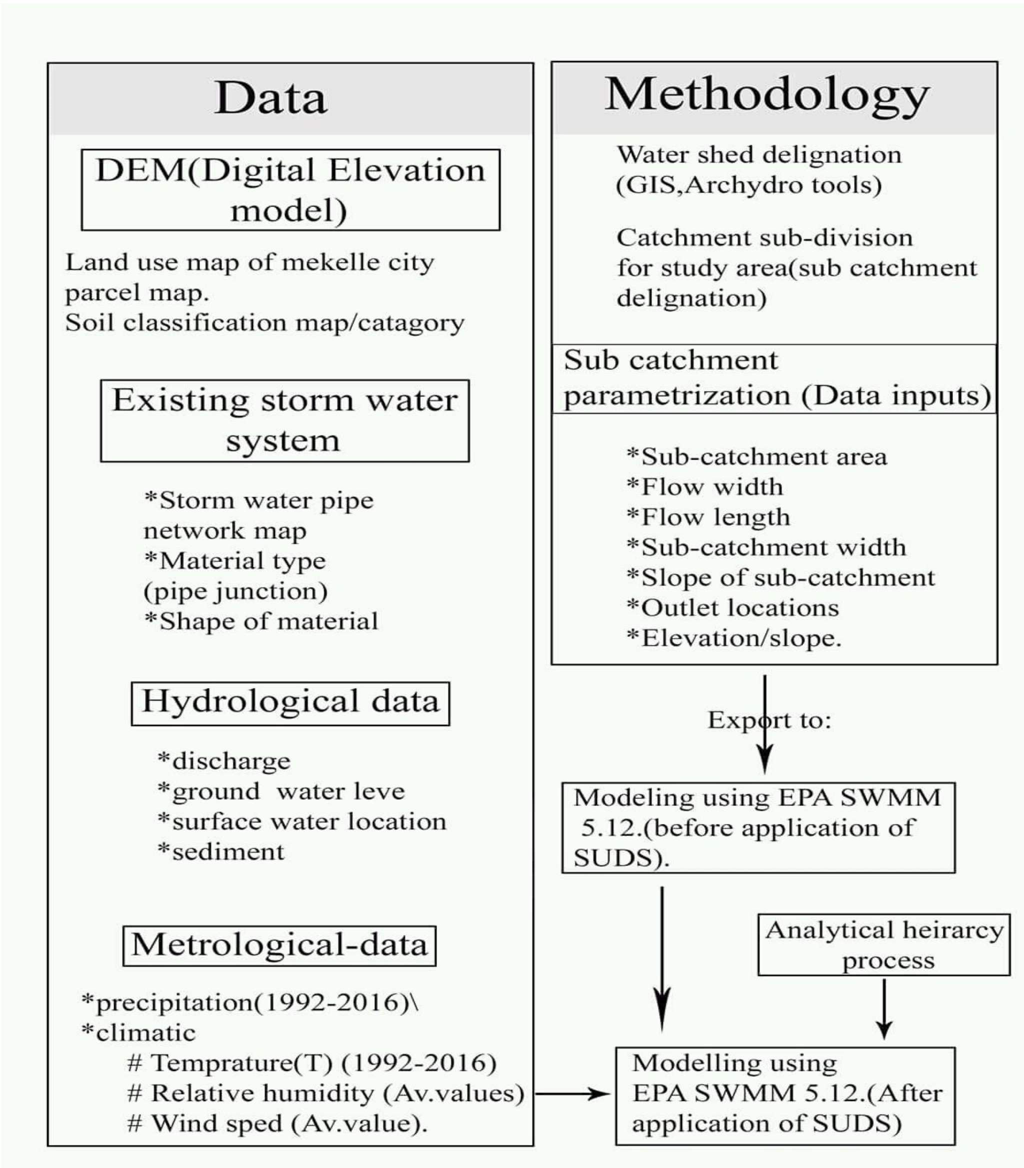


Figure 15: flowchart for methodology, (source: own analysis)

3.4.1 Data processing and quality checking

According to (WMO, 2013), detailed records and documentation should be accessible to users of the data. Knowledge of the data processing and quality control procedures allows a user of the data to assess the validity of the observation. With proper documentation and retention of the original data, future users are able to assess the impact of changes in procedures on the validity, continuity or homogeneity of the data record; apply new knowledge in atmospheric science to the older data; and perhaps revalidate the data based on new techniques and discoveries.

3.4.1.1 Data processing

Basic needs of data processing are to understand the following characteristics of the data set in order to develop a Quality Control method, an analysis technique, and a presentation tool. Although it is very difficult to maintain certain standards of reliability and accuracy of time series data, the collection and processing of data are crucial for many areas, especially for national databases (GPRB, 2015).The data character items are:

- Basic statistics (averages, max. min, range, percentiles),
- Data intervals / inconsistencies,
- Missing data / incomplete data,
- Frequency distribution,
- Identification of problem area,

3.5 Rainfall Frequency Analysis

The primary objective of frequency analysis is to relate the magnitude of extreme events to their frequency of concurrence with probability distributions. Data observed over an extended period in a river system or climatic records are analyzed in frequency analysis. The data are assumed independent and identically distributed. Assume the flood data are considered stochastic and may be even to be space and time independent. Further, is assumed that the floods have not been affected by natural or manmade changes in the hydrological regime in the system.

Extreme rainfall events and the resulting floods can take thousands of live and cause billions of dollars in damage. Flood plain management and design of flood control works, reservoirs, bridges, and other investigations need to reflect the likelihood or probability of such events. Hydrological studies also need to address the impact of unusually low rainfalls causing low stream flows which affects for example water quality and water supply. The term frequency analysis refers to the techniques whose objective is to analyze the occurrence of hydrologic variable within statistical framework, by using measured data and basin predictions on statistical laws. The historical rainfall data available is a 24hr duration rainfall hence appropriate IDF reduction methods need to be used to obtain rainfall intensities of shorter duration.

Any probability distribution can be used as the model but the reliability of the distribution is checked by the goodness of fit tests. Among many method, Gumbel and Log Pearson Type III methods are used for these research based on as suggested by Ethiopian Drainage Design Manual (ERA, 2013).how ever frequency analysis process for this study begins through comparing different distribution functions(probability functions) on the section below.

3.5.1 Identifying best fit distribution functions

3.5.1.1 Normal distribution

The normal distribution is used in frequency analysis for fitting empirical distributions to hydrological, and in simulation of data. As many statistical parameters are approximately normally distributed, the normal distribution is often used for statistical inferences. The probability density function of a normally distributed variable ‘x’ is given by:

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\, e^{\frac{1}{2\sigma^2}(x-\mu)^2} \qquad (3.1)$$

Where μ and σ are the parameters of the distribution. The variables x can take any value in the range (-∞, ∞). The standard normal variant u is a normal variable with a mean equal to zero and standard deviation equal to one (Khaled, 2000).

3.5.1.2 Gumbel extreme value distribution

The extreme value type-I(EVI) is the most widely used method for IDF analysis, and an asymptotic distribution for maximum or minimum events is the limiting mode for the distribution of the maximum or minimum of ‘n’ independent values from an initial distribution of its right or left tails is unbounded and is an exponential type. This distribution has been used for rainfall depth-duration-frequency studies. The theory of maximum events, the probability of occurrence of an event equal to or larger than a value xo is expressed as (Reddi, 2002).

$$P\ (X \geq X_o)=1-e^{-e^{-y}} \tag{3.2}$$

Where, y=α (x - β) is called the reduced variate

The mean and standard deviation of the variable μ and σ are related to its parameters through the following equations (Reddi, 2002)

$$\alpha = \frac{1.28255}{\sigma} \text{ and } \beta = \mu - 0.45005 * \sigma$$

where, α and β are called the parameters of the distribution. The cumulative distribution function is given by:

$$F(x) = e^{-e^{-\alpha(x-\beta)}},\ (-\infty \leq x \leq \infty).$$

$$F(x) = e^{-e^{-y}} \tag{3.3}$$

It may be noted that β is the mode of the distribution point of maximum probability density and 'x' is the variant (historically observed data). Simplifying and solving equation (3.3) for Y gives:

$$Y= -\ln\left(\ln\left(\frac{1}{F(x)}\right)\right) \tag{3.4}$$

Substituting F(X) into equation (1.4) yields:

$$F(x) = 1 - P \tag{3.5}$$

$$Y_T= -\ln\left(\ln\left(\frac{1}{1-P}\right)\right)= -\ln\left(\ln\left(\frac{T}{T-1}\right)\right) \tag{3.6}$$

Therefore, for the extreme value distribution, X_T is related to Y_T as follows:

$$Y = \alpha\ (X- \beta) \text{ then, } Y_T = \alpha\ (X_T - \beta) \tag{3.7}$$

Hence,

$$X_T = \beta + \frac{Yt}{\alpha} \text{ then } X_T = \ddot{x}+ K_T S_x, \tag{3.8}$$

Where, $\ddot{x}$, K_T and S_x are the mean, frequency factor and the standard deviation respectively.

3.5.1.3 Log- Normal distribution

A random variable x (variate) is said to be in log-normal distribution if the logarithmic values of x are distributed normally. The same procedure that is used for fitting the normal distribution can be used to fit the log-normal distribution. The underlying population is assumed to be log-normal.

The data must first be transformed to logarithms, Y = log X. This transformation creates a new random variable Y.

(McCuen, 1996) discusses that the mean and standard deviation of the logarithms are computed and used as the parameters of the population; it is important to recognize that the logarithm of the mean does not equal the mean of the logarithms, which is also true for the standard deviation. Thus, one should not use the logarithms of the mean and standard deviation as parameters; the mean and standard deviation of the logarithms should be computed and used as the parameters. Either natural or base 10 logarithms may be used, although the latter is more common in hydrology. The population line is defined by plotting the straight line on arithmetic probability paper between the points ($\bar{y}+ S_y$, 0.1587) and ($\bar{y} - S_y$, 0.8413), where $\bar{y}$ and S, are the mean and standard deviation of the logarithms, respectively.

In this distribution, the value of the random variable $\bar{y}$ and the moments of the logarithms ($\bar{y}$ and S,) are related by the equation:

$$Y= \bar{Y} + K\,Sy \qquad (3.9)$$

The logarithmic transformation of the normal distribution is given by (Haan, 1977) as:

$$f(x) = \frac{e^{-\frac{(y-\mu y)^2}{2\sigma y^2}}}{\sigma y(2\pi)^{0.5}}\ ,\ y > 0 \qquad (3.10)$$

Where, y = log(x), μ_y and σ_y are the mean and standard deviation of the population which are equivalent to $\ddot{x}$ and S for sample respectively.

The frequency factor (K_T) for log-normal distribution can be given by:

$$Z=w- \left[\frac{(2.516+0.8028w+0.0103w^2}{1+1.4328w+0.1893w^2+0.0013w^3}\right] \qquad (3.11)$$

And,

$$w= \left[\ln \left(\frac{1}{P^{0.5}}\right)\right]^{0.5} \text{ where } 0\leq P \leq 0.5 \qquad (3.12)$$

Where, P = probability of exceedance; when P > 0.5, 1- P is substituted for p. The Log-normal distribution has advantage over the normal distribution that it is bounded as X > 0 and the log transformation tends to reduce the positive skewness (cherkos, 2006).

3.5.1.4 Log-Pearson type III distribution

Log-Pearson Type III distribution is also called Log-Pearson distribution. It is the standard distribution for frequency analysis of annual maximum floods in the United States (Benson, 1968). As a special case, it has a special feature that when log x is symmetric about its mean, the Log-Pearson type III distribution reduces to the log-normal distribution. The location parameter of Log-Pearson Type III distribution depends on the skewness of the data (Chow, 1964).

Log-Pearson Type III distribution is a logarithmic transformation of the Gamma distribution. The fit of the distribution to data can be checked using the chi-square test or by probability plotting. From the following general equation, for any distribution form which the T-year event magnitude can be computed:

$$X_T = \mu + K_T \sigma x \quad (3.13)$$

where, X_T is event magnitude of the record, μ and σx are mean and standard deviation of the series and K_T is the frequency factor defined by a specific distribution, is a function of the probability level of X.

The Log-Pearson type III distribution differs from most of the distributions discussed above in that three parameters such as mean, standard deviation, and coefficient of skew are necessary to describe the distribution (Kite, 1988). By judicious selection of these three parameters, it is possible to fit just about any shape of distributions.

Finally, all the above techniques are computed using Easy Fit software and summarized as follows using histogram graph.

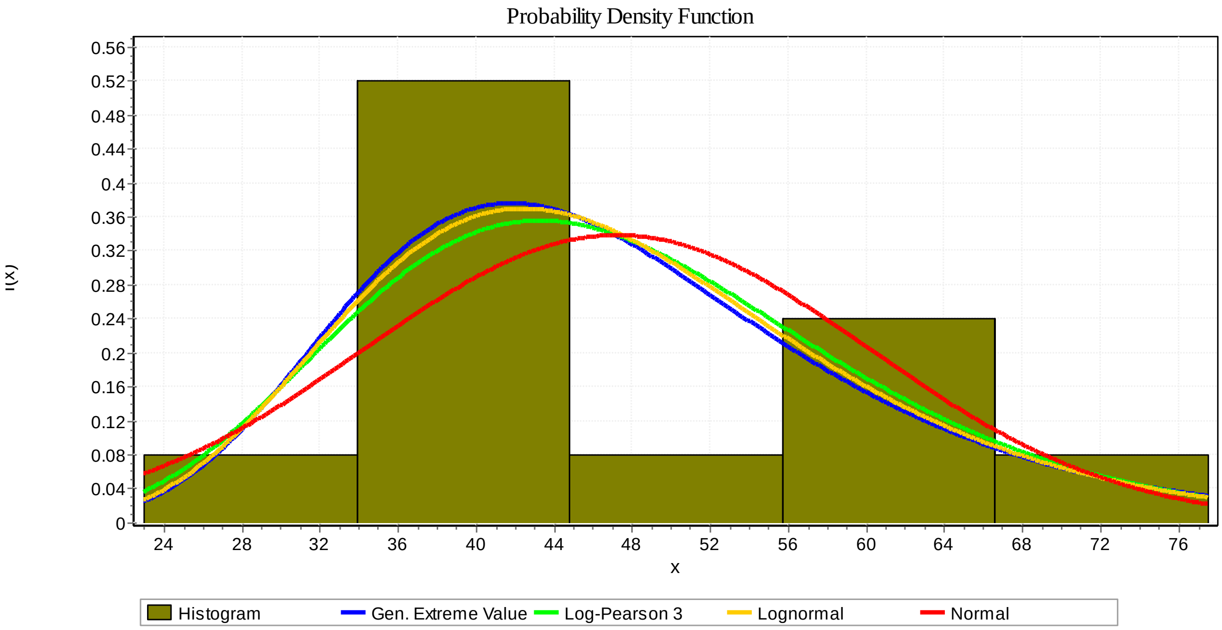


Figure 16: Probability density function for different Distributions

3.5.2 Goodness of Fit Test (GOF)

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.

3.5.2.1 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, Xn from some continuous distribution with CDF F(x). The empirical CDF is denoted by:

$$F_n(x) = \frac{1}{n}[\text{Number of observations } \leq x] \qquad (3.14)$$

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

$$D_n = \sup_x |F_n(x) - F(x)| \quad (3.15)$$

Therefore, after computation of different distribution lower statistics means better fit.

3.5.2.2 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:

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)[\ln F(Xi) + \ln(1 - F(X_{n-i+1}))] \quad (3.16)$$

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. Therefore, when comparing different distribution lower statistics means better fit.

3.5.2.3 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 formula which can be used to calculate this number based on the sample size (N). For example, Easy Fit software, a data analysis and simulation application-allowing fitting probability distributions to sample data, 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,

$$X^2=\sum_{i=1}^{k}\frac{(O_i - E_i)^2}{E_i} \quad (3.17)$$

where O_i is the observed frequency for bin i, and Ei 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.

Finally, as tabularized below, Easy-Fit 5.6 Professional software, a data analysis and simulation application-allowing fitting probability distributions to sample data, select the best model, and apply the analysis results to make better decisions. Moreover, can be used as a stand-alone Windows application or with Microsoft Excel and other third party Excel-based simulation tools, is used for testing goodness of the recommended Probability distribution functions described in the above sections.

Table 6: Results of different fitting parameters of selected distributions

Fitting Results

#	Distribution	Parameters
1	Gen. Extreme Value	$k=-0.03561$ $\sigma=10.679$ $\mu=41.448$
2	Log-Pearson 3	$\alpha=130.89$ $\beta=-0.02385$ $\gamma=6.9424$
3	Lognormal	$\sigma=0.26739$ $\mu=3.8201$
4	Normal	$\sigma=12.862$ $\mu=47.248$

Table 7: GOF Results of selected distribution functions

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.1211	1	0.40936	1	3.875	3
2	Log-Pearson 3	0.14097	3	0.43667	3	0.75983	1
3	Lognormal	0.13006	2	0.41851	2	2.3336	2
4	Normal	0.17852	4	0.63884	4	5.0731	4

Result indicates comparing the above four distributions by analyzing the rank given through the GOF test and the Gumbel or GEV-I have proved to be good fit in all the three tests.so this distribution function is chosen on this work for further IDF curve developments and Design storm of study area.

3.5.3 Design Rainfall of Shorter Durations

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. ERA (2013) suggests the following equation.

$$R_{Rt} = \frac{t(b+24)^n}{24(b+t)^n} \tag{3.18}$$

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 follows the selected frequency analyses methods, the Gumbel EV-I has better R^2 value, so for this thesis Log Pearson type III distribution are selected.

Using the trend line equation obtained from Gumbel EV-I distribution method of frequency analysis, i.e. 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

$$R_t = \frac{t(b+24)^n}{24(b+t)^n} * R_{24} \tag{3.19}$$

Substituting Intensity (mm/hr.) in the above equation

$$I_t = \frac{Rt}{t} = \frac{R24(b+24)^n}{24(b+t)^n} \tag{3.20}$$

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 plotted for each return period. Mentioning the frequency analysis plotted on the figure 13, the Gumbel EV-1 and Log-Pearson type III are correlated and GEV Type-I have better R^2 values and also used for this study for the analysis of design rain fall for the required return period or 10 years for design as recommended by (ERA, 2013)

Detailed fitting of the GEV-1, Log Normal and Log Pearson 3 distributions is analyzed using Microsoft excel tool and can be referred as tabulated form in appendix-1.

Table 8: 24-hr Rainfall duration for frequency analysis at selected return periods

T	P_{24}(GEV)	P_{24}(log-Pearson III)
2	45.14	45.99
5	56.50	57.50
10	64.03	64.34
25	73.54	72.29
50	80.59	77.79
100	87.59	83.00

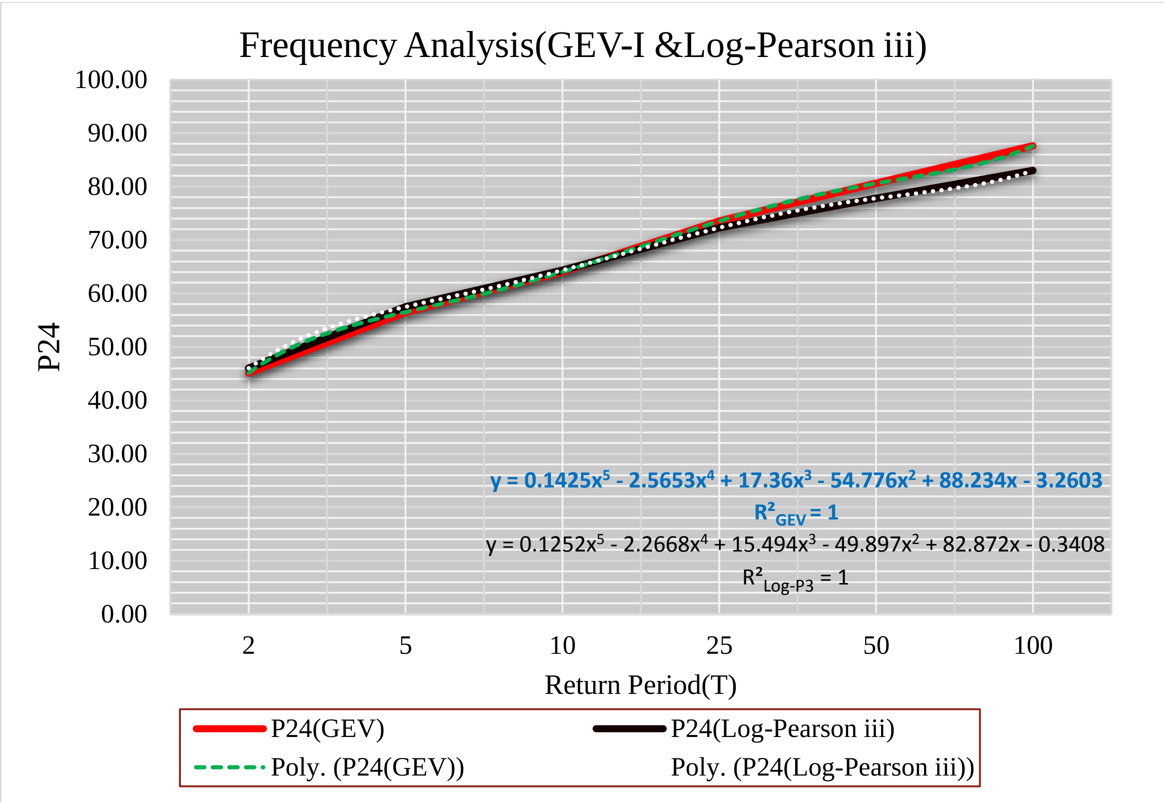


Figure 17: Frequency analysis graph

For instance, the coefficient of determination, R^2, of a 10 year return period for duration less than 180 minutes is approximated to one (1).

Table 9: Design rainfall computation using R_t: R_{24} (ratio method)

Durations (mins.)	Design rainfall, R_{24}-intensity, P_t (mm/hr.) at return period t					
	2	**5**	**10**	**25**	**50**	**100**
5	85.54	107.08	121.35	139.37	152.74	166.01
15	61.37	76.82	87.05	99.98	109.57	119.09
30	43.47	54.42	61.67	70.83	77.62	84.37
45	33.85	42.38	48.02	55.15	60.44	65.69
60	27.81	34.82	39.45	45.31	49.66	53.97
90	22.98	28.76	32.59	37.43	41.02	44.59
120	16.45	20.60	23.34	26.81	29.38	31.93
180	11.80	14.78	16.74	19.23	21.08	22.91
360	6.51	8.15	9.24	10.61	11.63	12.64
720	3.52	4.40	4.99	5.73	6.28	6.83
1440	1.88	2.35	2.67	3.06	3.36	3.65

3.5.4 IDF Curve Development

Statistics and evaluation of extreme rainfall data are important in water resources planning and management for design purposes in construction of sewerage and storm systems, determination of the required discharge capacity of channels, and capacity of pumping stations. So they are important in order to prevent flooding, thereby reducing the loss of life and property, insurance of water damage, and evaluation of hazardous weather. Studies on the rainfall IDF relationship have received much attention in past few decades.

These curves are also plotted on normal scale for Gumbel method (for T equals 2, 5 10, 25, 50&100 years) as shown on Figure below.

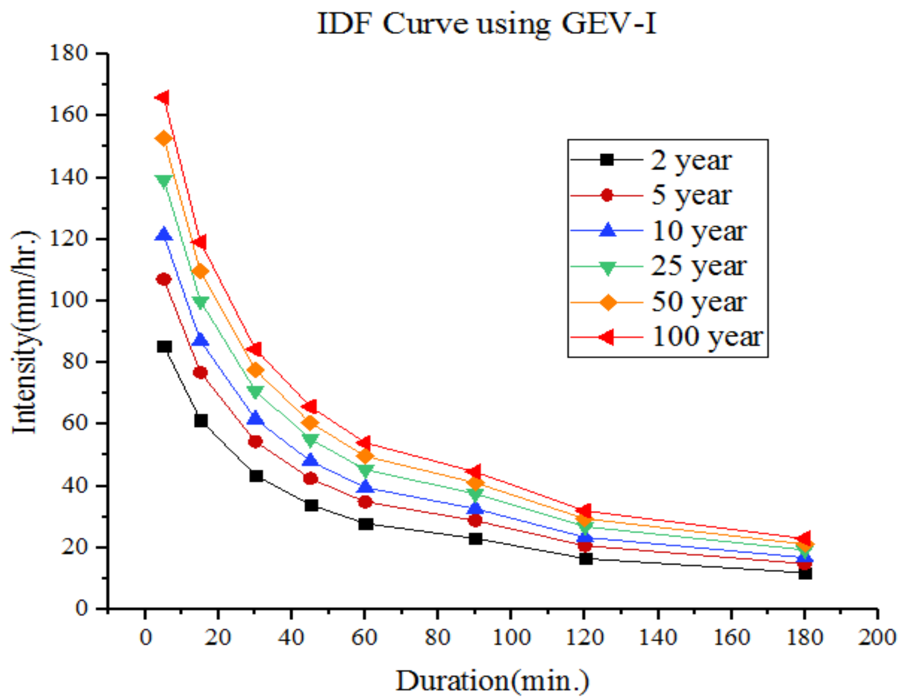


Figure 18: IDF-Curve representing Mekelle city using GEV-I

The IDF curve representing the study area is developed from 24-hour rainfall data of 24 years i.e. 1992 to 2016 where, Ethiopian Meteorological Agency rainfall gauge reported automatically from the Alula-abanega Airport found in Mekelle using the appropriate reduction equation (ratio method) stated in equation 3.19&3.20, which is provided by Ethiopian Road Authority.

3.6 Hydrologic Modelling using ArcGIS

3.6.1 General (flow chart)

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 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 of 30m resolutions. The model looks as follows.

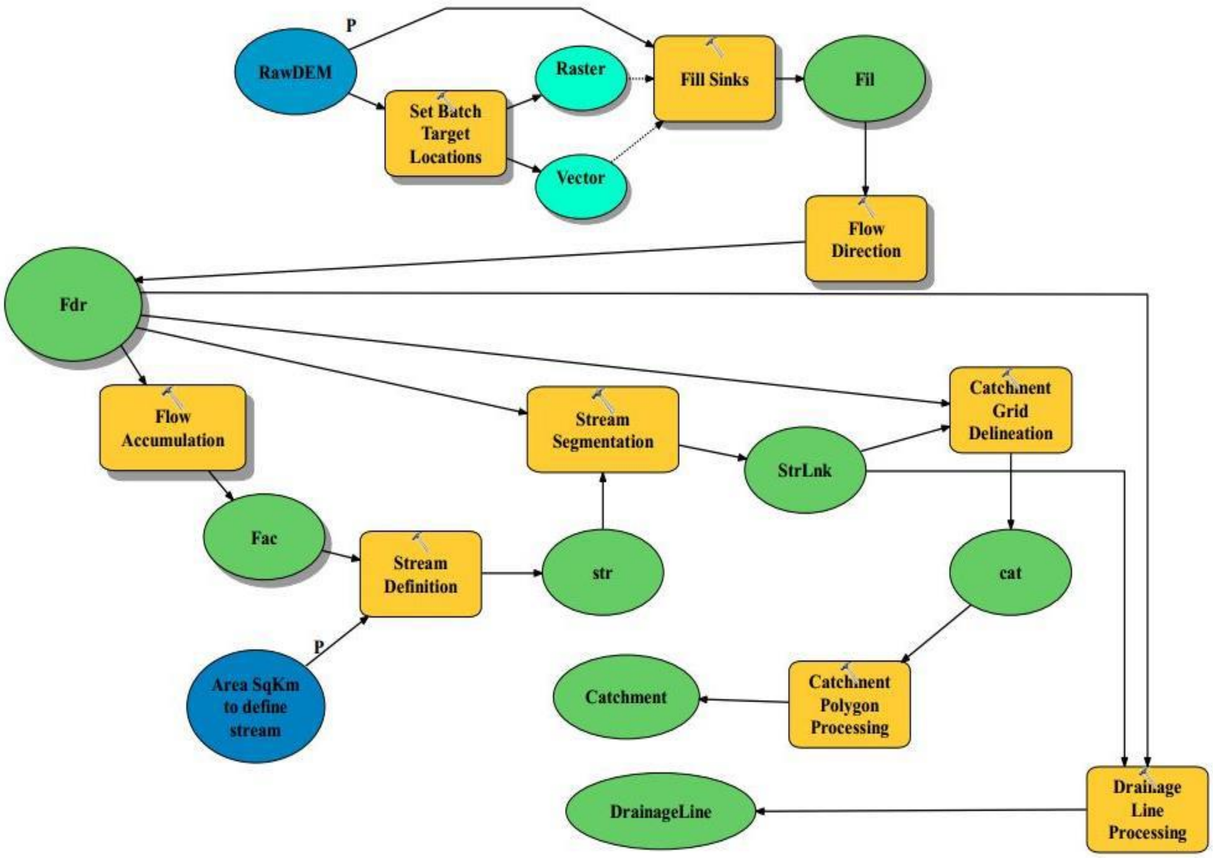


Figure 19**:** General flow chart for watershed delineation and stream identification

3.6.2 Watershed delineation

For the development of the watershed, arc-hydro tools, an extension of Arc Map was utilized. The arc-hydro tools are used to derive several data sets that collectively describe the drainage patterns of the catchments. Raster analysis is perform to generate data on flow direction, flow accumulation, stream definition, stream segmentation and watershed delineation. These data were then use to develop a vector representation of catchments and drainage lines from selected points.

These selected points in our case are the catch basins from which the catchment will drain. In addition, as shown in the (figure 20) possibly it is found eight watersheds that overlay with in the city boundary zone. The study area is looked-for to be located within the largest watershed of all the eight, which covers total area of 2394.9 ha. In addition, perfectly intersects the streams cross the old settlements with in the city.so this offers better way of comparing the existing and proposed infrastructure developments yet.

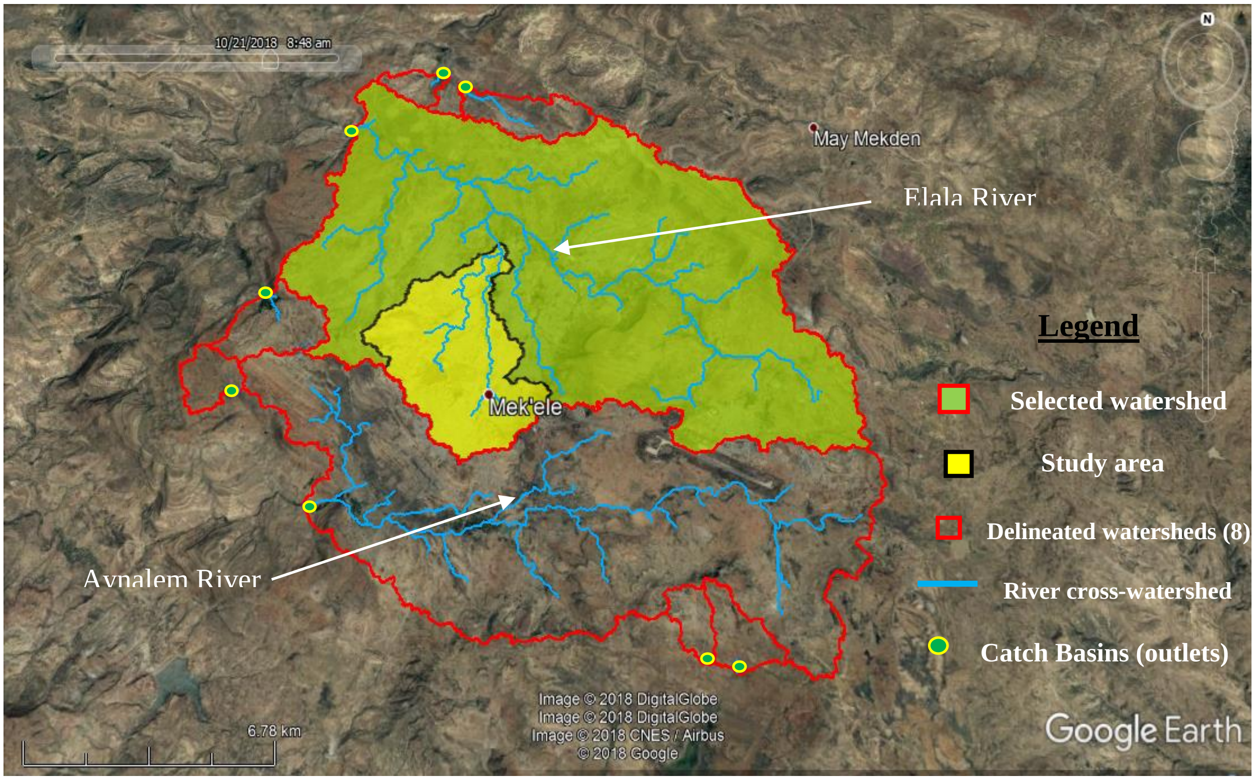


Figure 20: watersheds that overlay with in the city boundary zone and the study area

3.6.3 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 stream definition given while Arc-Hydro tool Process.

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 Arc Hydro extension tool of the ArcGIS and the result will be displayed automatically. Finally, displayed about 117 sub-catchments with in the delignated sub-watershed for study area selection (see figure 20&21).

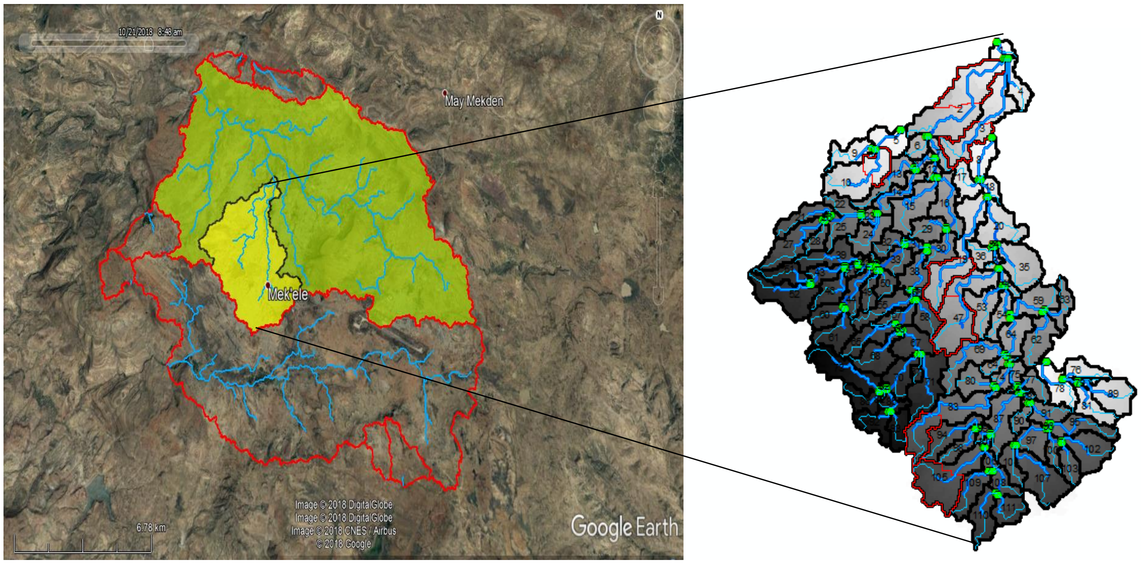


Figure 21: delineated catchments for study area

3.7 Rainfall – Runoff Transformation

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, drainage improvements and 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 (Tc), when the whole catchment is contributing flows to the outlet. This takes the assumption that peak runoff does not result from more intense rainfall of shorter duration. The peak runoff is given by the following expression:

$$\mathbf{Q = 0.00278\, C*I*A*\, C_f} \qquad (3.21)$$

Where: Q = is in m^3/s,

I = is rainfall intensity in mm per hour

A = is catchment area in hectares

C_f = frequency factor

C= runoff coefficient

The duration used for the determination of the modeling precipitation intensity I is according to the time of concentration ERA has provided.

3.7.1 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 playground 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.

Table 10: Runoff Coefficient for Use in Rational Method, (ERA, 2013)

Type of Drainage Area	Runoff Coefficient, C
Business, Downtown areas	0.7-0.95
Neighbor areas	0.5-0.7
Residential area: single family	0.3-0.5
Residential area: Multi units, detached	0.4-0.6
Residential area: Multi units, attached	0.6-0.75
Sub-urban	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/Undeveloped	0.1-0.3

3.7.2 Time of Concentration Tc Determination

Use of the Rational Method requires calculating the time of concentration (Tc) for each design point within the drainage basin. The duration of rainfall is then set equal to the time of concentration and used to estimate the design average rainfall intensity (I). The basin time of concentration defined as the time required water to flow from the most remote part of the drainage area to the point of interest, which also defined as travel time, for discharge calculations. The time of concentration computed as a summation of travel times within each flow path. Using the below two methods calculating time of concentration for rational formulas.

The time of concentration is the sum of sheet flow-travel time, shallow concentrated flow travel time and open channel flow-travel time.

3.7.2.1 Travel Time

Travel time is determined from average velocity computed for paved and unpaved channels in which and is the ratio of flow length to flow velocity (ERA, 2013).

$$Tt = L/ (3600V) \quad (3.22)$$

Where:

T_t = travel time, hr.

L = flow length, m

V = average velocity, m/s

3600 = conversion factor from seconds to hours.

i. **Sheet Flow**

Sheet flow occurs in the upper reaches of the watershed (Kassahun, 2016). Such flow occurs over short distance and at shallow depths prior to the point where topographic and surface characteristics cause the flow to concentrate in rills and swales. In relation to (ERA, 2013), Sheet flow of travel time computed using Manning’s kinematic equation as:

$$Tt = [0.091\ (n*L)\ 0.8 / (P_2)^{0.5} S^{0.4}] \quad (3.23)$$

Where:

Tt = travel time, hr.

n = Manning's roughness coefficient

L = flow length, m

P_2 = 2-year, 24-hour rainfall, mm

S = slope of hydraulic grade line (land slope), m/m

ii. **Over Land Flow Time**

Overland flow is the type of flow that occurs in small, flat or in upper reaches of catchments, where there is no clearly defined watercourse. Run-off, then, is in the form of thin layers of water flowing slowly over the uneven ground surface. According to (ERA, 2013), the catchment area or land use classification assumed as pervious in order to calculate the surface flow for over land flow velocity.

$$V=4.9178(S)^{0.5} \tag{3.24}$$

Then, the total overland flow time estimated using the equation (3.25).

$$T_{travel} = \frac{D}{60*V} \tag{3.25}$$

Where: Tt - travel-time of concentration (minutes):

D - Overland flow Distance (m)

V - Approximate flow velocity over the surface (m/s) based on catchment Characteristics (land use of the area)

iii. **Channels Flow**

For open channel flow, consider the uniform flow velocity based on bank-full flow conditions. That is, the main channel is flowing full without flow in the overbanks. This assumption avoids the significant iteration associated with other methods that employ rainfall intensity or discharges (because rainfall intensity and discharge are dependent on time of concentration). For conduit flow, in a proposed storm drain system, compute the velocity at uniform depth based on the computed discharge at the upstream. Otherwise, if the conduit is in existence, determine full capacity flow in the conduit, and determine the velocity at capacity flow. It is necessary to compare this velocity later with the velocity calculated during conduit analysis (Kassahun, 2016). When the channel section and roughness coefficient (Manning's n) are available, then the velocity can be computed using the Manning Equation. (ERA, 2013)

$$V= \frac{1}{n} (R^{2/3}S^{0.5}) \tag{3.26}$$

Where: V= average velocity, m/s

R= hydraulic radius, m (equal to a/pw)

A = cross sectional flow area, m2

Pw = wetted perimeter, m

S = slope of the hydraulic grade line, m/m

n = Manning's roughness coefficient

Finally, the time of concentration is the sum of Tt values for the various consecutive flow segments:

$$Tc = Tt_1 + Tt_2 + \ldots Tt_m \qquad (3.27)$$

Where, Tc is the time of concentration in hrs. and m is the number of flow segments.

3.8 Modelling using EPA Storm Water Management Model (EPA SWMM5.1)

There are numerous different rainfall-runoff simulation software packages such as EPA SWMM, Civil-Storm, Bentley Storm-CAD V8i, Bentley Sewer GEMS V8i, and other GIS friendly modelling tools. However, The EPA Storm Water Management Model (SWMM) is one of the most commonly used and easily available. Among all similar software, this study focuses on SWMM for a few reasons. (i) SWMM is widely used in analysis and design of stormwater drainage systems, especially on urban areas. (ii) There have been previous studies carried out on the same geographical area using the same software. (iii) The U.S. Environmental Protection Agency (EPA) provides the SWMM model and a related graphical user interface free of charge.

SWMM can be used for a range of applications. It is suitable for modeling either single precipitation events or continuous modeling of multiple events. The simulation period consists of multiple time steps, and SWMM can track both runoff quantity and quality for each time step.

The model is conceptually divided into four major environmental compartments: (i) the atmosphere compartment, accounting for precipitation and pollutants from air; (ii) the land surface compartment, modeling areas receiving precipitation and generating runoff; (iii) the transport compartment, routing flow from runoff source areas through a network of pipes, channels, etc.; and (iv) the ground-water compartment, receiving infiltration from the land surface and providing input to the transport compartment. Of these, (ii) and (iii) are discussed in more detail below. The objects and processes in these four compartments account for all the major components affecting the regional water balance (Rossman, 2010).

3.8.1 Stormwater system layout

Afterward the Arc Hydro tool (Esri, 2012), used to identify catchments contributing to the flow at each of the pour points. The tool creates a raster where cell values indicate to which pour point cells are draining.

As Visualized and described in the water delineation section, it has successfully delineated and chosen single watershed (see fig.20&21). However, difficulties come along the wide range of areas, complex land-use classes, parcel, and waterways to model on specific catchments of focused problems such as flooding. Consequently, a Drainage density (DD) map (see fig.22) executed using Arc-Hydro tools to focus on specific areas. Drainage density depends upon both climate and physical characteristics of the drainage basin. Soil permeability (infiltration difficulty) that affect the runoff in a watershed; impermeable ground or exposed bedrock will lead to an increase in surface water runoff.

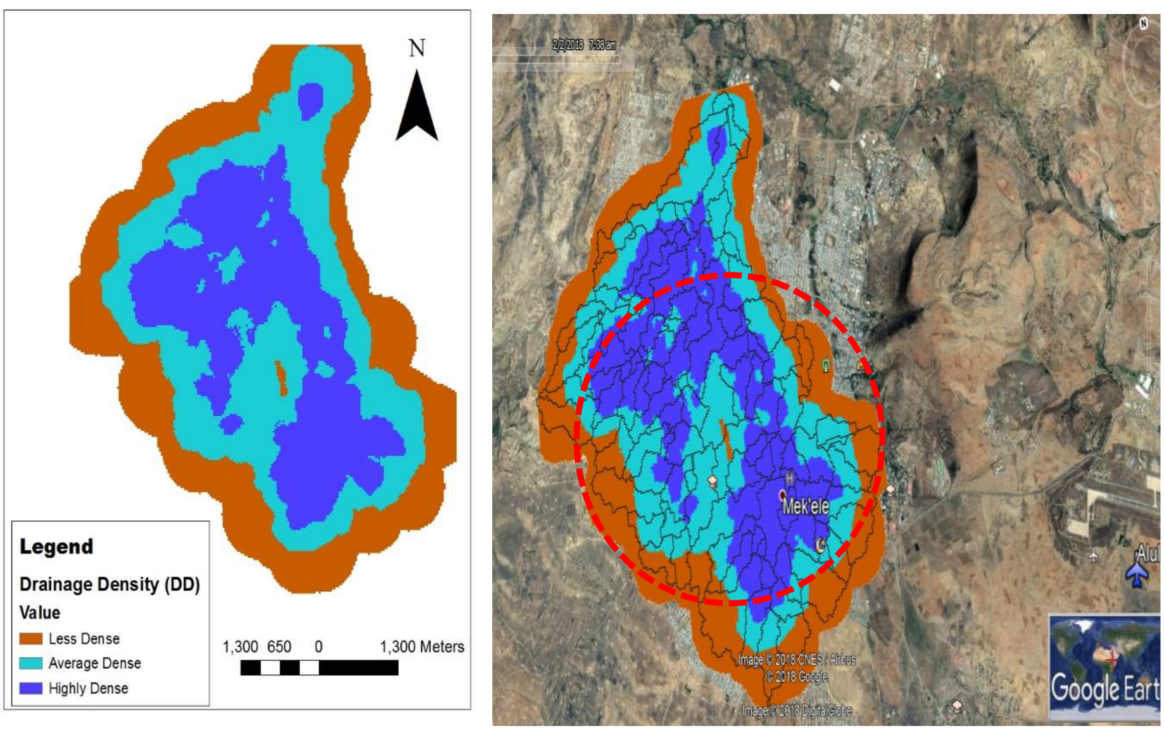


Figure 22: Drainage density map for study area (left) and location of Drainage-Density in Satellite view

Visual comparison carried out to observe the differences of the catchment delineation and the stormwater drainage-density map (see Figure 22). Accordingly, indicates possibility of high runoff rate are within the central settlements of the city and efforts has to be made on implementation of proper storm layouts. This is one signal that catchment delineation of an urban area should not solely base on terrain topography but should also consider the stormwater system. However, it is necessary to neglect non-developed areas or bare lands in the modeling of storm water layouts. For this reason, out of total 117 catchments, about 50 Subcatchments (see fig.23) that intersect the urban settlement and show the existing stormwater drainage layout are only modelled and circled in thick red line in (see fig.22) satellite catch.

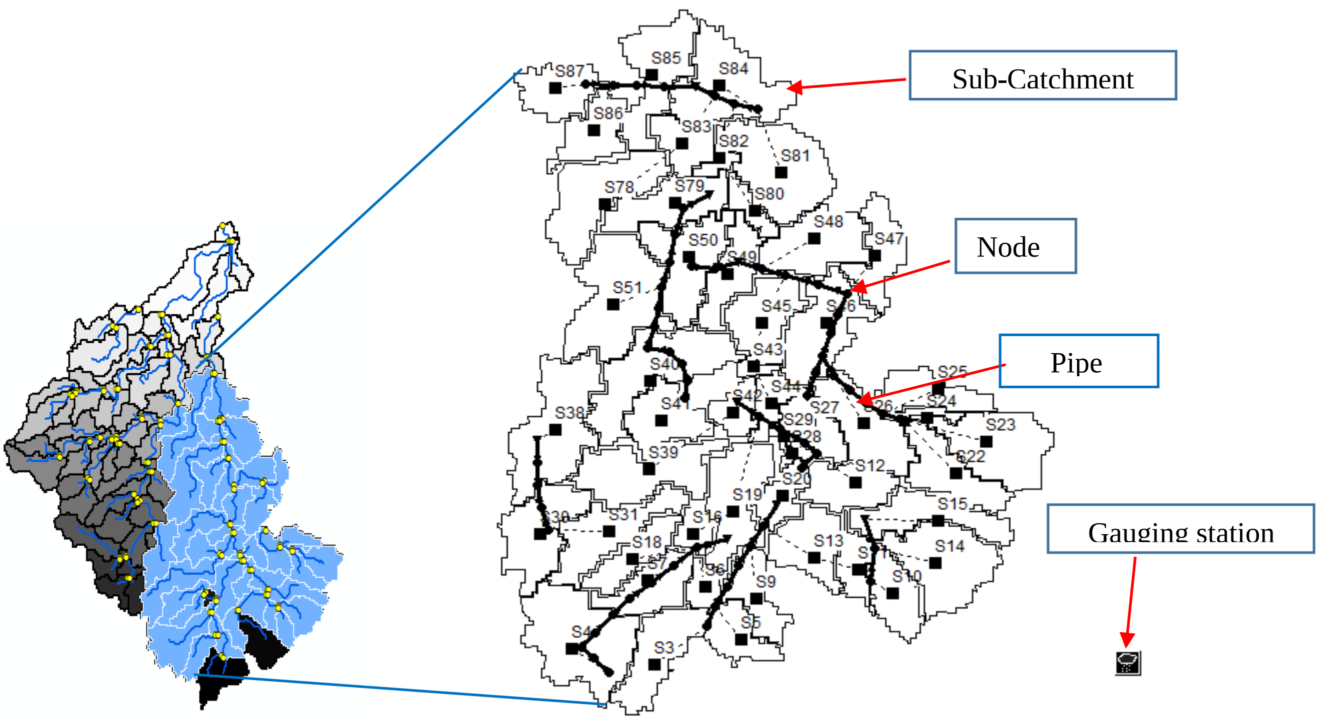


Figure 23: selected 50-sub catchment Over-laid with stormwater drainage network

The dark black lines (see figure 23, right) represent the existing stormwater drains or pipes typically arranged as they suit the natural drainage, slope and Parcel use of the study area while modelling.

3.8.2 Subcatchment parameterization

Subcatchments require a wide range of parameters until they can be modeled in SWMM. Some of these parameters (e.g. Subcatchment area) are easier to obtain, although uncertainties may be involved. In contrast, other parameters (e.g. flow width) require complicated GIS processing to reach even rough estimates. One of the objectives of this study was to develop parameter estimation methods and to evaluate their applicability to large areas with the data sources typically available.

Before going into detail on the Subcatchment-specific parameters, some general parameter settings are mentioned: (i) each Subcatchment was manually assigned to a correct outlet node in the drainage network, (ii) Subcatchments were named with numbers corresponding to the outlet node numbering, (iii) runoff from both the pervious and impervious fraction of a Subcatchment was set to be routed directly to the outlet, and (iv) all Subcatchments were linked to the same rain gage at Alua-Abanega airport.

Ways of defining the values of imperviousness are to estimate them based on land use data, or if possible, either using manual image processing of aerial or satellite orthophotos.

The percent imperviousness of a subcatchment is another parameter that can be, in principle measured accurately from aerial photos or land use maps. In practice, unless impervious layers are included in a GIS representation of the basin, such work tends to be tedious, and it is common to make careful measurements for only a few representative areas and extrapolate to the rest. Runoff volume and flow rates are strongly sensitive to estimates of imperviousness; hence, care should be taken in imperviousness estimates.

One approach to estimating impervious area across large areas with multiple land uses is to associate a percent impervious area with each category of land use. Then by knowing the percentage of each land use within a subcatchment one can calculate its percentage impervious area. The following steps are implemented to determine the percentage impervious of each catchment.

1. Identify all of the major land uses that exist within the subcatchment.
2. Compute the area Aj devoted to each land use j in the subcatchment.
3. Assign a runoff coefficient Cj to each land use category j. Typical values are available in drainage criteria and basic literatures.
4. Compute the imperviousness I as the area weighted average of the runoff coefficients for all of the land uses in the Subcatchment.

$I=\sum_j \frac{CjAj}{A}$, where A is the total area of the subcatchment.

The general calculation of percent imperviousness of subcatchments were analyzed in detail and tabulated in Appendix part.

3.8.3 An urban stormwater DSS to select suitable SuDS

The implementation of Best Management Practices (BMPs), like rain gardens, detention ponds and green roofs, aims to mitigate these negative effects, trying to mimic as much as possible the natural hydrology of the watershed, while also treating a wide range of pollutants through physical, chemical and biological processes. However, BMPs vary significantly in performance across different criteria, including the level of water quantity and quality control provided their physical constraints, the economic costs, and even social perception. As such, their selection process in a given watershed becomes a complicated process. Additionally, the stakeholders involved in land-development projects could present different views and priorities, adding to the complexity of the situation.

The use of Multi-Criteria Decision Aid (MCDA) methods has been the subject of different studies. These methods characterized by aiming to evaluate complex systems while recognizing that different criteria are at work (often at odds with each other) and that the decision ultimately leads to compromise or arbitrary choices. (Chen, 2012)

Nevertheless, direct application of MCDA for selecting BMPs has been relatively rare, with most of the research is being done on optimization through multiple objective constraints. As done by (Chen et al. 2012) concerning the selection of BMPs through MCDA methods, (Young et al. 2010) presented an application of AHP to rank the performance of a variety of different BMPs, though the criteria analyzed were different in both works.

3.9 The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was first developed by mathematician Thomas Saaty (Saaty, 1980). The AHP is an algorithm capable of assisting complex decision-making problems. Perhaps the greatest strength of the AHP is that, although its foundation lies in complex matrix manipulation, applied effectively without requiring the user to possess an in-depth knowledge of multi-criteria decision-making theory. "Fundamentally, the AHP works by developing priorities for alternatives and the criteria used to judge the alternatives."

The AHP can be used for the systematic evaluation and ranking of BMP alternatives that require a wide range of criteria for selection and implementation of BMPs. The paramount benefit of the AHP as it relates to BMP selection is its potential objective and simultaneously consider an unlimited number of these criteria. Selective inclusion of the criteria depicting physical site characteristics enables the user to adapt the selection process such that the chosen BMP is feasible and appropriate for the site. (Young, 2010).

Moreover, (Young et al.,2010) resumes the Stakeholders for this decision making possibly included engineer, town engineer and planner, planning district commission planner, university physical infrastructure engineer, watershed roundtable representative (citizen groups), land developer, and state agency stormwater management experts.

Below is an overview of the four steps for AHP application to BMP selection in chronological order.

- Step 1: Identifying the factors Influencing the BMP (Alternatives/Actions) Selection Process (Preliminary site analysis) (refer 3.9.1)

- Step 2: Developing a set of decision hierarchy of goal, main criteria and sub-criteria(Indicators) (refer 3.9.1.1)
- Step 3: Construct a set of pair-wise comparison(PWC) matrices, (refer 3.9.1.2)
  - ✓ PWC of Main criteria with respect to Goal
  - ✓ PWC of Indicators with respect to their Main criteria
  - ✓ PWC of Alternatives(actions) with respect to Sub-criteria
- Step 4: Extraction of Priority Vectors (refer 3.9.1.3)
- Step 5: Consistency Evaluation (refer 3.9.1.4)
- Step 6: Ranking of Competing BMP Alternatives (refer 3.9.1.5)

3.9.1 Identifying the factors influencing the BMP (Alternatives/Actions) Selection Process

Seeing as the municipality had little information concerning the relevant hydrologic parameters, with few resources to spare for on-site verification, most information taken from the literature.

In the site suitability category, a suitability matrix (table 11) were established according (Vancouver, 2012), to the sort of SuDS options included within the EPA SWMM software and the screening of the technical constraints to implement the available BMPs. along with considered for this case, using NA for "Not Applicable" and X for unspecified information.

Table 11: Preliminary Site Analysis for BMP's technical constraints

No.	SuDS Components(Alternatives)	Topography	Soil infiltration	Ground water	Drained area Treated	% of BMP area from totally drained area
1	Bio-Retention cell	<2% slope	* Min 25 mm/h	>1.2 m below bottom	<2 ha	>5%
2	Rain garden	<2% slope	* Min 25 mm/h	>1.2 m below bottom	<2 ha	>5%
3	Green roof	20^0 Roof slope	NA	NA	NA	NA
4	Infiltration trench	NA	Min 15 mm/h	>1 m below bottom	<2 ha	Variable
5	Permeable pavement	<5% slope	* Min 12.5 mm/h	>1.2 m below bottom	<4 ha	>50% **

6	Rain barrel/Rainwater capture/Cisterns	NA	NA	NA	NA	NA
7	Rooftop disconnection/downspouts	NA	NA	NA	NA	NA
8	Vegetation Swale	(1-4)% longitudinal	NA	NA	<2 ha	Variable

Here, "*" represents Smaller values accepted for partial infiltration,

"**" Proportional to impervious area drained

Visits carried out on-site showed the predominance of residential houses with sloped roofs, no sidewalks in the majority of roads, and similar driveways along house lots. Considering the space availability and infiltration characteristics presented and options of BMPs provided in EPA SWMM, five BMPs identified to be the best suited for implementation. However, future use of the results from this case study would require further verification of all the hydrological parameters.

Table 12: selected set of Alternatives for AHP Method of decision-making

Code	Alternatives (according to SWMM-LID)
A1	Bio-Retention cell
A2	Rain garden
A3	Infiltration trench
A4	Permeable pavement
A5	Vegetation swale

3.9.1.1 Structure for decision hierarchy of goal, main criteria and sub- criteria (Indicators)

As it is pointed out in (Saaty, 1980), during the construction of the hierarchy structure the problem must be represented as thoroughly as possible, the environment surrounding the problem should be considered, the issues or attributes that contribute to the solution should be identified and the stakeholders or participants associated with the problem should identified.

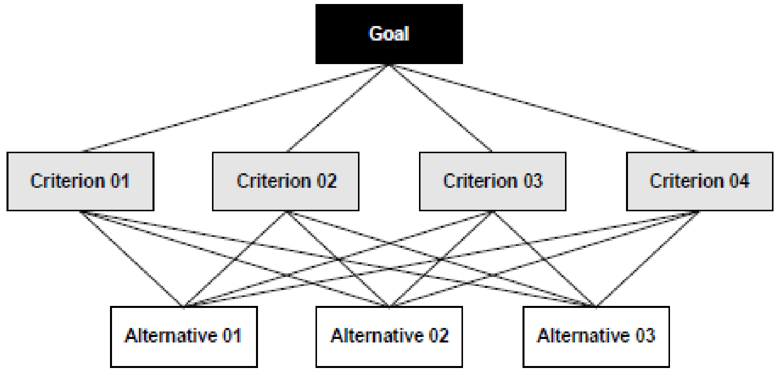


Figure 24: Hierarchy organization of criteria/objectives

Similarly, the hierarchy organization for this study discussed in detail in chapter four section 4.1.

3.9.1.2 Pair-wise comparison (PWC) of matrices

Upon identifying all possible BMP alternatives (from which a single alternative is to be selected), it is necessary to identify the relevant criteria influencing the selection process. Because the previously described criteria exhibit varying units (or in some cases no units at all), mathematical evaluation of the criteria requires the operator to determine the relative "scale," or performance, of the alternative BMPs in terms of each criterion. (Young, 2010).

This task accomplished by employing the Scale of Relative Importance Index according to Saaty 1980. This scale and others developed since Saaty's initial work, permits pairwise comparisons within the AHP. Saaty's scale of relative importance shown in Table below.

Table 13: Scale of relative importance

Intensity of importance	Definition
1	If Option A and Option B are equally important
3	If Option A is moderately more important than Option B
5	If Option A is strongly more important than Option B
7	If Option A is very strongly more important than Option B
9	If Option A is extremely more important than Option B
2,4,6,8	Use even numbers for intermediate judgments

For instance, consider a matrix comparing BMP alternatives “A1,” “A2,” and “A3” in terms of criterion “One.” “By convention, the comparison of strength is always of an activity appearing in the column on the left against an activity appearing in the row on top” (Saaty, 1980).An element in the matrix is equally important when compared with itself, and thus the main diagonal of all judgment matrices must be one. Employing Table 14, consider following scenario:

- In terms of satisfying criterion “One,” BMP A1 demonstrably outperforms BMP A2.
- In terms of satisfying criterion “One,” BMP A3 weakly outperforms BMP A1.
- In terms of satisfying criterion “One,” BMP A3 absolutely outperforms BMP A2.

Following the aforementioned convention, notice that the relative importance from table 13 are found in row one, while their reciprocal values are found in column one. At this point, the comparison matrix of criterion “One” appears as in table 14.

Table 14: BMP comparison matrix (criterion “one”).

"**one**"	A1	A2	A3
A1	**1**	7	1/3
A2	1/7	**1**	1/9
A3	3	9	**1**

The number of necessary comparisons for each comparison matrices is

$$\frac{n(n-1)}{2} \tag{3.28}$$

Where n is the number of alternatives/criteria**.** One always enters the whole number in its appropriate position and automatically enters its reciprocal in the transpose position.

Therefore, volunteered experts were about to perform PWC between main criteria with respect to Goal, sub-criteria with respect to Main criteria and Alternatives with respect to Indicators (sub-criteria) through questionnaire provided in tabular form as it suits the comparison technique. Sample questionnaire table appears as in table below. Detailed table of questionnaire and their benchmarks provided for respondents can be refer in Appendix-2 and Appendix-3.

Table 15: PWC of Sub-criteria or Indicators with respect to Main-criteria

Indicators	PWC of Sub-criteria or Indicators with respect to Main-criteria																	Indicators
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Technical (Cr-1)																		
(I-1)																		(I-2)
(I-2)																		(I-3)
(I-3)																		(I-4)

3.9.1.3 Extraction of Priority Vectors

Upon creating alternative judgment matrices for each selection criterion as well as the criteria judgment matrix, the analyst then proceeds to the next step in the analytic hierarchy process, which is to extract the relative importance implied by each matrix. This task accomplished by employing matrix algebra to determine the right principal eigenvector of each judgment matrix. Mathematically speaking, the principal eigenvector for each matrix, when normalized, becomes the vector of priorities for that matrix. As matrix size grows, the task of computing this principal eigenvector becomes increasingly complex, particularly in the absence of computing software specifically designed for such a task.

However, a number of computationally accessible methods exist to facilitate extraction of the priority vectors. These methods are illustrate as follows.

(A). Method 1

A more accurate estimate of the matrix’s principal Eigen vector consists of multiplying the n elements in each row of the matrix, and taking the nth root of this product. This step conducted for each row of the matrix, and then the values normalize to yield the principal eigenvector. (Saaty, 1980), pg. 19)

Table 16: Priority Vector Extraction, Method 1

"**one**"	A1	A2	A3	Row Product	n^{th} Root
A1	**1**	7	0.33	2.33	1.326
A2	0.143	**1**	0.11	0.016	0.252
A3	3	9	**1**	27	3

Σ Root Values = 4.578

$$\begin{Bmatrix} 0.290 \\ 0.055 \\ 0.655 \end{Bmatrix} \quad (3.29)$$

The Eq. 3.29 indicate the extracted priority vectors in terms of criteria "one," and alternative A3 is prioritized, with alternatives A1 and A2 ranking second and third respectively.

(B). Method 2

This method of priority vector extraction is an accurate, yet computationally simple method. This approach for obtaining the principal eigenvector is to divide the elements of each column by the sum of that column. This step effectively normalizes the elements of that column such that their sum is unity. Then, the elements in each row summed and divided by the total number of elements in the row. This step averages the normalized columns to yield the estimated principal eigenvector. This method is illustrate as follows.

Table 17: Priority Vector Extraction, Method 2

"**one**"	A1	A2	A3
A1	**1**	7	0.33
A2	0.143	**1**	0.11
A3	3	9	**1**
Col. Sum	4.143	17	1.444

Table 18: Normalized Column Values and Resulting Row Sums

"**one**"	A1	A2	A3	Row Sum
A1	**1**	7	0.33	0.884
A2	0.143	**1**	0.11	0.170
A3	3	9	**1**	1.946
Col. Sum	4.143	17	1.444	

$$\begin{Bmatrix} 0.295 \\ 0.057 \\ 0.649 \end{Bmatrix} \qquad (3.30)$$

The results of priority vector extraction method-2 reveals that all the two methods rank the competing alternatives similarly. Each priority vector extraction method clearly shows alternative C as the superior option in terms of criterion “one.”

It is important to understand that these methods of priority vector calculation are merely estimates. The exact solution to a matrix’s principal Eigen-vector obtained by raising the matrix to arbitrarily large powers and dividing the sum of each row by the sum of the elements of the matrix.

The validity of the judgment matrix weighting (in terms of intensity of importance) and priority vector extraction evaluated by performing a consistency evaluation on the judgment of matrix priority vector.

3.9.1.4 Consistency Evaluation

The first step in the consistency evaluation is to multiply the original judgment matrix by the estimated, normalized priority vector (termed A_{VE}) obtained by one of the previously described extraction methods. The resulting vector is termed A_W. Next, the first component of the A_W vector divided by the first component of the estimated solution vector. This process continued, dividing each entry of vector A_W by the corresponding entry of the estimated solution vector, A_{VE}. upon completing this step, the maximum or principal eigenvalue (λ_{Max}) is estimated as the average of the entries in vector $\left\{\frac{AW}{AVE}\right\}$.

This maximum Eigen value then used to compute the matrix's consistency index (C.I.) using:

$$C.I = \frac{(\lambda Max - n)}{(n-1)} \tag{3.31}$$

Where n is the total number of activities in the matrix. The final step in the consistency evaluation is to examine the ratio of the calculated consistency index and the random index (R.I.) derived from the number of matrix activities. Random indices for varying matrix sizes shown in Table 19.

Table 19: Random Indices

Criteria	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The ratio of C.I. to R.I. called the consistency ratio (C.R.). Generally, a consistency ratio of 0.10 or less is acceptable. In the event that the consistency ratio is greater than 0.10, the operator must re-evaluate the weight assignments within the matrix violating the consistency limits.

3.9.1.5 Ranking of Competing Alternatives

The final step in the AHP begins with construction of the decision matrix, whose priority vector determines the optimal alternative among those considered. Column entries in the decision matrix are simply comprised of the principal eigenvectors (priority vectors) obtained for each selection criteria-judgment matrix. The decision matrix is of dimensions M x" one", "M" representing the number of alternatives being considered, and "One" indicating the total number of influential criteria for which judgment matrices were constructed. Considering three possible alternatives (A1, A2, and A3), three selection criteria (i, j, k), and adopting the following priority vector-subscript convention:

$$\begin{bmatrix} A1 \\ A2 \\ A3 \end{bmatrix}$$ = Priority vector for criterion n judgment matrix

The decision matrix would appear as follows:

$$\begin{bmatrix} A1_i & A1_j & A1_k \\ A2_i & A2_j & A2_k \\ A3_i & A3_j & A3_k \end{bmatrix} \qquad (3.32)$$

To obtain the overall ranking of the alternatives, the decision matrix multiplied by the transpose (column version) of the row priority vector from the selection criteria-judgment matrix. Considering the following subscript convention for the row priority vector of the selection criteria:

$\{A_{VEi}, A_{VEj}, A_{VEk}\}$= Row priority vector for selection criteria matrix

The matrix multiplication operation then formulated as follows:

$$\begin{bmatrix} A1_i & A1_j & A1_k \\ A2_i & A2_j & A2_k \\ A3_i & A3_j & A3_k \end{bmatrix} \begin{bmatrix} A_{VEi} \\ A_{VEj} \\ A_{VEk} \end{bmatrix} \qquad (3.33)$$

Overall rank of each alternative shown as follows:

Rank of alternative A1 = $A1_iA_{VEi} + A1_j A_{VEi} + A1_kA_{VEi}$ (3.34)

Rank of alternative A2 = $A2_iA_{VEi} + A2_j A_{VEi} + A2_kA_{VEi}$ (3.35)

Rank of alternative A3 = $A3_iA_{VEi} + A3_jA_{VEi} + A3_kA_{VEi}$ (3.36)

Finally, the alternative with the greatest rank is the most desirable, while successively lower ranks indicate less desirable alternatives.

Chapter four

4. Result and Discussion

4.1 General decision hierarchy Result

The study while structuring set of criteria designed as it satisfies the general concept of SuDS or defines the water quantity, water quality, amenity and bio-diversity within the study area. Thus, four Main criteria (Cr-n), 11 sub-criteria or indicators (I-n) arranged to correlate the five alternatives (An) selection to the site. Analyzation of AHP was performed on a using excel according to responses using questionnaire cited in (appendix 3) for experts. However, only four among all were effective and the general system is based on those actual responses of the experts.

Every elements of indicator are defined with benchmarks or threshold value or condition (qualitative or quantitative), which can comprise a point of reference for decision-making. So that stakeholders or experts could easily manipulate their decision, while pairwise comparisons to the given options or next task of AHP. All the tables used for benchmarking the criteria shown in (Appendix 2&3) in details.

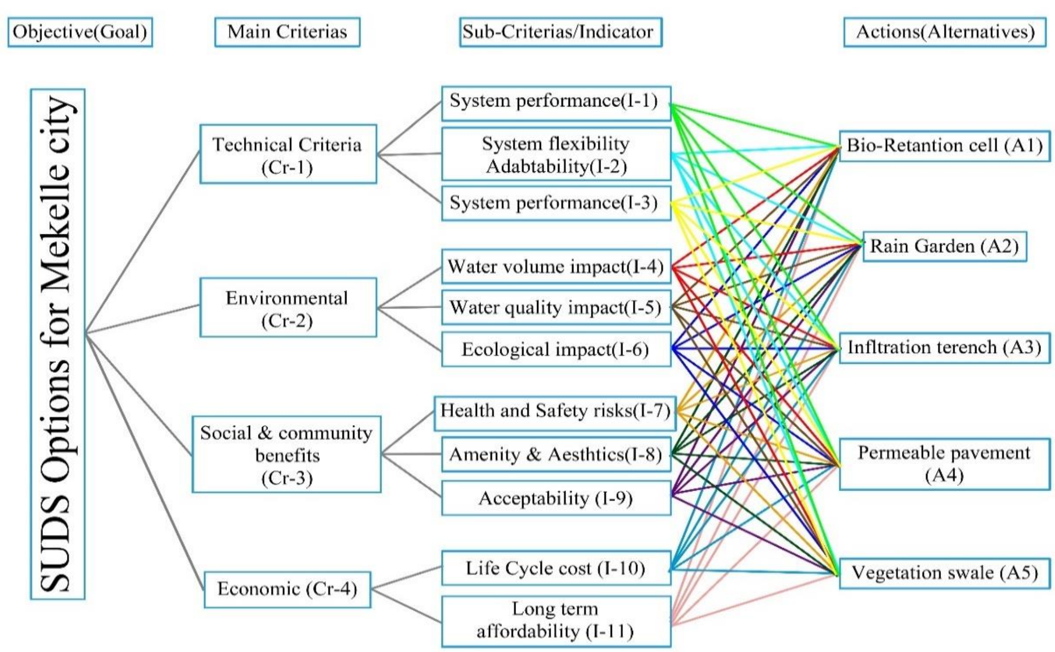


Figure 25: Structure for decision hierarchy of goal, main criteria and sub- criteria (Indicators)

4.1.1 Results of PWC of Main criteria with respect to Objectives

Evaluation of the Main criteria requires also determining the relative scale, or weight, of the 11 indicators that build the main criteria in terms of achieving the goal or the overall state of attaining SuDS.

The contribution of each criterion to the goal (SuDS options in Mekelle city), is determined by calculations made using the priority vector (or Eigenvector) stated in (appendix-4) and assures that the sum of all values from the vector is always equal to one (1). The evaluation of priorities of main criteria with respect to the term SuDS implementation explained in bar graph below.

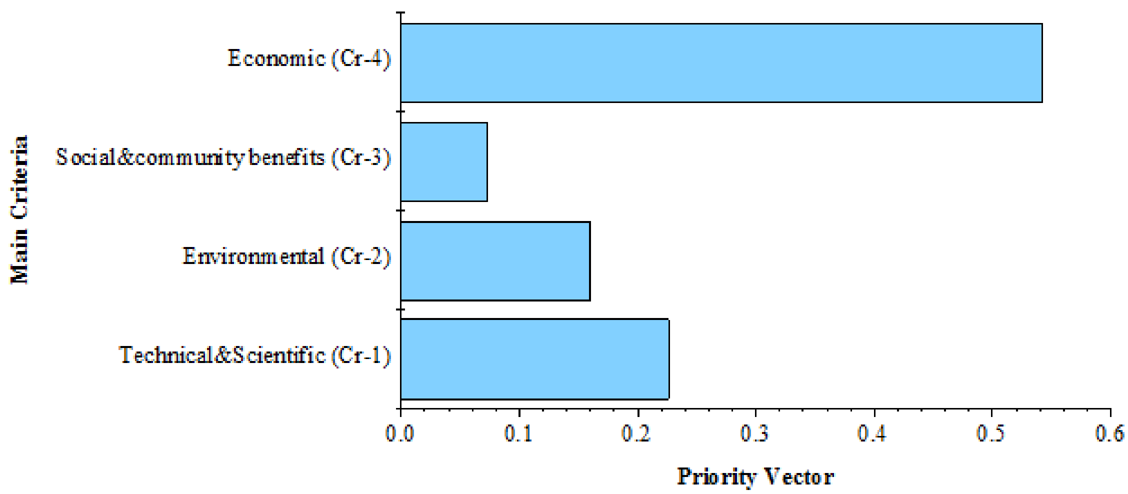


Figure 26: Results of the Comparison Matrix for Main Criteria Group, demonstrating the Contribution of each criterion to the goal defined

The result of Eigen vector shows relative first priority to Economic criteria with weightage of 0.542, following 0.226, 0.159 and 0.072 to technical, environmental and Social plus community benefits respectively. This weightage of Economic criteria explained as weight of 54.2% (percentage Eigen vector) relative to the total goal. A positive evaluation on this factor contributes approximately eight times more than a positive evaluation on the Social and community benefit (weight 7. 2%).

4.1.1.1 PWC of Technical and scientific Indicators

The contributions of the three different indicators to the technical criteria considered independently but the impacts on benchmarks (appendix 2) might treat differently. The priority results demonstrated on figure 27 which High priority given to system performance (I-1) of 0.66 weightage, 0.19 to system flexibility &adaptability (I-2) and 0.14 to System reliability. Particularly relevant in a developing country context where technical constraints associated with the deployment and exploitation of technology have resulted in the spectacular failure of many technologies.

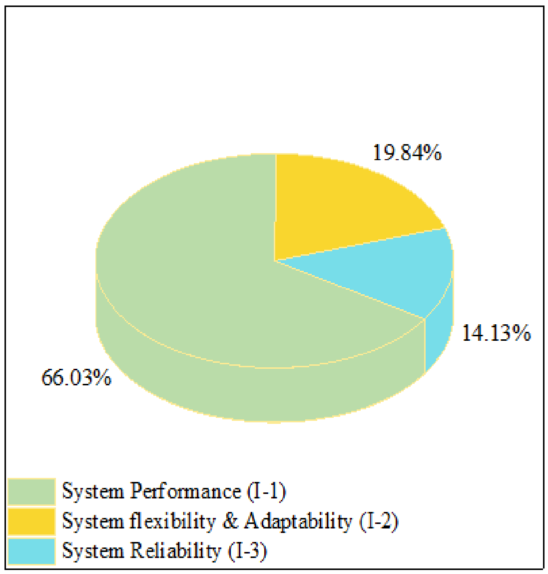


Figure 27: PWC of technical criterion Group

Performance indicators are considered very important because it defines the efficiency of individual components of SuDS or in general application of LID in providing the required outcome such as removal of pollutant, minimizing flooding effects and bringing the aesthetics of the environment, but with proper design and follow-ups after construction. However, the performance of each components of SuDS are measured through detail parameters, commonly through area coverage, surface properties (slope, vegetation volume, roughness etc.), soil infiltration capacity, capacity of storage under drain systems and Pavement properties. So ensuring of these parameters automatically align into the achievement of goal. The option that address flexibility and adaptability also considered averagely important since it measures the degree of altering the function in different scenarios with durable status and SuDS are ought to have dual or multi-functions during wet and dry climatic conditions or other purpose with in the community. Less priority given to system reliability, that indicates the negative implications of preliminary study before implementation of SuDS. This is to mean SuDS system dependability is studied before implementation with if scenarios to decrease the side effect that bring.

4.1.1.2 PWC of Environmental Indicators

The three indicators of receiving water (volume impact, quality impact and ecological impact) that are illustrated to define the criterion are benchmarked and measured through the thresholds that is defined in (appendix 2) and denote how installation of SuDS affects the environment. The weightage given by the experts is illustrated using pie chart in figure below.

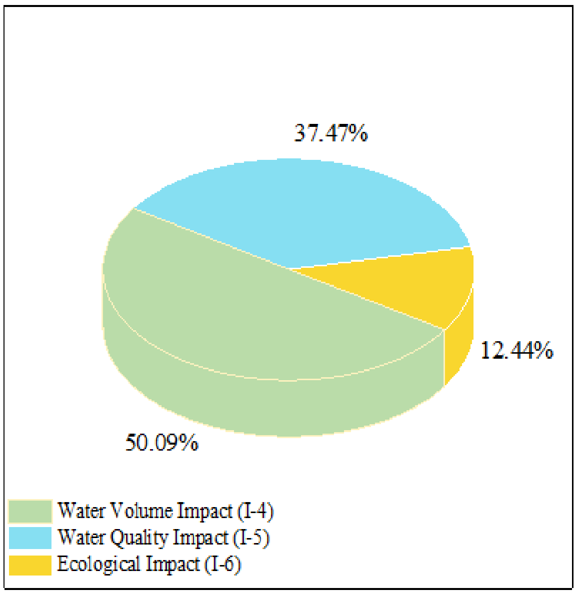


Figure 28: PWC of indicators of Environmental criteria Group

Priority Weightage of 0.501 to receiving water volume impact, 0.37 to receiving water quality impact and 0.12 to ecological impact. A number of hypothetical observations made from figure 28 above. However different literatures and as stated in this thesis indicate, the study area (Mekelle city) has higher impervious rate. Despite the impervious roofs and asphalts, most area covered with cobble stone tiles for subways. Those facilitate high discharges and volume on the urban catchment such as on road accesses and receiving water body by exaggerating the benchmarks used to define the volume impact such as downstream erosion. But water quality impacts on downstream flow protection value, groundwater recharge could be having average effect because of low pollution level from different land use category (Residential, Small-Medium industries, commercial and non-developed) and low pollutants buildups of due to longer dry period comparing to those developed countries situation. Lowest priority to ecological impact is resulted may according to (Thevenot, 2008) that natural ecological variability does not allow ecological standards in order be specified. In addition, since aquatic environment is at poor state in Mekelle the degree of effect to receiving ecological impact, which is measured through the benchmarks, is very low rather accomplishment of water volume and water quality impacts absolutely bring the ecologically sustainable environment.

4.1.1.3 PWC Social &community benefit Indicators

The priority results demonstrated on figure 29 which higher priority shifts weight to health and safety risks (I-7) of 0.58 weightage, 0.30 to system amenity &aesthetics (I-8) and 0.10 to acceptability.

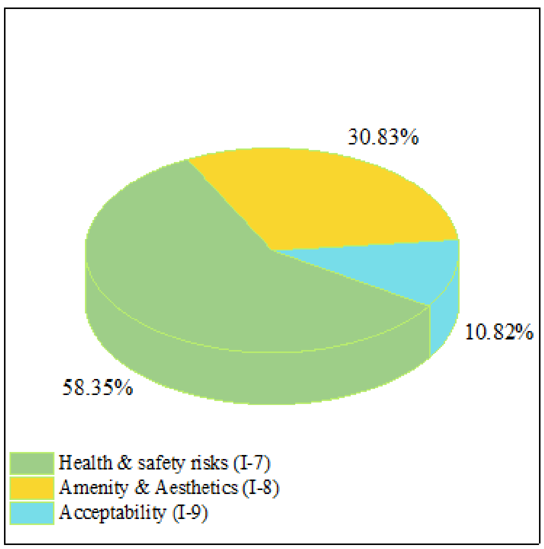


Figure 29: PWC of Social and community benefits criteria group

The reason why health and safety concerns get high priority is measured through the disease vectors, cross-connections and protection.it is an important social aspect of BMP implementation which the discharge of untreated stormwater disposal to surface water bodies are effectively treated and bring health to humans and environmental sustainability. This creates human health problems when people meet the contaminated water body, usually through recreational use. However, safety concerns can be mitigate by proper design. Acceptance of BMPs refers to the human perception of a BMP's value. Public participation in environmental and social impact assessments can produce higher quality decisions due to the incorporation of local knowledge and the public examination of 'expert' knowledge but alter with little efforts by the legislatives. Example, an individual home owner concerned about a BMP next to his house potentially devaluing his property, market and preference surveys, reported nuisance problems, and visual aesthetics.

4.1.1.4 PWC of Economic indicators

The experts give priority of 0.75 or (75%) to life cycle costs is specified because of quantification of SuDS needs to be based on not only on a consideration of design, project management, capital and O&M costs but also ranges of other costs including those related to replacement, risk and disposal costs. Consequently, assurance of life cycle costs also encompasses the assurance of the long-term affordability of the system in general. However, lifetime affordability shows variability in time and is averagely in the hands of the stakeholders.to insuring the long-term management techniques and economic add-on values required at different spatial locations. For such variability in long-term cost, study must be conduct over a period adequately illustrating the inevitable decline in performance.

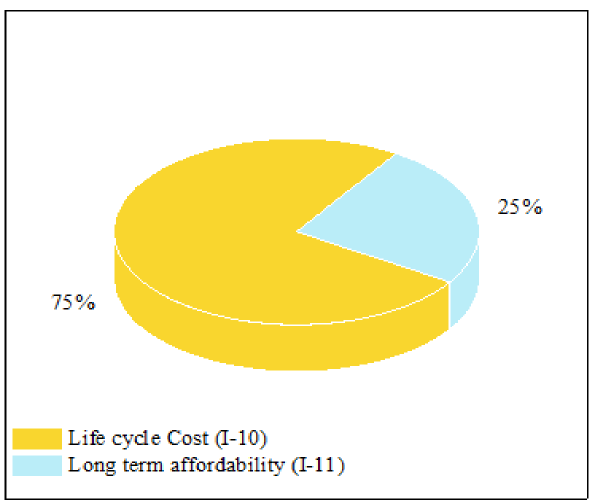


Figure 30: PWC of life cycle costs and long-term affordability in Economic criteria Group

4.1.2 PWC of Alternatives (actions) with respect to Sub-criteria

The PWC of the five alternatives (BC, RG, IT, PP and VS) are presented in radar diagram (see figure 31) to show the priorities or weightage assigned by experts according to the 11 indicators illustrated in (appendix 3). The diagram illustrates the range of the all priorities relative to the center or the reference point (Zero) and ending with the highest range of weightage (0.45). Yet again, it is necessary to see the reasons of weightage of each alternatives independently as follows:

i. Weightage of Alternatives in regard to System performance (I-1)

System performance indicates the efficiency of BMP to reduce both runoff volumes and improve stormwater quality and the SuDS components where greatest uncertainty arises concerning their performance for extreme events. However, Performance also depends heavily on design objectives, quality of construction and site constraints (LID:BMP, 2014). Accordingly, experts' positive priority assigned to Infiltration trenches (A_3) with weightage of 0.378 followed by 0.209, 0.149, 0.132 and 0.129 to PP (A_4), RG (A_2), BC (A_1) and VS (A_5) respectively.

Case studies show that in general, treatment of stormwater begins with filtration of particulates as runoff flows over the surface and through vegetation, and again when it infiltrates through covering and soil layers or conveyed properly into the under drain pipes. Because of the high performance of infiltration trench, Bio-cells/Rain Gardens and permeable pavements also designed to include infiltrating trenches from their bases (Woods, 2015).

Moreover, infiltration trenches are better for sites with low rainfall events and soil type of Mekelle city (study area, sandy clays) having high permeability facilitates function of infiltration. As (LID:BMP, 2014) defines that there is no exact guideline that measures system performance but infiltration trenches sometimes categorized under permeable pavement have over all high performance in capturing runoff volume and Some pollutants such as total suspended solids(TSS). Also, have good performance under extreme and ordinary rainfall conditions. However, the performance of the Vegetation swale systems varied greatly demonstrating that soil type, construction technique and topography will all significantly influence the system performance and given less priority.

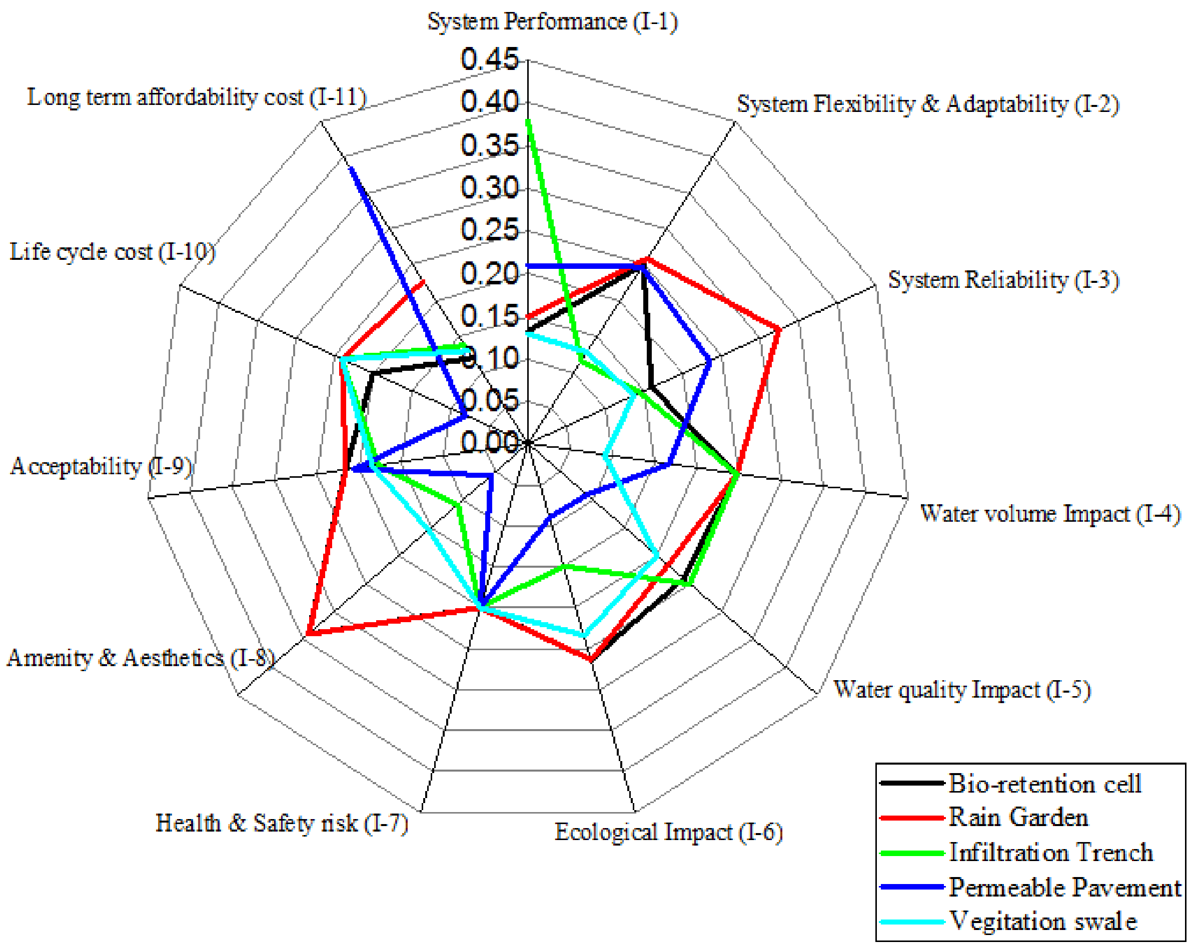


Figure 31: PWC alternative with respect to the 11 indicator

ii. Weightage of Alternatives in regard to System flexibility & Adaptability (I-2)

Experts' major priority under system flexibility and adaptability allotted to Rain Garden (A_2) with weightage of 0.258 followed by 0.250, 0.247, 0.128 and 0.116 to BC (A_1), PP (A_4), VS (A_5) and IT (A_3) respectively. Because Rain Garden option that address flexibility and adaptability are also considered highly important since it used in combination with Bio-cells, Vegetation swales and Infiltration trenches in different scenarios with durable status. Anyone could implement Rain garden with in each household, cemeteries, road sides, parks etc. to keep vegetation healthy, remove sediment and trash, and ensure that the facility is draining properly.it is also flexible with the area most households parcel in Mekelle city, which give much space to develop gardens and control stormwater at the source of production next to roof.

iii. Weightage of Alternatives in regard to System Reliability (I-3)

Priority under system reliability was analyzed under experts' choice to see dependability of the system to some constraints while design and application. Hence, Bio-cells (A_1) considered less reliable with weightage of 0.323 followed by 0.234, 0.159, 0.144 and 0.137 to PP (A_4), RG (A_2), IT (A_3) and VS (A_5) respectively.

iv. Weightage of Alternatives in regard to Water volume impact (I-4)

Under this comparison of alternatives experts, allocate equal weightage given to Bio-cell (A_1), Rain garden (A_2) and Infiltration trenches (A_3) with value of 0.247. However, less weightage given to Permeable pavement (A_4) and Vegetation swale (A_5). Thus, less weightage given to Permeable pavement and vegetation swale does not mean it have any effect on water volume reduction. Rather in addition to water interception (Infiltration, evaporation or slowing down flow rate etc.), other LID types such as bio-cells, rain-garden, infiltration trench possess storage/detention, under drain system of water by handling storm water independently from the conventional and this has much greater degree of reduction of flow on peak events.

v. Weightage of Alternatives in regard to Water Quality impact (I-5)

The alternative 3 (with a score of 0.250) followed by alternative 1 (with a score of 0.241) are selected as the enhanced options and alternative 2 (with score of 0.217) considered moderately important when water quality impact is assigned the comparison factor. Oppositely, alternative 5 (with a score of 0.200) found to be the least preferred option followed by alternative four (score of 0.090). what to understand here is most studies do agree that almost all LID types are capable of treating major pollutant with in stormwater but differ under reduction efficiency at different scenarios such as under high loading rate of pollutant, high wash-off situations. For this reason, infiltration trenches do high efficiency of stormwater quality protection through infiltration and protecting groundwater while recharging it by the other. Secondly, bio-cells are better of intercepting floods containing pollutants washed-off from different land use practices during peak rainfall events and retain it to protect mostly to the surface water-quality impact.

vi. Weightage of Alternatives in regard to Ecological impact (I-6)

BMPs evaluated on their ability to provide wildlife or wetland habitat, assuming that an effort made to landscape them appropriately. Objective criteria include size, water features, wetland features and vegetative cover of the BMP and its buffer. Hence, Bio-cells (A_1) and Rain garden (A_2) are reflected equally high priority with weightage of 0.263, moderately high to vegetation swale (A_5) scoring 0.234.for the reason that in construction of bio cells, rain garden and moderately in vegetation swale, vegetation cover area, ponding area of runoff and soil characteristics are the major factors that bring habitat within urban environment. Experts choice followed less priority to Infiltration trench (A_3) and Permeable pavement (A_4) weighted 0.148 &0.089 respectively.

vii. Weightage of Alternatives in regard to Health & safety risk (I-7)

The results should be that risks are reduced to acceptable levels by designing out hazards such as probability system failure, Consequences of storm event exceeding Design storm RI, local community concerns (injury, infection, drowning etc.), Formal technical risk exposure audit (flood risk, health risk, safety risk). Rainwater runoff in SuDS components is no different from the water that runs across roads and car parks and stands as puddles for lengthy periods after rainfall. Many existing water features in parks and public open spaces already take highway runoff. Indeed, with good SUDS design and effective source control, accessible SUDS components should contain “treated” runoff, and therefore any pollution levels should be very low. Accordingly, equal weight of 0.2 given to all SUDS components.

viii. Weightage of Alternatives in regard to Amenity & Aesthetics (I-8)

Amenity and Aesthetics indicates Contribution to urban sustainable development policies, Role in Biological Action Plans (BAPs), Additional benefits offered by different BMPs. The rankings obtained with higher weighting assigned to Amenity & Aesthetics show that the most preferred alternatives are BC (A_1) and RG (A_2) (with equal score of 0.340) followed by alternative 5, alternative 3, alternative 4 with scores of 0.154, 0.108, 0.056 respectively considered as average to least priorities.

ix. Weightage of Alternatives in regard to Acceptability (I-9)

Acceptability indicates Contribution to local Community willingness-to-pay, Acceptance of on-site treatment as opposed to conventional drainage systems, level of inhabitant willingness to participate in on-going site improvement. Consequently, experts again give highest score to bio-cells and Rain garden with score of 0.216.however lowest priority given to permeable pavements (A4), vegetation swale (A5), and Infiltration trench (A3) with priority value of 0.205, 0.184 and 0.177 respectively.

x. Weightage of Alternatives in regard to Life cycle cost (I-10)

Hence, RG (A_2), IT (A_3) and VS (A_5) equally weighted with value of 0.24, which indicates those BMP types have less life cycle costs. However, BC (A1) and PP (A4) tends to have weightage of 0.2 and 0.08 respectively. This implies high costs during life span, relative to other BMP practices, are expensive to construct and much of this cost arises from the intensive planting on an engineered mix of soil, which usually designed to have high infiltration rate. Even the output from both are effective in managing volume of water in urban area, need frequent operation and maintenance budgets. Example Porous pavements need to ensure that paving area is clean of debris, avoid sealing or repaving with non-porous materials, ensure that paving dewaters between storms, ensure that the area is clean of sediments etc. every week or month.

xi. Weightage of Alternatives in regard to Long-term affordability (I-11)

For variability in long-term cost, study must be conduct over a period adequately illustrating the inevitable decline in performance and insuring. The long term management techniques considering the economic add-on values, amenity provision, adoption of financing required at different spatial locations Hence, Permeable pavement (A4) are considered to be Affordable with weightage of 0.384 followed by 0.227, 0.138, 0.130 and 0.120 to Rain garden (A2), Infiltration trench (A3), Vegetation Swale (A5) and Bio-cells (A_1) respectively.

The priorities formulated as a combination of varying percentage adoptions of different suitable stormwater management measures identified after literature review. The overall summed weightage results showed that the alterative two with scoring 0.489 (adoption of 48.9% RG) is the preferred option based on expert's judgment. The analysis of composite priorities showed that, with the scoring and weighting employed are in maximum of one as showed in the chart below. In addition, the infiltration trench (A_3) alternative received the second highest score (Figure 32). This is due to its high performance in economy, technical, social and community benefit criteria. Rain gardens had the highest weighted scores in the environment category and slightly higher in the social aspects and health category, although it falls short of other alternatives in aesthetics and amenity. The best performing stormwater treatment solution over all MCA weightage were Rain garden (A_2), and infiltration trench (A_3) with summed weight of 0.489 and 0.232 respectively. Following Moderate, weight to Bio-cells (A_1) scoring 0.190, 0.18 to Vegetation swale (A_5) and finally lowest priority of 0.166 to Permeable pavement (A_4).

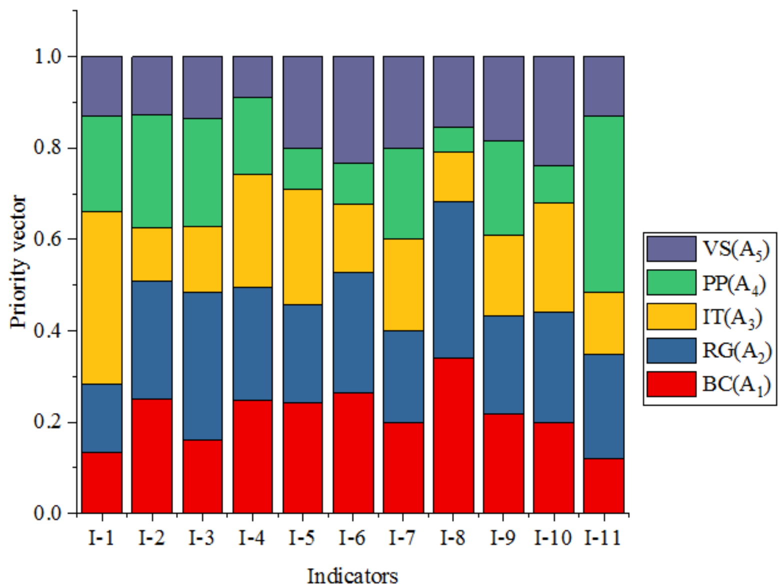


Figure 32: Overall sum weightage of indicators

4.1.3 Sensitivity analysis

In addition to the overall results illustrated in figure 32, sensitivity analysis undertaken to examine the reliability of the choice treatment alternative concerning the main criteria priorities. To start with, weightage of alternatives was set to range 0.1 and one of the three main criteria weights was increased or decreased keeping the others proportional the same. Figure 33 illustrates the results from the sensitivity analysis.

When Technical criteria not considered or given lesser weights, Rain garden (RG) is the dominant alternative followed by Bio-cells (BC). In contrast when economic is the only criterion (high priority), the most preferred treatment alternative is still RG but followed by Infiltration trench (IT), whereas PP, BC and VS are the least preferred (see Figure 33). Note that the points of intersections indicate where rank reversals will start to occur when priorities increase for 0 to 1. So, of all alternatives again Rain Garden shows positive feature following IT and PP. However, Bio-cells and Vegetation swale show negative effect after point of intersection of technical criteria.

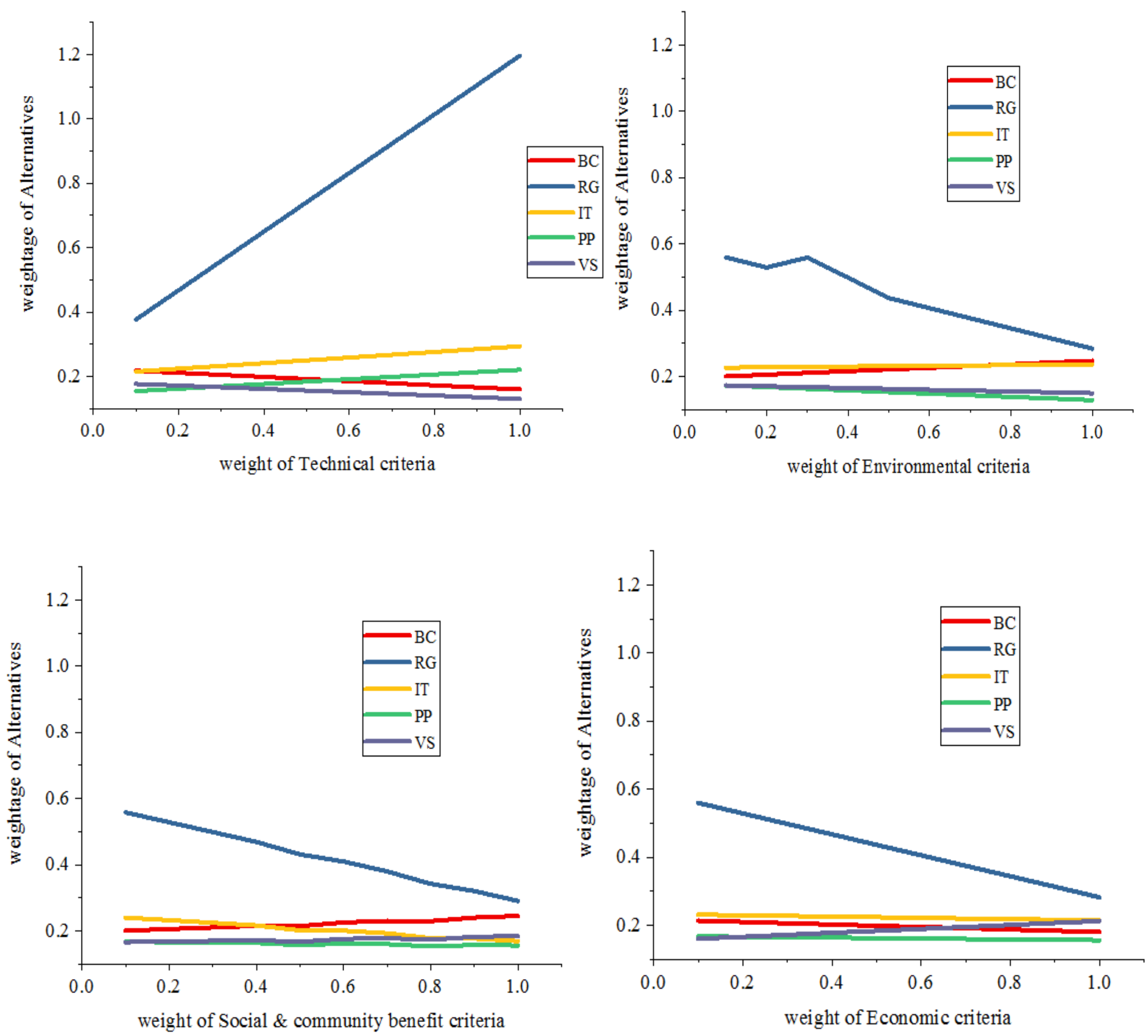


Figure 33: Sensitivity Analysis with respect to weighting of,Technical criteria, Environmental Criteria, social & community benefits criteria and Economic criteria

Under Environmental criteria (Figure 33), BC and IT show positive sensitivity while weightage of priorities increase (zero to one) while RG, PP and VS decrease for higher priority.

4.2 SWMM simulation Results

To test the influence of these systems to prevent flooding, three simulations run including each of the SuDS proposed. The aim at this point was to compare the behavior of the nodes, pipes Subcatchment highlighted in Figure 22&23 with and without SuDS installed.

The actual SWMM model developed from the ArcGIS data. All the features parameterized above had been stored and analyzed in separate Excel-files (Subcatchments, junctions, conduits, and outfalls). For modeling, the geometry and attributes of all features were then suited into a SWMM project file using a user defined mode. This worked well and the model created was usable right away (see Figure 34).

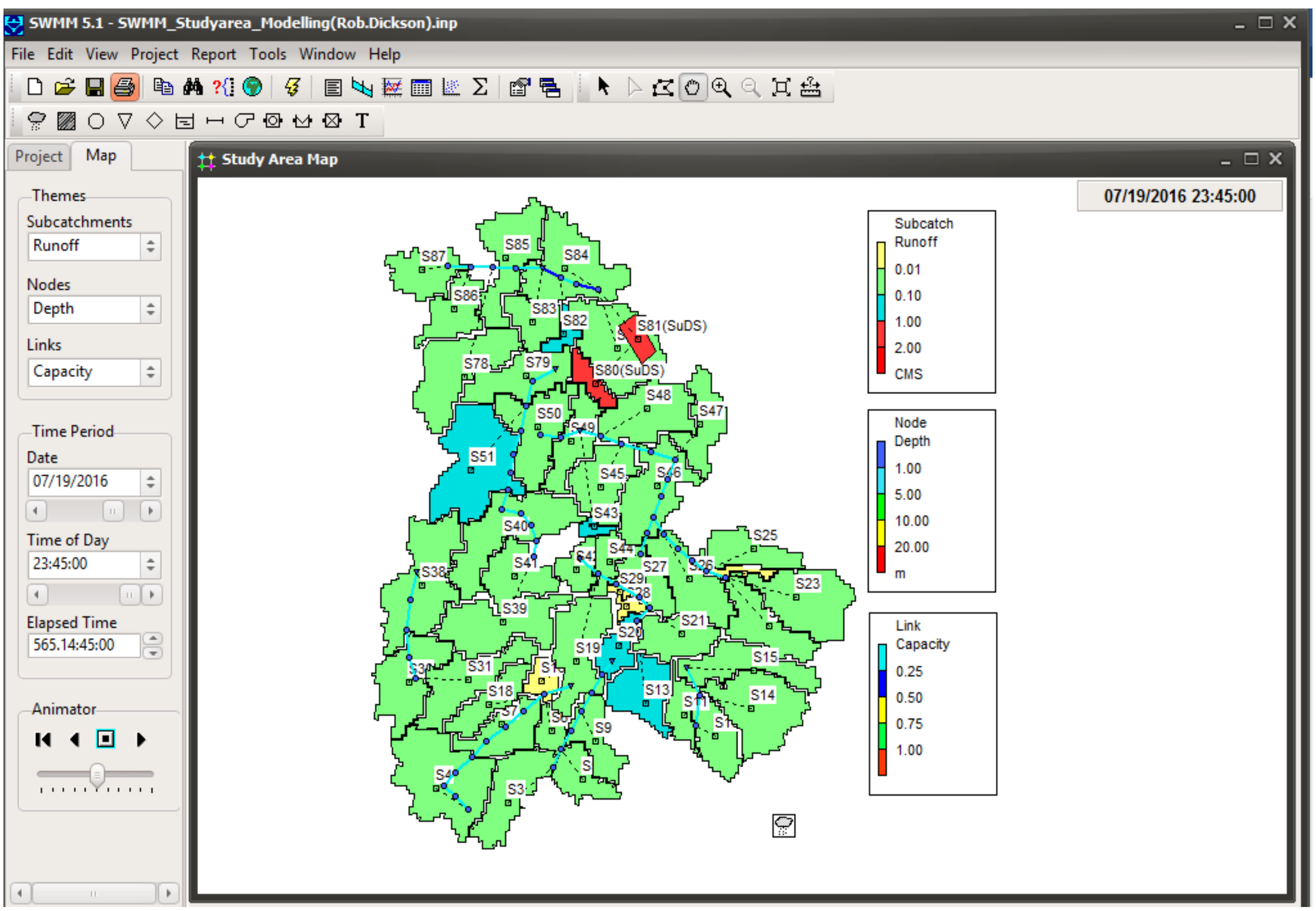


Figure 34: Structure of the SWMM model and arrows present flow direction in the conduits

The reporting time step and the dry-weather hydrologic time step were set to 15 minute and 1 hour respectively. The hydraulic routing time step was set to 30 s, which was expected to be sufficiently short for Kinematic wave routing *(Rossman, 2010)*.The wet-weather time step was also set to 5 minute and Modified Horton is used as an infiltration model to define the rate at which rainfall infiltrates into the upper soil zone of a Sub-catchment's pervious area.

The model run with daily precipitation data for the entire period covered by the weather observations, from 07/06/1992 until 07/06/2016 (later referred to as the 'long-term simulation'). However, for easy and recent checkup and crosscheck, the model is intend to estimate flow on an annual basis from 01/01/2015 to 22/12/2016 and to calculate annual estimates of inflows to junctions and Peak flows at each Subcatchment.

4.2.1 System links and Nodes

There were anyway on both links and nodes only 60 features each in the data. This routine worked well and 8 Outfalls are found as the drainage system conveys and dispose directly into river directions.

After pipe lengths and elevations analyzed, the Manning's roughness coefficient n had to be define. No data was available on the pipe materials in the study area. According to the SWMM User's Manual (Rossman, 2010), n value of 0.011 to 0.015 applies to both links and nodes. As many of the pipes in the city center area are relatively old, and thus probably not as smooth as new pipes. Thus, roughness coefficient of 0.013 used for all pipes. Pipes were given additional surcharge depth of 0.2m and allowed to pond in 2sq.m area to see node flooding and its time of occurrence. All links and nodes works fine but, at day 564 and 565, the simulated values for Node 58 possess maximum inflow and conveyed with no additional inflow to Node 59 and Node 60 (see Appendix-6). This were due to high runoff from S80 and S81.therefore possible flooding occurs and carried high loading at outfall 8.

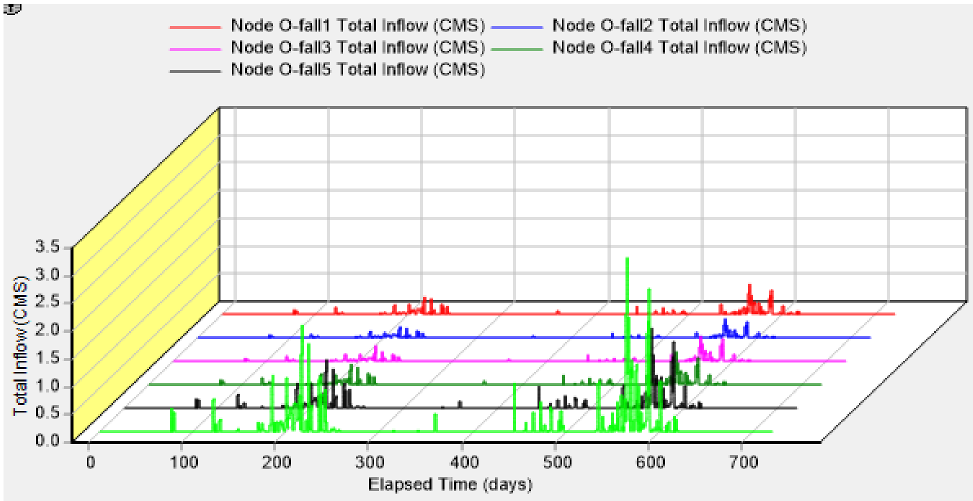


Figure 35: Total simulated inflow of outfalls (O-fall 1-6), (01/01/2015-22/12/2016)

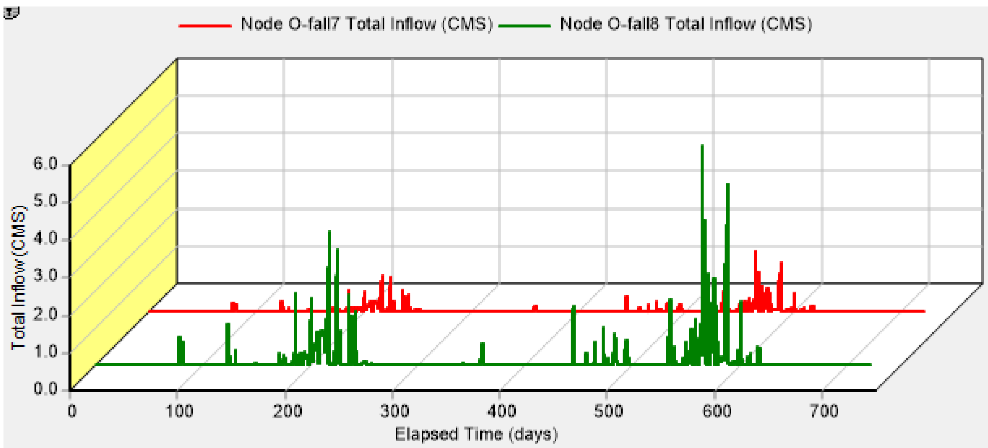


Figure 36: Total simulated inflow of outfalls (O-fall 7&8) , (01/01/2015-22/12/2016)

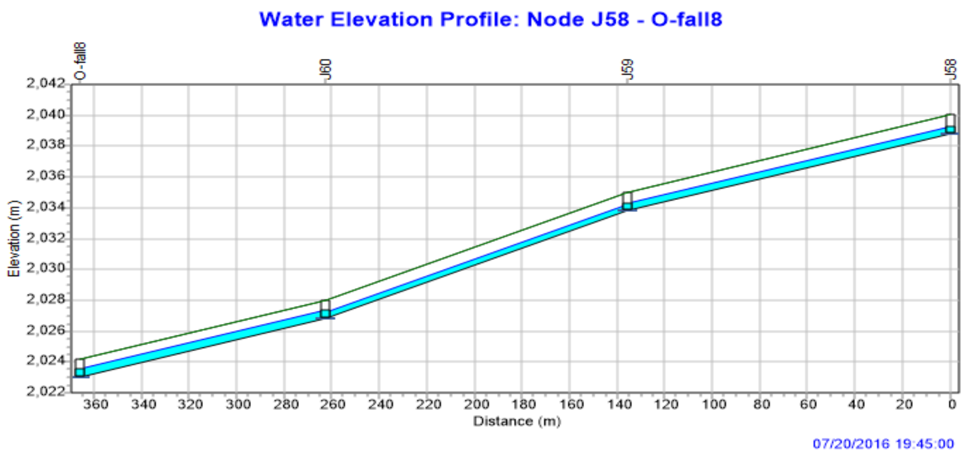
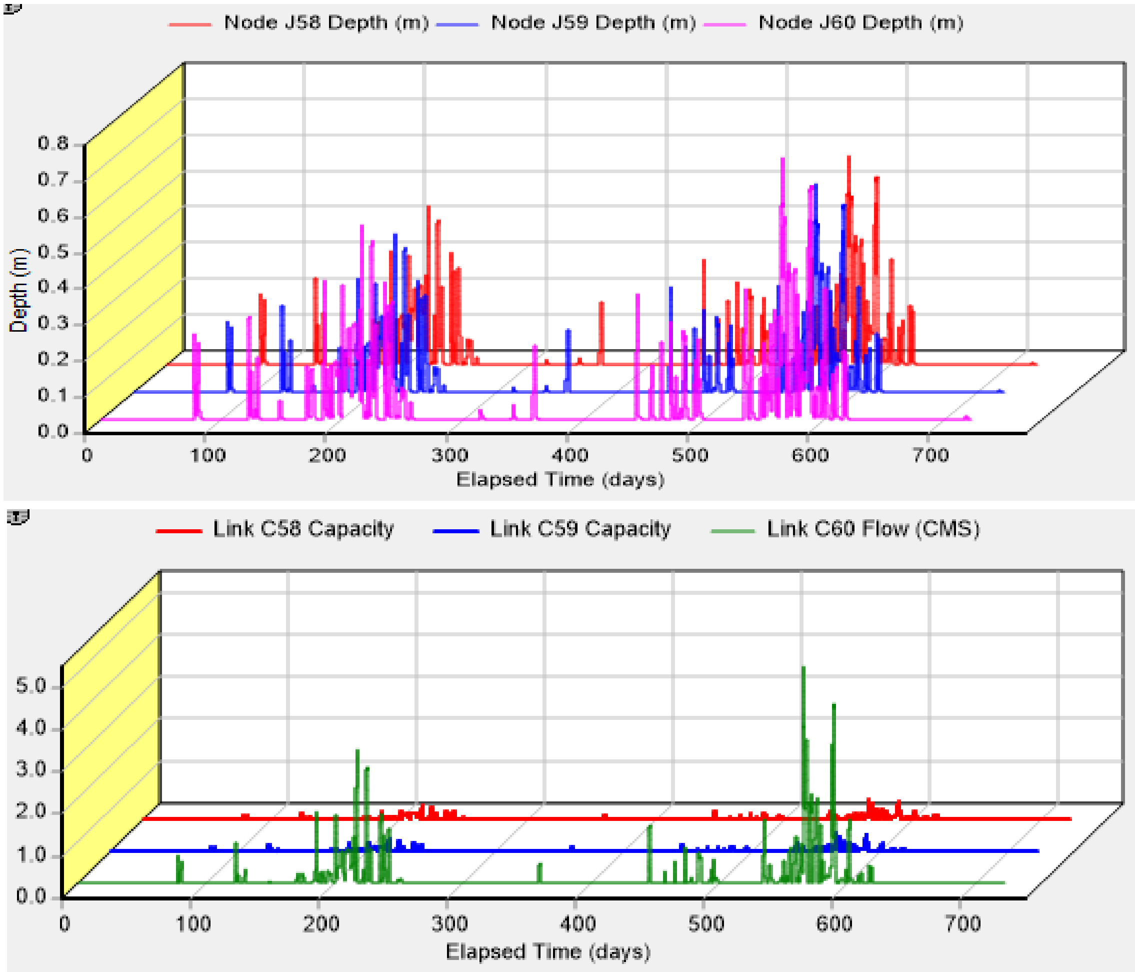


Figure 37: water elevation Profile for within affected nodes and final outfall



(A)

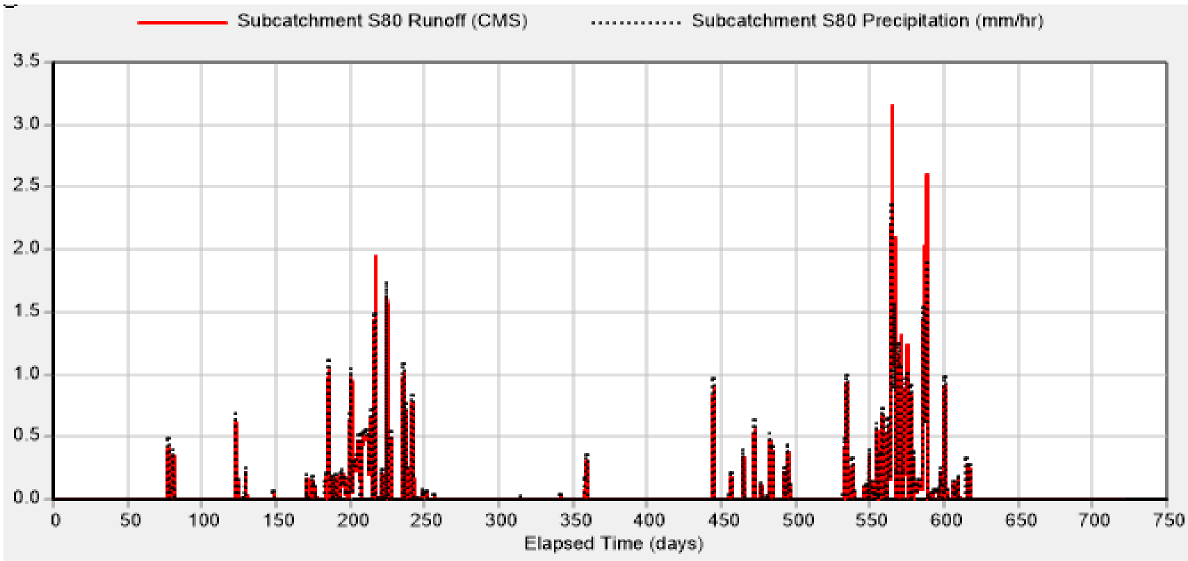
(B)

Figure 38: Max. Depth in selected nodes (A) & Capacity at selected links (B)

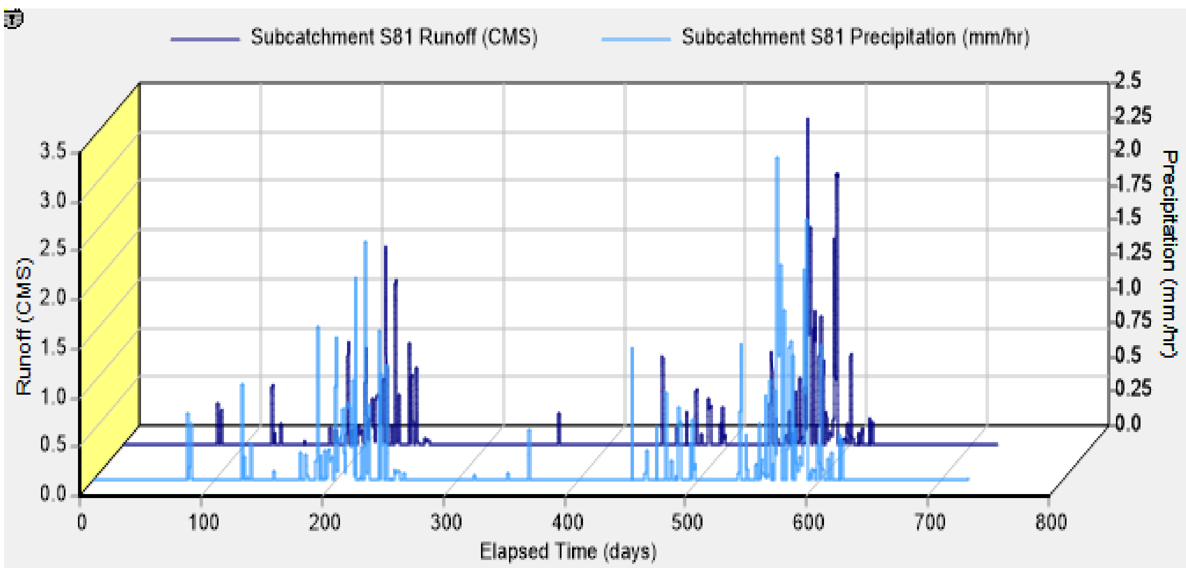
The rest Link and node were fine, but maximum inflows through nodes occurs at repeated elapsed time (days) and pipes 58, 59, 60 become over capacity. However, possible surcharging was not available as the slope perfectly suits the conveyance.

4.2.2 Subcatchments simulated result

The maximum peak runoff seen in three Subcatchments occurred as shown in Figures-40. The peak runoff similarly obtained from sub-catchment 80 and 81 with 3.16m^3/s & 3.34m^3/s respectively. Least peak runoff obtained from sub catchment with less imperviousness, area and slope distribution. The peak runoff obtained and respective peak time for all catchments are summarized in (appendix-5) and Node flooding's were null in the obtained model results for the rainfall event simulated. This implies no flooding scenario.



(A).



(B).

Figure 39: System runoff and precipitation graph in Subcatchments - S80 (A) and S81 (B)

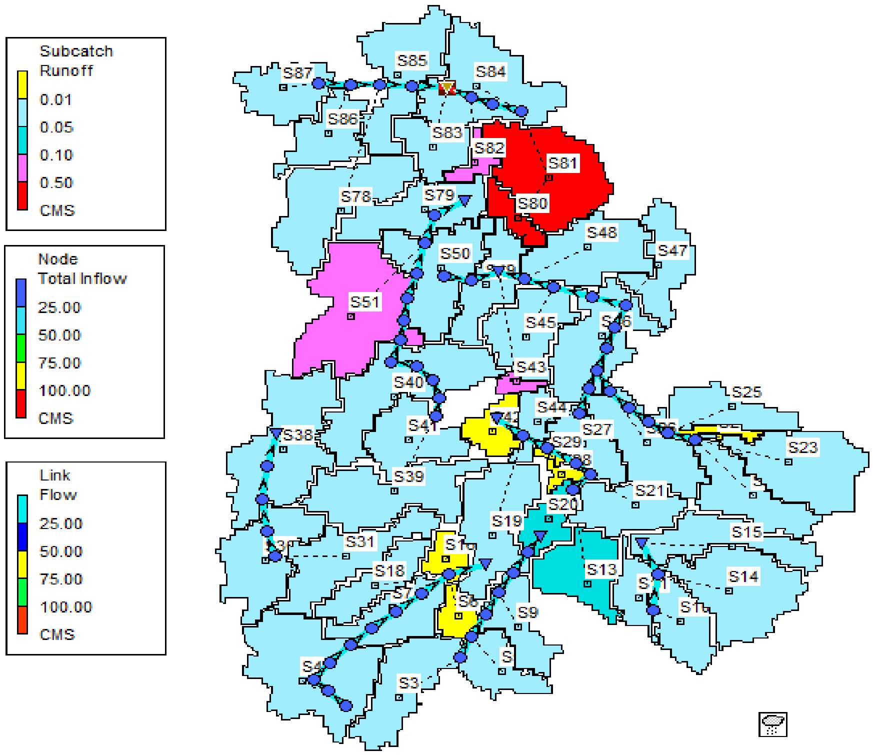
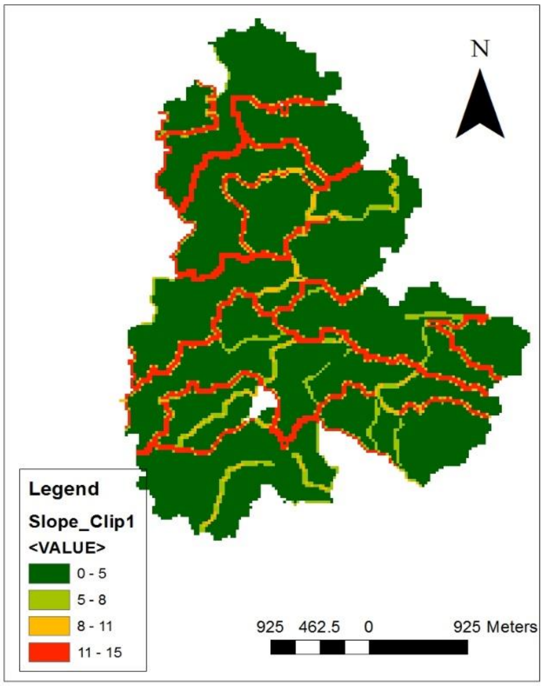


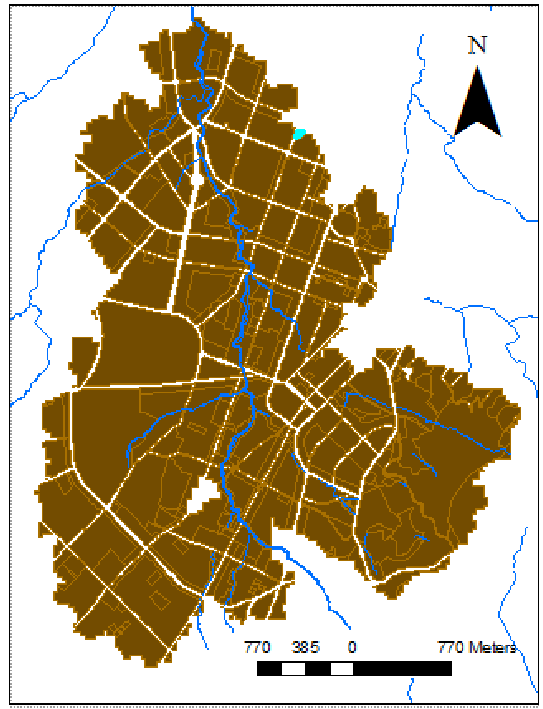
Figure 40: Sub-catch results in moderate runoff rate but high in S80 &S81

4.3 Feasible Locations for the Implementation of Sustainable Drainage Systems (SuDS)

The search for feasible locations for the implementation of SuDS in the study catchment started with the preparation of maps related to the geometric and hydrologic criteria to meet by each system according to Table 11: slope, Parcel buffer, road buffer, stream buffer, and Area. Since the dominating hydrological condition of the soil below the study catchment corresponded to an HSG of C (sandy clay), there was no restriction in these terms for any type of SuDS, which required at most a type B&C soil.

Slope in the catchment area was determined from the DEM and classified according to the thresholds defined in Table 11 and range of 0% to 5% (see Figure-41a) taken. The area corresponding to these thresholds covered 13.38% and 15.467% within the whole study sub-catchment S80&S81 respectively, which provided multiple opportunities to install different types of SuDS. Since the location of the downspouts in the buildings was unknown, the buffer-related calculations were limited to main roads (see Figure below), whose presence only restricted the implementation of bio-retention cells.



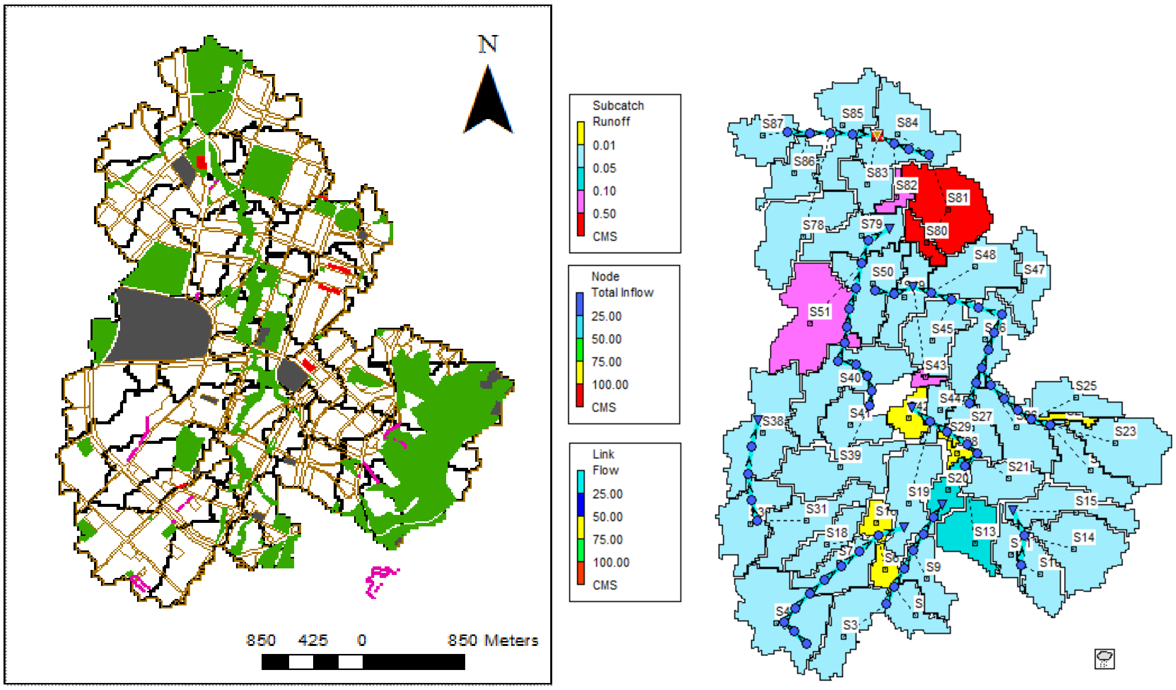


(A). (B).

Figure 41: Feasible identification on slope classes [(a)] and Road buffer and natural streams [(b)]

The intersection of areas in which these criteria met separately resulted in table 11. In which the selected feasible areas are available from existed and proposed green area (Green color), mixed-use (light black), road side parking's (red color), social municipal and business and commercial land use types (see Figure-42(a)). The refined map (see figure 42a), shows the available spaces for implementation of SuDS, excluding marginal and disconnected feasible areas whose consideration was irrelevant in practical terms.

Data imported from the stormwater simulations run in SWMM and resulted in the priority map shown in Figure-42b. Although the values of peak runoff obtained in SWMM varied depending on climate periods, the priority order was constant in all cases and, as expected, mainly given by the size of Subcatchments an imperviousness. As for overlap, the area associated with vegetative swales in table 11 was also valid for infiltration trenches.



(a). (b).

Figure 42: Feasible areas location for the main types of SuDS [(a)] values of peak runoff [(b)].

According to the five different SuDS alternatives analyzed using analytical hierarchy process (AHP) done in section 4.1.2, all alternatives, two extensive RG (RG_1-RG_2) each covering 1ha, one unit of infiltration trench(IT) covered 0.35ha and one unit of vegetation swale (VS) which covers 0.44 ha were assigned for Subcatchment (S80) comprising 13.38% of impervious surface and gorge. Equivalently, one unit of extensive RG to treat 1.66 ha, three Bioretention cell(BC) units each 0.4 ha, five pervious pavement structure (PP) each 1ha inside Subcatchment (S81) to compensate total 15.467% of imperviousness with permeable surface, were included in the model to assess their storm attenuation capability. Each of them was located in a Subcatchment connected to the flooded nodes (or junctions) and overcapacity pipes and/or in any of the previous Subcatchments to these conflictive elements.

Even if Permeable pavements were less prioritized in AHP-MCA session, the existing sub roads were original constructed with cobble stones which are semi porous and was feasible to replace by

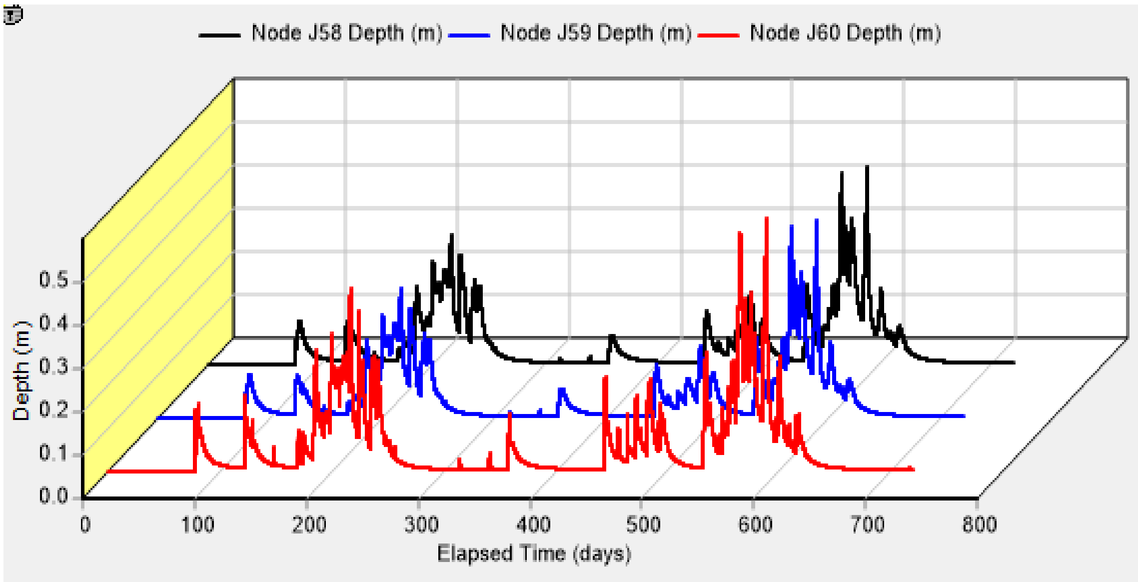
PP. Regarding this, PP were the type of SuDS that involved larger feasible area, covering and 9.839% followed by RG replacing 9.592% of the study sub catchments respectively. This fact, which was consistent with the wide applicability of PPS introduced for such surface types.

The places selected for fitting these SuDS are located in the kedamay weyane sub-city, road to Ayder referral hospital, near Primary& secondary school by identifying impervious workspace and reserved area for green infrastructure with in the catchment area (see Figure 43).

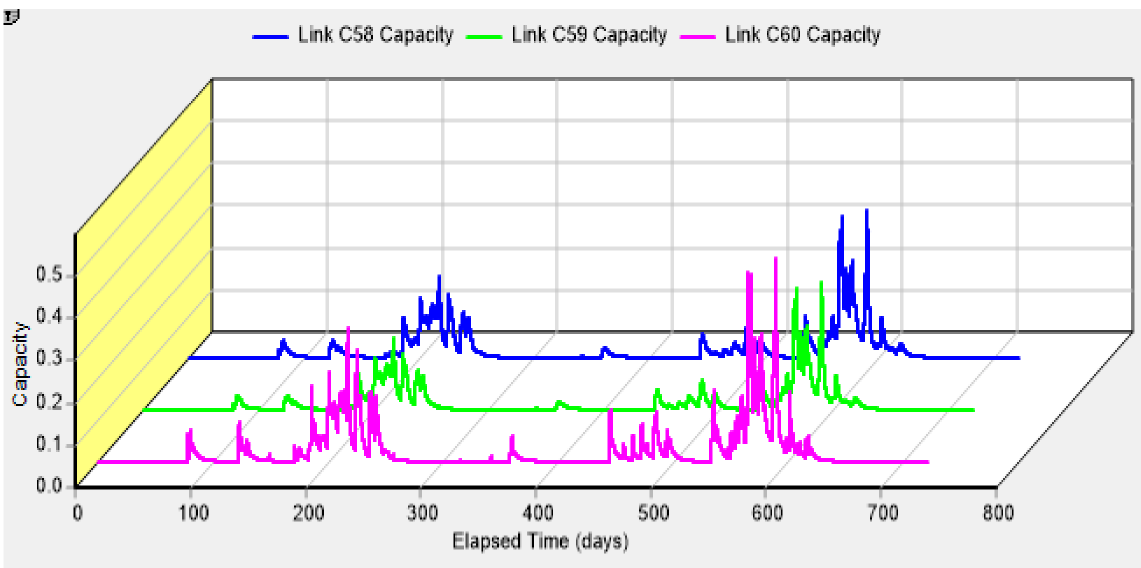
Figure 43: Layout of SuDS allocation with in S80&S81

These values derived from those suggested in a SuDS-related reviews, in order to replicate the typical drainage systems that could be implement in Mekelle. To test the influence of these systems to prevent flooding, two simulations run, including each of the SuDS proposed. The aim at this point was to compare the behavior of the Subcatchments, nodes and pipes highlighted in section 4.2.1 and 4.2.2 without SuDS and compared with proposed SuDS allocated in Figure 43.

To a greater or lesser extent, the inclusion of SuDS proved to be positive when avoiding localized moderate to high floods and surcharges. In fact, the results were occur due to a combined effect of SuDS types used and subarea is routed to pervious surfaces or flow ordered direct into pervious.

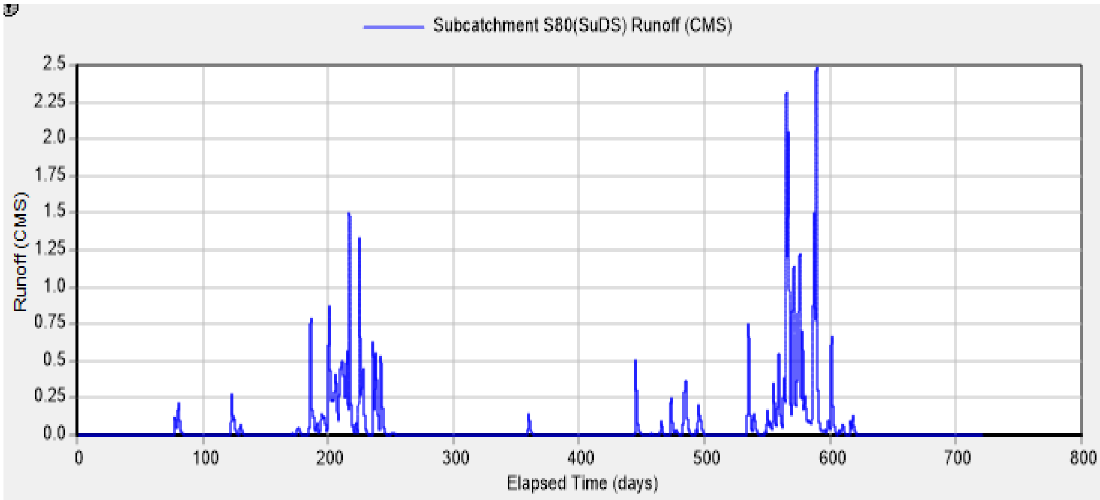


(a).

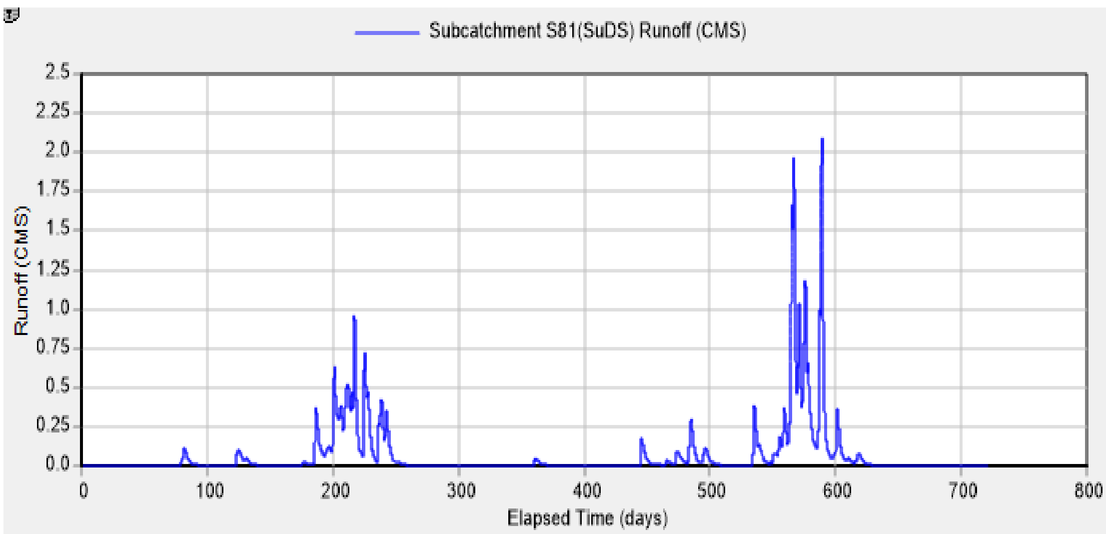


(b).

Figure 44: Maximum depth [(a)], Capacity at selected links after SuDS implemented [(b)]



(a)



(b)

Figure 45: System runoff and precipitation after SuDS applied in S80 (A) & S81 (B)

The above graphs show the difference in runoff management within Subcatchments comparing the conventional way of conveyance (existing system) simulated in section 4.2.2 and implementation of best management practices. Both Subcatchments decrease in Peak runoff production possessed by the surface type, which was moderate to high impervious that alters even small precipitation direct into runoff.

This session summarizes the performance of the five SuDS types in terms of their impact on the volume generated as a result of the storm event in the originally flooded nodes, before (V_o) and after (V_{SuDS}) inclusion of these systems which also gives a successful result.

4.4 Sensitivity analysis results

The sensitivity analysis indicates that how likelihood in the output of a model can be qualified to different sources of uncertainty in the model input (Ali Moafi Rabori, 2017). For sensitivity analysis, at the first stage, the model run using the initial parameter of the model. Then sensitivity analysis was perform by changing each parameter either side of their standard values while all others parameter was constant. The parameters used as input and their allowable range extracted in table 20. The results of the sensitivity analysis were illustrate in Figure 47.

Table 20: Parameters used in SWMM Modeling and their allowable range

Variables	Category	Initial values used	Allowable range	Reference
Percent of impervious area (%)	-	26.37%	±30	Temprano et al (2006)
Average surface slope	-	0%	±30	Temprano et al (2006)
Manning's roughness coefficient	impervious area	0.013	0.011-0.033	Huber and Dickinson (1992)
	pervious area	0.05	0.02- 0.8	Huber and Dickinson (1992)&Temprano et al (2006)
Depth of depression storage(mm)	impervious area	1	0.3- 2.5	Huber and Dickinson(1992)
	pervious area	5	2.5- 5.1	ASCE (1982)Design & Construction of Urban Stormwater Management Systems, New York)

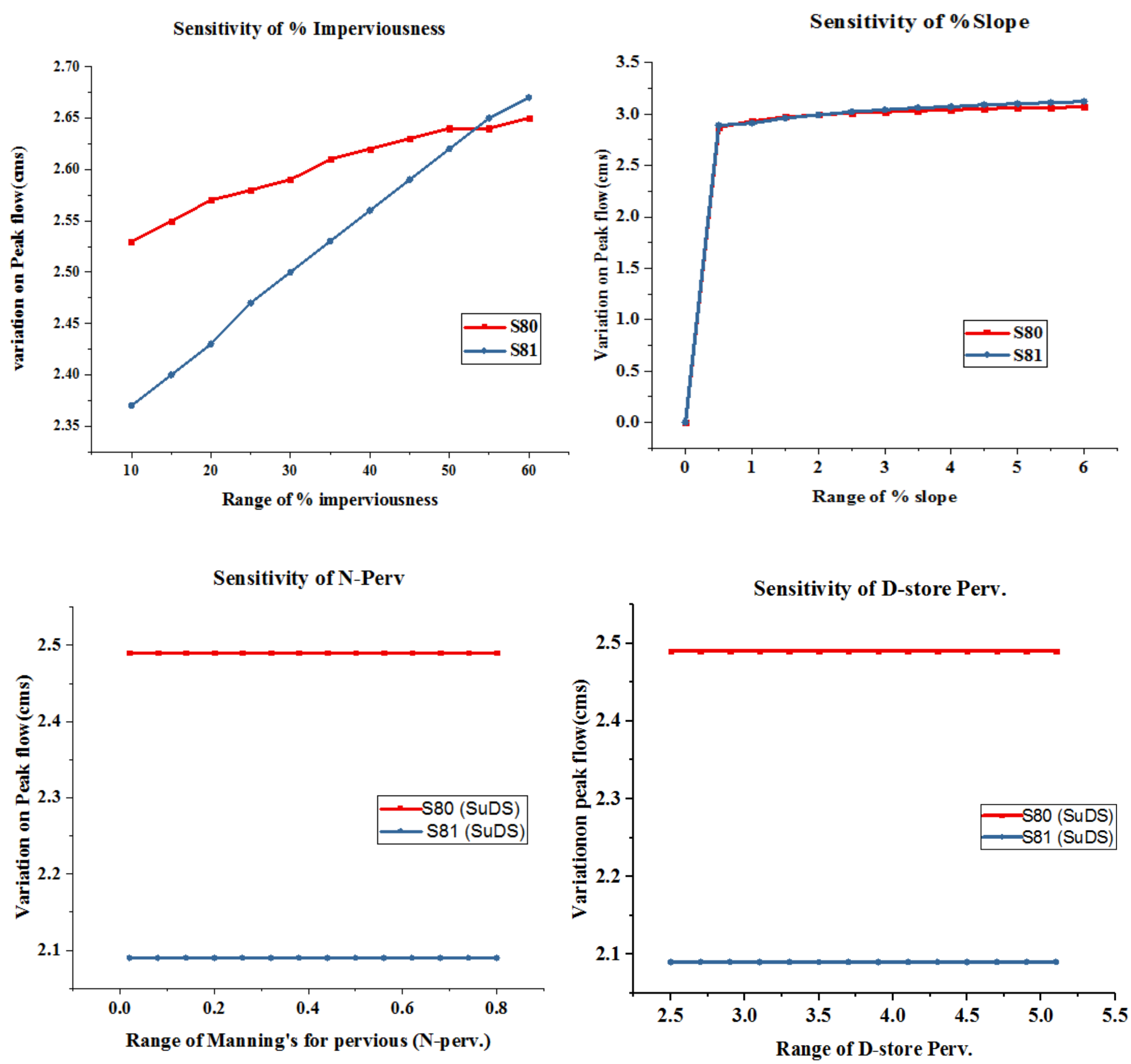


Figure 46: Sensitivity Analysis of Variable Parameters

The results of the sensitivity analysis indicated that percent of impervious area, average surface slope were the most important parameters that influence estimation of the peak runoff via SWMM model in the study area (Fig.47). According to the second sensitivity scenario, the Manning's roughness coefficient and depth of depression storage for pervious area have not effects on peak runoff estimation or insignificant on the change it brings.

Chapter five

5. Conclusion and Recommendation

5.1. Conclusion

Organization of the thesis consists of coupling GIS, Analytical hierarchy process and stormwater management model (SWMM) frameworks to prioritize implementation of SuDS component and see their hydrological impacts on urban catchment before and after installations.

The methodology was tested on a case study of walkways, impervious road and conserved area. The case study evaluated RG, BC, IT, PP and VS over a range of economic, Environmental, social and community benefits, and technical criteria by applying AHP, under three different stakeholder final weights. Finally, stormwater management model (SWMM) LID-edition tool is used to compute the difference in impacts.

The results verified that effective actions on prioritization of SuDS in accordance to spatial location, drainage capacity of urban catchment and other pre-studies in Mekelle city could accomplish the optimization of system performance. Therefore, it directed to conclude a series of points to be drawn, as listed below.

- The response of weightage from stakeholders showed that misconceptions of AHP-MCA method, with initially no clear detail preference of BMP alternative and performance. Furthermore, very detail criteria and evaluation in the MCA method could result in consistency error. Nevertheless, correlations, comparisons of the top choices and the sensitivity analysis could provide better bases for recommendations.
- Of course, AHP-MCA also has limitations while application like other systems analysis methods, such as limitation in identification of factors in each hierarchy and criteria used for evaluation may result inconsistency. However, for Understanding complex system with multi variables and large hierarchical tree systems such as SuDS, AHP gives possible and reasonable decision options.
- Based on the chosen criteria for this particular study, the MCA results showed that the Rain garden (RG) was the best choice for the study area. The Infiltration trench (IT) and Bio-cells (BC) scored the second and third place, thus the sensitivity analysis of MCA showed

that the results can be considered as relatively robust under the criteria developed for this study.

- The comparison technique of MCA is shows sensitivity towards the criteria developed by the researcher. This indicates, the overall alternative scores could be very different under dissimilar hierarchical system or detail Multi criteria's and indicators.
- The magnitude of total inflows in the nodes that result in higher flow rates was mainly a function of slope, depression storage and high impervious land cover of its Subcatchments that proved to have a statistically significant correlation to peak runoff rates.
- While modeling using SWMM, the percentage of feasible area available in the study catchment for the location of SuDS indicated that PP were the easiest systems to implement in developed areas of Mekelle city as it were already practiced with poorly permeable cobblestone surface.
- Combination of Rain Garden, Infiltration Trench, Vegetation Swale with in Sub-catch (S_{80}) and grouping of Rain Garden, Bio Cell, Permeable Pavement with in Sub-catch (S_{81}) reduced discharge by 0.67m^3/s and 1.25 m^3/s respectively in comparison with situations exclusively based on conventional drainage systems. This demonstrates, it has a statistically significant hydrological impact on the response of the study catchment and apart from their intrinsic infiltration capacity, the degree of effectiveness of these systems depended on their geometric relationship with the existing drainage network.
- Sensitivity analysis showed that the parameters that had most influence on the hydrology and hydraulic parameters were slope, and percent of impervious and variation in parameters such as depression storage and manning's' roughness coefficient for pervious area had no significance or show no change.
- The road surface drainage of the study area found to be inadequate due to insufficient road profile with in sub-ways that is fully blanketed with cobble stone tiles. Thus, insufficient drainage structures and lack of proper interconnection between the road and drainage infrastructures thereby resulting outdating stormwater system and damages to road surfacing material.
- In summary, the integration of GIS tools, AHP-MCA and stormwater models highlights the opportunity to improve urban water resources management. Moreover, the LID editor of SWMM allows the definition of different SuDS techniques and the simulation of their impact

on urban drainage, in order to compare the effectiveness of various stormwater strategies. In other words, the findings of this research can help to better design drainage plans that can restore the natural water cycle in urban areas as far as possible.

5.2. Recommendation

- Recorded Climatology data of shorter durations (1min., 15 min., 30min., hourly and 3hours) are highly recommended and effective inputs for analyzation of rainfall runoff simulations. However, data provision from responsible agencies usually available with extremely long missing periods of shorter duration or daily-recorded data. For such reasons researchers could not accurately find the output or ought to do disaggregation of data into shorter durations, which is one thesis by itself. Therefore, responsible agencies should effectively record the data with automatically gaging systems.
- Proper road geometry need to be maintained even with the sub ways constructed with cobblestone which could easily be altered to pervious pavements with effective construction at every site of the city and proper side drainage structures need to be provided to upgrade the system with the best management practices.
- Lack of commitment in volunteered experts or sample size arise when questionnaire paper is large in size and complication to effectively focus on a detailed weightage of criteria's which is tough when dealing with individuals. For this reason, recommended way for such invitations of stakeholders or experts may be fruitful as a group discussion session or as project teams of professionals for governmental agency conducts.
- Because of the most SuDS solutions discussed are source control solutions and objective criteria's such as stated in multi-criteria analysis(AHP-MCA) section necessitate participation of different stakeholders. The supporting policy that enhance the use of source control solutions should be prioritize by the governing body. In addition to placing the policies, plans on awareness creation campaigns is required for durable integrated urban drainage system.
- In addition to this finding, future researchers are recommended to include modelling of water quality problems that is produced by different land use categories and identify the pollutants that disturb urban drainage system. In fact, the SuDS implementation goals are all satisfied if existing stormwater quality are improve with such best management practices and enhance sustainable environment.

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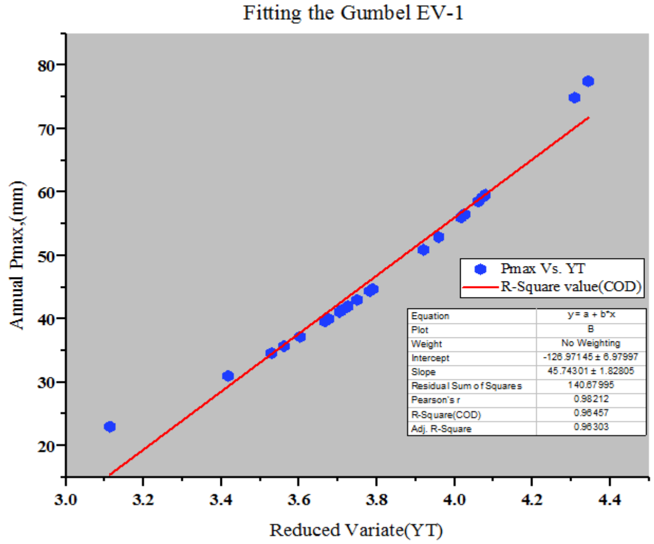
Appendix 1

Table 1: Fitting Gumbel EV-1

Year	Annual Daily Max.	Rank(m)	P=1/T or Rank/n+1	Return Period,(T)	YT=-ln(ln(T/T1))
1992	42.00	14	0.54	1.86	0.257
1993	56.30	7	0.27	3.71	1.159
1994	77.50	1	0.04	26.00	3.239
1995	40.00	18	0.69	1.44	-0.164
1996	50.90	10	0.38	2.60	0.723
1997	44.40	12	0.46	2.17	0.480
1998	43.00	13	0.50	2.00	0.367
1999	52.90	9	0.35	2.89	0.856
2000	59.20	4	0.15	6.50	1.789
2001	35.70	22	0.85	1.18	-0.627
2002	41.20	16	0.62	1.63	0.046
2003	41.10	17	0.65	1.53	-0.059
2004	39.80	19	0.73	1.37	-0.272
2005	44.70	11	0.42	2.36	0.598
2006	74.90	2	0.08	13.00	2.525
2007	59.60	3	0.12	8.67	2.099
2008	23.00	25	0.96	1.04	-1.181
2009	56.00	8	0.31	3.25	1.000
2010	37.20	21	0.81	1.24	-0.500
2011	58.50	5	0.19	5.20	1.544
2012	34.60	23	0.88	1.13	-0.770
2013	31.00	24	0.92	1.08	-0.942
2014	39.60	20	0.77	1.30	-0.383
2015	41.60	15	0.58	1.73	0.151
2016	56.50	6	0.23	4.33	1.338

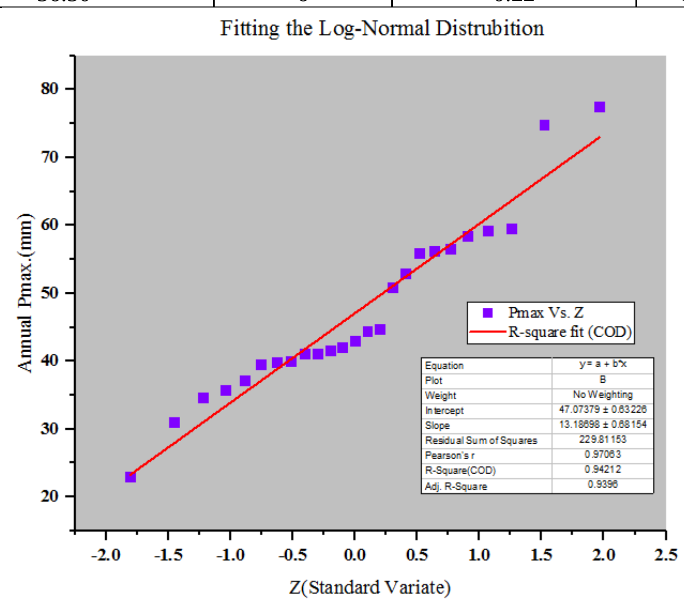
Fitting the Gumbel EV-1



R^2 Fitting Value = 0.964

Table 2: Fitting Log-Normal Distribution

Year	Annual Daily Max.	Rank(m)	P= ((m-3/8)/(n+0.25))	w	z
1992	42.00	14	0.54	1.111	-0.099
1993	56.30	7	0.26	1.636	0.636
1994	77.50	1	0.02	2.720	1.965
1995	40.00	18	0.70	0.848	-0.514
1996	50.90	10	0.38	1.389	0.302
1997	44.40	12	0.46	1.246	0.099
1998	43.00	13	0.50	1.177	0.000
1999	52.90	9	0.34	1.466	0.408
2000	59.20	4	0.14	1.970	1.064
2001	35.70	22	0.86	0.557	-1.041
2002	41.20	16	0.62	0.980	-0.301
2003	41.10	17	0.66	0.914	-0.405
2004	39.80	19	0.74	0.780	-0.629
2005	44.70	11	0.42	1.316	0.199
2006	74.90	2	0.06	2.342	1.519
2007	59.60	3	0.10	2.128	1.259
2008	23.00	25	0.98	0.224	-1.803
2009	56.00	8	0.30	1.548	0.518
2010	37.20	21	0.82	0.636	-0.888
2011	58.50	5	0.18	1.842	0.903
2012	34.60	23	0.90	0.469	-1.221
2013	31.00	24	0.94	0.365	-1.451
2014	39.60	20	0.78	0.710	-0.753
2015	41.60	15	0.58	1.045	-0.199
2016	56.50	6	0.22	1.733	0.763

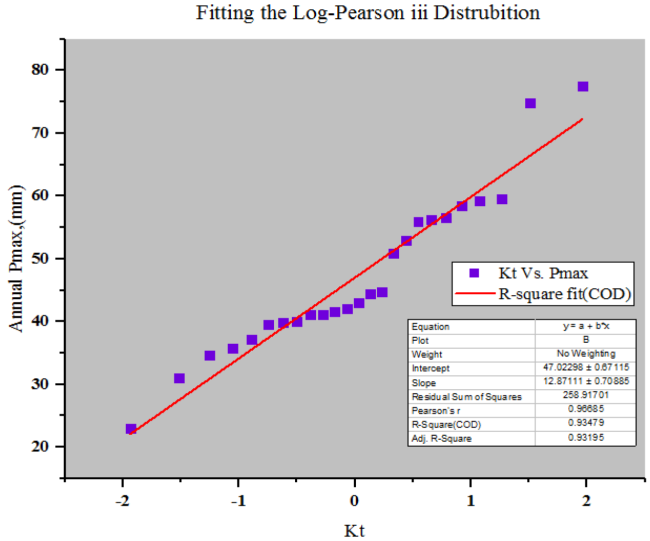


R^2 Fitting Value = 0.942

Table 3: Fitting Log-Pearson type (iii) Distribution

Year	Annual Daily Max.	P=log(Pi)	Rank(m)	P=(m-0.5)/n	W	K	Z	Kt
1992	42	1.62	14	0.54	1.110	-0.029	-0.100	-0.071
1993	56.3	1.75	7	0.26	1.641	-0.029	0.643	0.659
1994	77.5	1.89	1	0.02	2.797	-0.029	2.054	1.959
1995	40	1.60	18	0.7	0.845	-0.029	-0.520	-0.498
1996	50.9	1.71	10	0.38	1.391	-0.029	0.305	0.331
1997	44.4	1.65	12	0.46	1.246	-0.029	0.100	0.129
1998	43	1.63	13	0.5	1.177	-0.029	0.000	0.029
1999	52.9	1.72	9	0.34	1.469	-0.029	0.412	0.435
2000	59.2	1.77	4	0.14	1.983	-0.029	1.080	1.074
2001	35.7	1.55	22	0.86	0.549	-0.029	-1.056	-1.058
2002	41.2	1.61	16	0.62	0.978	-0.029	-0.304	-0.277
2003	41.1	1.61	17	0.66	0.912	-0.029	-0.410	-0.385
2004	39.8	1.60	19	0.74	0.776	-0.029	-0.637	-0.618
2005	44.7	1.65	11	0.42	1.317	-0.029	0.201	0.229
2006	74.9	1.87	2	0.06	2.372	-0.029	1.555	1.512
2007	59.6	1.78	3	0.1	2.146	-0.029	1.282	1.261
2008	23	1.36	25	0.98	0.201	-0.029	-1.866	-1.937
2009	56	1.75	8	0.3	1.552	-0.029	0.524	0.544
2010	37.2	1.57	21	0.82	0.630	-0.029	-0.900	-0.893
2011	58.5	1.77	5	0.18	1.852	-0.029	0.915	0.919
2012	34.6	1.54	23	0.9	0.459	-0.029	-1.241	-1.255
2013	31	1.49	24	0.94	0.352	-0.029	-1.481	-1.514
2014	39.6	1.60	20	0.78	0.705	-0.029	-0.762	-0.749
2015	41.6	1.62	15	0.58	1.044	-0.029	-0.201	-0.173
2016	56.5	1.75	6	0.22	1.740	-0.029	0.772	0.782
Mean (Pav.)	47.248	1.659						
St. Dev (S)	12.862	0.119						
Skew (Cs)	0.660	-0.175						

Fitting the Log-Pearson iii Distrubition



R^2 Fitting Value = 0.934

Appendix 2

Table 4: Tabulated description of the analytical hierarchy process (AHP-MCA*)*

Main criteria	Indicators (sub-Criteria)	Benchmarks	Threshold values/units
Technical and Scientific (Cr-1)	(i). System Performance (**I-1**)	* Hydraulic retention time	Hours
		*efficiency of pollutant removal	%
		*efficiency of detaining runoff	%
	(ii). System flexibility /Adaptability (**I-2**)	* Alarm/intervention procedures	yes/no
		* Safety level/provision for accidental pollution etc.	H/M/L
		* Number of in-basin/Receiving water pollution complaints	Number/yr.
		* in-basin quality condition and health hazards	Trophic state; smell; stagnant water; bacteriology etc.
	(iii). System Reliability (**I-3**)	* Operational lifetime	Years
		* Sedimentation rates and storage volume	m^3/yr.; % reduction in storage volume/yr.
		* system robustness	H/M/L
Main criteria	Indicators(sub-Criteria)	Benchmarks	Threshold values/units
Environmental (Cr-2)	(i).Water volume impact or Flooding (I-4)	* Draw-down times	Hours
		* Downstream erosion	H/M/L
		* Groundwater recharge	m^3/year
		* Downstream flow protection value	H/M/L
	(ii). Water quality impact(Pollution control) (I-5)	* Treatment retention times	Hours/av. storm event
		* Dilution ratios	Ratio
		* Litter/gross solids; floating matter; surface oils	H/M/L
		* Receiving water classification	1…n
		* Groundwater quality	1…n
		* Thermal effects	H/M/L
		* %age compliance with consent/receiving water WQOs and standards	%/year
	(iii) Habitat and ecological diversity (I-6)	* Receiving water hydro biological scores	1….n
		* Number of key species introduced/attracted	1….n
		* Pests/vermin introduced	yes/no
		* Invasive/unwanted species	yes/no
		* Conservation status (plant/insect/invertebrate/mammal)	H/M/L

Main criteria	Indicators(sub-Criteria)	Benchmarks	Threshold values/units
Social and Urban Community Benefits (Cr-3)	(i). Health and safety Risks (I-7)	* Probability of system failure	% probability
		* Consequences of storm event exceeding Design storm RI	Flooding depth (m)
		* local community concerns (injury, infection, drowning etc.)	% user survey
		* Formal technical risk exposure audit (flood risk, health risk, safety risk)	H/M/L
	(ii).Perceived Acceptability and Impacts (I-8)	* local Community willingness-to-pay	H/M/L
		* Acceptance of on-site Treatment as opposed to conventional drainage systems	H/M/L
		* level of inhabitant willingness to participate in on-going site improvement	H/M/L
	(iii).Amenity Aesthetics or Sustainable urban living (I-9)	* Contribution to urban sustainable development policies	H/M/L
		Role in Biological Action Plans (BAPs)	H/m/l
		* Additional benefits offered by different BMPs	yes/no
Main criteria	Indicators(sub-Criteria)	Benchmarks	Threshold values/units
Economic (Cr-4)	(i).Life cycle cost (I-10)	*Design and capital costs	Birr
		* O&M Costs	Birr/year
		* Sediment Disposal costs	Birr/year or life time
		*Community costs including storm fees	Increase/decrease
		*Renewal and replacement costs	Birr/year
	(ii).Long term Affordability (I-11)	*Adoption and financial Viability	H/M/L
		*Long term insurability	H/M/L
		*Economic add-on values(enhanced land/property values)	Birr/ha
		*Amenity income streams	Birr/year
		*Long term Management provision	H/M/L

Appendix 3

Questionnaire used to survey priorities

Dear Participants

I am requesting you to take part in a research entitled "**Sustainable Urban Drainage Options for Mekelle City**". This study through questionnaire is part of an MSc. research at the Addis Ababa University institute of technology, School of Civil and Environmental Engineering, supervised by Dr. Ing. Geremew Sahilu.

The objective of this paper is to model, analyze and point out the problems driving the failures in the present stormwater system in study area (Mekelle city). Evidently, there is a need for stormwater management for the city to adapt to sustainable level by developing more effective implementation and policies to reduce its destructive impacts and complexity. The stormwater management model (EPA SWMM) is chosen to execute the above stated purposes. Consequently, Sustainable urban drainage system (SuDS components) are held as alternatives or actions to undertake the recognized complications and optimize the system performance.

Selection or prioritization of the alternatives portfolio (SuDS components) is analyzed through Analytic Hierarchy Process (AHP) type of multi-criteria decision support system. The AHP introduced by Thomas Saaty (1980) is one of the main mathematical models currently available to support the decision theory. Likewise, an effective tool for dealing with complex decision-making, and may aid the decision maker to set priorities and make the best decision. By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, the AHP helps to capture both subjective and objective aspects of a decision. In addition, the AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the bias in the decision making process.

Through a survey questionnaire, Decisions are based on values and preferences of the decision makers. A set of criteria or specific objectives can be used while prioritizing actions and determining the real meaning of an optimal relationship between them. In addition, a complete example on how AHP works is included in order to assist respondents (experts) on how to apply their compared value towards the pairwise comparison between criteria, sub-criteria, indicators and alternatives (actions) in a matrix form.

Finally, I am so pleased and hopeful requesting you to take some of your time and complete the questionnaire. The information you provide will be of great value for this research, and accordingly, your participation is anticipated and very much appreciated

If you have questions or ideas at any time about the survey or the procedures, you may contact me through the address stated below.

Sincerely: Teamir Abraha

MSc candidate in Water supply and Environmental Engineering department

Email:teamirabraha@gmail.com

Phone: +251932348384

Questionnaire table 1

Main criteria	1). PWC of Main criteria or main objectives (technical, environmental, economic,)																	Main criteria
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Cr-1																		Cr-2
Cr-1																		Cr-3
Cr-1																		Cr-4
Cr-2																		Cr-3
Cr-2																		Cr-4
Cr-3																		Cr-4
Indicators	PWC of Sub-criteria or Indicators with respect to Main-criteria																	Indicators
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Technical Criteria (Cr-1)																		
(I-1)																		(I-2)
(I-1)																		(I-3)
(I-2)																		(I-3)
Indicators	PWC of Sub-criteria or Indicators with respect to Main-criteria																	Indicators
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Environmental Criteria (Cr-2)																		
(I-4)																		(I-5)
(I-4)																		(I-6)
(I-5)																		(I-6)
Indicators	PWC of Sub-criteria or Indicators with respect to Main-criteria																	Indicators
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Social and Urban Community Benefits-(Cr-3)																		
(I-7)																		(I-8)
(I-7)																		(I-9)
(I-8)																		(I-9)
Indicators	PWC of Sub-criteria or Indicators with respect to Main-criteria																	Indicators
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Economic-(Cr-6)																		
(I-10)																		(I-11)

Questionnaire Table 2

Alternatives	PWC of Alternatives with respect to Indicators																	Alternatives
	Technical and scientific (Cr-1)																	
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
System performance (I-1)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5
System flexibility & adaptability (I-2)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5
System reliability (I-3)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5

Questionnaire Table 3:

Alternatives	PWC of Alternatives with respect to Indicators																	Alternatives
	Environmental Criteria-(Cr-2)																	
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Water Volume Impact (I-4)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5
Water Quality Impact (I-5)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5
Ecological Impact (I-6)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5

Questionnaire Table 4:

Alternatives	PWC of Alternatives with respect to Indicators																	Alternatives
	Social & community benefits-(Cr-3)																	
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Health and Safety Risks (I-7)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5
Amenity & Aesthetics (I-8)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5
Acceptability (I-9)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5

Questionnaire Table 5:

Alternatives	PWC of Alternatives with respect to Indicators																	Alternatives
	Economic criteria-(Cr-4)																	
	9	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Life cycle cost (I-10)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5
Long term Affordability (I-11)																		
A1																		A2
A1																		A3
A1																		A4
A1																		A5
A2																		A3
A2																		A4
A2																		A5
A3																		A4
A3																		A5

Appendix 4: Work Process of MCA and priority analyzation

I-1	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1	0.83	0.45	0.63	0.83	0.14	0.13	0.17	0.12	0.10	**0.13**	5.07	0.019	**0.021**
A2	1.2	1.00	0.47	0.67	1.00	0.17	0.15	0.18	0.13	0.12	**0.15**			
A3	2.210	2.14	1.00	2.33	3.50	0.31	0.33	0.38	0.45	0.42	**0.38**			
A4	1.578	1.50	0.43	1.00	2.00	0.22	0.23	0.16	0.19	0.24	**0.21**			
A5	1.2	1.00	0.29	0.50	1.00	0.17	0.15	0.11	0.10	0.12	**0.13**			
Total	7.189	6.476	2.63	5.13	8.33									

I-2	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1	1	2.5	0.833	2	0.24	0.26	0.28	0.21	0.26	**0.25**	5.04	0.009	**0.010**
A2	1	1	2.5	1	2	0.24	0.26	0.28	0.25	0.26	**0.26**			
A3	0.4	0.4	1	0.633	0.833	0.10	0.10	0.11	0.16	0.11	**0.12**			
A4	1.2	1	1.578	1	2	0.29	0.26	0.18	0.25	0.26	**0.25**			
A5	0.5	0.5	1.2	0.5	1	0.12	0.13	0.14	0.13	0.13	**0.13**			
Total	4.1	3.9	8.778	3.966	7.833									

I3	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1.00	0.63	1.00	0.67	1.00	0.16	0.20	0.14	0.15	0.13	**0.16**	5.033	0.008	**0.009**
A2	1.58	1.00	2.50	1.50	2.50	0.26	0.32	0.36	0.35	0.33	**0.32**			
A3	1.00	0.40	1.00	0.67	1.00	0.16	0.13	0.14	0.15	0.13	**0.14**			
A4	1.50	0.67	1.50	1.00	2.00	0.25	0.22	0.21	0.23	0.27	**0.23**			
A5	1.00	0.40	1.00	0.50	1.00	0.16	0.13	0.14	0.12	0.13	**0.14**			
Total	6.0789	3.1	7	4.33	7.5									

1. Technical (cr-1)

2. Environmental (Cr-2)

I-4	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1.00	1.00	1.00	1.67	2.50	0.25	0.25	0.25	0.26	0.23	**0.25**	5.034863636	0.008715	**0.00968**
A2	1.00	1.00	1.00	1.67	2.50	0.25	0.25	0.25	0.26	0.23	**0.25**			
A3	1.00	1.00	1.00	1.67	2.50	0.25	0.25	0.25	0.26	0.23	**0.25**			
A4	0.60	0.60	0.60	1.00	2.50	0.15	0.15	0.15	0.16	0.23	**0.17**			
A5	0.40	0.40	0.40	0.40	1.00	0.10	0.10	0.10	0.06	0.09	**0.09**			
Total	4	4	4	6.4	11									

I-5	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1.00	1.00	1.33	2.50	1.00	0.24	0.22	0.32	0.23	0.20	**0.24**	5.044	0.011	**0.012**
A2	1.00	1.00	0.83	2.50	1.00	0.24	0.22	0.20	0.23	0.20	**0.22**			
A3	0.75	1.20	1.00	3.00	1.50	0.18	0.26	0.24	0.27	0.30	**0.25**			
A4	0.40	0.40	0.33	1.00	0.50	0.10	0.09	0.08	0.09	0.10	**0.09**			
A5	1.00	1.00	0.67	2.00	1.00	0.24	0.22	0.16	0.18	0.20	**0.20**			
Total	4.15	4.6	4.166	11	5									

I-6	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1.00	1.00	2.00	3.00	1.00	0.26	0.26	0.29	0.27	0.24	**0.26**	5.03	0.01	**0.008**
A2	1.00	1.00	2.00	3.00	1.00	0.26	0.26	0.29	0.27	0.24	**0.26**			
A3	0.50	0.50	1.00	2.00	0.67	0.13	0.13	0.14	0.18	0.16	**0.15**			
A4	0.33	0.33	0.50	1.00	0.47	0.09	0.09	0.07	0.09	0.11	**0.09**			
A5	1.00	1.00	1.50	2.14	1.00	0.26	0.26	0.21	0.19	0.24	**0.23**			

Total	3.833	3.833	7	11.142	4.133

3. Social (Cr-3)

I-7	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1	1	1	1	1	0.2	0.2	0.2	0.2	0.2	**0.2**	5	0	**0**
A2	1	1	1	1	1	0.2	0.2	0.2	0.2	0.2	**0.2**			
A3	1	1	1	1	1	0.2	0.2	0.2	0.2	0.2	**0.2**			
A4	1	1	1	1	1	0.2	0.2	0.2	0.2	0.2	**0.2**			
A5	1	1	1	1	1	0.2	0.2	0.2	0.2	0.2	**0.2**			
Total	5	5	5	5	5									

I-8	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1.00	1.00	3.50	5.00	2.50	0.35	0.35	0.35	0.30	0.36	**0.34**	5.061726619	0.0154317	**0.017146**
A2	1.00	1.00	3.50	5.00	2.50	0.35	0.35	0.35	0.30	0.36	**0.34**			
A3	0.29	0.29	1.00	2.50	0.67	0.10	0.10	0.10	0.15	0.10	**0.11**			
A4	0.20	0.20	0.40	1.00	0.30	0.07	0.07	0.04	0.06	0.04	**0.06**			
A5	0.40	0.40	1.50	3.33	1.00	0.14	0.14	0.15	0.20	0.14	**0.15**			
Total	2.885	2.885	9.9	16.833	6.966									

I-9	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1.00	1.00	1.00	1.00	1.50	0.21	0.21	0.18	0.21	0.27	**0.22**	5.037751222	0.0094378	**0.010486**
A2	1.00	1.00	1.50	1.00	1.00	0.21	0.21	0.26	0.21	0.18	**0.22**			
A3	1.00	0.67	1.00	0.83	1.00	0.21	0.14	0.18	0.17	0.18	**0.18**			
A4	1.00	1.00	1.20	1.00	1.00	0.21	0.21	0.21	0.21	0.18	**0.21**			
A5	0.67	1.00	1.00	1.00	1.00	0.14	0.21	0.18	0.21	0.18	**0.18**			
Total	4.666	4.666	5.7	4.833	5.5									

4. Economical (Cr-4)

I-10	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1.00	0.83	0.83	2.50	0.83	0.2	0.2	0.2	0.2	0.2	**0.2**	5	0	**0**
A2	1.20	1.00	1.00	3.00	1.00	0.24	0.24	0.24	0.24	0.24	**0.24**			
A3	1.20	1.00	1.00	3.00	1.00	0.24	0.24	0.24	0.24	0.24	**0.24**			
A4	0.40	0.33	0.33	1.00	0.33	0.08	0.08	0.08	0.08	0.08	**0.08**			
A5	1.20	1.00	1.00	3.00	1.00	0.24	0.24	0.24	0.24	0.24	**0.24**			
Total	5	4.167	4.167	12.5	4.167									

I-11	A1	A2	A3	A4	A5	Normalization					priority vector	λmax(maximum eigenvalue)	CI	CR
A1	1.00	0.63	0.83	0.30	0.83	0.1	0.1	0.1	0.1	0.1	**0.120**	5.021	0.005	**0.0058**
A2	1.58	1.00	1.50	0.67	2.00	0.2	0.2	0.2	0.3	0.3	**0.227**			
A3	1.20	0.67	1.00	0.33	1.00	0.1	0.2	0.1	0.1	0.1	**0.138**			
A4	3.33	1.50	3.00	1.00	3.00	0.4	0.3	0.4	0.4	0.4	**0.384**			
A5	1.20	0.50	1.00	0.33	1.00	0.1	0.1	0.1	0.1	0.1	**0.130**			
Total	8.312	4.3	7.33	2.633	7.833									

Table 7: Overall weightage of Alternatives

Main criteria	Weight	Indicator	Weight	BC	RG	IT	PP	VS
				Alternative				
				A-1	A-2	A-3	A-4	A-5
Cr-1	0.23	I1	0.660	0.133	0.150	0.379	0.210	0.129
		I2	0.198	0.250	0.259	0.116	0.247	0.128
		I3	0.141	0.160	0.324	0.145	0.235	0.137
Cr-2	0.16	I4	0.501	0.248	0.248	0.248	0.167	0.091
		I5	0.375	0.241	0.217	0.251	0.091	0.200
		I6	0.124	0.264	0.264	0.149	0.090	0.234
Cr-3	0.07	I7	0.584	0.200	0.200	0.200	0.200	0.200
		I8	0.308	0.340	0.340	0.109	0.056	0.154
		I9	0.108	0.217	0.216	0.177	0.206	0.184
Cr-4	0.54	I10	0.750	0.200	0.240	0.240	0.080	0.240
		I11	0.250	0.120	0.227	0.138	0.384	0.130
Total Weight				0.191	0.490	0.233	0.166	0.182

Appendix 5

Table 8: Sub-catchment Runoff Summary report before LID implementation

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff CMS
S3	1205.50	0.00	0.00	348.81	856.01	219.36	0.15
S4	1205.50	0.00	0.00	396.93	807.94	365.84	0.27
S5	1205.50	0.00	0.00	535.22	669.79	100.64	0.09
S6	1205.50	0.00	0.00	315.73	889.08	63.93	0.04
S7	1205.50	0.00	0.00	372.75	832.11	159.37	0.12
S9	1205.50	0.00	0.00	514.81	690.18	118.33	0.10
S10	1205.50	0.00	0.00	603.92	601.14	94.75	0.09
S11	1205.50	0.00	0.00	441.92	763.00	86.51	0.07
S20	1205.50	3866.16	0.00	526.93	4544.03	515.16	0.40
S22	1205.50	0.00	0.00	722.43	482.75	109.02	0.12
S23	1205.50	0.00	0.00	744.42	460.77	149.50	0.16
S24	1205.50	0.00	0.00	603.16	601.86	22.74	0.01
S25	1205.50	0.00	0.00	380.92	823.94	139.74	0.10
S26	1205.50	0.00	0.00	322.48	882.32	254.55	0.17
S27	1205.50	0.00	0.00	246.10	958.64	139.61	0.09
S28	1205.50	0.00	0.00	180.93	1023.77	37.75	0.02
S29	1205.50	0.00	0.00	202.86	1001.87	16.62	0.01
S30	1205.50	0.00	0.00	335.06	869.76	233.61	0.16
S31	1205.50	0.00	0.00	395.21	809.67	235.09	0.17
S38	1205.50	0.00	0.00	432.58	772.33	333.16	0.25
S40	1205.50	0.00	0.00	376.10	828.75	330.76	0.24
S41	1205.50	0.00	0.00	347.58	857.25	184.10	0.13
S42	1205.50	0.00	0.00	440.71	764.21	73.96	0.06
S44	1205.50	0.00	0.00	430.87	774.04	79.19	0.06
S46	1205.50	0.00	0.00	191.92	1012.76	327.65	0.20
S47	1205.50	0.00	0.00	350.07	854.76	150.47	0.11
S48	1205.50	0.00	0.00	388.52	816.34	240.02	0.18
S49	1205.50	0.00	0.00	398.48	806.40	156.83	0.12
S50	1205.50	0.00	0.00	274.09	930.67	264.20	0.18
S79	1205.50	0.00	0.00	363.03	841.82	217.25	0.16
S84	1205.50	0.00	0.00	514.40	690.58	269.23	0.22
S85	1205.50	0.00	0.00	521.92	683.08	229.16	0.19
S86	1205.50	0.00	0.00	306.89	897.91	170.48	0.12
S87	1205.50	0.00	0.00	329.00	875.82	167.89	0.12
S51	1205.50	1779.02	0.00	705.49	2278.48	1026.94	0.85
S13	1205.50	2261.32	0.00	509.71	2956.43	662.22	0.59
S21	1205.50	0.00	0.00	222.97	981.75	189.12	0.12
S39	1205.50	0.00	0.00	357.89	846.94	315.08	0.22
S18	1205.50	0.00	0.00	458.51	746.43	124.53	0.10
S16	1205.50	0.00	0.00	273.95	930.85	25.74	0.02
S19	1205.50	69.98	0.00	502.63	772.31	284.04	0.23
S78	1205.50	0.00	0.00	459.00	745.94	237.20	0.19
S14	1205.50	0.00	0.00	743.88	461.31	160.74	0.16
S15	1205.50	0.00	0.00	583.02	622.02	164.55	0.15

S81	1205.50	10246.96	0.00	1359.77	10238.67	4076.65	3.34
S83	1205.50	0.00	0.00	439.71	765.22	105.09	0.08
S82	1205.50	153384.35	0.00	1431.33	153157.60	2070.70	1.60
S80	1205.50	59244.49	0.00	1267.46	59561.01	4079.95	3.16
S45	1205.50	0.00	0.00	467.20	737.74	250.24	0.20
S43	1205.50	113499.00	0.00	1432.01	113272.30	1774.99	1.44

Table 11: Sub-catchment Runoff Summary Report After LID implementation on S_{80}&S_{81}

S81(SuDS)	1205.50	7220.61	0.00	201.39	8247.29	4190.97	2.09
S80(SuDS)	1205.50	19466.79	0.00	3125.04	17598.21	3669.25	2.49

Appendix 6: *System Identity*

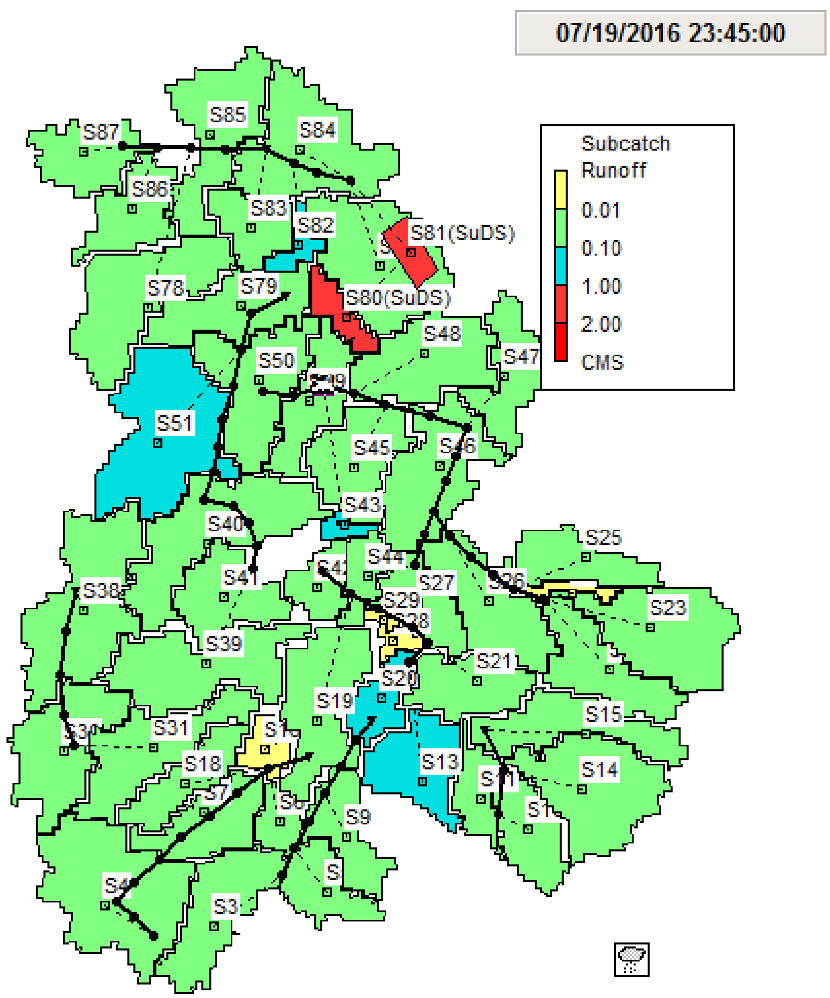


Figure 1: Subcatchment ID

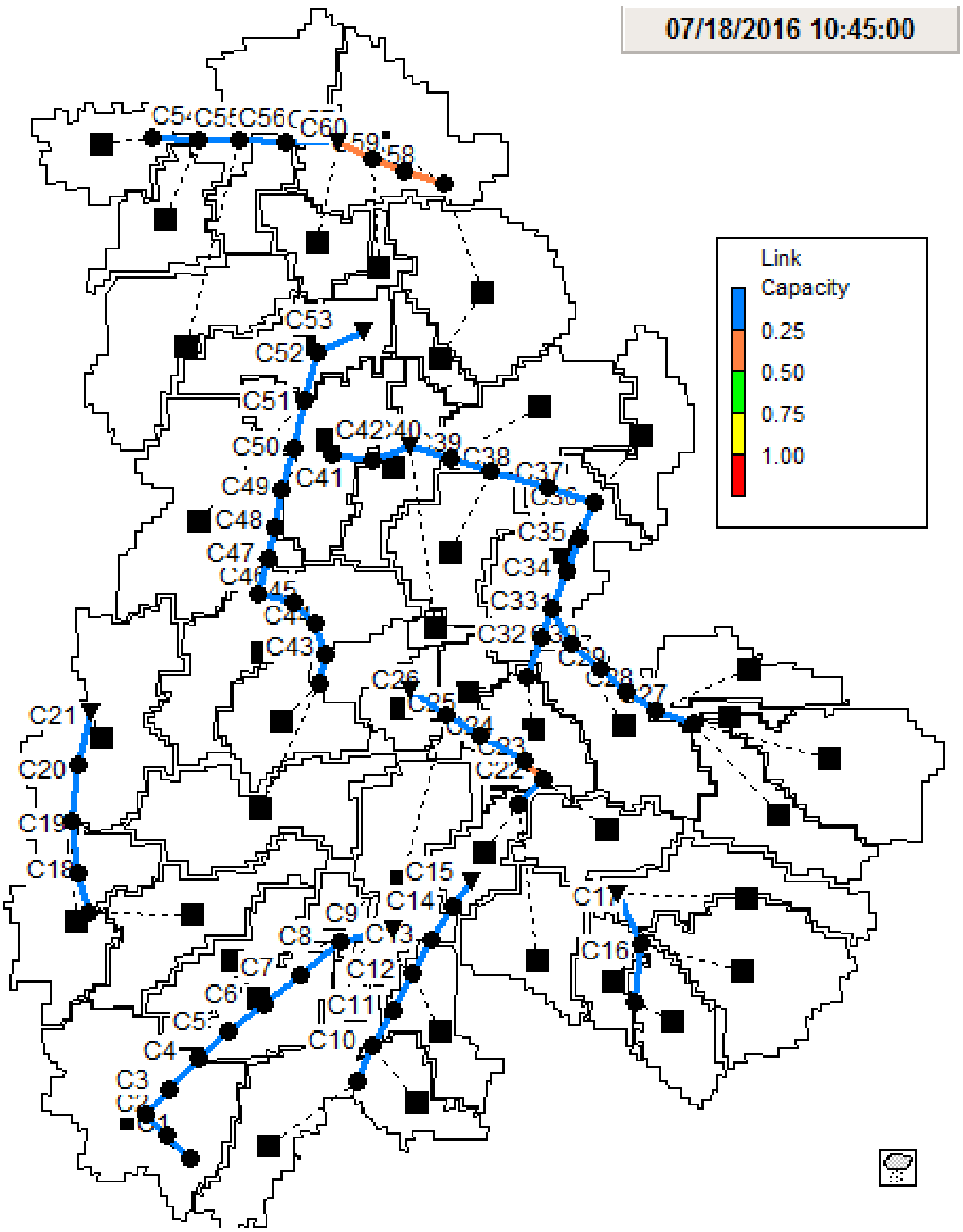


Figure 2: Links (Conduit) ID

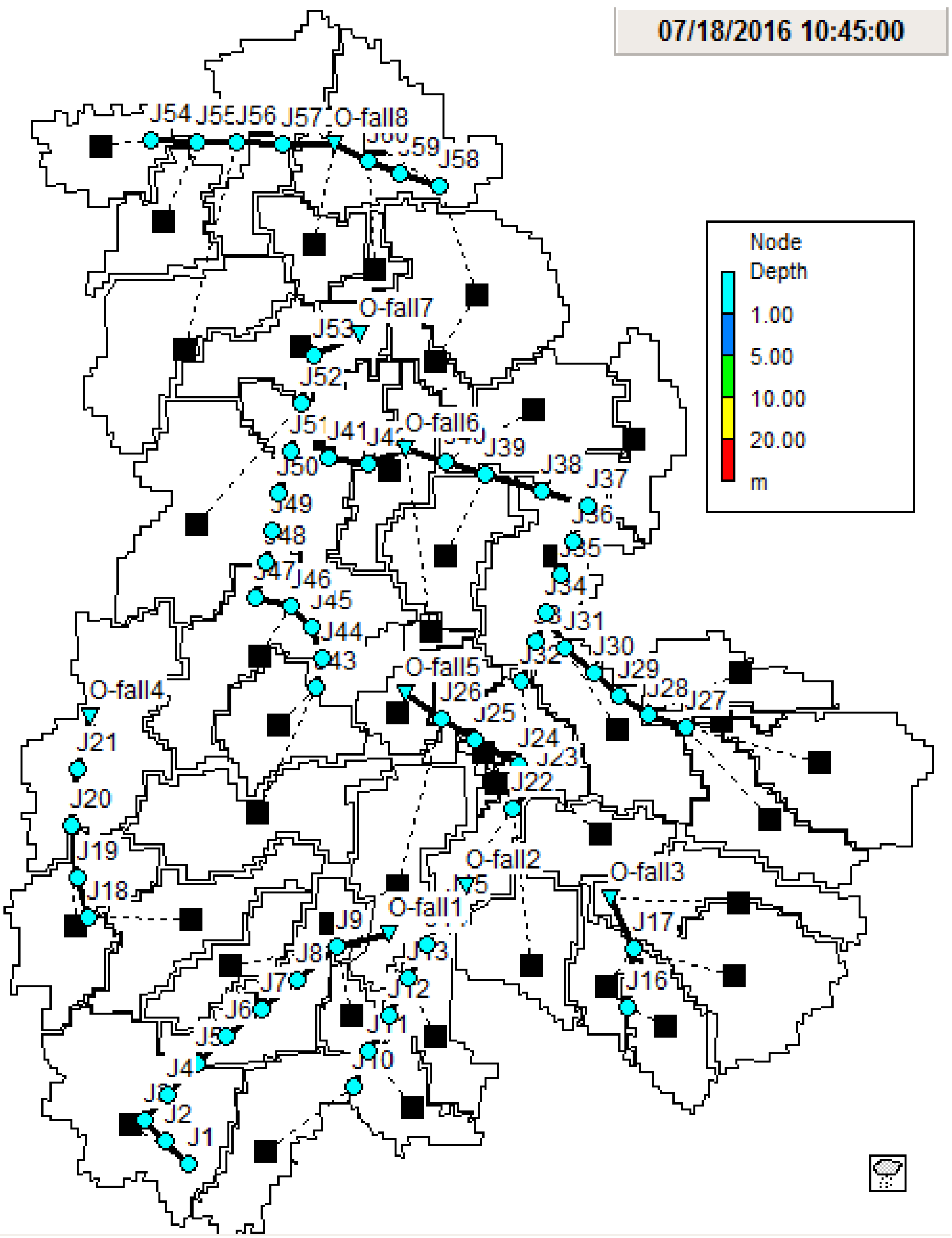


Figure 3: Node (Manhole) ID