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ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Risk Assessment of the Impact of Landfill on Surface Water Resources - a Case Study of the New Sendafa Landfill

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The undersigned have examined the thesis entitled '**Risk Assessment of the Impact of Landfill on Surface Water Resources - a Case Study of the New Sendafa Landfill'** presented by **Hanna Getachew** a candidate for the degree of **Masters of Science** and hereby certify that it is worthy of acceptance.

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I certify that research work titled "Risk Assessment of the Impact of Landfill on Surface Water Resources - a Case Study of the New Sendafa Landfill" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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ABSTRACT

River catchments in the vicinity of landfill site are highly vulnerable to leachate contamination and are exposed to increased risk due to storms and flooding driven by special weather conditions. The objective of this research, thus, was to better understand how the new Sendafa Landfill which is located in the Akaki River catchment might interact with extreme storm events and to investigate associated future risks. The study evaluated potential release of liquid contaminants from the Landfill and examined a broad spectrum of potential conditions that may contribute to these releases. The first step was to investigate how surface water runoff from a storm event at the Landfill contributes to the risk of contaminant release from waste sites based on the source - pathway - receptor approach. Water balance model was used to quantify leachate flow that would be released into the water resource system. Analyses were performed to evaluate the exposure of Akaki catchment to contaminant. Finally, possible mitigation measures were proposed.

The result from the risk assessment confirmed that the risk associated with accidental release of leachate from the landfill would lead to contamination of surface water bodies in the vicinity. It was estimated that under 10 year, 100 year and 200 year return period 6 hours duration rainfall, maximum leachate volume of 2160.6 m^3\day, 3039 m^3\day and 3297.2 m^3\day will be generated from the landfill respectively, out of which leachate flow of 824.6 m^3/day, 1703 m^3/day and 1961.2 m^3/day will be above the capacity of the leachate collection system for the respective storm events. This could potentially cause transport of waste solution that may result in a severe pollution risk.

Therefore it is recommended that further studies on the determination of risks and its future implications based on a wide range of climatic, environmental and socio-economic scenarios would give a broader picture of the issues involved and to be able to address them for a better future environment.

Key words: Landfill, surface water resources, risk analysis, extreme storm events, leachate, Water Balance Method

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LIST OF ACRONYMS AND ABBREVIATIONS

AACAHB	Addis Ababa City Administration Health Bureau
AACG-EFC	Addis Ababa City Government - Ethio-French Cooperation
AACSBPDA	Addis Ababa City Sanitation, Beautification and Park Development Agency
Arc GIS	Arc Geographic Information System (Software package)
DEM	Digital Elevation Models
DFID	Department for International Development
DTM	Digital Terrain Model
DWAF	Department of Water Affairs and Forestry
EA	Environmental Agency
EEA	European Environment Agency
EHP	Environment and Heritage Protection
GSE	Geological Survey of Ethiopia
HDPE	High Density Poly Ethylene
LCRS	Leachate Collection and Removal System
m.a.s.l	Meters above sea level
MSW	Municipal Solid Waste
MUDCUP	Ministry of Urban Development and Construction Urban Planning
NMA	National Meteorological Agency
S.D.	Standard Deviation
SS	Suspended Solids
TDS	Total dissolved solids
TIFF	Tag Image File Format
TIN	Triangulated Irregular Network
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UN-HABITAT	United Nations Human Settlements Programme
USACE	United States Army Corps of Engineers
US EPA	United States Environmental Protection Agency
UTM	Universal Transverse Mercator
WHO	World Health Organization

GLOSSARY OF TERMS

Catchment: the total watershed draining into a river, creek, reservoir or other body of water. The limits of a given catchment are the heights of land (such as hills or mountains) separating it from neighboring catchments. Catchments can be made up of smaller sub-catchments. (EHP, 1994)

Closure: the construction of a final cover for a landfill including replacement of topsoil and subsoil as required for the intended future use of the landfill site; (DWAF, 1998)

Hazardous waste: any unwanted material that is believed to be deleterious to human safety or health or the environment; (Federal Negarit Gazeta, 2002)

Landfill: waste disposal facility used for the deposit of waste on to or into land. (EPA, Ireland, 2000)

Leachate: any liquid percolating through the deposited waste and emitted from or contained within a landfill. (EPA, Ireland, 2000)

Municipal Solid Waste: solid waste resulting from or incidental to municipal, community, commercial, institutional and recreational activities, and includes garbage, rubbish, ashes, street cleanings, abandoned automobiles, and all other solid wastes except hazardous waste, industrial solid waste, oilfield waste and biomedical wastes; (UNEP, 2003)

Non-hazardous waste: waste that is considered to be not harmful. (US EPA, 1996)

Pathway: the route by which contaminants are transported between the source of landfill leachate and water receptor. (EA, 2002)

Post-closure: the period of time after completion of the final landfill closure; (UNEP, 2003)

Receptor: a groundwater or surface water resource, amenity or abstraction point. (EA, 2002)

Return period: Statistical measurement denoting the average recurrence interval over extended period of time.

Risk: a quantitative or qualitative combination of the probability of a defined hazard causing an adverse consequence at a receptor, and the magnitude of that consequence. (EA, 2002)

Risk assessment: the process of identifying and quantifying a risk, and assessing the significance of that risk in relation to other risks. (EA, 2002)

Run-off: any rainwater or melt water that drains as surface flow from the active landfill area, including leachate. (UNEP, 2003)

Scavenger: a person who searches through refuse for useful items.

Surface water: any accumulation of water on the ground surface, which includes ponds, lakes, wetlands, drains, ditches, springs, seepages, streams and rivers. (EA, 2002)

Waste: an undesirable or superfluous by-product, emission, or reside of any process or activity which has been discarded, accumulated or stored for the purpose of discarding or processing. It may be gaseous, liquid or solid or any combination thereof and may originate from a residential, commercial or industrial area. (DWAF, 1998)

1 CHAPTER ONE

1.1 INTRODUCTION

1.1.1 Background

River catchments in the vicinity of landfill site are highly vulnerable to leachate contamination. Linked to this, consequences associated with extreme natural events have the potential to be relatively large. The largest offsite risks will probably be associated with a single storm event that exposes liquid wastes to direct transport into surface water. Therefore, extreme rainfall together with topographic condition of the area could be a determining factor in accidental release of contaminants from the landfill to surface water. Uncertainty in the risk will be dominated by uncertainty in the frequency of flooding events and uncertainty in the amount of waste material exposed to surface water transport.

Globally, several studies investigating the flooding of landfill sites conclude that releases of hazardous substances during flood events are generally a major environmental concern (U.S. Environmental Protection Agency, 1997; Prat et al., 1999; Lin et al., 2007). Municipal solid waste (MSW) landfills and their emissions have been investigated by numerous studies during the last decades. Most of these studies focused on leachate (Laner et al., 2008). The impact of discharging leachate to the waterways is the degradation of river water quality and consequently affecting the habitats of the aquatic organisms (Chew et al., 2005). Based on these reports, it was concluded that landfill emissions will stay above an environmentally compatible level for several hundreds of years (Belevi and Baccini, 1989; Stegmann and Heyer, 1995; Ehrig and Krümpelbeck, 2001). Consequently, MSW landfills contain a large pollution potential over a long period of time (Laner et al., 2008).

Leachate is generated primarily from precipitation and thus is principally influenced by climatic conditions such as rainfall and evaporation (UNEP, 2003). Regional projections of climate models indicate a substantial rise in mean temperatures in Ethiopia over the 21st century and an increase in rainfall variability, with a rising frequency of both extreme flooding and droughts due to global warming (Sherman et al., 2013). The variation of short-term rainfall may lead to runoff more than infiltration. Thus, the presence of landfill site in vulnerable river catchment areas can give rise to added challenges to deal with due to the possible contamination risks and water catchments within the new Sendafa Landfill can happen to be a spot to experience this challenge.

1.1.2 Description of the Study Area

The new sanitary landfill site is located on the territory of the city of Sendafa, more precisely at Chebi Weregenu, (Artelia & MCE, 2013) 25km away from Addis Ababa city center and about 5km south-west of Lagedadi dam (ZTS-EDCE & MTS, 2014), in Oromya special zones named Legetafo.

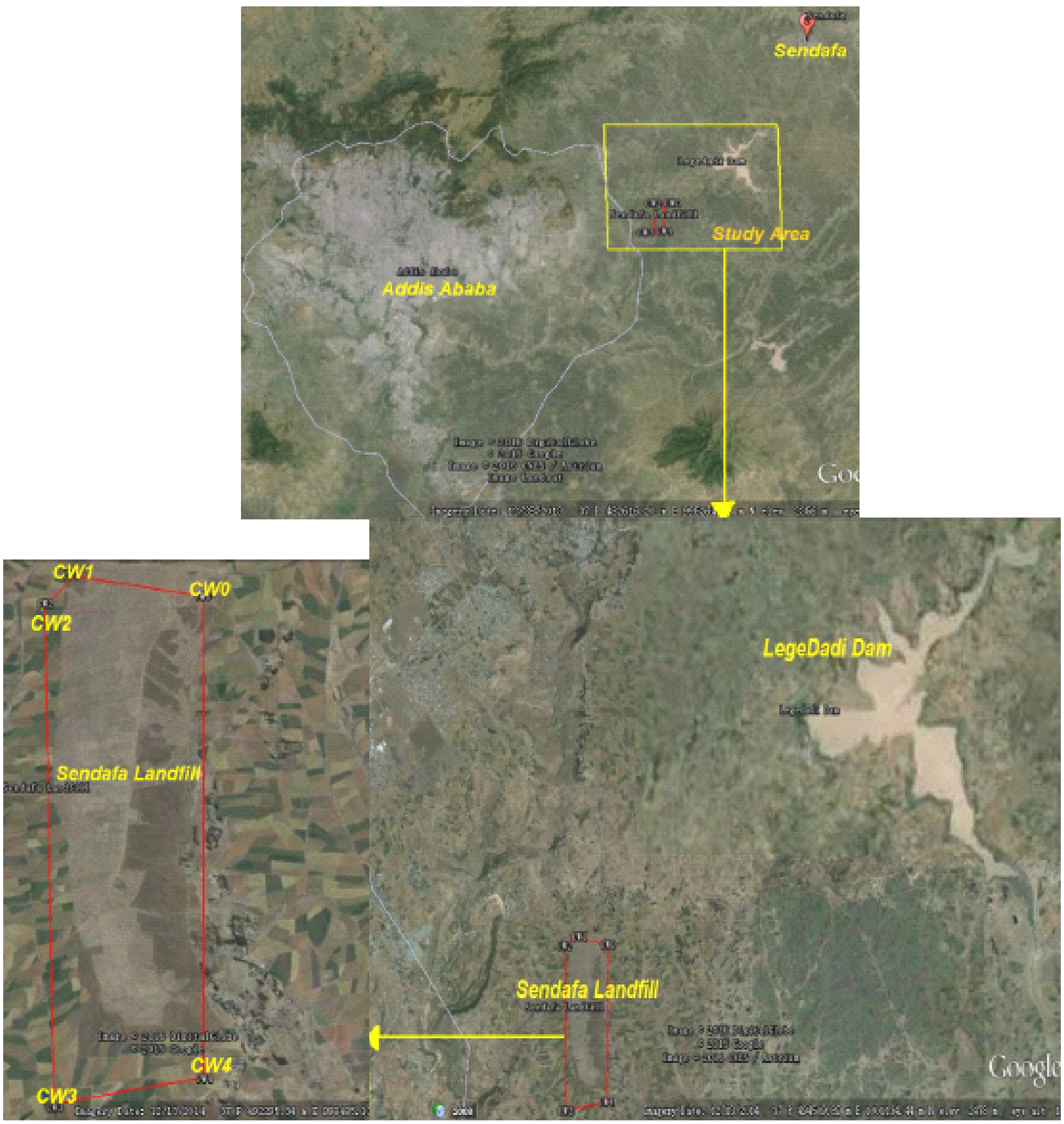


Figure 1: Study Area - Sendafa- Sendafa Landfill- Legedadi Dam (Google Earth, 2016)

The geographical location of the landfill site is between latitude 9° 01' 22.19" N - 9° 02' 27.52" N and longitude of 38° 55' 22.12" E–38° 55' 50.70" E (Kala et al., 2013).

Table 1: Mercator Coordinates of few corner points at Sendafa Landfill Site (Source: Artelia & MCE, 2013)

Corner Point	Northern (m)	Eastern (m)
CW0	999501	492458
CW1	999595	491843
CW2	999470	491727
CW3	997392	491785
CW4	997507	492460

The location of the new landfill is in suburb area with land cover including: bare land, cultivated land, plantation forest, settlement, water body (Legedadi Dam), open grassland, woodlot and bush shrub land.

Figure 2: The New Sendafa Landfill (Photo by the Author, January 10, 2015)

Solid, non-hazardous waste (residential waste; industrial, commercial and institutional waste; and construction and demolition waste) and hazardous waste generated in Addis Ababa and the surrounding service area will be disposed in the new Sendafa sanitary landfill. The waste mass accumulated in Sendafa over the next 20 years would be approximately 8,200, 000 tones, and until 2034, the volume is around 9, 500,000 m^3 (including hazardous and non-hazardous waste) (AACG - EFC, 2013).

The new site for a landfill of 120 hectare, for an estimated exploitation of 20 to 30 years (Agence Francaise de Develppement, 2013). Sendafa Sanitary Landfill is under construction since the 31st of December 2014 (Artelia, 2015). The site is being managed by Addis Ababa Cleansing Management Agency (AACMA).

1.1.2.1 Physiography

The study area is part of the western plateau margin of Ethiopia and has an altitude ranging 2250m - 2550m above sea level (GSE, 2007).

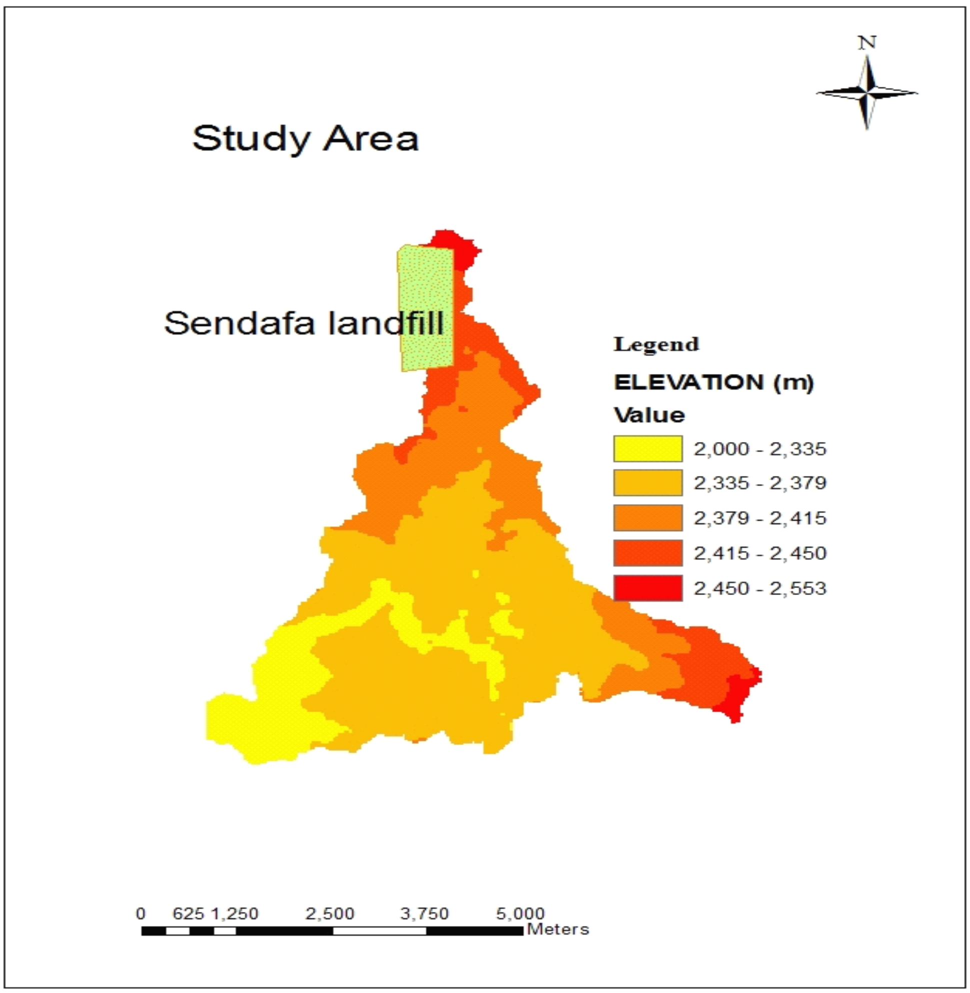


Figure 3 Digital Elevation Model (DEM) of Study Area

1.1.2.2 Climate

The area is largely characterized by a wet climate in which the rainy season prevails from June to

September. The largest part of the area is represented by "Weina Dega" climate zone with mean annual temperature of 20°c and seasonal rainfall from June to September (GSE, 2007). The mean annual rainfall from 1964 to 2013 at the Addis Ababa Bole and Sendafa stations are 1068mm and 1171mm.

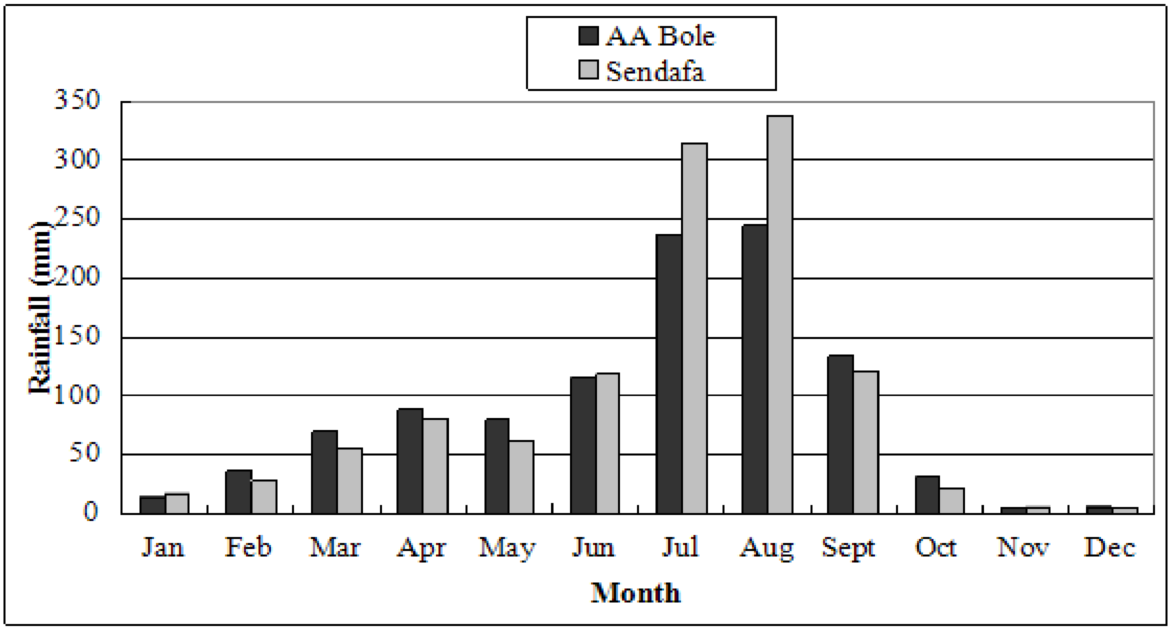


Figure 4: Seasonal Rainfall in the Study Area

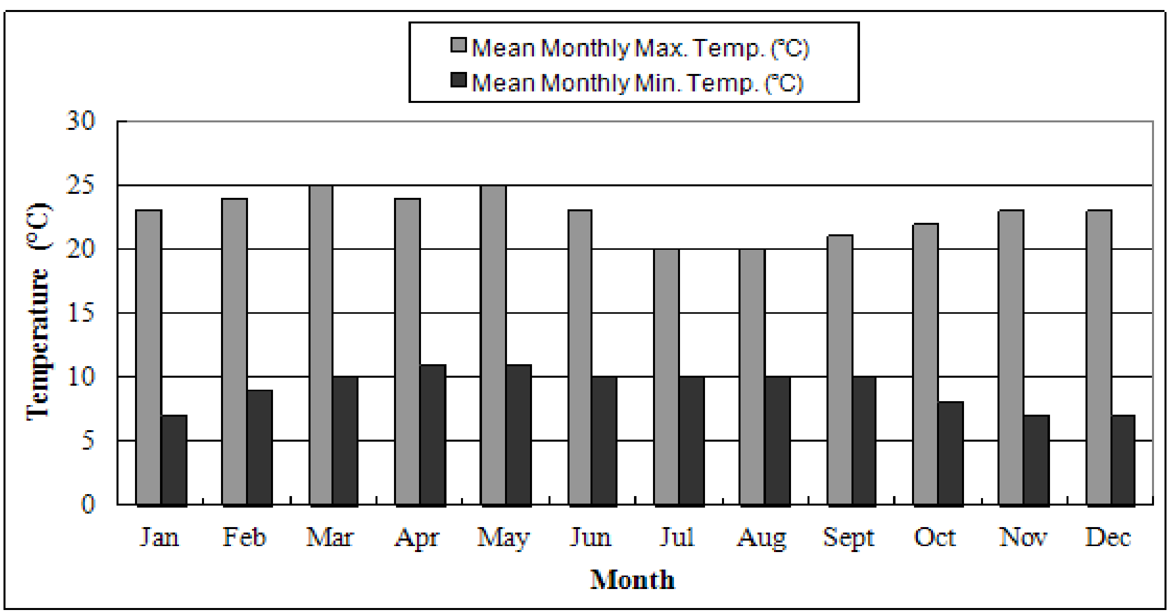


Figure 5: Mean Monthly Temperature

1.1.2.3 Land - Use

The landfill site is known for its teff production. Teff is a dominant cereal crop which occupies about 45% of cultivated land and followed by wheat 43%, chickpea 5% and others occupy 7% (Kala et al., 2013).

Figure 6: Land use at Sendafa Landfill (Photo by the Author, January 10, 2015)

1.1.2.4 Soil

According to the Geological Survey of Ethiopia feasibility study, soils in Sendafa Landfill site are classified as residual according to their genesis. Residual soil is an in-situ developed soil from the underlying parent rock by mechanical and chemical composition (GSE, 2010). Beneath the residual soil, there is Ignimbrite rock which is slightly weathered. The Ignimbrite has medium mass strength (GSE, 2010).

1.1.2.5 Geology

Geology of the area is dominated by tertiary upper basalt sediment. This basalt is grayish, black or light to dark gray. It shows alternating layers of either porphyritic basalt or aphanitic basalt (Geological Map of the Addis Ababa Area, 2011).

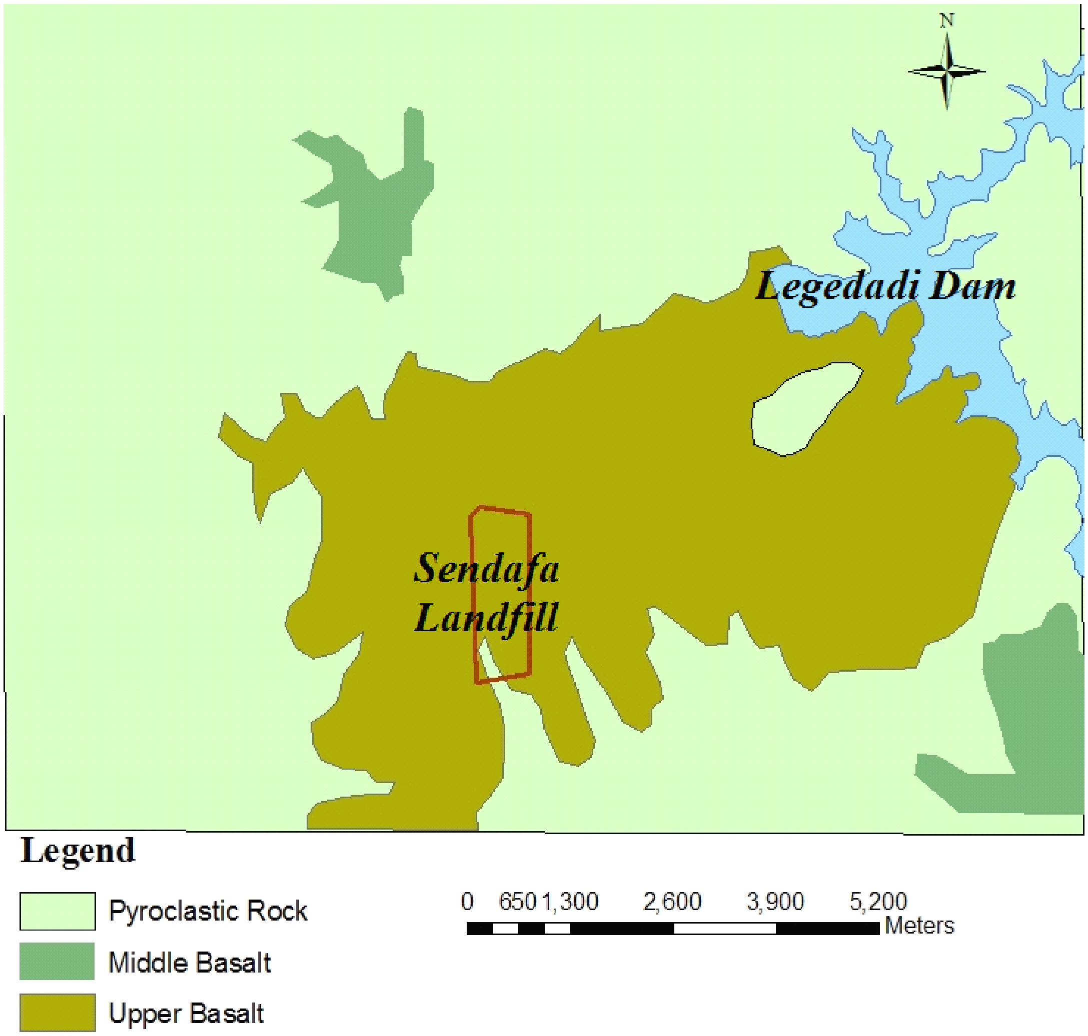


Figure 7: Geology of the Study Area (Source: Geological Map of the Addis Ababa Area, 2011)

1.1.2.6 Hydrogeology

From the hydro-geological point of view, the proposed site and its surroundings are not promising for water well development and the lithologies are low to moderately permeable. The soil permeability of the landfill site is 0.007 cm/sec (Addis clean project phase III, 2011). Due to the deep groundwater table the probability of interaction of waste disposal with groundwater is relatively less, which suggests less chance of groundwater pollution (GSE, 2012).

1.1.2.7 Hydrology

The site area lies in the upper part of the Awash River drainage basin. It is drained from almost north to south by rivers such as Lege Tafo and Lege Dadi and their tributaries Lege Beri and Secoru into Akaki River and finally into Awash river outside the site area.

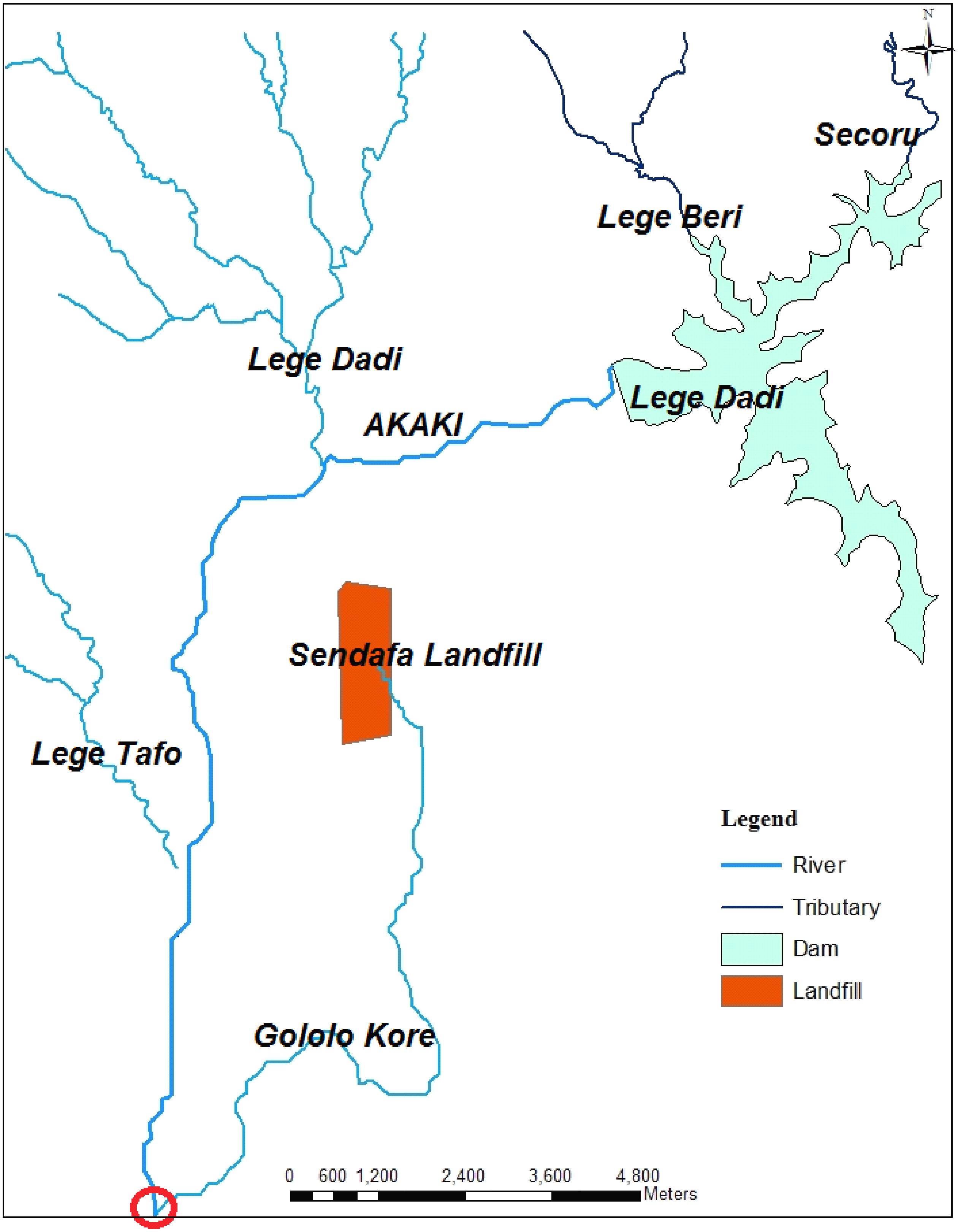


Figure 8: Existing Surface Water Bodies in the Study Area

Gololo Kore, a stream that flows seasonally, originates from the landfill and feeds into Akaki River.

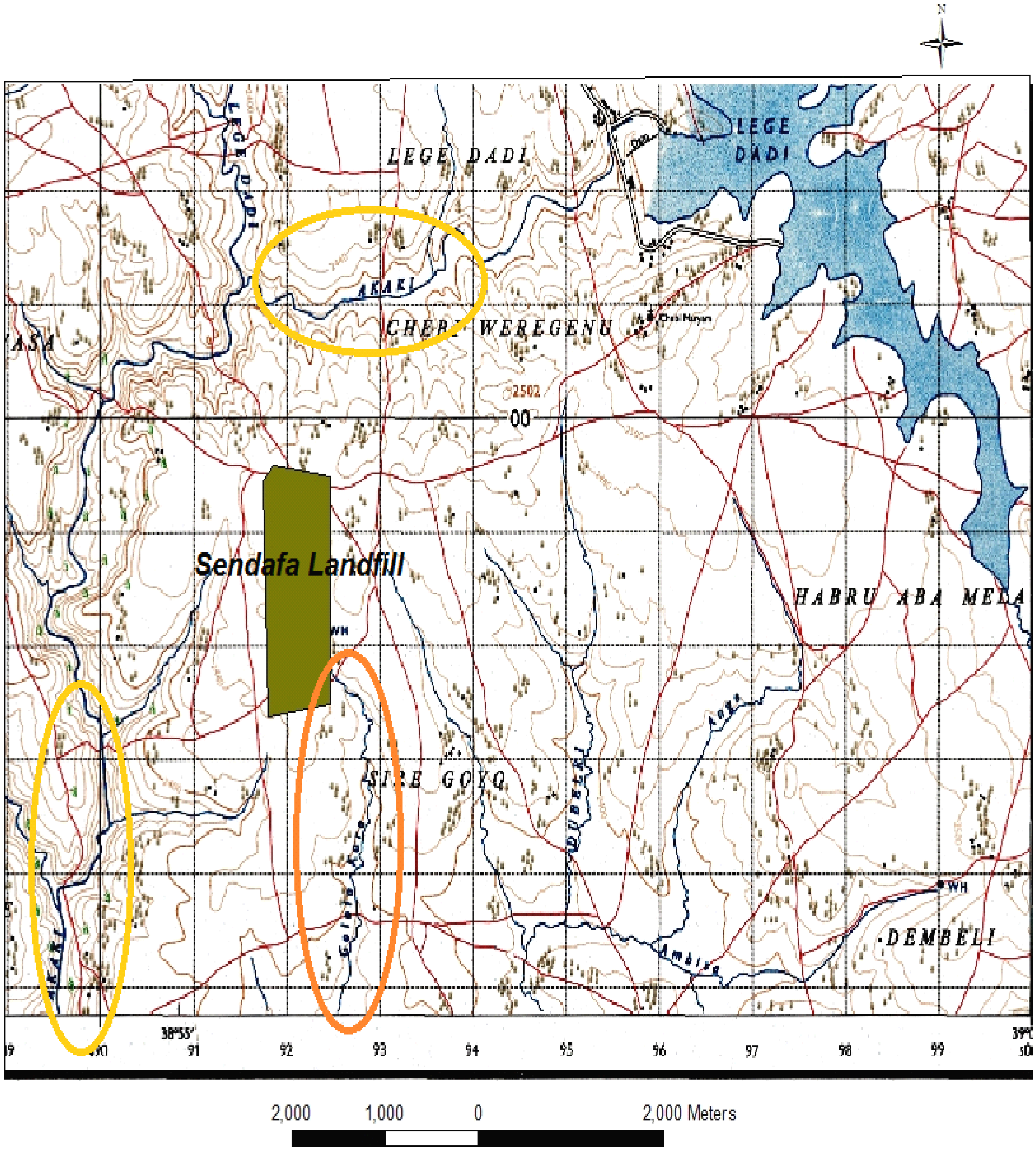


Figure 9: Akaki River- Gololo Kore -Legedadi Dam (Source: Ethiopian Mapping Agency, 1982)

Great Akaki (Tiliku Akaki) River is one of the two major rivers flowing through the city of Addis.

This river, which is tributary of Awash River, originates from Entoto Mountains that are located north to Addis Ababa and flow to Aba Samuel Lake (Gebre & Van, 2009).

Figure 10: Surface water near Sendafa Landfill (Photo by the Author, January 10, 2015)

1.1.3 Details of Landfill Design

The Sendafa Landfill site consists of storm water drainage systems, leachate collection systems, leachate treatment plant and landfill gas management system (ZTS-EDCE & MTS, 2014).

1.1.3.1 Site Layout

The area used for the construction of the landfill cells and leachate treatment plant is about 82 hectares (ZTS-EDCE & MTS, 2014). The landfill is composed from four cells and one for dangerous waste (cell 5). Cell 1 has an area of 240,000 m^2, cell 2 has an area of 123,000 m^2, cell 3 has an area of 85,000 m^2 and cell 4 has an area of 198,000 m^2 (Artelia & MCE, 2013).

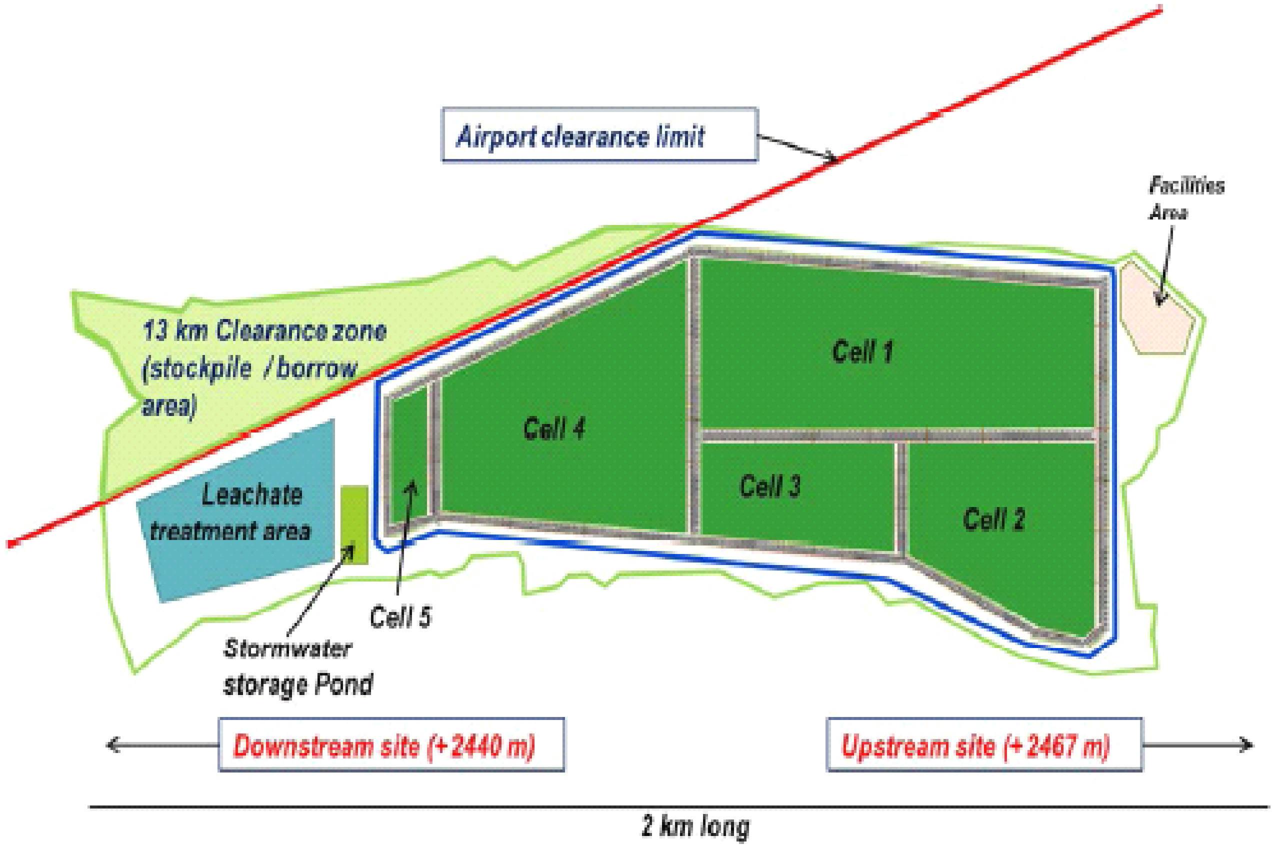


Figure 11: Design layout of the New Sendafa Landfill (Source: Artelia & MCE, 2013)

1.1.3.2 Nature and Quantities of Waste

The type of waste expected to be disposed in the new Sendafa sanitary landfill will be composed of hazardous and non hazardous waste that will be generated from the residential, industrial, institutional and commercial sources as well as from service areas of Addis Ababa City, Legetafo, Sendafa, Sebeta, Gelan and Burayu towns. However the new Sanitary landfill will not accept medical wastes for disposal in the cells. The new sanitary landfill is expected to handle about 8,200,000 tons in five cells over the next 20 years (ZTS-EDCE & MTS, 2014).

1.1.3.3 Phasing

The landfill is developed in a series of phases to allow progressive use of the landfill area so that construction, operation (filling) and restoration can occur simultaneously in different parts of the site. During the operational phases of the sanitary landfill, final cover will be applied progressively to portions of the landfill area that are completed.

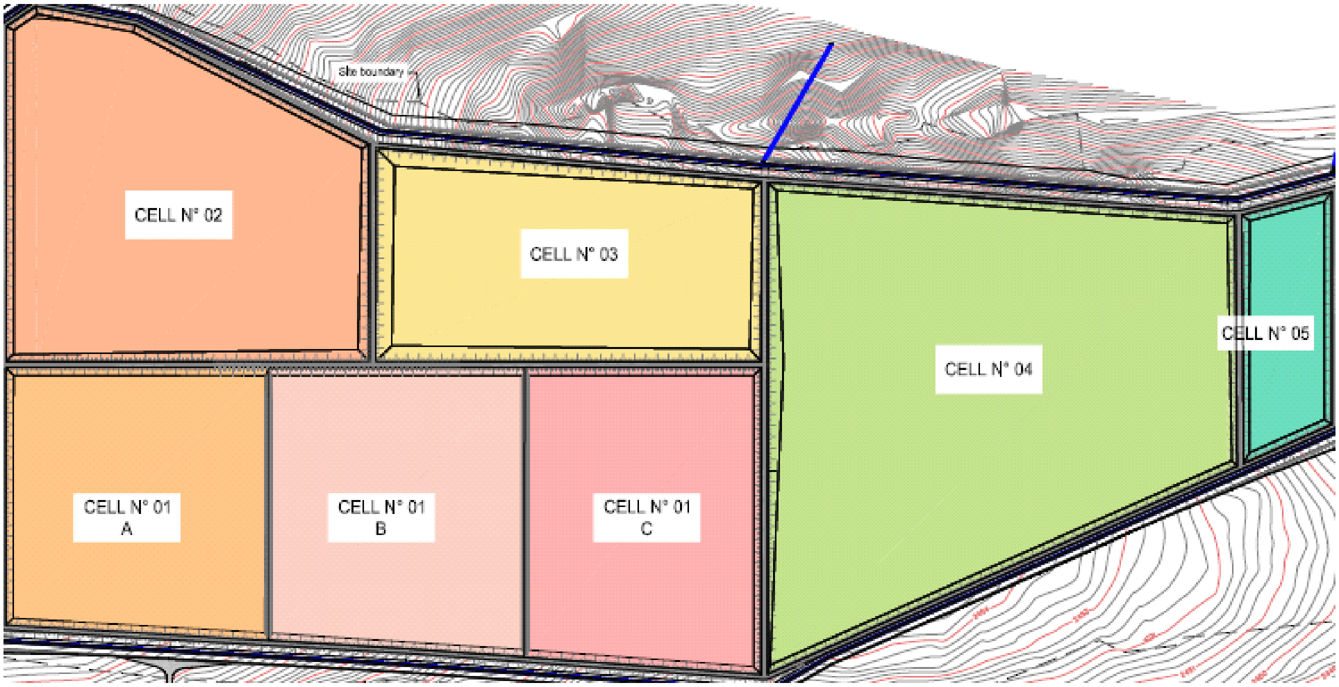


Figure 12: General Site Layout Plan for Sendafa Landfill for Phasing Work (Source: Artelia & MCE, 2013)

Table 2: Operational Phases of Sendafa Landfill (Source: Artelia & MCE, 2013)

		Beginning of operation	Lifespan
CELL N° 01-A + LTP + Buildings :		06/2015	3.7 years
CELL N° 01-B :		03/2019	3.5 years
CELL N° 01-C :		10/2022	2.9 years
CELL N° 02 :		06/2025	4 years
CELL N° 03 :		05/2029	2 years
CELL N° 04 :		04/2031	3.9 years
CELL N° 05 :		?	?

1.1.3.4 Final Cover Material

The cap of the landfill overlays the compacted waste mass. This will consist of compacted waste, mounded and compacted to provide base for profiled cap, uncompacted non-purely cohesive material (sand or selected material but no pure clay) as leveling layer, gravels as biogas drainage layer, a non-woven filtration geotextile, compacted clay, gravels as storm water drainage layer and top soil. The top soil cover will be planted with native local low vegetation (grasses or shrubs) (Artelia & MCE, 2013).

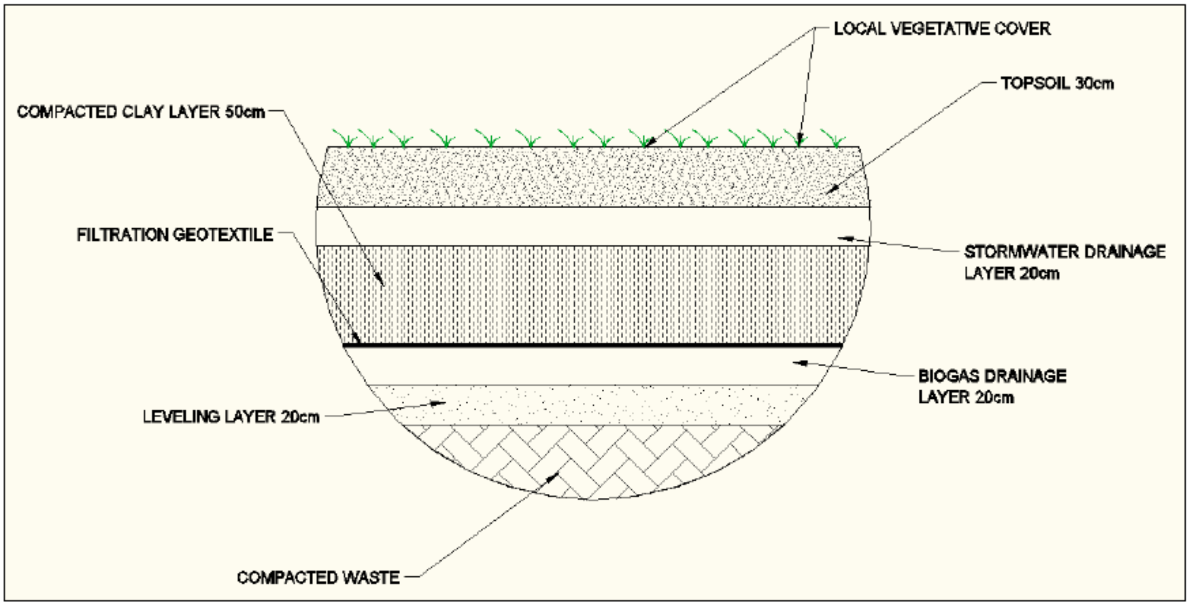


Figure 13: Final Cover Design (Source: Artelia & MCE, 2013)

1.1.3.5 Surface Runoff from Landfill Cells

Surface water runoff arising within the landfill area is classified as that from cells under construction, operational areas and restored areas. Non-contaminated storm water, originating from non-operated cells or sub-cells or areas completed with final cover will be collected through the leachate collection network in place and will be conveyed to storm water management system via another storm water piping network parallel to the leachate transmission network. Potentially contaminated storm water, such as that originating from operated areas will be collected and managed as leachate (Artelia & MCE, 2013).

1.1.3.6 Storm Water Management System

The design of the sanitary landfill consists of a storm water management system to control flow within the waste-relief boundary and external surface water flow to prevent flooding and erosion. The storm water management system will include peripheral storm water ditches made of reinforced concrete. In addition, berm will be made on top of the waste mass and ditches, on the slopes and on the final cover to protect slopes from erosion (ZTS-EDCE & MTS, 2014).

Non-contaminated storm water, originating from non-operating areas of the landfill (i.e., all facilities and road areas, landfill cells or sub-cells not in operation or areas completed with final cover) will be collected and conveyed downstream of the cells. The internal ditching and piping will be designed to accommodate the peak flow generated from the 5-year period rainfall. Internal bunds and piping networks will be used to divert any non contaminated storm water away from landfill cells where it may cause operational problems and from operating areas where it may come in contact with waste.

1.1.3.7 Leachate Collection System

The leachate collection system is entirely separated from the storm water management system. Leachate will be collected from the lined cells area and sent to the downstream leachate treatment plant. No leachate will be discharged to the storm water management system (ZTS-EDCE & MTS, 2014).

A leachate collection system typically comprises a high permeability drainage layer, perforated or slotted collection pipes, and geotextiles to protect any geomembrane and prevent clogging of the drainage layer. The liner is sloped toward the leachate collection pipes which ones are also sloped toward the leachate transmission pipes (Artelia & MCE, 2013).

Figure 14: Sendafa Landfill under Construction (Photo by the Author, February 16, 2016)

A drainage layer will be placed all over the bottom liner system and at the bottom of the cells and on the side slopes. A geo-textile filter will be placed over the drainage layer to protect it from clogging as a result of solids transport. To avoid clogging and capillary action holding water in the drainage layer, coarse material is used so that there is space within the drainage layer for leachate to drain freely. A geo-composite drainage layer with at least the same hydraulic conductivity will be laid below the granular drainage layer on the side slope allowing for a safe discharge of sides slopes collected leachate into the bottom LCRS. Slotted collection pipes will be laid (embedded) within the gravel layer in such a manner that the leachate will be drained within the gravels layer to these slotted pipes. The collectors shall lead to HDPE transmission pipes in the peripheral trenches near the ground level and along the perimeter bunds. These pipes will lead the leachate to the leachate treatment plant (ZTS-EDCE & MTS, 2014). The figure below shows in red the collection slotted pipes and the collector full pipes along the perimeter.

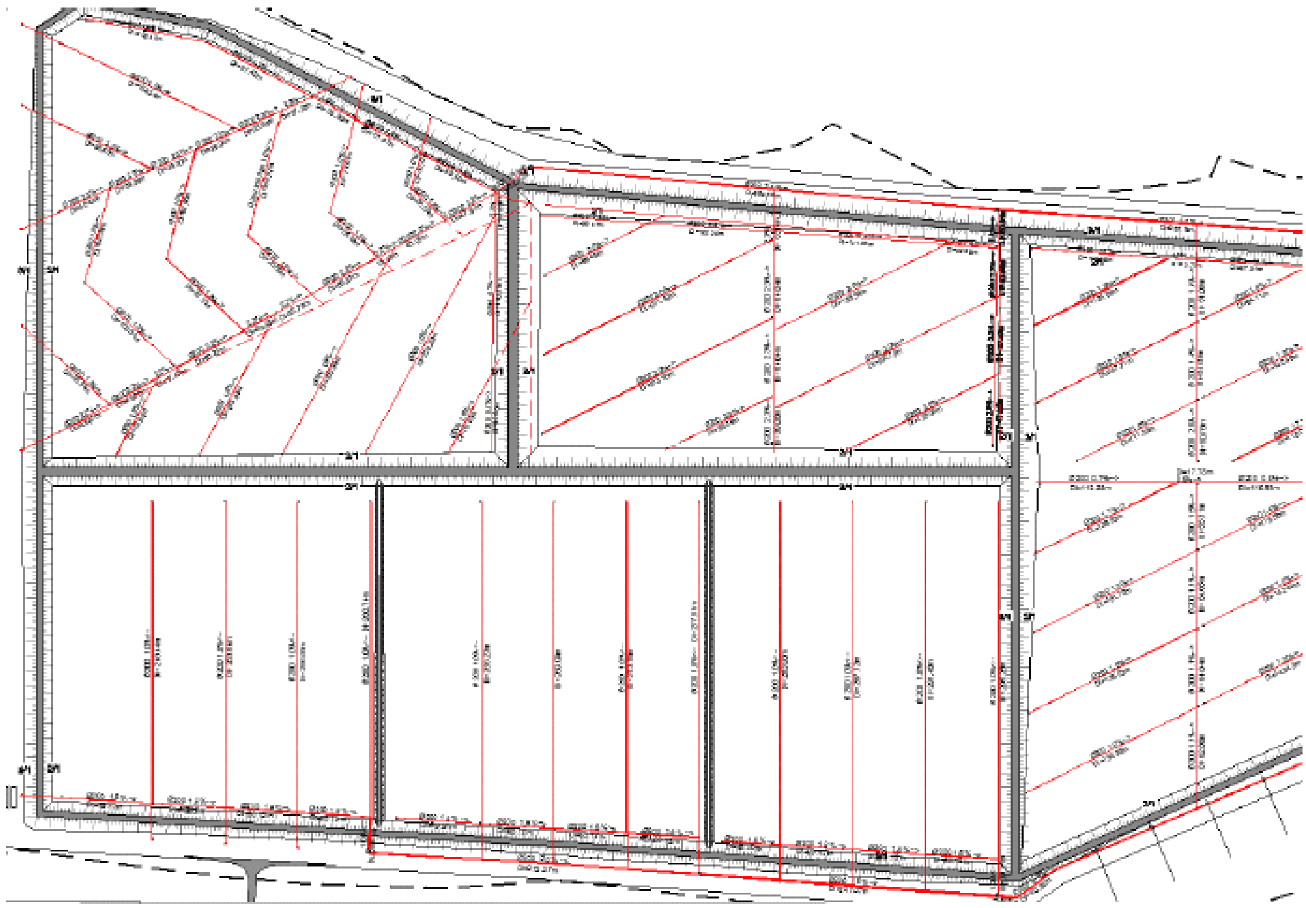


Figure 15: Extract from Leachate Collection and Removal System (Source: Artelia & MCE, 2013)

1.1.3.8 Leachate Volume

It is proposed to construct five waste disposal cells and the fifth cell will be dedicated for the disposal of hazardous waste. The water balance method was used for estimating the leachate generation rates and for the aim of this detailed design it takes into consideration the phasing and planned operation of the site. The volume of leachate that will be generated from this disposal cells is anticipated to range from 645m^3/day when cell one (1a) is operating and the rest of the cells are closed to 1336 m^3 /day when cell 4a is operated and other cells are closed during the lifetime of the sanitary landfill (ZTS-EDCE & MTS, 2014). Table 3 shows water balance model parameters for Sendafa Landfill and Table 4 shows leachate generation rate at Sendafa Landfill.

Table 3: Water Balance Model Parameters for Sendafa Landfill

Year	Month	Average précipitation P	Pan Evaporation *** E	Area with open liner A_l	Area of open waste A_o	Area with intermediate cover A_i	Area with final cover A_f	Cumulative area with final cover	Cumulative area covered with waste	Conta-minated runoff (Area * Factors)	Clean runoff from final cover (Area * Factors)	Potential Evaporation E * Factor	Leachate generated due to rainfall	Potential storage in waste (field capacity-natural moisture)	Excess as leachate collected in pipe network	Leachate + contam runoff into pond	Leachate + runoff into pond
	Units	mm	mm	m²	m²	m²	m²	m²	m²	m^3	m^3	mm	m^3	m^3	m^3	m^3	m^3/day
	Status	(Input)	(Input)	(Input)	(Input)	(Input)	(Input)	(Calc)	(Calc)	(Calc)	(Calc)	(Calc)	(Calc)	(Calc)	(Calc)	(Calc)	(Conv)
	Factors			100%	0%	15%	75%					30%		0%			
				runoff	runoff	runoff	runoff										

Table 4: Leachate Generation Rates at Sendafa Landfill (Artelia & MCE, 2013)

Cell (area m²) \ Operation phase	1	2	3	4	5	6	7	8	9	max flow (m3/day)	from active landfill (m3/day)	from covered areas (m3/day)
Cell 1a (80 000m²)	operated	closed	closed	closed	closed	closed	closed	closed	closed	654	654	0
Cell 1b (80 000m²)		operated	closed	closed	closed	closed	closed	closed	closed	755	654	101
Cell 1c (80 000m²)			operated	closed	closed	closed	closed	closed	closed	861	654	207
Cell 2a (75 000m²)				operated	closed	closed	closed	closed	closed	927	613	314
Cell 2b (48 000m²)					operated	closed	closed	closed	closed	809	393	416
Cell 3 (85 000m²)						operated	closed	closed	closed	1172	695	477
Cell 4a (75 000m²)							operated	closed	closed	1205	613	592
Cell 4b (53 000m²)								operated	closed	1127	434	693
Cell 4c (70 000m²)									operated	1336	573	763

1.1.4 Problem Statement

Landfill sites contribute to pollution of surface water and groundwater to a large extent. Historically, landfills have created various problems, such as groundwater contamination. Reppi or "Koshe", the only solid waste dumping site in Addis, located 13kms away from the city center, has been giving service since 1968 and has a surface area of 25 hectares (AACSBPDA, 2003). The solid waste disposed at Reppi is mostly from domestic, industrial, trade, hospital and commercial sources (Gizachew et al., 2012). Most of these wastes contain leachable toxic components such as carbon dioxide, hydrogen, hydrogen sulfide, methane and nitrogen (GSE, 2010). A study performed in the year 2007 to analyze groundwater pollution and public health risks in the vicinity of Reppi solid waste dumping site in Addis Ababa City, revealed high concentration of pollutants prevailed in leachate and well water except copper (Tesfaye, 2007). Leachate and well water produced during sampling showed higher concentration of pollutant particularly of conductivity, SS, TDS, alkalinity, phosphate and lead (Tesfaye, 2007).

Solid, non-hazardous waste (residential waste; industrial, commercial and institutional waste; and construction and demolition (C&D) waste) and hazardous waste (excepted medical waste) generated in Addis Ababa and the surrounding serviced area will be disposed in the new Sendafa sanitary landfill. It is fore casted that Sendafa sanitary landfill would receive approximately 8,200,000 tons of waste over the next 20 years. The waste that will be disposed at the Sendafa Landfill is composed of organic (57.1 %), plastic (8.8%), paper (4.1 %), cardboard (3.3 %), textile (3.0%), hygienic textile (2.7%), glass (2.6%), unclassified combustible and incombustible (5.3 %), health care waste (1.1 %) and others (9.7 %) (Artelia & MCE, 2013).

Extreme rainfall together with topographic condition of the area could be a determining factor in accidental release of contaminants from the landfill to surface water. Addis Ababa received intense rain events in March, 1969 with record 78.5mm; in June, 1984 with record 82.5mm and in April,1986 with record 98.1mm over one day period. In July, 1988, Sendafa received a record one day rainfall total of 102.6 mm. This shows that the frequency and intensity of rain events have increased in the study area. Increasing heavy precipitation can contribute to increased leachate generation.

River catchments in the vicinity of landfill site are highly vulnerable to leachate contamination and are exposed to increased risk due to storms driven by special weather conditions. No landfill should be constructed within 90 m of a navigable river or stream. The distance may be reduced in some instances for non meandering rivers, but a minimum of 30 m should be maintained in all cases (Bagchi, 2004). The new Sendafa landfill is located in the Akaki catchment with a stream originating from the landfill and feeding Akaki River. This will have an effect throughout the interconnected watershed formed by the Akaki watershed.

In the new Sendafa Landfill the leachate from waste will be controlled by a leachate collection system to protect the environment from pollution originating in the landfill. However, this landfill is likely to be a long term concern and source of potential risk to the environment under extreme storm events due to leachate emission. The impact of discharging leachate to the waterways is the degradation of river water quality and consequently be a threat to human health and affect the habitats of the aquatic organisms. Akaki River is used for irrigation and cattle consumption resulting in additional potential doses through these food chain pathways. In addition, surface water is the main transmitter of pollutant into the groundwater body. The new Sendafa landfill site will be operational for 20 years and still can be active following its closure. Residual wastes will remain in the landfill site for many years after degradation processes have ceased during operation, closure and post-closure stages. With these risks, the issue of the impact of Sendafa Landfill on surface water quality has to be a concern.

1.1.5 Research Questions

In investigating the future impacts of the landfill on surface water quality, the following research questions were addressed:

1. Is there any potential risk on surface water bodies located in the vicinity of the new Sendafa Landfill due to landfill leachate?
2. What are the potential impacts of the Sendafa Landfill site on surface water bodies under extreme storm events?
3. What needs to be done to prevent, control or minimize the risk?

1.1.6 Objectives of Research

1.1.6.1 General Objective

The general objective of this research is to better understand surface water bodies in the vicinity of the new Sendafa Landfill and establish a broader picture of the future risks associated with the

Landfill.

1.1.6.2 Specific Objectives

The specific objectives of the study are:

1. To identify surface water bodies in the vicinity of Sendafa Landfill site that are at risk of pollution.
2. To investigate the contribution of extreme storm events to landfill leachate production.
3. To examine the potential risk associated with Sendafa Landfill on surface water bodies in the vicinity, under extreme storm events.
4. Finally, based on analysis result, to recommend on how to mitigate the contamination due to leachate from Sendafa Landfill on the surrounding surface water bodies.

1.1.7 Scope of Research

This research focuses on the potential release of waste solution from landfill to the surrounding surface water bodies. Although one of the concerns of contamination of surface water bodies as a result of landfill, solid waste erosion and mobilization were not included within the scope of this thesis. The research also focuses on storm water as the main impacter for leachate generation. Leachate from other sources such as groundwater infiltration, surface water runoff originating from areas separated from landfill operations, and biological decomposition of waste were not addressed but should be included in future research.

1.1.8 Limitations of the Study

This research is aimed to outline the future environmental concerns that could be raised due to the waste sites within the water catchment area. However, the depth and scale of analysis and risk assessment are limited due to lack of knowledge and data availability. The limitations of the research encountered throughout the study period are presented in this section.

Change in the land use patterns affects hydrological processes in watersheds and disrupts the natural balance of water flow. In this study the impact of landfill on surface water resources is assessed by assuming that the land cover will remain the same at future time horizons due to lack of knowledge and data availability. However, in physical world the land covers change.

Another limitation is that historical rainfall data are used to predict future observations in terms of magnitude and frequency. In doing this, it is assumed that the data are stationary, which not hold true in case of climate would change.

1.1.9 Thesis Structure

Chapter 1: *Introduction* part presents a general introduction about the research, describes the study area and details of the Landfill design, defines the research problems, clarifies aims and objectives of research and discusses limitations of the study.

Chapter 2: *Literature Review* presents facts to familiarize the reader with the context in which the investigations are performed. It gives a brief picture of landfill in Addis Ababa, problems that can be encountered by landfill on river catchment area, description of landfill as a source of pollution, surface water flow as means of contaminant transport and surface water bodies as a receptor. It also gives a background description about a Source-Pathway-Receptor-Consequence approach of risk analysis.

Chapter 3: *Materials and Methods* give overview of the methods, model brief and data sets used in the research. It also provides the overall data analysis procedure followed throughout the study.

Chapter 4: *Results and Discussions* present main results and findings from data analysis discuss and evaluate the results in the context of the problems specified.

Chapter 5: C*onclusion and Recommendation* summarizes the overall results of the research and recommendations are made for the mitigation of contamination over the surrounding surface water bodies. It also provides list of recommended measures, and suggestions for future studies.

Chapter 6: *References* gives the list of references used throughout the research work.

2 CHAPTER TWO

2.1 LITERATURE REVIEW

This chapter provides the literature review and background as a basis for the discussions about risks associated with surface water bodies located in the vicinity of landfill site in the following chapters. It is intended to present the necessary facts to familiarize the reader.

2.1.1 Landfills

One of the main emission pathways for pollutants from landfills is leachate. Leachate is generated through percolation of water through the landfill. Storm water is the main contributor to leachate generation, but this water can also come from other sources such as groundwater infiltration, surface water runoff originating from areas separated from landfill operations, and biological decomposition of the waste (Reinhart, 1998). The quantity of leachate depends mainly on storm water percolation through waste mass. A combination of physical, chemical and microbial processes transfers pollutants from the waste material to the leachate making it a complex solution containing dissolved organic matter, inorganic macro components, heavy metals and pathogens (Kjeldsen et al. 2002; Schiopu and Gavrilescu 2010). Pollution of surface water and groundwater is considered the most severe environmental impact of landfills (Kjeldsen et al. 2002; Scharff et al. 2011). The constituents in leachate, some of which may be toxic, have often posed serious challenges in terms of cost of treatment, remediation and, in particular, possible eco - toxicological implications resulting from both short term and long term exposure of leachate constituents (Rafiqul et al., 2013). Therefore, waste disposal sites, whether active or closed, can result in serious pollution of the environment due to leachate.

For centuries human have been disposing off waste products by burning, discharging in streams and storing them on ground (Maqbool et al., 2009). Apparently, waste management practice causes a significant strain on the environment. When Addis Ababa was built as an administrative center in 1880s there was hardly any thought of waste as a threat. Never the settlement pattern, nor the mind setup of residents was in conformity with waste management issues (Tadesse, 2004). Addis Ababa started its solid waste management some four decades back (UNDP, 2004). Reppi or "Koshe" sanitary landfill site, located 13kms away from the city center, has been giving service since 1968 and has a surface area of 25 hectares (AACSBPDA, 2003). When this was chosen as landfill site, this seemed like a sensible option. However, the site is characterized by no odour or vector control, no rainwater drain-off, no fencing, the area is unprotected area for children, women and scavengers and there is no large scale composting facility available as a disposal option. All of waste collected from the city is dumped in this single place without separation of even organic waste (AACSBPDA, 2003). A research performed in the area in the year 2007 revealed that the surrounding groundwater resource is polluted due to leachate from the landfill.

As observed from past experiences, many of the problems associated with landfill occurred as a result of non engineered facilities. Koshe or Reppi, the first dumpsite in Addis was not equipped by a leachate management system which prevents the toxic liquid waste leaking into the environment. However, with advancing times, growing public awareness and scientific knowledge, this kind of dumping is not acceptable any more (Enger and Smith, 2008). Recently, Addis Ababa City Government has set solid waste management as one of its top priority and its immediate priority is to close the Koshe or Rappi dumpsite and to replace it by a new sanitary landfill located on the territory of Sendafa (Oromiya) (ARTELIA & MCE, 2013). The sanitary landfill includes leachate management system as well as a separate storm water management system. However, the fact that the landfill is located in sensitive river catchment area makes it vulnerable to continuous challenges and risks due to accidental spill of leachate into the surrounding surface water resources under extreme storm events.

2.1.2 Landfill in River Catchment Area

Landfill is the simplest, cheapest and most cost-effective method of disposing of waste (Barrett & Lawlor, 1995). However, most discarded waste can be reused or recycled, one of the principles of most waste management philosophies (Taylor & Allen, 2006). In most low- to medium-income developing nations, almost 100 percent of generated waste goes to landfill (EEA, 2003). It is forecasted that Sendafa landfill would receive approximately 9,000,000 tons of waste over the next 20 years (ARTELIA & MCE, 2013). A report by Community Development Research in the year 2011 showed that from the daily solid waste generated in Addis Ababa, 65% was collected, 5% recycled and 5% composted. The remaining 25% is simply dumped on open sites, drainage channels, rivers and valleys as well as on the streets (Community Development Research, 2011).

According to Philip Rushbrook, Michael Pugh (1999) in the selection of sanitary landfill site, the site should not be within a floodplain subject to 10-year floods. If landfill site is within areas subject to a 100-year flood, it must be amenable to an economic design which would eliminate the potential for washout (Philip & Michael, 1999). The construction of a landfill within the 100-year flood stage of a minor river or stream is not safe (Bagchi, 1994). There is visible evidence of climate change such as global average air and ocean temperature increases, glacial melting and higher sea levels. According to the "WHO Vision 2030 - Technology projection study" (WHO & DIFID, 2010) the climate change will not only affect the average weather (climate) but also result in more extreme weather. Other studies have also shown that extreme weather events will become more frequent and severe in the future. It will then result in increasing risks of drought and flooding, leading to increased risk to health and life (Few et al., 2004). Poor housing structures and poor drainage systems can be disastrous if there is a severe flooding and these are problems that can be found in Addis Ababa (UN-Habitat, 2008). The climate prediction models used in "UNDP Climate Change Country Profile of Ethiopia" are indicating an increase of intense rainfalls, or as they called it, "heavy events". (Daniel, 2011)

Facing the era of climate change and the growing needs of flood adaptation measures, landfills located in potential flood zones are deemed to represent a threat to surrounding areas and surface/groundwater bodies due to waste emissions and subsequent pollution. However, compared to other environmental risks in non-emergency status such as ground water contamination by landfill leachate (Schiopu, 2010 and Li, 2012) and atmospheric pollution by landfill gasses (Seung, 2012), less studies about environmental risks due to floods have been reported (David, 2009).

In the context of this study, increased storm, increased rain fall, increased flood risk are some of the extreme weather events directly or indirectly related to extreme weather events. Whereas the normal operation of landfills and the associated emissions can be well investigated, the behavior of waste deposits in case of flooding is widely unknown. Mass movement of contaminants into surface water encompasses both physical and chemical processes. The stability of a slope is governed by the balance between resisting and driving forces. When the driving forces exceed the resisting forces by cohesion and friction between particles, the contaminants starts to move. Mass movement causes physical disturbance, redistribution of sediments, and an increase in suspended particle matter (SPM), which affects both the physical environment and the ecology. The pollutants may occur dissolved, free or in complexes, or associated with the particulates either adsorbed or precipitated. From a risk perspective, the possible shifts between different states and species have large implications (Goransson et al., 2012). Such shifts towards dissolved species imply significant impact due to their higher bioavailability (Goossens and Zwolsman, 1996). Therefore, addressing long term emissions due to flooding in relation to future landfill management should be a critical issue.

The aim of this research is, therefore, to investigate methods to better understand the possible interaction of extreme storm events with the new Sendafa Landfill, to predict and reduce the future impact on the water quality of the surrounding river catchment area.

2.1.3 The Source - Pathway - Receptor Concept as the Basis for Risk Assessment

Risk is a combination of the probability, or frequency of occurrence of a defined hazard and the magnitude of the consequences of the occurrence. In the context of contamination from landfill, there are three essential elements to risk.

The 'source' for waste management facilities is defined by the hazardous properties of the waste types and operations to which they will be subjected on the proposed site. It may also include the events which lead to the hazards associated with those wastes and/or operations being transferred into the environment, although, as used in this study, it is more appropriate to link such hazardous events with the 'pathways' by which the hazards are transferred. (EA, 2000).

The 'pathways' for a defined source of environmental hazards are the means by which the identified hazards are transferred into the environment, and hence to any defined 'receptors' in the environment. The risk from leachate migration to a receptor is dependent on surface water drainage and the distance to each receptor. 'Hazardous events' and the 'pathways' by which the resulting hazards are transferred into the environment are intimately linked (EA, 2000).

The environmental 'receptors' (or 'targets') are those entities which are liable to be adversely affected by the identified hazards transferred from the defined 'source' into the environment by the identified 'pathways' (EA, 2000).

Risk assessment involves the separate consideration of the likelihood and the consequences of an event, for the purposes of making decisions about the nature and significance of any risks, and how best to manage any unacceptable risks (Simon et al., 2000). Environmental risk assessment requires an understanding of the source of a hazard to, or from, the environment, the characteristics of an environmental receptor that may be at risk from that hazard, and the means, or pathway, by which the receptor may be affected by that hazard (Simon et al., 2000)..

Without a pollutant linkage, there is no risk – even if a contaminant is present. Where there is a pollutant linkage, and therefore some measure of risk, it is important to identify whether that risk is significant. The level of risk needs to justify the actions taken to deal with the risk.

2.1.3.1 ***Landfill Waste as Sources of Pollution***

Municipal solid waste is defined to include refuse from households, non-hazardous solid waste from industrial, commercial and institutional establishments (including hospitals), market waste, yard waste and street sweepings (Peter et al., 1996). Pollution Probe (2004) mentioned that landfill site leachate is classified as point source pollution which enters the environment at a specific place from an identifiable source. Municipal solid waste landfill has many adverse effects on surrounding environment. Such landfills often produce leachate, i.e. the liquid that usually drains from landfills due to infiltration by water and/or biogeochemical decomposition processes, which serves as an important point source of pollution in many environmental media around the world (Rafiqul et al., 2013).

The contribution to the total generation of waste by the different sources in the city of Addis is estimated to be around 76% for households, 18% for commercial, institutional and industrial sources, and 6% from streets and public areas (AACAHB, 1997; UN-HABITAT 2007). Around 495,130 tons of waste in the year 2015 and 1,187,487 tons of waste in the year 2035 could be generated in Addis Ababa. The potential of recycling waste represent not more than 60,000 tons of waste in 2015 and around 130,000 tons in 2,035 for all the waste produced in the area. It represents around 11 % of the waste generated ((ARTELIA & MCE, 2013).

2.1.3.2 Surface Water Flow as a pathway

The primary means by which pollutants are transported to surface-water bodies is via overland flow or "runoff." Runoff to surface water is the amount of precipitation after all "losses" have been subtracted. Losses include infiltration into soils, interception by vegetation, depression storage and ponding, and evapotranspiration (i.e., evaporation from the soil and transpiration by plants) (US EPA, 1996). In this study mobilization of waste solution due to excess rainfall will be considered. Rain hitting an exposed waste management unit will liberate and pick up particulates and pollutants from the unit and can also dissolve other chemicals it comes in contact with (US EPA, 1996). The amount of water that enters a fill has an important bearing on physical reactions. Water acts as a medium for the dissolution of soluble substances and for the transport of unreacted materials. The unreacted materials consist of animate and inanimate particulates (UNEP, 2005). The amount of rainfall, as well as the timing and intensity, are very important considerations (UNEP, 2005).

Flood risk is becoming an increasingly pressing issue for the reason that the number of floods is increasing, presumably due to climate change. The extent of potential damage is therefore increasing (Macchi & Tiepolo, 2014). Floods are usually caused by the overflowing of large rivers, by flash floods from their tributaries, runoff following intense local rain, and sea level rise, as well as ground water floods and artificial systems failures (Bloch et al., 2012). In the next three decades, temperatures in Southern Africa are expected to rise and rainfall in Eastern Africa is expected to increase (including in the Horn of Africa) (Macchi & Tiepolo, 2014). Ethiopia experiences two types of floods: flash floods and river floods.

Unlike river floods which are caused by rivers that overflow or burst their banks and inundate downstream plain lands, flash floods are the ones formed from excess rains falling on upstream watersheds and gush downstream with massive concentration, speed, force (Kebede, 2012). As hydrometeorological phenomena, flash floods are best characterized by their magnitude (total amount and intensity of inducing rainfall), return interval and total runoff. In the case of a sophisticated hydrological approach, in addition to precipitation, several environmental factors are also to be considered in flash flood modeling as boundary conditions. Soil characteristics (actual moisture content, permeability, and vertical soil profile) influence runoff production and help to define flash flood prone areas. Various catchment characteristics (e.g. size, shape, slope, land cover) also affect runoff and the potential occurrence of flash floods (Lóczy et al., 2012). Often, flash floods are sudden and appear unnoticed (Kebede, 2012). In the context of this research flash flood is thought to be the main impacter for accidental release of liquid waste from the landfill to surface water bodies downstream.

The extent and severity of flood depends on the frequency and intensity of rainfall as well as topography of the area. There is a correlation between the amount of waste solution entering to surface water and the amount of precipitation (rainfall, snow, etc.) that falls on the watershed in which a waste management unit is located. The duration of flood determines the extent of saturation of landfill. In consideration of the long residence time of a landfill even flood events of low probability of occurrence (e.g. 200-year recurrence interval) need to be considered, when evaluating the potential risks emanating from landfills (David, 2009). Topographic information is necessary in order runoff from the waste is prevented from damaging the environment (UNEP, 2005). Runoff the pollutants from the waste management unit as it flows down gradient following the natural contours of the watershed to nearby lakes, rivers, or wetland areas (US EPA, 1996).

Soil properties also influence the relationship between runoff and rainfall since soils have differing rates of infiltration (OCCMCG, 2014). There are four hydrologic soil groups (USDA, 1986): A; soil having high infiltration rates, B; soils having moderate infiltration rates, C; soils having slow infiltration rates, and D; soils having very slow infiltration rates (Jeffry, Frans & Koichiro, 2012).

2.1.3.3 Existing Surface Water Resources in the Study Area as a Receptor

Surface water bodies in the vicinity of landfill site are liable to be adversely affected by hazards associated with exposure to contaminants. Surface water bodies include river, lake and coastal water bodies and the proximity to these receptors is an important factor. Leachate contamination may affect surface water resources in a number of ways depending on the contaminant loading of waste solution. When leachate leaves the landfill and reaches water resources, it may adversely affect the resource by hazards associated with contaminants.

Landfill site should not be placed within surface water or water resources protection areas to protect surface water from contamination by leachate. Safe distances from rivers should be achieved to prevent landfill leachate from spilling into rivers and major streams. A landfill should not be located within 30.48 m of any non-meandering stream or river, and at least 91.44 m from any meandering stream or river (Bagchi, 1994). Based on the landfill siting regulations of the Iran Department of Environment, disposal of solid waste near to any surface water body, such as seas, lakes and rivers, is forbidden; the minimum distance of landfill sites from surface water should be more than 300 m (Nadali et al., 2012). On the other hand, international studies require minimum distance of 500 m from any surface water (Kontos et al., 2005).

The new Sendafa Landfill is located within the Akaki River catchment and there are several rivers flowing in the vicinity of the project site. The total catchment area of the Akaki river basin, which includes Addis Ababa, is divided into two sub-catchment areas by approximately north-south running surface water divide. These are the Great Akaki River (Eastern) sub-catchment and the Little Akaki River (Western) sub catchment (UNEP, 2003). The new Sendafa is found within the eastern sub catchment.

The development of a landfill needs to be based on a thorough understanding of the site setting, the sensitivity of the surrounding surface water resource to leachate pollution and the potential migration pathways between the site and surface water body.

2.1.3.4 Consequences

Consequences associated with landfills have the potential to be large. The largest risks will probably be associated with liquid waste emission during storm events that expose leachate to surface water.

The risks from waste leachate are due to its high organic contaminant concentrations and high level of ammonia and nitrogen. Pathogenic microorganisms and toxic substances that might be present in the waste at the initial stage are often cited as dangerous (ZTS-EDCE & MTS, 2014). The general consequence on receptors include surface water contamination, stress on flora and fauna and health problem to human beings in case of contamination interference of food chain pathways.

The complexity of the measures needed will depend upon the type and level of risks that the landfill presents to the environment. There is also a need to increase the knowledge on possible environmental consequences in the near and far field, in a short- and long- time perspective.

3 CHAPTER THREE

3.1 METHODS AND MATERIALS

The methods applied in this study include the collection of data from different organizations; Ethiopian Mapping Agency, Ministry of Water, Irrigation and Energy, National Meteorological Agency and Geological Survey of Ethiopia. These data were required for delineation of the study area, determination of basin characteristics, analysis of rainfall frequency and maximum leachate volume from the landfill. HEC-GeoHMS applications were used for pre processing the basin characteristic, water balance model was used to determine leachate volume and HEC-HMS model was used to consider the dilution of leachate at the potential point of exposure.

3.1.1 Data Sets

The research presented in this thesis is based mainly on meteorological and topographical data. Brief descriptions of datasets used to make risk analysis in the study are presented here:

- ❖ Topographical map
- ❖ Area of cells
- ❖ Land use/ Land cover
- ❖ Soil type data
- ❖ Evaporation data
- ❖ Rainfall data
- ❖ Drainage
- ❖ Digital Elevation Model (DEM) of the watershed stream network
- ❖ Stream flow gauge data
- ❖ Stream flow gauge location

3.1.1.1 Topographical Map

Topographic map format consisting of Digital Contour Map (1: 50,000 scale) with GeoTIFF of the study area obtained from Ethiopian Mapping Agency. Topologic map was used to cross check geo spatial data. Digital Elevation Model (DEM) of the study area downloaded from United States Geological Survey (USGS) web site was also used to delineate the watershed of the stream in the study area.

3.1.1.2 Area of Waste Cells

Mercator coordinates of the boundaries of the landfill site were obtained from Solid Waste Management Strategy and Institutional Report for Addis Ababa City Government (2013). The area used for the construction of the landfill cells and leachate treatment plant is about 82 hectares (ZTS & MTS, 2014). The landfill is composed from four cells (AACG - EFC, 2013). The cells constitute a total area of 646,000 m^2 (Cell 1 = 240,000 m^2, Cell 2=123,000 m^2, Cell 3=85,000 m^2, Cell 4=198,000 m^2)

3.1.1.3 Land Use/ Land Cover

Land use of the study area (Awash River Basin shape file) was obtained from Ministry of Water, Irrigation and Energy of Ethiopia. Land use data comprise the basic data set for rainfall - runoff model. This data is used for curve number computation.

3.1.1.4 Soil Type Data

Geological map (1: 250,000 scale) of Addis Ababa and information on the permeability of the study area were obtained from Geological Survey of Ethiopia. Due to the fact that rainfall - runoff models include both spatial and geomorphologic variation, soil data comprise the basic data set for rainfall - runoff model. This data was used for curve number computation.

3.1.1.5 Temperature

The monthly maximum and minimum air temperatures in degree Celsius (°C) from Addis Ababa meteorological station for the year 2000 - 2012 were obtained from National Meteorological Agency. These data were used to estimate evapotranspiration.

3.1.1.6 Wind Speed

The average daily wind speed measured from Addis Ababa meteorological station at 2m above the ground level for the year 2000 - 2012 was obtained from the National Meteorological Agency.

These data was used to estimate evapotranspiration.

3.1.1.7 Solar Radiation (Sunshine)

The average daily net radiation from Addis Ababa meteorological station for the year 2000 - 2012 was obtained from National Meteorological Agency. These data was used to estimate evapotranspiration.

3.1.1.8 Humidity

The relative humidity in percent from Addis Ababa meteorological station for the year 2000 - 2012 was obtained from National Meteorological Agency. These data were used to estimate evapotranspiration.

Table 5: Evapotranspiration Date Set (Source: National Meteorological Agency)

Month	T_{max} (°C)	T_{min} (°C)	Sunshine (hr\day)	Wind Speed (hr\day)	Relative Humidity (%)
Jan	23.0	7.0	8.1	3.0	50.0
Feb	24.0	9.0	6.5	3.0	49.0
Mar	25.0	10.0	7.3	3.0	54.0
Apr	24.0	11.0	5.9	3.0	58.0
May	25.0	11.0	7.6	3.0	52.0
Jun	23.0	10.0	5.6	2.0	64.0
Jul	20.0	10.0	2.8	2.0	82.0
Aug	20.0	10.0	3.1	2.0	80.0
Sep	21.0	10.0	5.2	2.0	74.0
Oct	22.0	8.1	8.1	3.0	57.0
Nov	23.0	7.0	8.7	3.0	58.0
Dec	23.0	7.0	9.7	3.0	54.0

3.1.1.9 Rainfall Data

Precipitation data was required for water balance calculations and for rainfall - runoff modeling of the study area. For individual landfill, it is common practice to estimate rainfall from the nearest rainfall gauging stations. Rainfalls from 3 meteorological stations which represent the area were used. Daily rainfall data of 3 rainfall gauging stations (A.A. Bole, Debre Ziet and Sendafa stations) for period 1985 - 2014 and monthly rainfall data (A.A. Bole, Aleltu, Chancho, Debre Ziet and Sendafa stations) for period 1964 - 2013 were obtained from National

Meteorological Agency. The data size depends on the availability of data. Rainfalls of various return periods for the study area were calculated using daily and monthly rainfall data.

3.1.1.10 Drainage (Rivers and Other Water Bodies)

Geo referenced map (1:50,000 scale) showing rivers and their tributaries in the study area was obtained from Ethiopian Mapping Agency.

3.1.1.11 Digital Elevation Model (DEM) of the Watershed Stream Network

The DEM at 30-by-30 meter resolution was generally used for modeling terrain because of their widespread availability. DEM with resolution of 30-by-30 meter implies having an elevation value for each 30 x 30 meter portion of the coverage area.

3.1.1.12 Stream Flow Gauge Data

Stream flow data at the Mutinicha gauging station was used for this research. The measurement of discharges at Mutinicha gauging station from 1990 to 2005 was carried out by Ministry of Water, Irrigation and Energy. Stream flow data was required for the purpose of calibrating hydrologic model.

3.1.1.13 Stream Flow Gauge Location

The Arc GIS compatible shape file of the location of the Mutinicha gauging station was obtained from Ministry of Water, Irrigation and Energy. The Mutinicha gauging station was located downstream of the Legedadi dam (9° 03' 0" N, 38° 55' 0" E) near to the study area.

3.1.2 Model Brief

3.1.2.1 Water Balance Model

Water balances were used to assess likely leachate generation volumes. Parameters include waste volume, input rates and absorptive capacity, infiltration, effective and total rainfall.

The calculation is of the form:

$$Lo = [ER(A) + IRCA] - [aW] \quad (1)$$

Where,

$Lo =$ Leachate produced (m^3)

ER = effective rainfall (m)

A = area of cell (m^2)

IRCA = infiltration through restored and capped areas (m)

a = absorptive capacity of waste (m^3/t)

W = weight of waste deposited (t)

For water balances carried out on active phases of landfills, it was assumed that all the Actual Rainfall would infiltrate into the waste. In areas that have been restored an infiltration rate of 25% of the annual rainfall was used.

3.1.2.1.1 Effective Rainfall

Effective Rainfall (ER) is total rainfall (R) minus Actual Evaporation (AE) i.e.

$$ER = R - AE \quad (2)$$

Total rainfall was estimated by using data from the nearest gauging stations. Evaporative losses are a combination of evaporation of water from the surface and transpiration of water by plants where vegetation is present. Transpiration due to vegetation can effectively be ignored for the purposes of water balance calculations on uncompleted landfills.

3.1.2.1.2 Potential Evapotranspiration

The Potential Evapo-Transpiration (PET) estimation was based on climatological records of solar radiation (sunshine), air temperature, humidity and wind speed. The FAO Penman-Monteith was used to compute evapotranspiration loss from restored areas. The FAO Penman-Monteith method was maintained as the sole standard method for the computation of evapotranspiration from meteorological data.

The FAO Penman-Monteith equation for hypothetical crop is given as:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (3)$$

Where,

ETo = evapotranspiration (mm\day)

R_n = net radiation at the crop surface (MJ\m$^{2/}$day)

G = soil heat flux density (MJ\m$^{2/}$day)

T = air temperature at 2m height (°C)

U_2 = wind speed at 2m height (m\s)

e_s = saturation vapour pressure (KPa)

e_a = actual vapour pressure (KPa)

e_s - e_a = saturation vapour pressure deficit (KPa)

Δ = slope vapour pressure curve (KPa\°C)

ɤ = psychrometric constant (KPa\°C)

Mean daily temperature is calculated by:

$$Tmean = \frac{T\max + T\min}{2} \quad \text{.......} (4)$$

Where,

T_{mean} = mean daily air temperature (°C)

T_{max} = maximum daily air temperature (°C)

T_{min} = minimum daily air temperature (°C)

The average daily net radiation (R_s) is expressed as a simple average of solar radiation values obtained from a meteorological station in the period of 24 hour.

The slope of the relationship between saturation vapour pressure and temperature, Δ is calculated as:

$$\Delta = \frac{4098[0.6108\exp(\frac{17.27 * Tmean}{Tmean + 237.3})]}{(Tmean + 237.3)^2} \quad \text{.......} (5)$$

The atmospheric pressure, P, is the pressure exerted by the weight of the earth's atmosphere. Evaporation at high altitudes is promoted due to low atmospheric pressure. This effect is, however, small and in the calculation procedures, the average value for a location is sufficient. A simplification of the ideal gas law, assuming 20°C for a standard atmosphere, was employed to calculate P in KPa at a particular elevation:

$$P = 101.3[\frac{293 - 0.0065z}{293}]^{5.26} \quad \text{.......} (6)$$

Where,

z = elevation above sea level, m

Psychrometric constant (ɤ) is the ratio of specific heat of moist air at constant pressure (Cp) to latent heat of vaporization. The specific heat at constant pressure is the amount of energy required to increase the temperature of a unit mass of air by one degree at constant pressure.

$$\gamma = \frac{C_p P}{\varepsilon\lambda} = 0.000665P \qquad (7)$$

Where,

ɤ = psychrometric constant KPa\ °C

P = atmospheric pressure (KPa)

λ = latent heat of vapourization, 2.45, (MJ\kg)

C_p = specific heat at constant pressure, $1.013*10^{-3}$ (MJ\kg)

Saturation vapor pressure was calculated from the air temperature. The relationship is expressed by:

$$e_{(T)} = 0.6108\exp[\frac{17.27T}{T+237.3}] \qquad (8)$$

Where,

$e_{(T)}$ = saturation vapour pressure at the air temperature T (KPa)

T = air temperature (°C)

Therefore, the mean saturation vapor pressure was calculated as the mean between the saturation vapor pressure at both the daily maximum and minimum air temperatures.

$$e_{(T\max)} = 0.6108\exp[\frac{17.27T_{\max}}{T_{\max}+237.3}] \qquad (9)$$

$$e_{(T\min)} = 0.6108\exp[\frac{17.27T_{\min}}{T_{\min}+237.3}] \qquad (10)$$

Where,

T_{max} = maximum daily air temperature

T_{min} = minimum daily air temperature

The mean saturation vapor pressure is computed as:

$$e_s = \frac{e_{(T\max)} + e_{(T\min)}}{2} \quad (11)$$

The actual vapor pressure was also calculated from the relative humidity.

$$e_a = \frac{e_{(T\min)}[\frac{RH_{\max}}{100}] + e_{(T\max)}[\frac{RH_{\min}}{100}]}{2} \quad (12)$$

Where,

E_a = actual vapour pressure (KPa)

$E_{(Tmin)}$ = saturation vapour pressure at daily minimum temperature (KPa)

$E_{(Tmax)}$ = saturation vapour pressure at daily maximum temperature (KPa)

RH_{max} = maximum relative humidity (%)

RH_{min} = minimum relative humidity (%)

The inverse relative distance Earth - Sun, dr and the solar declination, δ are given by:

$$dr = 1 + 0.033\cos[\frac{2\pi}{365}J] \quad (13)$$

$$\delta = 0.409\sin[\frac{2\pi}{365}J - 1.39] \quad (14)$$

Where,

J = number of the day in the year between 1 and 365/366

The sunset hour angle (ω_s) is given by:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta) \quad (15)$$

Where,

φ = latitude in radians

δ = solar declination

The extraterrestrial radiation, Ra, for each day of the year and for the given latitude was estimated from the solar constant, the solar declination and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin\varphi \sin\delta) + \cos\varphi \cos\delta \sin\omega_s] \quad (16)$$

Where,

R_a = extraterrestrial radiation (MJ\m^2\day)

G_{sc} = solar constant = 0.082 MJ\m^2\min

dr = inverse relative distance Earth-Sun

ω_s = sunset hour angle (rad)

φ = latitude (rad)

The net radiation (R_n) is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \quad (17)$$

$$R_{nl} = \sigma[\frac{(T_{max} + 273.16)^4 + (T_{min} + 273.16)^4}{2}](0.34 - 0.14\sqrt{e_a})[1.35\frac{R_s}{R_{so}} - 0.35] \quad (18)$$

$$R_{so} = (0.75 + 2E10^{-5} z)R_a \quad (19)$$

$$R_{ns} = (1 - \alpha)R_s \quad (20)$$

Where,

R_{ns} = net solar or shortwave radiation (MJ\m^2\day)

α = albedo or canopy reflection coefficient = 0.23

R_{nl} = net outgoing long wave radiation (MJ\m^2\day)

σ = Stefan-Boltzmann constant [4.903*10^{-9}MJ\K^4\day]

T_{max} = maximum absolute temperature during the 24-hour period (K)

T_{min} = minimum absolute temperature during the 24-hour period (K)

e_a = actual vapore pressure (KPa)

R_s = the incoming solar radiation

R_{so} = clear sky solar radiation (MJ\m^2\day)

z = elevation above sea level (m)

R_a = extraterrestrial radiation (MJ\m^2\day)

The soil heat flux, G, is usually taken as:

$$G = 0.38(T_i - T_{i-1})$$

Where,

T_i = average temperature

3.1.2.1.3 Waste Input

The volume of the waste and the input rate which will vary during the active life of the landfill were considered. The rate of waste input was required in order to complete the water balance calculation.

3.1.2.1.4 Absorptive Capacity

The amount of water that can be absorbed without generating leachate depends on the type of waste, its initial moisture content and the density to which it is compacted. The field capacity of the waste (potential storage capacity) was taken as 0%, making the assumption that during the rainy season the field capacity of waste will be saturated.

3.1.2.2 Hydrologic Engineering Center (HEC) Model

In recent years, advances in the HEC models have provided many opportunities for enhancing hydrologic modeling of watershed systems. These models not only save time and effort but also improve accuracy over traditional methods. Hydrologic Engineering Center (HEC) tool was used to accomplish the research objectives in this research. Mainly two software were used in this study. The first software was HEC-GeoHMS and the second one was HEC-HMS. HEC-GeoHMS is a GIS add-in used in ARC View software. However, HEC-HMS version 3.0.0 is standalone hydrologic modeling computer software. The choice of method to establish rainfall - runoff model with the aim of determining runoff volume depends on data requirement and data availability. Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) was used to build the hydrologic model for the study catchment. The author believes an effort to give all the details about the program would most likely end with a perfect copy of the user's manuals of the program. Therefore, it is recommended to refer the user's manuals of the programs for those who are interested in detail explanations. For HEC-GeoHMS and HEC-HMS software refer to *"Geospatial Hydrologic Modeling Extension HEC-GeoHMS Version 5 User's Manual, USACE,* October 2010".

3.1.2.2.1 HEC-GeoHMS

The U. S. Army Corps of Engineers' Arc Map software, version 9.3 was used in this study. Arc Map is the main component of USACEs' ArcGIS suite of geospatial processing software. HEC-

GeoHMS 5.0 is a public-domain extension for ArcGIS 9.3. The program was used to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate sub basins and streams, construct inputs to hydrologic models and assist with report preparations. HEC-GeoHMS allows creating hydrologic inputs that can be used directly with the Hydrologic Engineering Centers Hydrologic Modeling System, HEC-HMS.

3.1.2.2.2 Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS)

The Hydrologic Engineering Centers Hydrologic Modeling System, HEC-HMS, released by US Army Corps of Engineers, simulates the precipitation-runoff processes of watershed systems. HEC - HMS enables the user to perform hydrological modeling based on a wide selection of common mathematical models used in hydrology.

For modeling purpose, the hydrologic cycle is divided into three components, which are modeled separately.

Loss Method: A model to account for the losses that occur during a rainfall event as a result of infiltration and evapotranspiration. For each time interval in the modeling process, the loss method calculates the amount of water that contributes to the runoff from the landfill (effective rainfall).

Transform Method: Model of direct runoff also called transform method, convert the effective rainfall over a watershed into a hydrograph at the outlet of the watershed.

Base flow Method: Base flow models are used to simulate the fraction of the runoff contributed by groundwater.

3.1.2.3 Software Components

A schematic overview of the HEC-HMS software is shown in Figure 16.

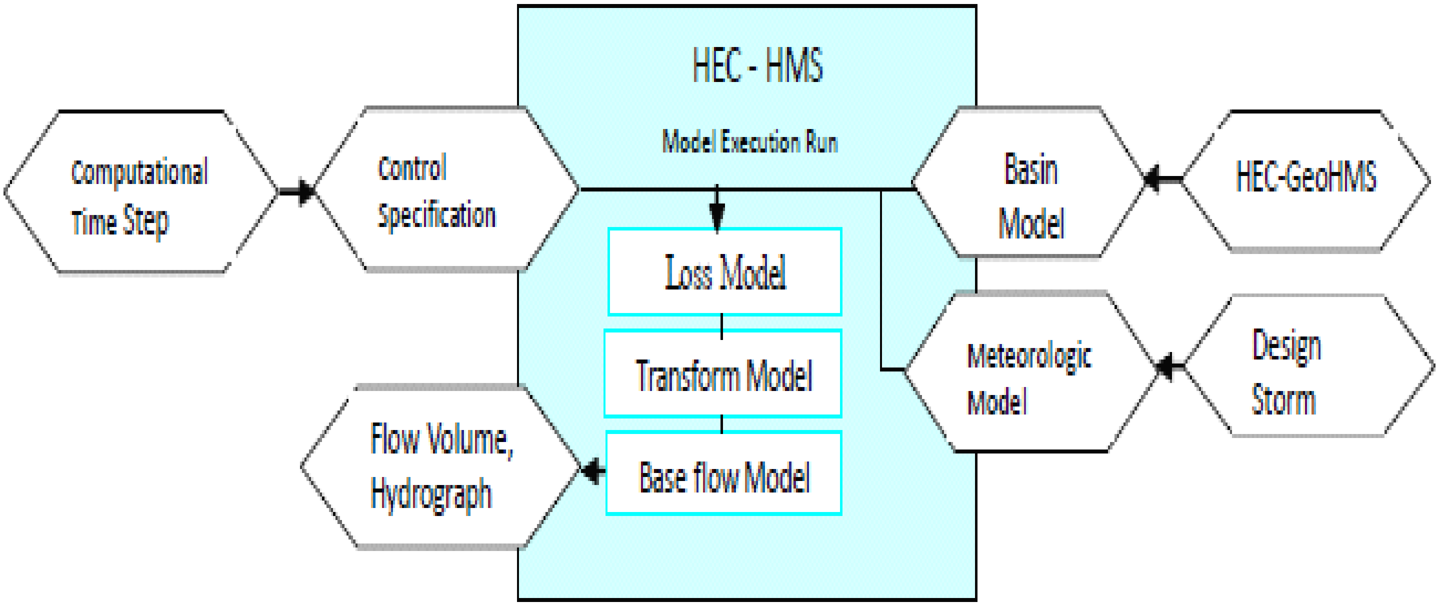


Figure 16: HEC - HMS Software Components

The basin model is a physical representation of the watershed which was prepared with HEC-GeoHMS in this study. The main features of the basin model are sub-basins and junctions. Subbasin element handles the infiltration loss and base flow computations, and rainfall runoff transformation process. Junction element handles the observed flow data and is mainly used for the comparison of the observed flow hydrographs with the simulated flow hydrographs (Yener et al., 2006). The meteorological model is the representation of the rainfall event that is intended to be modeled. The control specification defines the computational time step and the date of the simulation run. The modeling results comprise runoff hydrograph for the sub-basin as well as graphical and numerical representation of rainfall, losses and direct runoff for the sub basin.

3.1.2.4 Hydrologic Model Selection and Description

The transport of liquids originating at the Landfill release point was analyzed using surface water modeling methods to determine the surface water flow rates. In this study, the hydrologic modeling was performed with certain statistical return periods to determine maximum flow volume from precipitation events. Gololo Kore is a watercourse in the study sub basin that was considered in HEC-HMS modeling. Since base flow does not occur in the Gololo Kore watercourse, it can be neglected in the modeling process.

Table 6: Hydrologic Model Selection

Component	Chosen Model
Loss Method	SCS Curve Number
Transform Method	SCS Unit Hydrograph

The two models chosen were designed to model single storm events rather than continuous precipitation data (USACE, 2000). Furthermore, they are lumped models, meaning that spatial variations of processes and characteristics are not considered explicitly rather averaged for the watershed. The two chosen models and the underlying mathematical equations are described in detail in the following sections.

3.1.2.4.1 SCS Curve Number Method

Soil Conservation Service (SCS) Curve Number method used in this study estimates the effective rainfall as a function of the cumulative rainfall, the land use, the soil type and the antecedent moisture condition of the soil. The basic runoff equation of the CN method is:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad \text{For } P > I_a \text{ ......} \quad (21)$$

$$Q = 0 \quad \text{for } P \leq I_a \text{ ......} \quad (22)$$

Where P is the total rainfall (mm),

I_a is the initial abstraction,

Q is the direct runoff (mm)

S is the potential maximum retention after runoff begins (mm)

The initial abstraction includes water retained in surface depressions as well as water intercepted by vegetation, evaporation and infiltration. Based on a second assumption, that the amount of initial abstraction is a fraction of the potential maximum retention

$$I_a = 0.2S \text{ ......} \quad (23)$$

The potential retention S is further related to the soil and cover conditions of the analyzed watershed through the CN

$$S = \frac{25400}{CN} - 254 \quad (24)$$

In the HEC-HMS modeling process, the incremental excess rainfall for each computation time interval was computed as the difference between the accumulated excess at the end of and the beginning of the period. The cumulative excess Pe is computed as:

$$Pe = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (25)$$

One of the major limitations of the Curve Number method is that during the modeling of a storm event of large duration, the infiltration rate eventually approaches zero (NRCS, 1986). Furthermore, the intensity and duration of the rainfall is neglected in this method so that a 25 mm rainfall in one day, results in the same cumulative loss as a 25 mm rainfall in one hour. Nevertheless it is a simple, predictable and stable method that is widely accepted (HEC, 2000).

3.1.2.4.2 SCS Unit Hydrograph

The time to peak T_P is related to the duration of the unit of excess precipitation D through the following equation:

$$Tp = \frac{D}{2} + t_L \quad (26)$$

D is the excess precipitation duration and t_L is the lag time. In the case of ungaged watersheds such as the one in this study, the lag time is related to the time of concentration as:

$$t_L = 0.6 * Tc \quad (27)$$

The time of concentration is defined as the time for runoff to travel the distance from the hydraulically most distant point in the watershed to the outlet, also referred to as the longest flow path (LFP) in HEC-HMS. The SCS method for watershed lag developed by Mockus in 1961 spans a broad set of conditions ranging from heavily forested watersheds with steep channels and a high percent of runoff resulting from subsurface flow, to meadows providing a high retardance to surface runoff, to smooth land surfaces and large paved areas.

$$Tc = \frac{L^{0.8}(0.0394S + 1)^{0.7}}{440.7Y^{0.5}} \quad (28)$$

Where,

L = flow length (m)

Tc = time of concentration (hr)

Y = average watershed land slope (%)

S = maximum potential retention (mm)

These advanced modeling techniques have become feasible because many time consuming data manipulations can now be generated efficiently. HEC-HMS model was selected because it provides a graphical user interface making it easier to use the software and the program is widely used and accepted for many purposes including floodway determination. The user can choose a suitable combination of models depending on the availability of data; the purpose of modeling and the required spatial and temporal scales. HEC-HMS draws on more than 30 years of experience in hydrologic simulation. (US EPA, 1996).

In this study, HEC-HMS was used to perform rainfall-runoff modeling based on a combination of the SCS Curve Number model and the SCS Unit Hydrograph model.

In this study, with the objective of identifying surface water resources at risk, investigating the impact of storm events to leachate production and assessing the potential risk associated with leachate from landfill on the surrounding surface water network, HEC models were applied.

The methodology for the calculation of maximum leachate volume from the landfill area under storm events and surface water bodies - landfill interaction will be explained in the following sections.

3.1.3 Identifying Surface Water Bodies in the Vicinity of Sendafa Landfill

In this research, an attempt was made to identify surface water bodies at risk of liquid contaminants under storm events. As mentioned in Chapter 2, the landfill site is located within the Akaki River catchment. Surface water bodies prone to contamination were identified by performing GIS based analysis of the terrain elevation (DEM) data.

In the first stage topographic data needed for developing the watershed stream network were obtained through geospatial datasets; Digital Elevation Models (DEM). DEM was used to develop elevation related characteristics for the study site with the help of a GIS based tool called Geospatial Hydrologic Modeling System (HEC-GeoHMS). Then the watershed stream network for the study area was developed and its properties were derived in GIS. In this section, the landfill boundary and surface water bodies in the vicinity of Sendafa Landfill that are at risk of pollution were identified using a GIS add-in software HEC-GeoHMS.

3.1.3.1 Catchment Delineation (HEC-GeoHMS)

The Akaki catchment is located in central Ethiopia along the western margin of the Main Ethiopian Rift. The city of Addis Ababa is located at the center of the catchment. The study area is found within the Akaki catchment between 8°58' - 9°01' N and 38°57' - 38°58' E.

Gololo Kore is a stream originated from the landfill and feeding Akaki River (Fig. 17). The release of leachate at the point of confluence of Akaki with its tributary Gololo Kore will have an effect throughout the interconnected watershed formed by the Akaki watershed.

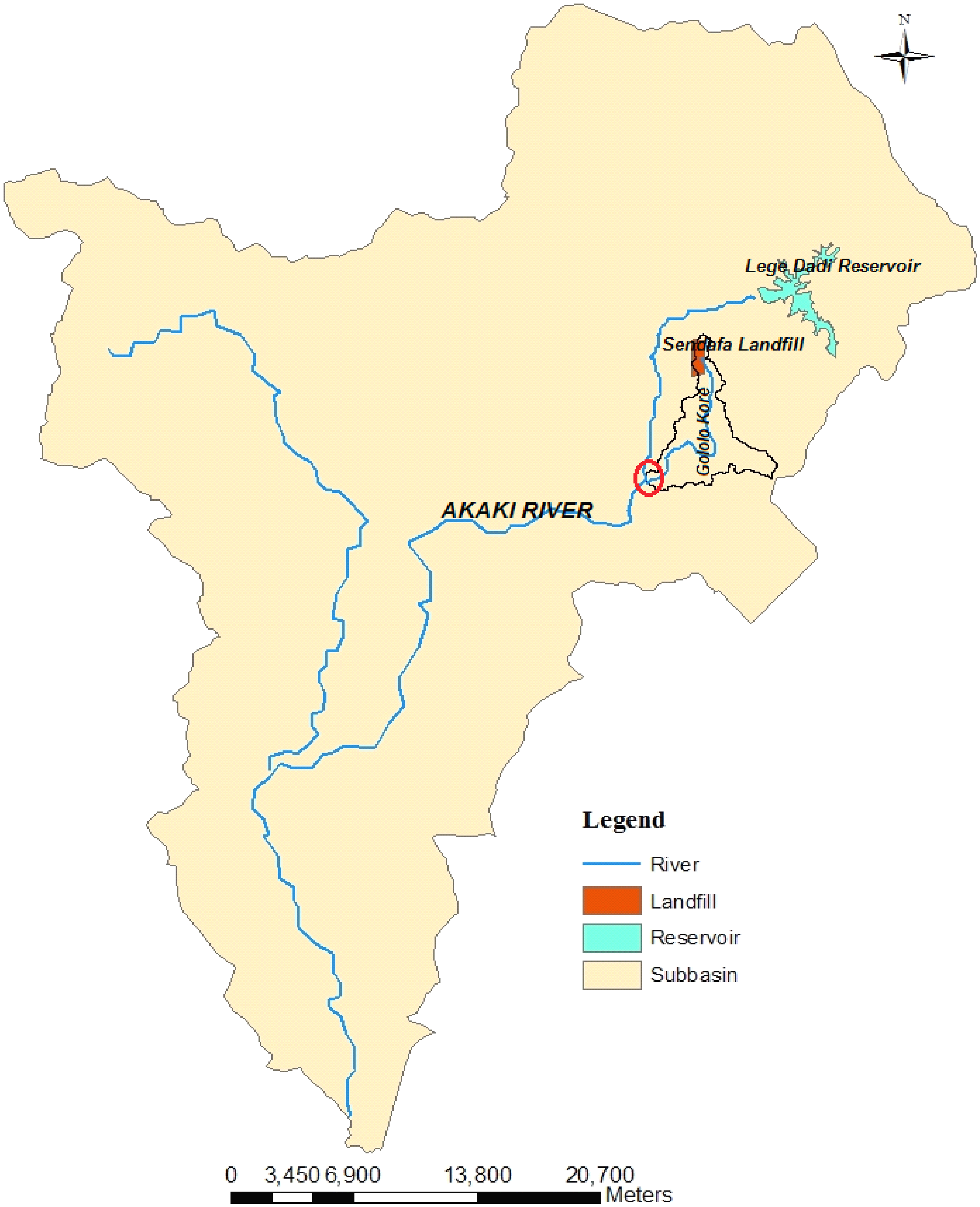


Figure 17: Akaki Catchment - Akaki River - Study Area - Gololo Kore Watercourse - Sendafa Landfill

Based on the outcomes of the terrain preprocessing and the definition of subbasin outlet (confluent point of Akaki river with Gololo Kore watercourse), HEC-GeoHMS delineates the project area.

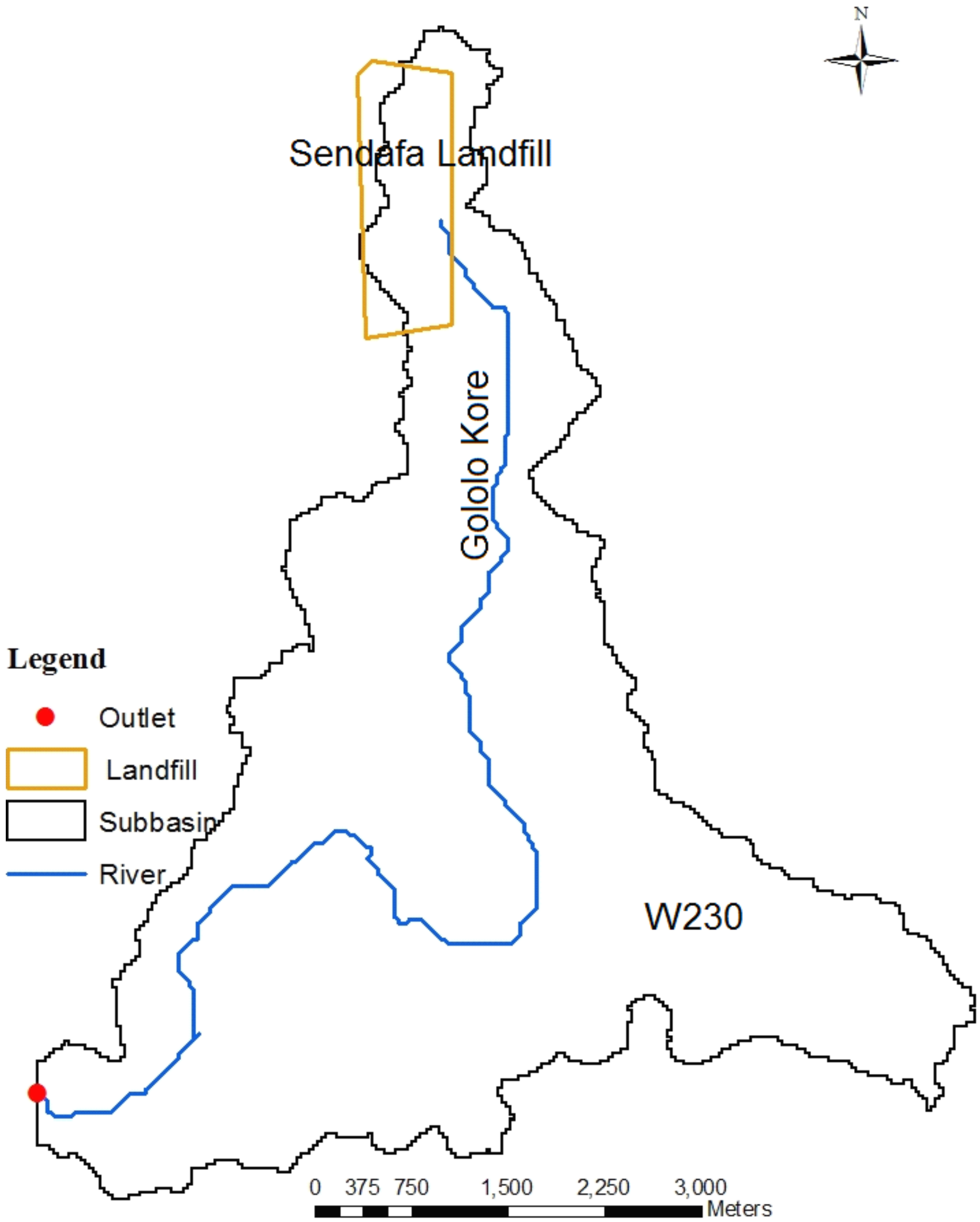


Figure 18: Catchment in the Study Area Delineated using HEC-GeoHMS

3.1.3.2 Basin Properties (HEC-GeoHMS)

Physiographic variables used to describe the characteristics of the subbasin include drainage area, basin length, and basin slope.

Table 7: Basin Properties for the Study Sub basin generated by HEC-GeoHMS

Sub basin Name	***Drainage Area (km^2)***	***Basin Length (km)***	***Basin Slope***
W230	*24.46*	*43.23*	*7.83*

3.1.4 Effects of Extreme Storm Events on Leachate Generation

Under extreme storm events, the volume of leachate generated from the landfill depends on the size of the landfill, absorption capacity of the waste and recurrence interval of the storm event. The frequency, intensity and duration of storms are potentially serious because they can transport contaminants from the landfill to the surrounding water resource.

In this section, meteorological data analysis was used to investigate the impact of different storm events on leachate production (Table 14) and water balance calculations were performed to predict the maximum volume of leachate generated.

3.1.4.1 Meteorological Data Analysis for Water Balance Calculations

The meteorological component is the computational element by means of which precipitation input for water balance calculations was determined.

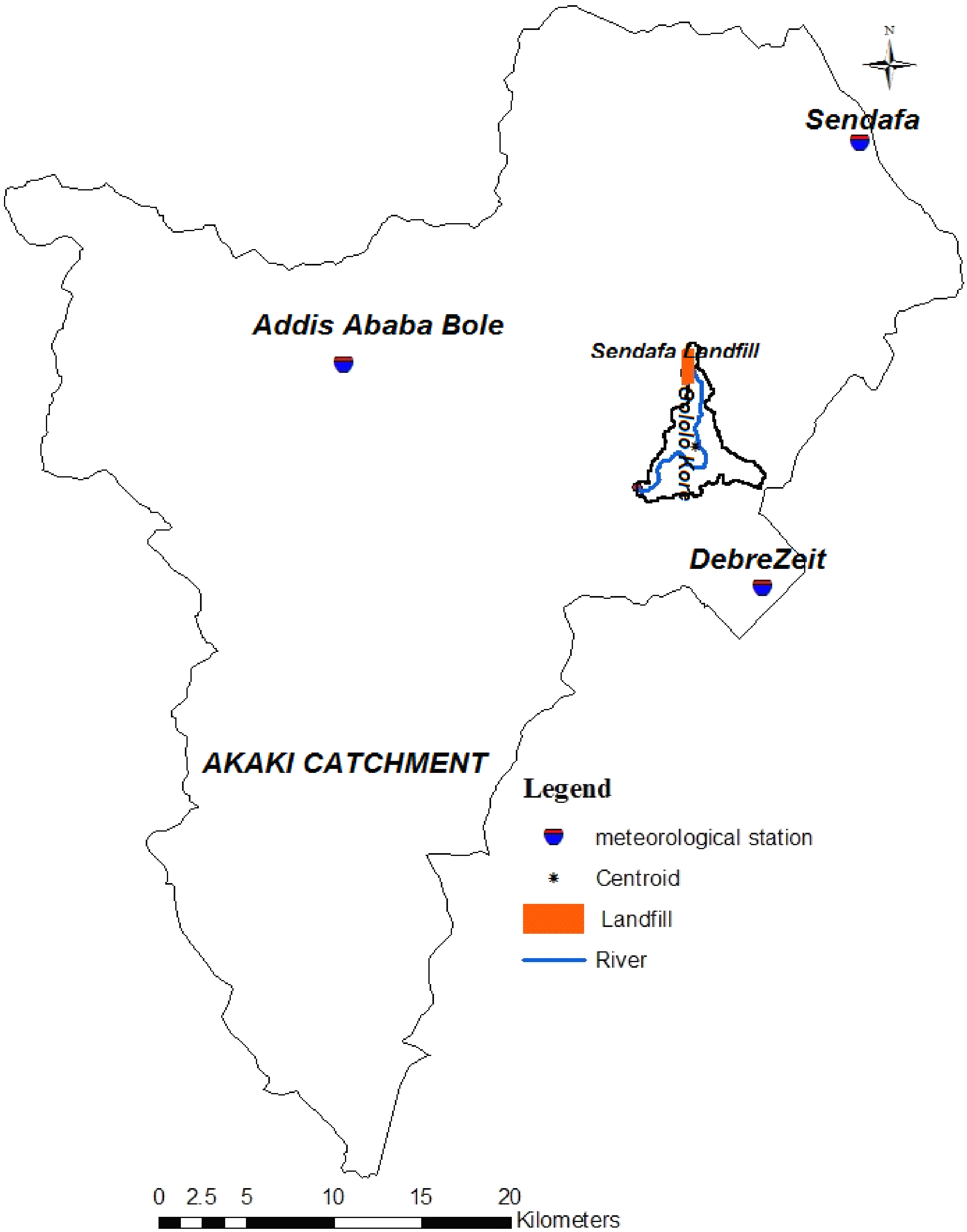


Figure 19: Representative Gauges to Sendafa Landfill

Table 8: Study Area Gauging Station Details (Source: Ministry of Water Resource and Energy)

Gauging Station	*Latitude*	*Longitude*	*Distance from Sendafa site (km)*	*Elevation (m) (a.m.s.l)*
AA Bole Station	9°02'N	38°45'E	19.6	2324
Debre Ziet Station	8°55'N	38°58'E	13.6	1955
Sendafa Station	9°09'N	39°01'E	16.1	2560

3.1.4.1.1 Estimation of Missing Precipitation Records

For this study, the monthly rainfall data between 1964 to 2013, a period of 50 years, were used. However, gauge records with a continuous 50 year of record are not available. Some data were missed in the records used for this research.

Deterministic spatial interpolation technique such as the inverse-distance weighting method is most commonly used for estimation of missing data. The weighting distance method used in this research for estimation of missing value of an observation, θ_m, using the observed values at other stations is given by:

$$\theta_m = \frac{\sum_{i=1}^{n} \theta_i d_{m,i}}{\sum_{i=1}^{n} d_{m,i}} \quad \text{.......} (29)$$

Where,

θ_m = the observation at the base station m

n = the number of stations

θ_i = the observation at station i

$d_{m,i}$ = the distance from the location of station i to station m

3.1.4.1.2 Data Analysis of Recorded Rainfall

Monthly rainfall data for three stations around the study area, Addis Ababa Bole, Debre Ziet and Sendafa stations were collected from National Meteorological Agency.

In this research, monthly rainfall was used to describe the seasonal evolution of rainfall in the study area.

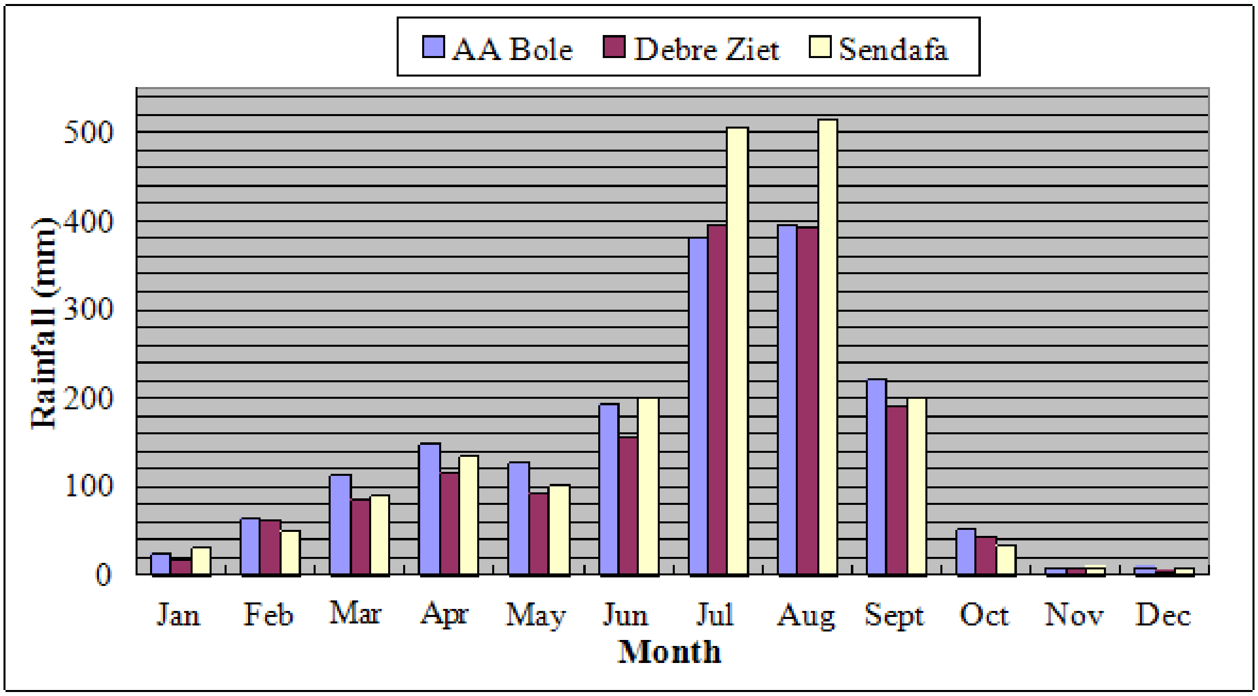


Figure 20: Monthly Rainfall for Addis Ababa Bole, Debre Ziet and Sendafa Stations during 1964 - 2013 (Source: National Meteorological Agency)

Figure 20 shows the monthly precipitation for Addis Ababa Bole, Debre Ziet and Sendafa stations based on the gauge observations from 1964 - 2013. Generally, maximum rainfalls occur in about two months from July to August while the driest period of the year is between November and January. A relatively high precipitation was observed in Sendafa area for the two wettest months.

Table 8: Mean Monthly Rainfall in mm at the Three Stations

Station	Recorded Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AA Bole	1964-2013	15.1	36.5	70.1	89.6	79.7	116.2	236.9	245.2	133.5	32.4	5.8	6.8
DebreZeit	1964-2013	10.5	34.9	53.3	70.1	57.3	92.7	244.6	243.5	114.4	26.1	5.3	4
Sendafa	1964-2013	18.6	28.4	55.5	80.6	62.6	119.9	313.4	319.6	120	21	6.6	6.1
AVERAGE		14.7	33.3	59.6	80.1	66.5	109.6	265	269.4	122.6	26.5	5.9	5.7

In order to determine variability of the maximum rainfall data and spatial distribution of these data, a detailed analysis was required. One month rainfall duration was used. Once the three sets of rainfall gauge records for one month duration were obtained, they would be used in determining the maximum rainfall over the period of record with respect to spatial location of the rain gauge stations. The maximum rainfall depths for one month duration for the three gauges show variability. A frequency analysis of the maximum rainfall data for one month duration was performed. The result is presented in the following figure;

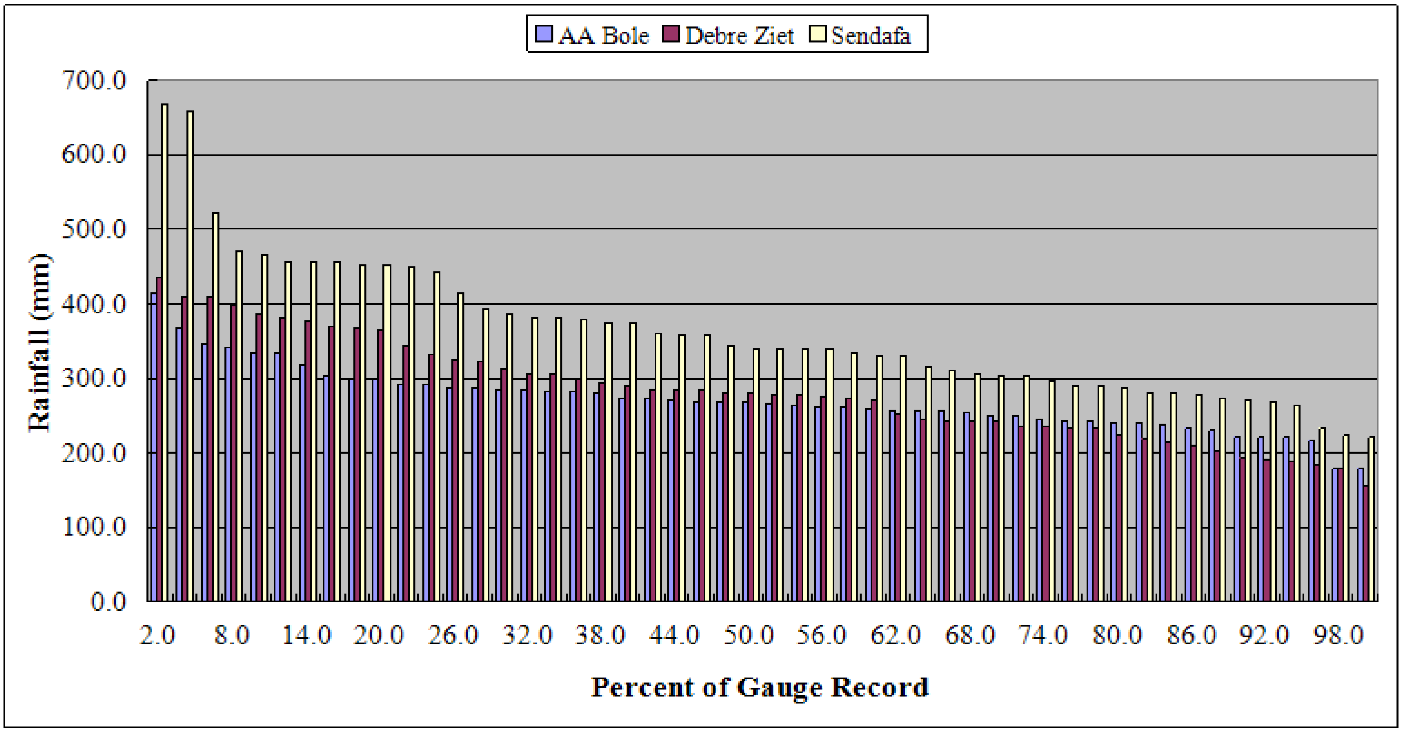


Figure 20: Monthly maximum recorded rainfall for Addis Ababa Bole, Debre Ziet and Sendafa Stations during 1964 - 2013 (Source: National Meteorological Agency)

Table 9: Percent of Gauge Records with Maximum Monthly Recorded Rainfall during 1964 - 2013

Rainfall (mm) (equal to or greater than)	Percent of Gauge Records		
	A. A Bole	Debre Ziet	Sendafa
250	68	42	94
300	14	34	72
400	2	6	28
500	0	0	6
600	0	0	4

3.1.4.1.3 Checking Consistency of Precipitation Records

Precipitation records are affected by works of man. Moreover, records of precipitation are often longer than records of other hydrologic data. For these reasons, precipitation records should be tested by double mass curve technique to ensure that any trends detected are due to meteorological causes and not to changes in gauge location, in exposure, or in observational methods. Double mass curve technique was used for testing consistency of precipitation data on seasonal basis.

The mean monthly records of the Addis Ababa Bole, Aleltu, Chancho, Debre Zeit and Sendafa stations were tabulated and cumulated in chronological order as in Appendix 2. The mean of the cumulative precipitation shown in the last column of Appendix 2 is the pattern for testing the individual station records. The cumulative precipitation for each station was then plotted against the cumulative precipitation of the pattern shown in Figure 21.

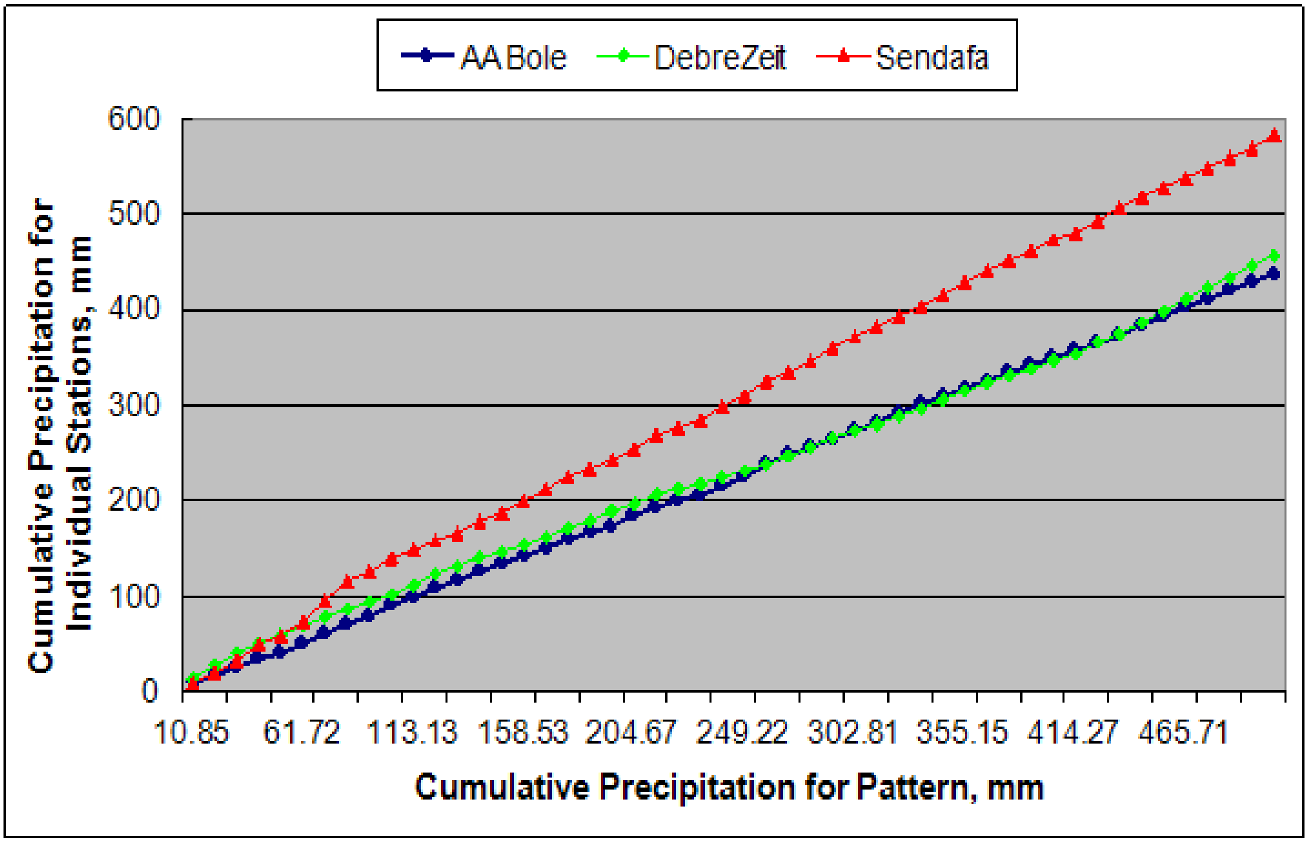


Figure 21: Double Mass Curve for Precipitation Data

The double mass curve for the Sendafa station shows a break in slope at the year 1970. The double mass curve for the Addis Ababa Bole and Debre Zeit stations which are unbroken straight line with a slope of 0.86 and 0.89 respectively, indicate that the record is consistent although the points scatter slightly on both sides of the line.

The theory of the double mass curve suggests the method of adjusting inconsistent record. Under adjustment is preferable to over adjustment. The observed data for 1970 - 2013 were adjusted by multiplying them by the ratio of the slope of the double-mass curve for 1970 - 2013 to the slope for 1964 - 1970, or

$$P_a = \frac{b_a}{b_o} P_o \qquad (30)$$

Where,

Pa = adjusted precipitation

Po = observed precipitation

ba = slope of graph to which records are adjusted

bo = slope of graph at time Po was observed

Table 10: Adjusted Precipitation Data for Sendafa Station

Year	1964	1965	1966	1967	1968	1969	1970
$P_{original}$	9.0	10.6	12.7	16.9	9.3	15.0	21.5
$P_{adjusted}$	7.4	8.7	10.4	13.8	7.6	12.3	17.6

3.1.4.1.4 Probability Distribution for Rainfall Analysis

Statistical procedures were employed for estimating rainfall and were used in the study for further analysis. The frequency storm method was used to produce a frequency storm from statistical precipitation data for the prediction of maximum leachate runoff from landfill site. The method requires probability, output type, storm duration, storm area and precipitation depth values as input.

Table 11: Summary of Statistics for Mean Monthly Rainfall (1964-2013)

Parameters	**STATIONS**		
	A. A. Bole	**Debre Zeit**	**Sendafa**
Sample Size	50	50	50
Mean Value, $\bar{x}$ (mm)	8.75	9.128	11.32
Standard Deviation, σ (mm)	1.41	2.226	2.825
Skewness Coefficient, G	0.73	0.34	1.04
Coefficient of Variation, Cv	0.16	0.25	0.25
Maximum (mm)	13.3	14	21.5
Minimum (mm)	5.8	5.03	7.4

It is necessary to establish a probability distribution that provides a good fit to the rainfall data. The probability distributions exponential, normal, Weibull, Pearson, Gumbel, and Generalized Extreme Value (GEV) were identified to evaluate the best fit probability distribution for rainfall. Chi-square test was used for the selection of the best fit probability distribution.

The Chi-Squared statistics is defined as:

$$x^2 = \sum \frac{(O-E)^2}{E} \quad \text{.......} (31)$$

Where,

O = observed frequency

E = expected frequency

The goodness of fit test mentioned above was fitted to the maximum rainfall data in order to determine the best - fit model at each station. Accordingly, the ranking of different probability distributions were marked from 1 to 6 based on minimum test statistic value. A distribution is awarded a six (6) score for a test if the test indicates that there is a significant difference between the rainfall values estimated by the distribution model and the observed rainfall data.

Table 12: Goodness of Fit Summary

No.	**Distribution**	**Chi - Square for Stations**					
		A.A. Bole	**Rank**	**DebreZeit**	**Rank**	**Sendafa**	**Rank**
1	Exponential	0.90	3	2.49	4	1.8	2
2	Gumbel	0.37	1	0.61	1	0.68	1
3	Normal	0.61	2	0.68	2	2.36	3
4	Weibull	1.50	5	3.57	5	7.21	5
5	Pearson Type III	1.19	4	2.33	3	5.38	4
6	Generalized Extreme Value	2.8	6	10.53	6	8.13	6

Table 13: Selected Model for the Mean Monthly Rainfall

STATION	**Best - Fit Model**
A. A. Bole	Gumbel
Debre Zeit	Gumbel
Sendafa	Gumbel

Gumbel's distribution which is one of the probability distribution was used to model the annual maximum precipitation of the study area for a period of 50 years (1964 to 2013). The primary focus of the application is on engineering problems in particular in modeling of meteorological phenomena.

Statistical analyses were performed for the return periods of 2, 5, 10, 50, 100 and 200 years, corresponding to 50, 20, 10, 2, 1, 0.5 percent exceedance probabilities, respectively.

3.1.4.1.5 Extreme Rainfall Frequency Calculation using Gumbel's Distribution

The monthly rainfall data for the study area from 1964 - 2013 (50 years rainfall data) were obtained from National Meteorological Agency (NMA) and subjected to frequency analysis applying the Gumbel's distribution. The design precipitation for the study area was estimated for 2, 5, 10, 50, 100, 200 years return period for mean monthly maximum rainfall using Gumbel's distribution as given by Ven Te Chow (1988). The annual peak rainfall data of the Addis Ababa Bole (Table A1-1) , Debre Ziet Air Force (Table A1-2) and Sendafa (Table A1-3) stations obtained from the monthly rain gauge measurement carried out from 1964 - 2013 were used to calculate expected rainfall in the study area using the equation:

$$X_T = \overline{X} + K.S_x \qquad (32)$$

Where,

$\overline{X}$ Is mean of the population

S_x is standard deviation of the population

K is frequency factor depending on a certain return period T, K is computed using:

$$K = \frac{-\ln\left[\ln\left(\frac{T}{T-1}\right)\right] - 0.5772}{1.2825} \qquad (33)$$

Table 14: Expected Mean Monthly Rainfall on Addis Ababa (Bole), Debre Ziet, Sendafa Stations

Return Period (T) in years	Expected Rainfall on Stations			Average Rainfall
	Addis Ababa Bole	Debre Ziet	Sendafa	
2	8.11	8.12	10.04	8.76
5	9.40	10.16	12.64	10.73
10	10.26	11.52	14.36	12.05
50	12.15	14.50	18.14	14.93
100	12.95	15.76	19.74	16.15
200	13.74	17.02	21.33	17.36

For this study, 1 - in-10, 1- in -100 and 1- in- 200 year storm events were used to calculate the probable leachate generation from the landfill site.

3.1.4.2 Meteorological Data Analysis for Hydrologic Analysis

3.1.4.2.1 Gauge Weight Method

This study used inverse distance gauge weight method to account for rain gauge distribution. This was used to estimate average basin rainfall. For precipitation gauge input data the most representative rain gauges for the subbasin were selected and weights of each gauge were computed externally via inverse distance squares (i.e. the weights being reciprocal to the square distances from the unsampled location). The inverse distance method is useful when the observed rainfall data contains missing values that should not be set to zero (USACE, 2001). Since the daily rainfall records available for the study area contain some portions of missing values, this method was adopted.

The spatial locations of the rain gauge stations used in this research are shown in Figure 19 and their respective maximum daily rainfall records during the years 1985 - 2014 are presented in Table A1-4.

Table 15: Study Area Gauging Station Details (Source: Ministry of Water Resource and Energy of Ethiopia)

Gauging Station	*Latitude*	*Longitude*	*Distance from the centroid of the study subbasin (km)*	*Elevation (m) (a.m.s.l)*
AA Bole Station	9°02'N	38°45'E	20.5	2324
Debre Ziet Station	8°55'N	38°58'E	9.05	1955
Sendafa Station	9°09'N	39°01'E	19.9	2560

Weights of each gauge were found using the equation,

$$Wi = \frac{1/di^2}{\sum_{i=1}^{n} 1/di^2} \quad \text{.. (34)}$$

Where,

Wi - weight of i[th] rain gauge

di - distance of i[th] rain gauge to centroid

n - number of gauges

Centroid of the subbasin was found by HEC-GeoHMS. The weight distributions of the rain gauges in the study area are as follows:

Table 16: Basin Precipitation Gauge Weights

Sub basin	***Gauge Weights***		
	AA Bole Station	***Debre Ziet Station***	***Sendafa Station***
W230	0.124	0.680	0.196

Table 17: Extent of Missing Daily Rainfall Data

Gauging Station	**Percent Missing Data from 1985 - 2014**
A. A Bole station	0
Debre Ziet Air Force station	18.89
Sendafa station	14.17

For the purpose of hydrologic analysis, one day duration rainfall was used to determine the maximum rainfall over the period of 30 years with respect to spatial location of the rain gauge stations. One day rainfall duration was used because of its availability. A frequency analysis of the maximum rainfall data for one day duration was performed and the maximum rainfall depths for the three gauges show variability. The result is presented in Figure 22.

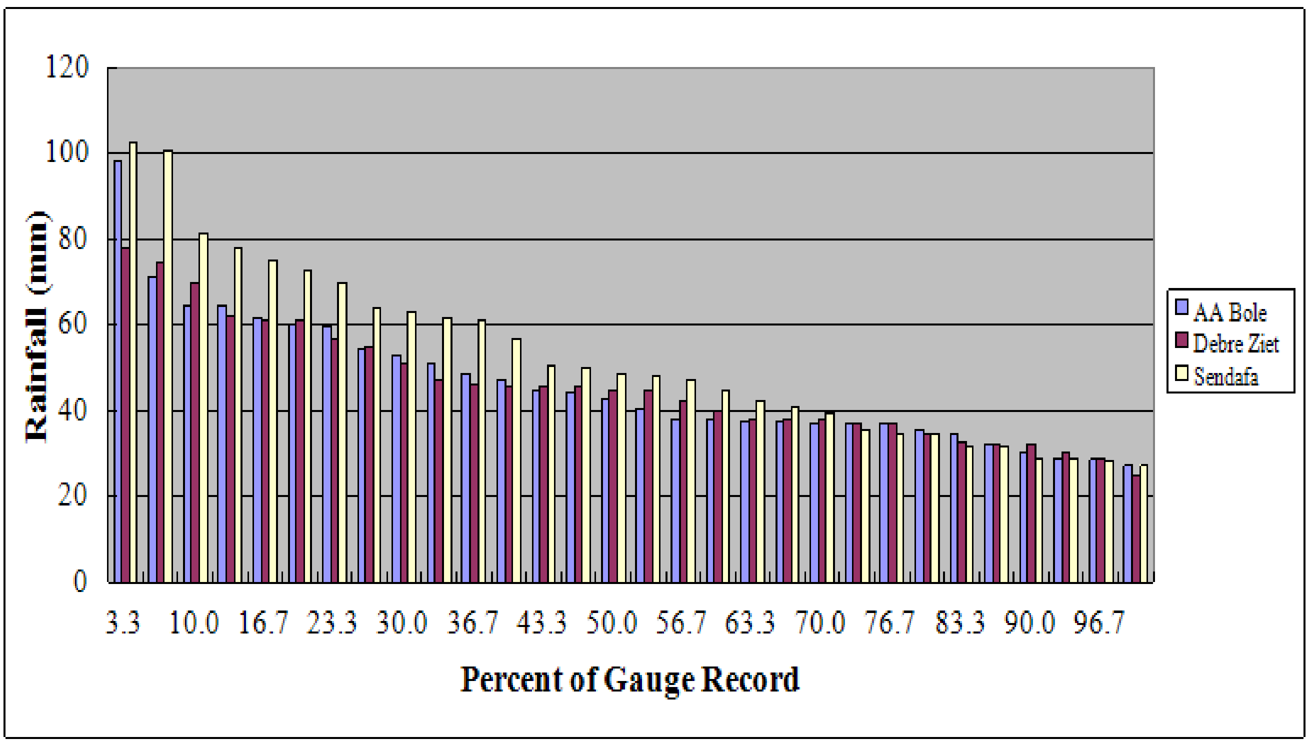


Figure 22: One day maximum recorded rainfall for Addis Ababa Bole, Debre Ziet and Sendafa Stations during 1985 - 2014 (Source: National Meteorological Agency)

Table 18: Percent of Gauge Records with Maximum Recorded Rainfall during 1985 - 2014

Rainfall (mm) (equal to or greater than)	Percent of Gauge Records		
	A. A Bole	Debre Ziet	Sendafa
30	90	93	87
40	53	57	67
60	23	20	37
80	3	0	10
100	0	0	7

3.1.4.2.2 Frequency Storm Method for Hydrologic Analysis

Frequency storm method involves the estimation of greatest rainfall depth for various recurrence intervals. For drainage areas in Ethiopia, the rainfall intensity can be calculated at any required time using the 24hr rainfall depth, which is known as a rainfall intensity-duration-frequency (IDF). Ethiopia is divided into eight hydrological regions displaying similar rainfall patterns (ERA Revised Drainage Design Manual, 2012) as shown in Figure 23.

The study area is found in A2 zone. However, this information is reviewed with the available data up to 2010, and further data may indicate the need for a further refinement in both values and regional boundaries (Revised Ethiopian Road Authority Drainage Manual, 2012).

Table 19: 24 hours Rainfall Depth Vs Frequency (ERA Revised Drainage Design Manual, 2012)

24 hr Rainfall Depth (mm) vs Frequency (yr)								
Return Period Years	**2**	**5**	**10**	**25**	**50**	**100**	**200**	**500**
RR-A1	50.30	66.02	76.28	89.13	98.63	108.06	117.48	130.00
RR-A2	51.92	65.52	74.45	85.70	94.07	102.45	110.91	122.27
RR-A3	47.54	59.61	67.66	77.92	85.62	93.34	101.13	111.58
RR-A4	50.39	63.83	72.28	82.55	89.97	97.20	104.32	113.63
RR-B1	58.87	71.26	79.29	89.35	96.84	104.37	112.02	122.41
RR-B2	55.26	69.95	79.68	92.03	101.29	110.61	120.07	132.87
RR-C	56.52	71.04	80.54	92.52	101.48	110.50	119.66	132.06
RR-D	56.23	76.84	90.37	107.46	120.23	133.05	146.00	163.44

Note: RR - Rainfall Region

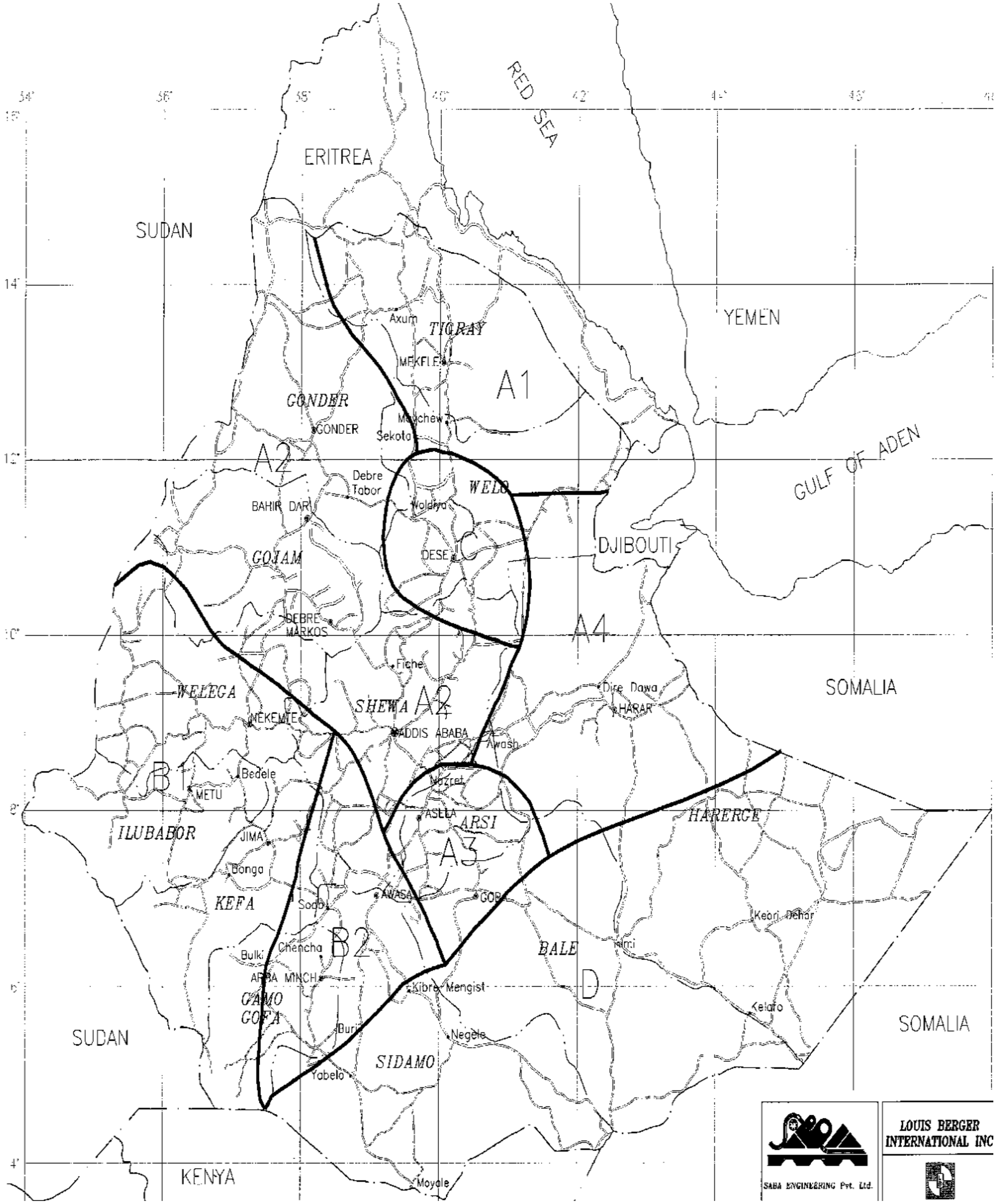


Figure 23: Rainfall Regions (Source: Revised Ethiopian Road Authority Drainage Manual, 2012)

Gumbel's distribution was used to model the annual maximum precipitation of the study area for a period of 30 years (1985 to 2014) for the return periods of 2, 5, 10, 50, 100 and 200.

Table 20: Expected Rainfall on Addis Ababa (Bole), Debre Ziet and Sendafa Stations

Return Period (T) in years	Expected Rainfall on Stations		
	Addis Ababa Bole	Debre Ziet	Sendafa
2	42.558	43.605	49.227
5	54.898	55.718	67.643
10	63.068	63.738	79.836
50	81.050	81.390	106.672
100	88.652	88.852	118.017
200	96.226	96.286	129.320

The expected rainfalls for different storm events that were obtained from ERA intensity-duration-frequency curve and the ones calculated using Gumbel's distribution were close to each other. However, the results obtained using Gumbel's distribution were based on updated data and were chosen for runoff calculation. For this study, 1 - in-10, 1- in -100 and 1- in- 200 year storm events were used to calculate excess runoff from the landfill site.

3.1.4.2.3 Design Storm

The main input data for the calculation of incremental design storm distribution with a specified return period was the total storm duration, the precipitation depths for a number of given durations within the total storm duration, the position of highest intensity within the storm and the storm area.

The peak discharge was also assumed to be the critical parameter in hydrologic modeling because it is the point where maximum release of contaminated runoff is likely to occur at the confluence of Gololo Kore watercourse with Akaki River. The 10 years, 100 years, 200 years return period, one day annual maximum rainfall for the three rain gauges were converted into incremental rainfall because hourly rainfall data were not available.

The actual duration of a one day rainfall is much less than 24 hour. For this reason, two options were considered for meteorological modeling:

i. Assuming a one day rainfall to have occurred over 24 hour period

ii. Assuming a one day rainfall to have occurred over 6 hour period

Therefore, the annual maximum daily rainfall was changed into incremental rainfall for the three rainfall stations. For the purpose of this study, in order to distribute the rainfall data into hourly time step, equation from similar studies in the same hydrological region was adopted.

$P = M * \sqrt{T}$ .... (35)

Where P is the total rainfall,

T is rainfall duration

M is a constant

Using the known precipitation values and their durations in the equation, it was possible to determine the M values for each one of the precipitation durations.

Besides the total duration of the storm, also the position of maximum intensity had an influence on the peak discharge. For this reason, the 200 year 24 hr storm was created with 33%, 50% , 67% position of the maximum intensity and gives maximum peak discharge of 48.74 m^3/s, 58.42m^3/s, 63.97m^3/s respectively. Therefore, an intensity position of 67% was chosen because the resulting hyetograph was proven to cause the highest peak discharge at the outlet of the watershed while still having realistic rainfall intensity distributions.

I. Using 24 hours Duration Storm

Addis Ababa (Bole) Rainfall Station

The 10 years, 100 years, 200 years return period daily maximum rainfall were 63.068mm, 88.652 mm, 96.226mm respectively.

M_{10} = 12.87 mm/hr M_{100} = 18.1 mm/hr M_{200} = 19.64 mm/hr

The 24 hours incremental rainfall for the AA Bole rainfall station for 10 years, 100 years and 200 years return period daily maximum rainfall is given in Table A1-5.

Debre Ziet Rainfall Station

The 10 years, 100 years, 200 years return period daily maximum rainfall were 63.738mm,88.852mm, 96.286mm respectively.

M_{10} = 13.01 mm/hr M_{100} = 18.14 mm/hr M_{200} = 19.65 mm/hr

The 24 hours incremental rainfall for the Debre Ziet rainfall station for 10 years, 100 years and 200 years return period daily maximum rainfall is given in Table A1-6.

Sendafa Rainfall Station

The 10 years, 100 years, 200 years return period daily maximum rainfall were 79.836mm, 118.017 mm, 129.320mm respectively.

M_{10} = 16.30 mm/hr M_{100} = 24.09 mm/hr M_{200} = 26.4 mm/hr

The 24 hours incremental rainfall for the Sendafa rainfall station for 10 years, 100 years and 200 years return period daily maximum rainfall is given in Table A1-7.

II. Using 6 hours Duration Storm

Addis Ababa (Bole) Rainfall Station

The 10 years, 100 years, 200 years return period daily maximum rainfall were 63.068mm, 88.652mm, 96.226mm respectively.

M_{10} = 25.75 mm/hr M_{100} = 36.19 mm/hr M_{200} = 39.28 mm/hr

The 6 hours incremental rainfall for the AA Bole rainfall station for 10 years, 100 years and 200 years return period daily maximum rainfall is given in Table A1-8.

Debre Ziet Rainfall Station

The 10 years, 100 years, 200 years return period daily maximum rainfall were 63.738mm,88.852mm, 96.286mm respectively.

M_{10} = 26.02 mm/hr M_{100} = 36.27 mm/hr M_{200} = 39.31 mm/hr

The 6 hours incremental rainfall for the Debre Ziet rainfall station for 10 years, 100 years and 200 years return period daily maximum rainfall is given in Table A1-9.

Sendafa Rainfall Station

The 10 years, 100 years, 200 years return period daily maximum rainfall were 79.836mm, 118.017 mm, 129.320mm respectively.

M_{10} = 32.59 mm/hr M_{100} = 48.18 mm/hr M_{200} = 52.79 mm/hr

The 6 hours incremental rainfall for the Sendafa rainfall station for 10 years, 100 years and 200 years return period daily maximum rainfall is given in Table A1-10.

The incremental rainfall for 1-in-10 years, 1-in-100 years and 1-in-200 year's storm events were used as input to HEC-HMS for watershed runoff modeling.

3.1.5 Estimation of Contaminated Runoff

Estimating runoff from excess rainfall on the study subbasin was a major step in the assessment of potential risk. This is due to the fact that runoff is the path way by which contaminants from the landfill migrate to the surrounding surface water network.

SCS (Natural Resources Conservation Service) Curve Number method was used to handle infiltration loss in this research. For the rainfall-runoff transformation process SCS unit hydrographs were used. To reflect the spatial characteristic of precipitation this study employs the gauge weight precipitation method via inverse distance square under specific hydrological event periods of 10 years, 100 years and 200 years.

3.1.5.1 Precipitation Loss

SCS Curve Number method was selected to consider the time distribution of the rainfall, the losses to interception and depression storage, and an infiltration rate that decreases during the course of a storm. The SCS method was chosen for this analysis because it is most suited for computing flood peaks and runoff volumes for catchments smaller than $65km^2$, with slopes of less than 30% and a time of concentration (Tc) less than 10 hours (ERA, 2012).

SCS Curve Number method also features environmental inputs and it accounts for many of the factors affecting runoff generation, incorporating them in a single CN parameter. Due to these facts and for the availability of the data, SCS CN method was adopted for this study.

The curve number is a hydrologic parameter used to describe the storm water runoff potential for drainage area as function of land use and soil type. The first step in the estimation of the CN is the determination of land use in the subbasin. Arc GIS compatible shape file showing the Awash Basin land cover was developed by MoWE in which the study subbasin is described as cropland with shrub land. Cropland includes areas used for production of adapted crops for harvest. The cover type was defined based on the comparison of the major land cover as listed in the CN table (Appendix 3) and the observed vegetation cover on site. The next step was to categorize the soils in the watershed into one of the possible hydrologic soil groups (HSGs). The lithologies in the study area are low to moderately permeable (GSE, 2012); therefore, the soil is classified into HSG C. Curve number for the corresponding land cover type and hydrologic soil group are presented in Appendix 3. In this case it was found reasonable to take a curve number of 87.

3.1.5.2 Transforming

After the precipitation losses were accounted, a transform method was specified for transforming overland flow into surface runoff. Due to simplicity and ease to use SCS hydrograph method have been used for this study to transform the excess precipitation into a flow hydrograph at the outlet of the subbasin.

The main input parameter for SCS hydrograph method is the basin lag time of the study subbasin. Basin lag time is the time from the center of mass of excess precipitation to the center of mass of the corresponding runoff. In this method, the basin lag was approximated to be 0.6 times the time of concentration. The determination of the time of concentration was done based on the methodology described in Technical Release 55 (TR-55) which was integrated into the HEC-GeoHMS 5.0 software environment.

Table 21: Basin Lag Calculation according to TR-55 method (HEC-GeoHMS)

Sub basin Name	Drainage Area (km^2)	Flow Length (km)	Basin Slope (%)	Channel Slope (%)	Land use/ Land cover	Basin CN	Basin Lag (min)
W230	24.46	14.74	8.76	1.76	Cropland with Shrub land	87	120

3.1.5.3 Base flow

For large watersheds with contribution from groundwater flow and for watershed with year-round precipitation, the contribution to base flow may be significant and should not be ignored however, in small, seasonal streams as in the case of this research the base flow contribution is negligible (Gonzales et. al., 2009).

3.1.6 Hydrologic Modeling using HEC-HMS

After the completion of the basin model with HEC - GeoHMS, the model was exported into a HEC-HMS project file. The model consists of a basin and the main outlet.

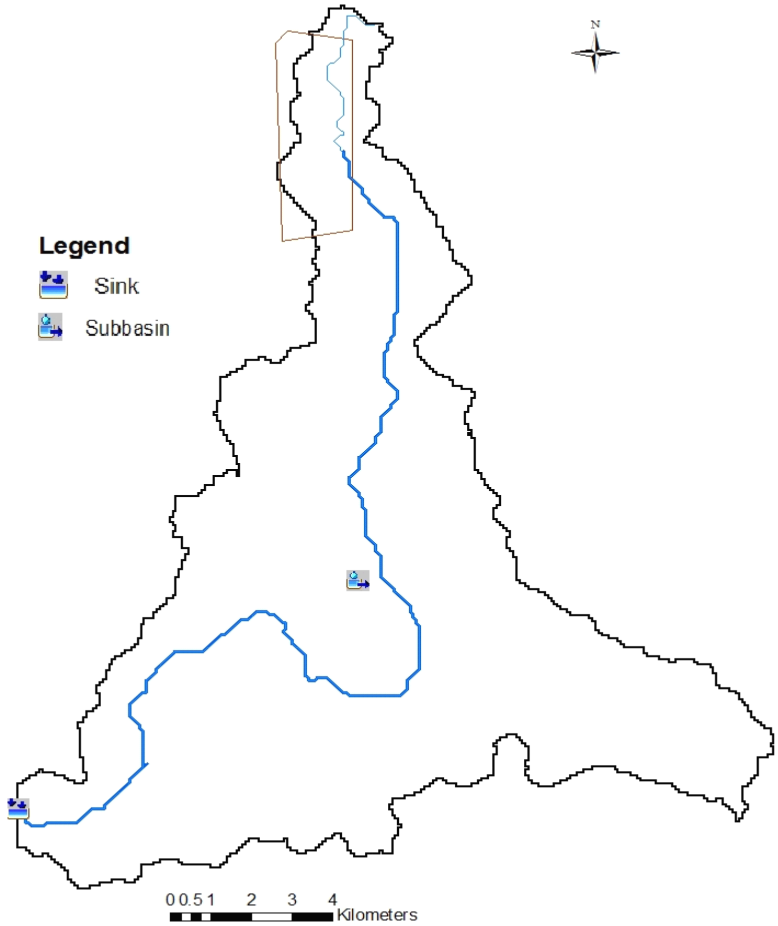


Figure 24: Model Representation of the Study Watershed in HEC-HMS

The performance of rainfall - runoff simulation in HEC - HMS requires basin model, meteorological model and the control specifications. The meteorological model is the representation of rainfall in the model in the form of a storm hyetograph with a defined start and end time. The control specifications define the beginning and end date of the simulation run as well as the computational time step. The computational time step is suggested to be smaller than 0.29 times the smallest basin lag time (HEC, 2000). Therefore, it was chosen as 20 minutes. The main data required for rainfall-runoff modeling was the DEM, incremental rainfall from meteorological analysis, land use and soil type data.

Hydrologic modeling was performed in order to get maximum flow from Gololo Kore watercourse for storms with various statistical return periods. The rainfall-runoff from the study area was simulated using 10 years, 100 years and 200 years return period rainfall and the current land use.

4 CHAPTER FOUR

4.1 RESULTS and DISCUSSIONS

In this chapter, the water balance and hydrologic modeling results are presented. The hydrologic model outputs are adjusted to observed flow and verified.

It is known that contaminated surface water bodies as a result of landfill site could raise potential danger to the environment. Therefore, the interaction of landfill site and surface water bodies and associated future challenges will be discussed in this section.

4.1.1 Water Balance Calculation

Leachate generation for each cell in Sendafa Landfill was carried out using the water balance calculation. Water balances were used to assess likely potential for leachate generation using 10 years, 100 years and 200 years return period storm. Penman Monteith equation was used to account for evapotranspiration loss. Evaporative losses are a combination of evaporation of water from the surface and transpiration of water by plants where vegetation is present. Transpiration due to vegetation was ignored for the purposes of water balance calculations on uncompleted landfills.

For water balances carried out on active phases of landfills, it was assumed that all the actual rainfall will infiltrate into the waste. In areas that have been restored an infiltration rate of 25% of the annual rainfall was used and evapotranspiration loss was accounted.

Table 22: Evapotranspiration Loss using Penman Monteith Equation

Month	T_{max} °c	T_{min} °c	Sunshine hrs|day	Wind Speed hrs|day	Humidity (%)	$e°(T_{max})$	$e°(Tmin)$	e_s	$e_a(RH)$	T	Δ	G	Radiation $MJ/m^2/d$	γ	ETo
Jan	23	7	8.1	3	50	2.81	1	1.91	0.96	15	0.123	-0.57	21.1	0.051	6.824
Feb	24	9	6.5	3	49	2.98	1.15	2.07	1.01	16.5	0.132	-0.38	21.3	0.051	7.113
Mar	25	10	7.3	3	54	3.17	1.23	2.2	1.19	17.5	0.139	0	21.3	0.051	6.972
Apr	24	11	5.9	3	58	2.98	1.31	2.15	1.25	17.5	0.136	-0.19	19.1	0.051	6.26
May	25	11	7.6	3	52	3.17	1.31	2.24	1.16	18	0.141	0.57	18.1	0.051	6.227
Jun	23	10	5.6	2	64	2.81	1.23	2.02	1.29	16.5	0.129	0.57	16.9	0.051	5.084
Jul	20	10	2.8	2	82	2.34	1.23	1.79	1.47	15	0.115	0	13.6	0.051	3.688
Aug	20	10	3.1	2	80	2.34	1.23	1.79	1.43	15	0.115	-0.19	15	0.051	4.123
Sep	21	10	5.2	2	74	2.49	1.23	1.86	1.38	15.5	0.119	0.171	16.9	0.051	4.714
Oct	22	8.1	8.1	3	57	2.64	1.08	1.86	1.06	15.05	0.12	0.019	17.2	0.051	5.489
Nov	23	7	8.7	3	58	2.81	1	1.91	1.11	15	0.123	0	19.5	0.051	6.025
Dec	23	7	9.7	3	54	2.81	1	1.91	1.03	15	0.123	-0.369	21.7	0.051	6.765
AVG		9.18	6.55	2.67	61	2.77	1.16	1.97	1.2	15.97	0.126	-0.031	18.475	0.051	**5.72**

Table 23: Water Balance Calculation for Sendafa Landfill for 10 Year Return Period

Active Phases	Active Area (m^2)	ActiveArea Infilt.(m^3/d)	Restord PhaseNo.	Restored Area(m^2)	Restord Infilt.(m^3) (25%infilt.)	Absorptive Capacity (m^3)	Total Water (m^3)
1a	80000	*964*		*0*	*0*	*0*	***964***
1b	80000	*964*	1a	*80000*	*183*	*0*	***1147***
1c	80000	*964*	1a, 1b	*160000*	*366*	*0*	***1330***
2a	75000	*904*	1a, 1b, 1c	*240000*	*549*	*0*	***1453***
2b	48000	*578*	1a, 1b, 1c,2a	*315000*	*720.6*	*0*	***1298.6***
3	85000	*1024*	1a, 1b, 1c,2	*363000*	*830.4*	*0*	***1854.4***
4a	75000	*904*	1a,1b,1c,2,3	*448000*	*1024.8*	*0*	***1928.8***
4b	53000	*638*	1a,1b,1c,2,3,4a	*523000*	*1196.4*	*0*	***1834.4***
4c	70000	*843*	1a,1b,1c,2,3,4	*576000*	*1317.6*	*0*	***2160.6***

Table 24: Water Balance Calculation for Sendafa Landfill for 100 Year Return Period

Active Phases	Active Area (m^2)	ActiveArea Infilt.(m^3/d)	Restord PhaseNo.	Restored Area(m^2)	Restord Infilt.(m^2) (25% infiltr.)	Absorptive Capacity (m^3)	Total Water (m^3)
1a	80000	*1292*		*0*	*0*	*0*	***1292***
1b	80000	*1292*	1a	*80000*	*265*	*0*	***1557***
1c	80000	*1292*	1a, 1b	*160000*	*530*	*0*	***1822***
2a	75000	*1211*	1a, 1b, 1c	*240000*	*795*	*0*	***2006***
2b	48000	*775*	1a, 1b, 1c,2a	*315000*	*1043.4*	*0*	***1818.4***
3	85000	*1373*	1a, 1b, 1c,2	*363000*	*1202.4*	*0*	***2575.4***
4a	75000	*1211*	1a,1b,1c,2,3	*448000*	*1484*	*0*	***2695***
4b	53000	*856*	1a,1b,1c,2,3,4a	*523000*	*1732.4*	*0*	***2588.4***
4c	70000	*1131*	1a,1b,1c,2,3,4	*576000*	*1908*	*0*	***3039***

Table 25: Water Balance Calculation for Sendafa Landfill for 200 Year Return Period

Active Phases	Active Area (m^2)	*ActiveArea Infilt.(m^3/d)*	Restord PhaseNo.	Restored Area(m^2)	*Restord Infilt.(m^2) (25%Infilt.)*	*Absorptive Capacity (m^3)*	*Total Water (m^3)*
1a	*80000*	*1389*		*0*	*0*	*0*	***1389***
1b	*80000*	*1389*	*1a*	*80000*	*105.6*	*0*	***1678.2***
1c	*80000*	*1389*	*1a, 1b*	*160000*	*211.2*	*0*	***1967.4***
2a	*75000*	*1302*	*1a, 1b, 1c*	*240000*	*316.8*	*0*	***2169.6***
2b	*48000*	*833*	*1a, 1b, 1c,2a*	*315000*	*415.8*	*0*	***1971.7***
3	*85000*	*1476*	*1a, 1b, 1c,2*	*363000*	*479.16*	*0*	***2788.2***
4a	*75000*	*1302*	*1a,1b,1c,2,3*	*448000*	*591.36*	*0*	***2921.5***
4b	*53000*	*920*	*1a,1b,1c,2,3,4a*	*523000*	*690.36*	*0*	***2810.6***
4c	*70000*	*1215*	*1a,1b,1c,2,3,4*	*576000*	*760.32*	*0*	***3297.2***

4.1.2 Hydrologic Model Calibration

The model was calibrated for the identified parameters to improve the agreement between the simulated and observed data. HEC-HMS computation results include information on peak flow and total volume. The watershed parameters used in HEC-HMS were SCS CN loss and the SCS UH transformation. The parameters were adjusted until the observed and simulated hydrograph were fitted well.

Each method in HEC-HMS has parameters. The values of these parameters should be entered as input to the model to obtain the simulated runoff hydrographs. In the presence of rainfall and runoff data the optimum parameters were found as a result of a systematic search process that yield the best fit between the observed runoff and the computed runoff.

It was very important to develop and use methods that are able to predict runoff resulted from rainfall in ungauged catchments. This was done by using flow data from the nearby gauging station. Due to lack of measured data in the study subbasin, the runoff data recorded in the Mutinicha station have been used to calibrate the model.

The Mutinicha Station which is located downstream of the Lege Dadi dam and near to the study subbasin was used due to the hydrological similarity with the study subbasin as assigned by the Ministry of Water, Irrigation and Energy and then the parameters were transferred to the study subbasin. Geographically, the Mutinicha station is located at 09°03' N and 38°55' E. Arc GIS compatible shape file showing the Awash Basin land cover developed by MoWIE described the subbasin for the Mutinicha station as cropland with shrub land and cropland with grassland Savanna. The lithologies in the area are low to moderately permeable. Curve number for the corresponding land cover type and hydrologic soil group are presented in Appendix 3. In this case it was found reasonable to take a curve number same as the study subbasin, 87.

The daily rainfall data of the watershed for the rainy season (June - September) for the year 2000 - 2002 were collected from Addis Ababa (Bole) and Sendafa stations which are located near to the watershed for the Mutinicha station. The weights of each gauge were computed externally via inverse distance squares. The daily runoff data of the watershed measured at the Mutinicha station for the rainy season (June - September) for the year 2000 - 2002 were also used for the calibration. Loss method and transform method similar to the study area were selected. The average of runoff data of the months February to May for the 3 years recorded data was taken as constant base flow.

Table 26: Basin Properties for the Mutinicha Catchment generated by HEC-GeoHMS

Sub basin Name	***Drainage Area (km^2)***	***Basin Length (km)***	***Basin Slope (%)***
Mutinicha	*112.32*	*74.53*	*12.77*

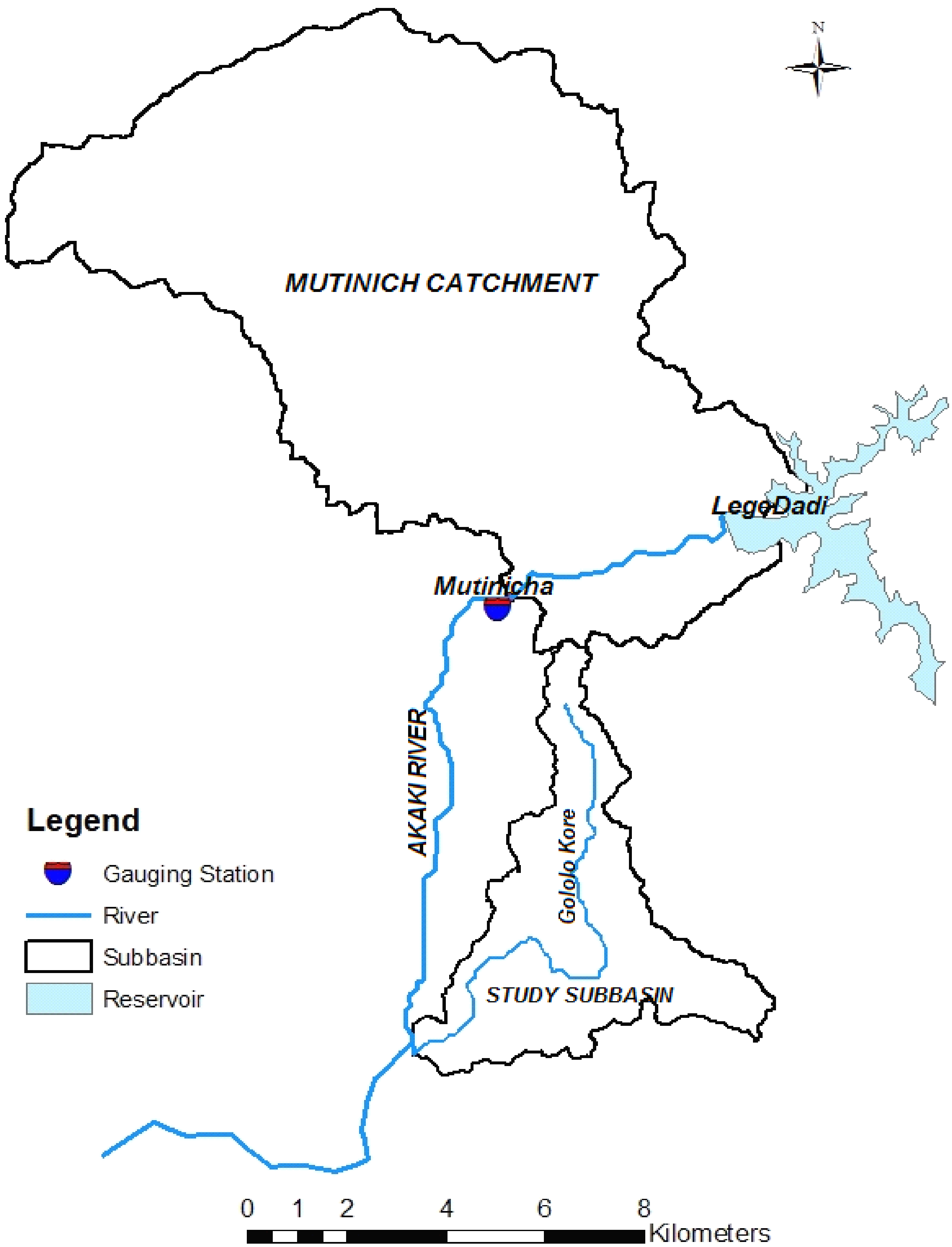


Figure 25: Location of Mutinicha Catchment

4.1.2.1 Sensitivity Analysis

Sensitivity analysis of the model was adopted to determine the important parameters which need to be precisely estimated to make accurate prediction of subbasin yield. Thus, at first the model was run with the model input values (the base data file), estimated by methods presented above and base output was collected. This was followed by varying each input parameter within prescribed range keeping the others constant and running the model. The output values were analyzed to determine their variations with respect to the base output set. Sensitivity analysis was performed for curve number, initial abstraction and lag time parameters.

4.1.2.1.1 Sensitivity Analysis for Initial Abstraction Parameter

The initial abstraction accounts for the interception and depression storage and represents basin initial condition and it is given as a function of curve number. In order to get the effect that the initial abstraction has on the modeling result, the curve number was increased/ decreased by $\pm 15\%$. Figure 26 shows the resulting hydrographs at the outlet of the study watershed generated from the 200 year 6 hour storm.

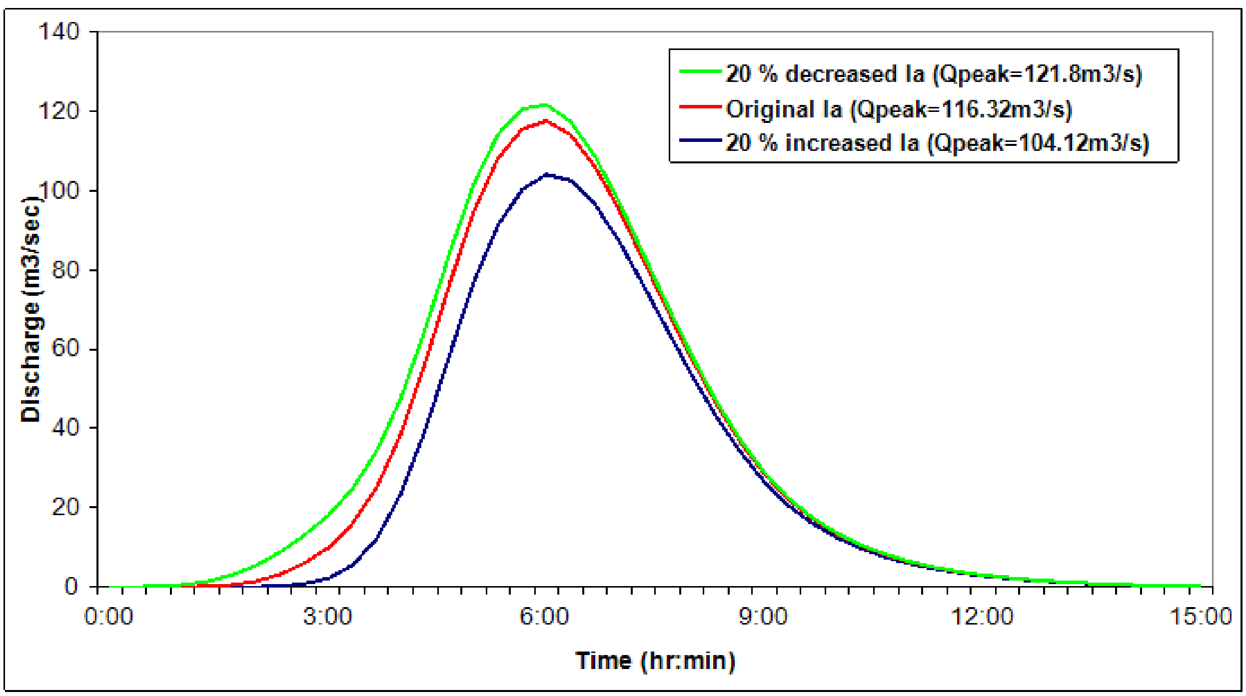


Figure 26: Comparison of hydrograph resulting from 15% increased & decreased initial abstraction

A 15% decrease of the initial abstraction of the study subbasin leads to a increase of the peak discharge of 4.7%. The 15% increase results in a decrease in peak discharge of 10.5%. Therefore, it can be expected that the deviation of the resulting peak discharges from the actual peak discharges is in the range of $\pm 10\,\%$.

4.1.2.1.2 Sensitivity Analysis for Curve Number Parameter

The stream flow hydrographs generated from the 200 year 6 hour storm where the curve number was adjusted by $\pm 15\%$ is shown in Figure 27.

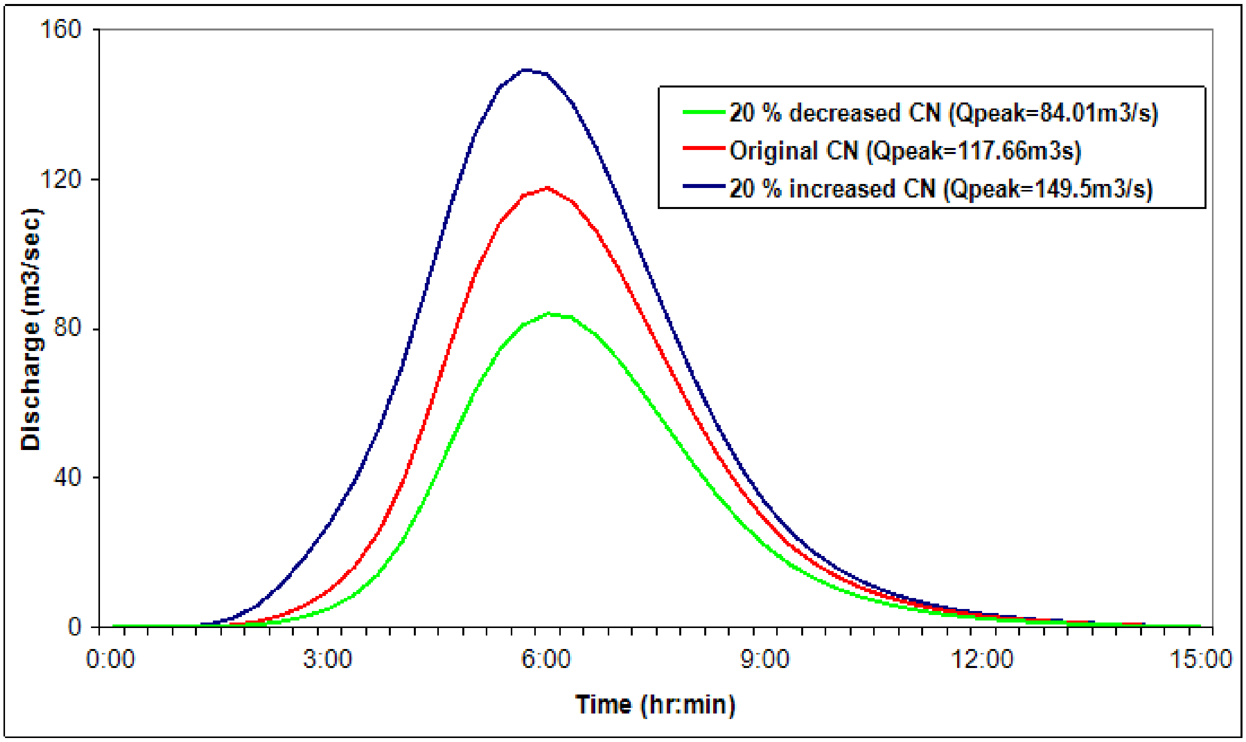


Figure 27: Comparison of hydrograph resulting from 15 % increased and decreased curve number

A 15% decrease of the initial abstraction of the study subbasin leads to a decrease of the peak discharge of 28.6%. The 15% increase results in an increase in peak discharge of 18.0%. Therefore, it can be expected that the deviation of the resulting peak discharges from the actual peak discharges is in the range of $\pm 30\,\%$.

4.1.2.1.3 Sensitivity Analysis for Lag Time Parameter

In order to get the effect that the concentration time has on the modeling result, the 200 year 6 hour storm was modeled with lag time that was 20 % shorter and longer as the one resulting from the TR-55 method used for this study. Figure 28 shows the resulting hydrographs at the outlet of the study watershed.

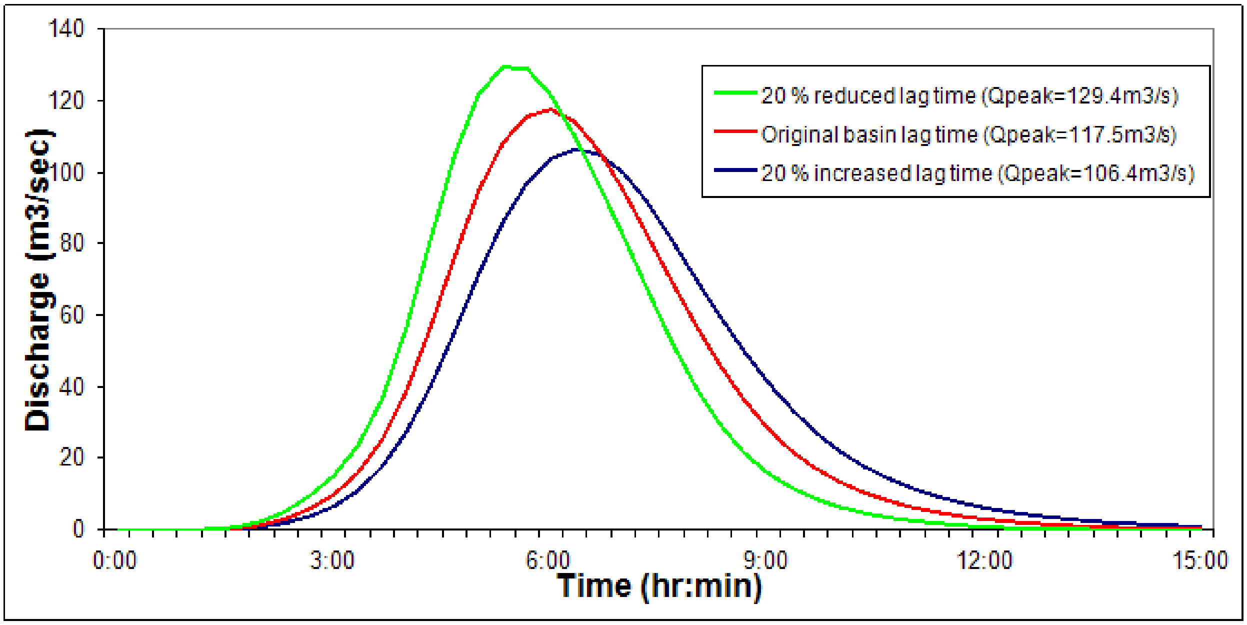


Figure 28: Comparison of flood hydrograph resulting from 20 % increased and decreased lag times

As seen on the figure, an increase in lag time leads to a decrease in the peak discharge. A 20% decrease of the lag time of the study subbasin leads to an increase of the peak discharge of 10.1%. The 20% increase results in a decrease in peak discharge of 9.4%. Assuming that the estimated time of concentration does not deviate more than 20% from the actual time of concentration of the watershed, it can be expected that the deviation of the resulting peak discharges from the actual peak discharges is in the range of $\pm 10\,\%$.

From the analysis, only curve number parameter was found to be sensitive parameter for the study subbasin.

4.1.2.2 Optimization

The calibration process was done programmatically in a systematic manner, namely optimization that shows best fit between observed and simulated runoff at the Mutinicha station. Given the initial estimates of the curve number parameter, the models included in the program were used with the observed boundary conditions (rainfall) to compute the watershed runoff hydrograph. Therefore, the program compares the computed hydrograph to the observed hydrograph with the aim of judging how well the model fits the hydrologic system. The program systematically adjusts the parameter and reiterates. When the fit is satisfactory, the program report the optimal parameter values and these parameter values were used for runoff computations in this study.

The quantitative measure of goodness of fit between the computed result from the model and the observed flow, called the objective function include sum of absolute residuals, sum of the squared residuals, peak weighted root mean square error, percent error peak and percent error volume measures the degree of variation between computed and observed hydrographs. The goal of the optimization schemes was to find reasonable parameters that yield the minimum value of the objective function. Peak weighted root mean square error, percent error peak and percent error volume was used to measures the degree of variation between computed and observed hydrographs in this study.

Two different search algorithms are provided that move from the initial estimates to the final best estimates: Nelder and Mead search algorithm and Univariate Gradient search algorithm. For the easiness to simulate a single parameter, the Univariate Gradient method was applied for this simulation.

The curve number parameter was selected for calibration. Therefore, curve number parameter need modification to produce best fit between model and observation.

Table 27: Optimized parameter result

Optimized Parameter Results for Trial "Trial 1"

Project: CalibratKiremt   Optimization Trial: Trial 1

Start of Trial: 01Jun2000, 00:00   Basin Model: Month
End of Trial: 01Oct2002, 00:00   Meteorologic Model: Month
Execution Time: 05Jul2016, 08:38:05   Control Specifications: Control 1

Element	Parameter	Units	Initial Value	Optimized Value	Objective Function Sensitivity
W100	Curve Number		87	78.641	0.00

As seen from the Table 27, the optimization result shows computed and observed stream flow best fits at CN value of 78.641. The model performance is highly correlated with the quantity and quality of data. The gauge station is not automatic, personal error may occur during recording. And from Figure 29, the shape of the modeled hydrograph generally follows the observed hydrographs. The simulated peak flow during calibration was somewhat similar to observed values. The CN value was adjusted for the study subbasin with the ratio:

$$\frac{78.641}{87} = 0.904$$

Therefore, using this ratio, the adjusted CN value for the study subbasin is 78.641.

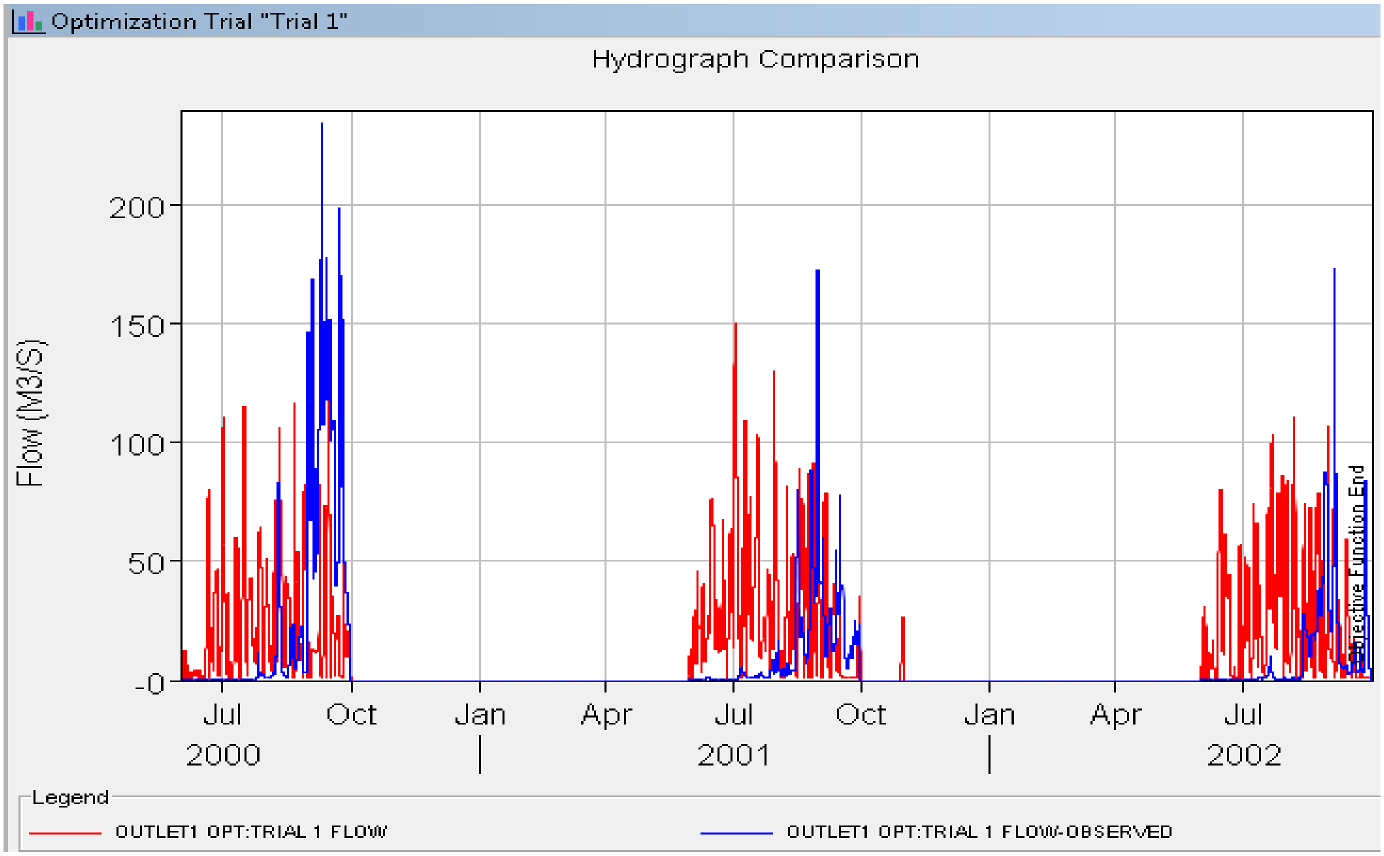


Figure 29: Comparison of Simulated and Observed Flow

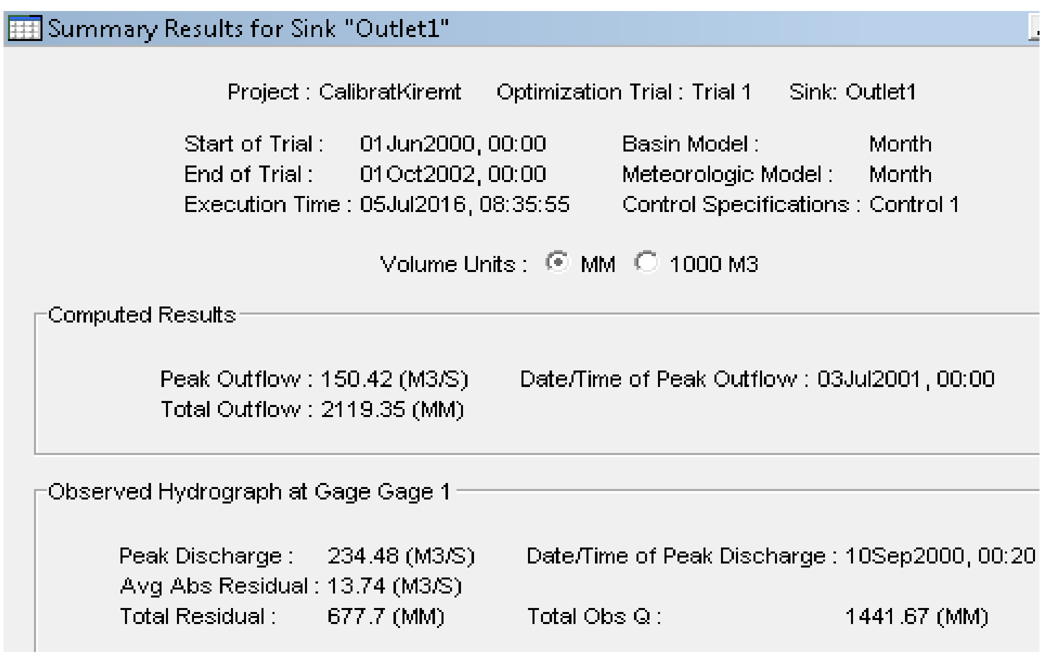


Figure 30: Summary Result for the Mutinicha Watershed

4.1.3 Hydrologic Model Validation

The calibrated model was then used to estimate stream flow for the years 1990 to 1992 using the daily rainfall data of the watershed for the rainy season (June - September) for the year 1990 - 1992 collected from Addis Ababa (Bole) and Sendafa stations and daily runoff data of the Mutinicha station for the rainy season (June - September) for the year 1990 - 1992. The average runoff data of the months February to May for the 3 years recorded data was taken as constant base flow. The observed and simulated hydrograph for the Mutinicha catchment is shown in Figure31.

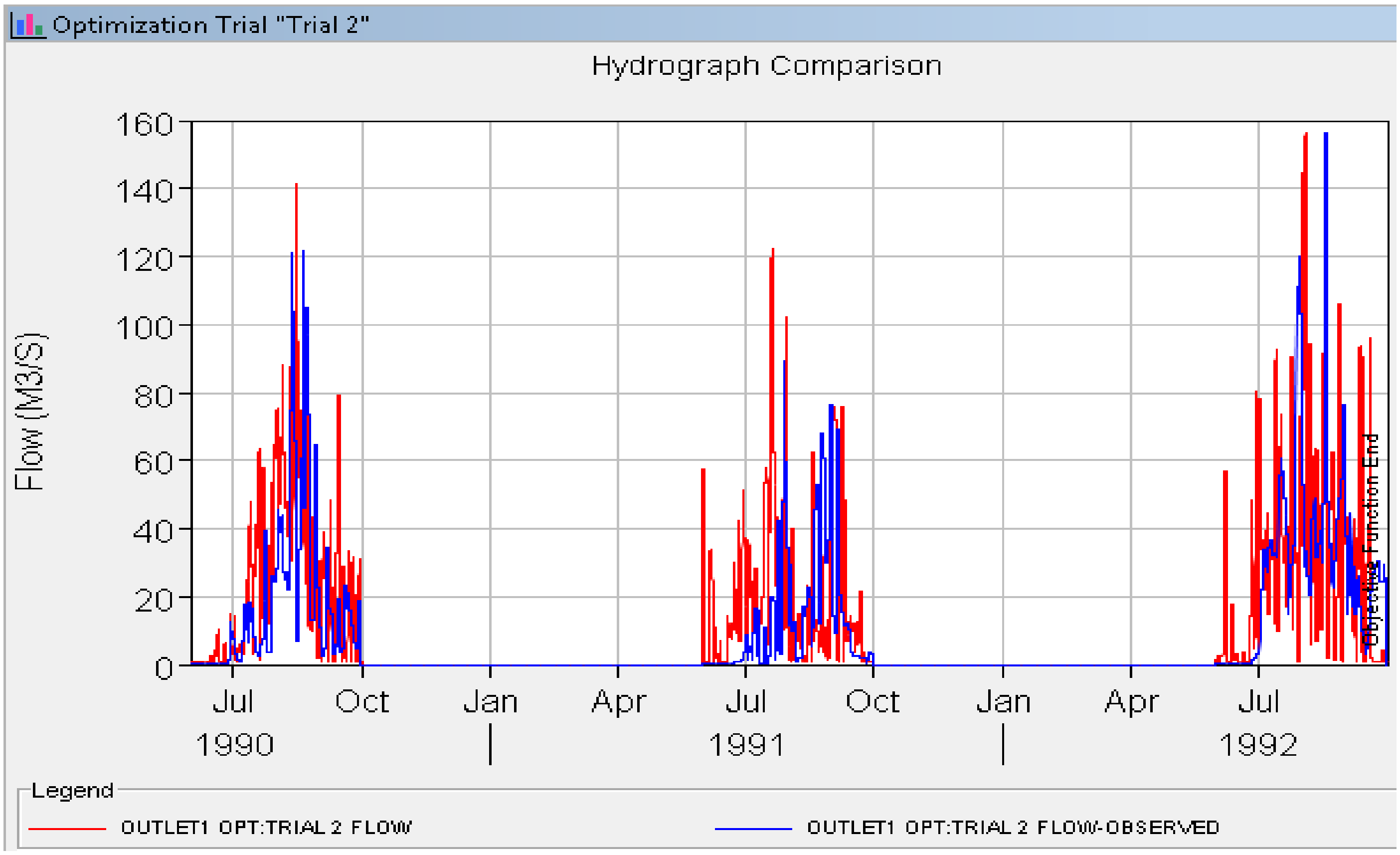


Figure 31: Comparison of Observed and Calibrated Hydrograph

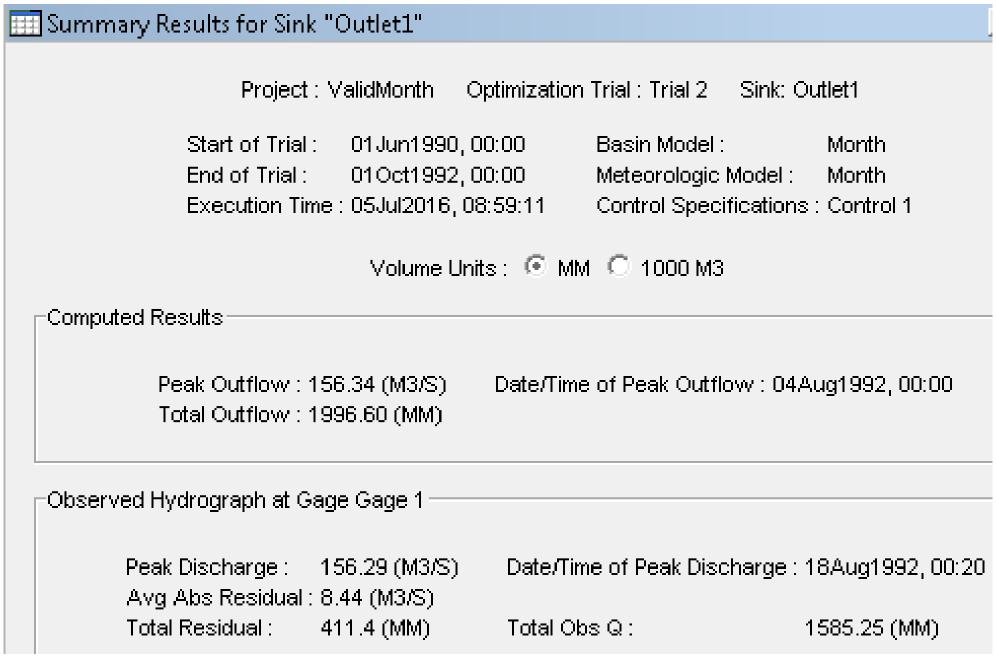


Figure 32: Summary result for the Hydrologic Model Validation

The model gives acceptable level ($\pm 20\%$) of accuracy for simulations of the study subbasin. Therefore, the performance of HEC-HMS for modeling runoff was considered satisfactory.

4.1.4 Hydrologic Model Verification

In this section, the hydrographs resulting from hydrologic modeling of 6 hours frequency based design storms shown in the Figure 33 are presented.

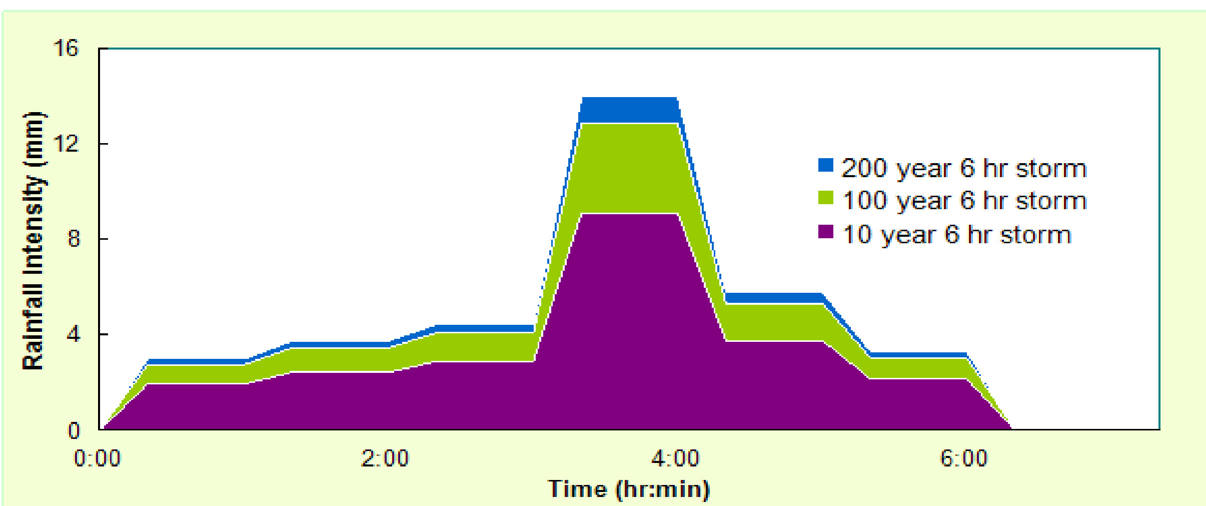


Figure 33: Six hours design storm hyetographs used for rainfall - runoff modeling

The model predicted flood hydrographs for the study watershed outlet for return periods of 10, 100 and 200 years. The hydrographs related to the design storms with maximum rainfall intensity at 67 % of the total storm duration are shown in the Figure 34.

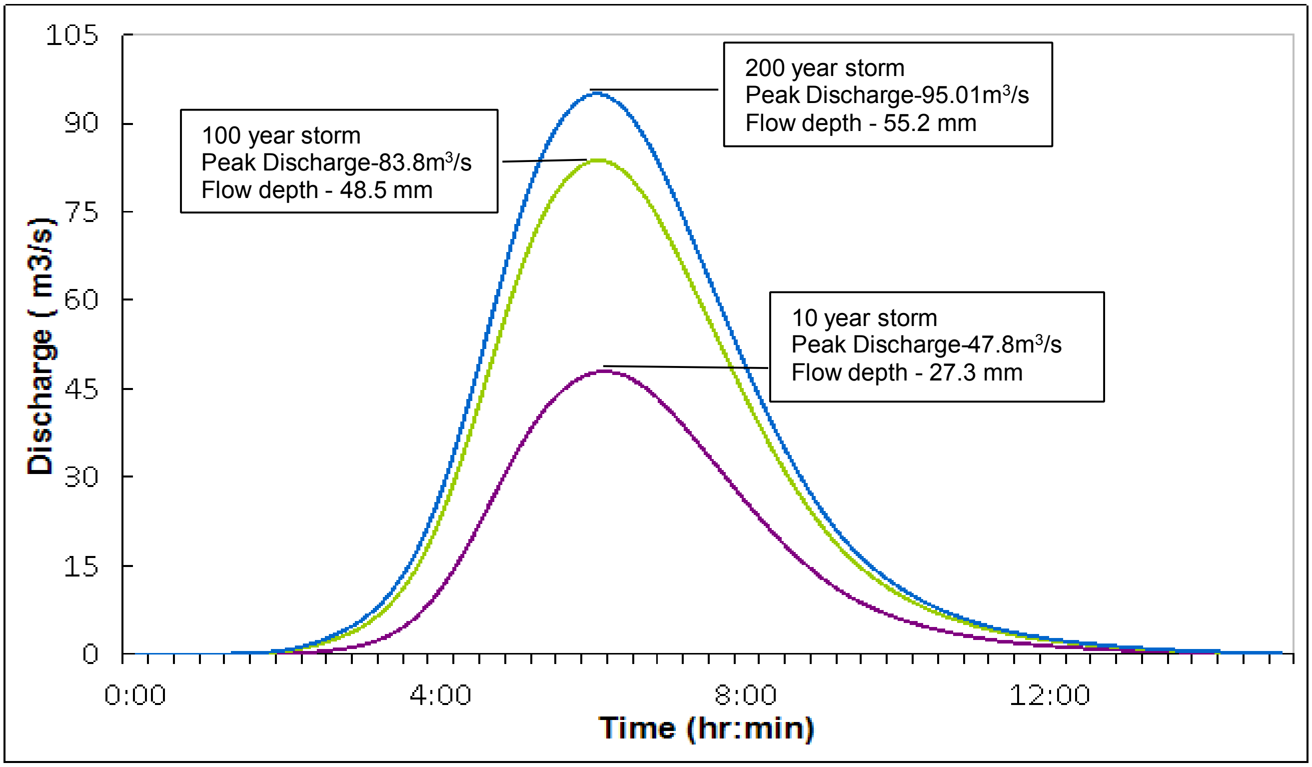


Figure 34: Flood Hydrographs for the Study Subbasin with Return Periods of 10, 100 and 200 years

As seen from Figure 34, 10 year, 100 year and 200 year storm events lead to peak discharges of 47.8 m^3/s, 83.8 m^3/s and 95.0 m^3/s respectively and flow depths of 27.3mm, 48.5mm and 55.2mm respectively. This observation implies that the study watershed produces runoff in response to precipitation events. Furthermore, the presented hydrographs are a function of the design storms and the models were used in the transformation of rainfall into runoff. Therefore, the loss calculation was analyzed and discussed in detail.

The total amounts of precipitation along with the total infiltration losses that resulted in the hydrographs are shown in Figure 35.

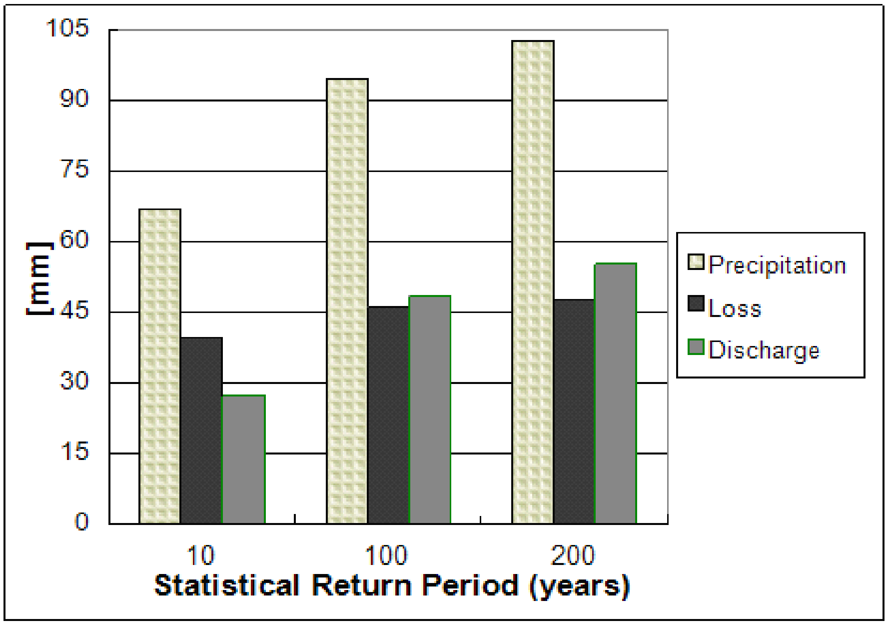


Figure 35: Total precipitation, losses and discharge for return periods of 10, 100 and 200 years

Considering 6 hr 200 year storm with the extreme rainfall intensity of 14 mm/min in the most intense 1 hour of the 200 year storm, the model predicted losses of 48% of the total rainfall. However, the model predicts higher losses for short duration of the same rainfall depth. The reason for this is that the CN model does not directly account for the intensity and duration of the rainfall and gives the exact same overall losses for storm durations of 6 hr and other shorter durations for the same total rainfall depth. This is because the CN model dos not directly account for the intensity and duration of the rainfall. The absolute loss of a certain event is only a function of curve number and absolute rainfall depth regardless of the intensity distribution. However, a time component was introduced in the model when it is applied for the estimation of runoff from successive intervals in a storm as done in this study. HEC-HMS first calculated the accumulated discharge from the accumulated precipitation of each time step and then derived the runoff for each time step as the difference between the accumulated discharge at the beginning and end of each time interval.

After the beginning of the rain event, no runoff begins until the accumulated precipitation equals the initial abstraction. After the accumulated rainfall exceeds the initial abstraction *(I_a)*, runoff was calculated by subtracting water retained in the watershed *(F)* from the accumulated rainfall. Maximum potential retention *(S)* is reached in very long storms. The development of water retention in the watershed after initial abstraction is exceeded during a storm was approximated by linear regression until $I_a + F$ equals the maximum retention S.

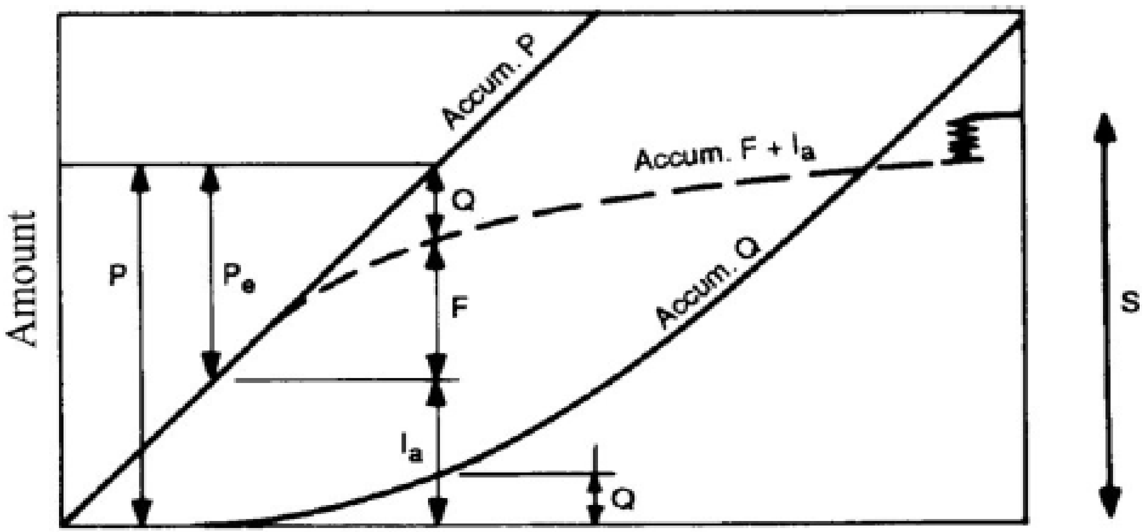
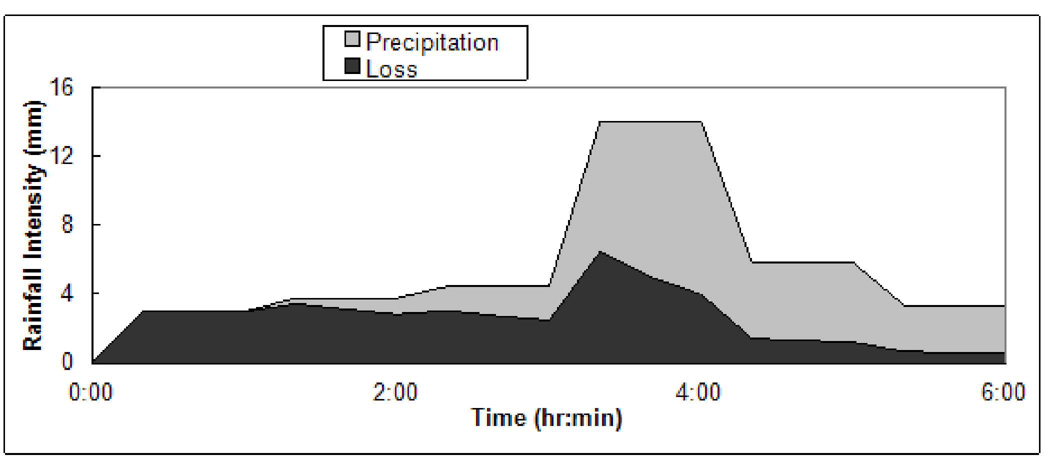


Figure 36: Rainfall runoff relation of the Curve Number method

These relations were designed for constant rainfall intensities; however, the capacity of the model to account for the intensity distribution of different rainfall events was analyzed in more detail. This was done by comparing the modeling outputs resulting from three different 200 year 6 hr storm hyetographs with the same overall precipitation depth of 102.75 mm. The three hyetographs are: the hyetograph from incremental rainfall shown in Figure 33 (top), a block rain with constant intensity (middle), and a triangular hyetograph with the maximum intensity occurring at 50% of the overall storm duration (bottom). The three hyetographs along with the losses that the model predicted for each time interval are shown in Figure 37.



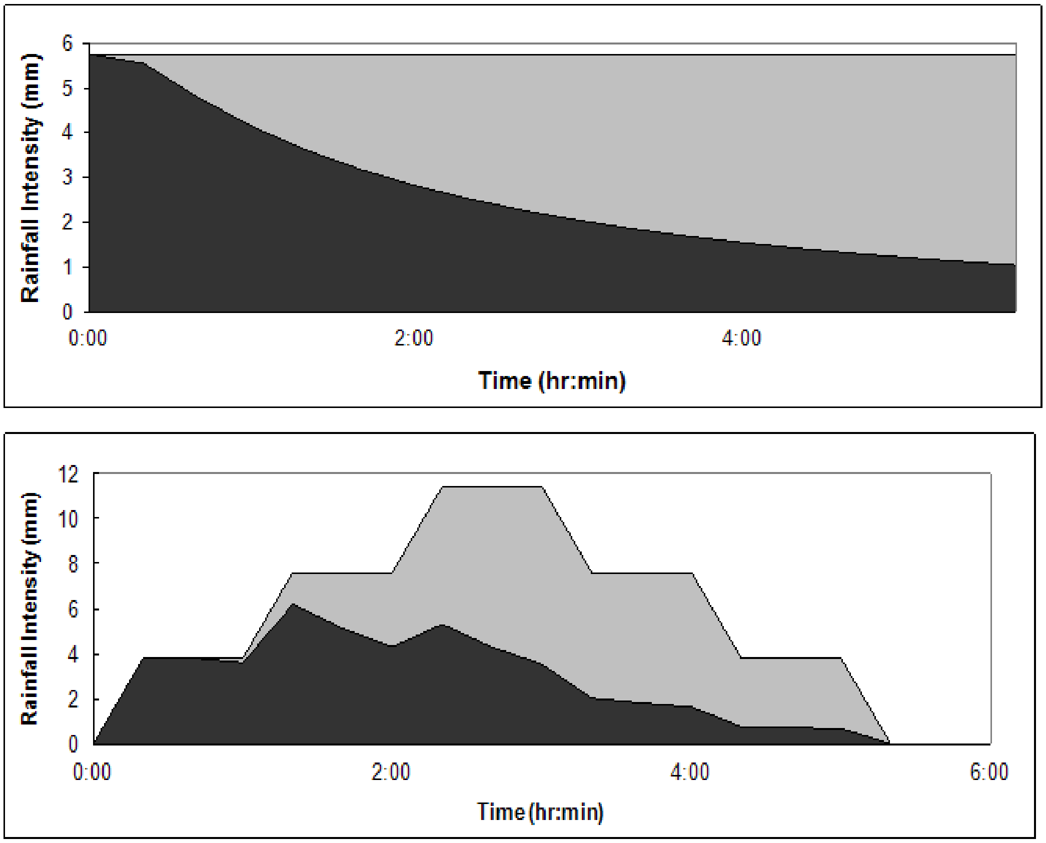


Figure 37: Loss computation for 6 hr 200 year storms with three different intensity distributions

The rainfall runoff relation of the CN method shown in Figure 37 was well explained by the block rain. In case of block rain, after the initial abstraction, the losses would eventually approach zero (when $F+I_a = S$) if the duration of the block rain would be increased sufficiently. The drawback in incremental rainfall hyetograph lies in that when the CN method was applied for extreme precipitation pattern. Since, the losses for each time interval were proportional to the difference in accumulated rainfall at the beginning and end of each time interval, the infiltration increase drastically if the rainfall intensity does. Hereby, the maximum infiltration rate of the top soil is neglected. However, these analyses proofed that the model was capable of accounting for different precipitation patterns, since the resulting effective rainfall patterns reflect the original hyetographs in a fairly realistic way. The hydrographs for the outlet of the study watershed resulting from the three analyzed hyetographs are shown in the figure below.

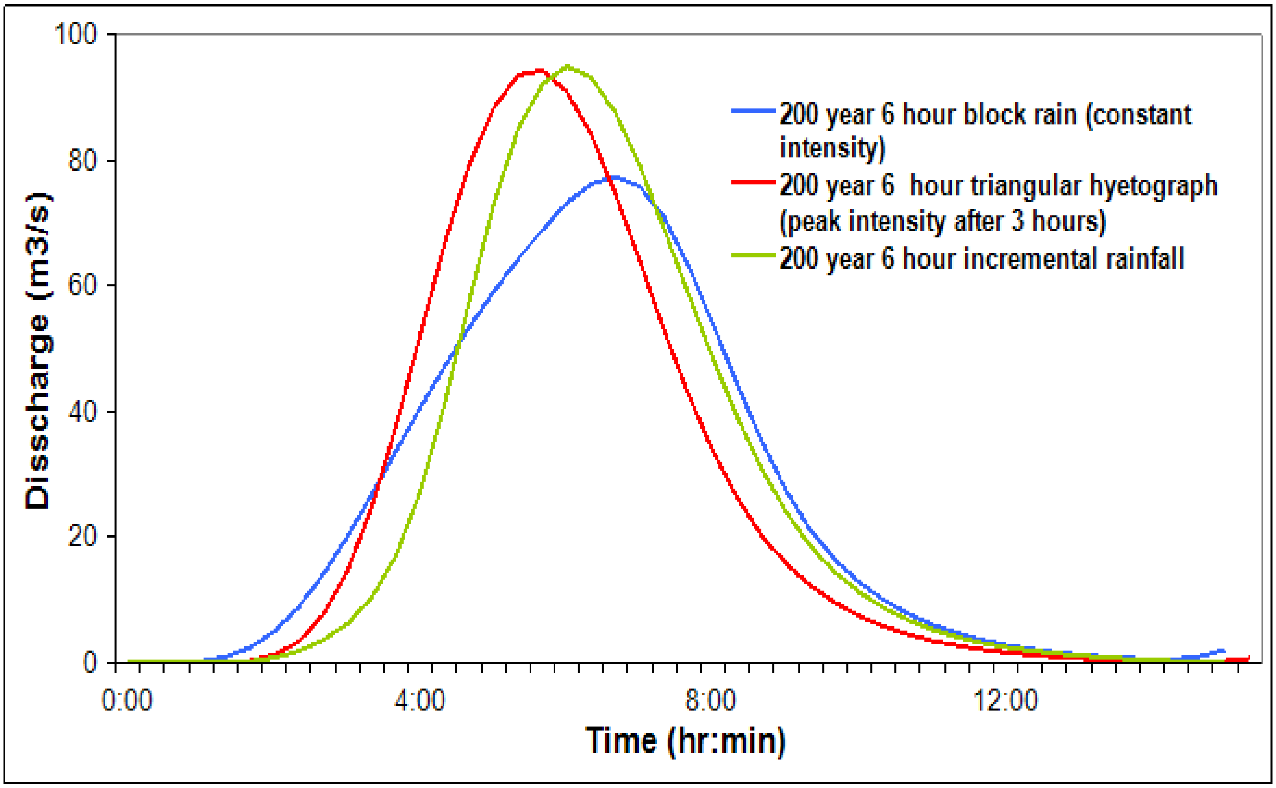


Figure 38: Hydrographs resulting from 6 hr storms with three different rainfall patterns

All the three 6 hr storms resulted in the same rainfall - runoff coefficient of 52 %. However, the temporal distributions of the three 6 hr storms significantly influenced the temporal distribution of the effective rainfall. As seen in the above figure, the choice of an appropriate storm duration and pattern directly influences the peak discharge. For instance, the analyzed 6 hr storms with rainfall depth 102.75 mm lead to a peak discharge of 95.0 m^3/s for the incremental rainfall distribution, 94.4 m^3/s for triangular pattern and 77.5 m^3/s for the block rain.

Based on the above stated considerations, it was evaluated that the applied incremental design storms were appropriate for the description of the actual storm patterns of the study area.

4.1.5 HEC-HMS Output for the Study Subbasin

The parameter set that was calibrated and verified in daily simulations was used in the loss methods. Precipitation data by three precipitation gauges (AA Bole, Debre Zeit and Sendafa stations) was input to the model. Therefore, weight of these gauges was done by inverse distance method. Three storm events (10 year, 100 year and 200 year return period) were used for simulations.

Using the annual maximum daily rainfall as 24 hours duration storm and 6 hours duration storm for the three storm events (10 year, 100 year and 200 year return period), the corresponding peak values and volumes are presented here.

Table 28: Result Summary for Daily Maximum Rainfall

	24 Hour Storm			**6 Hour Storm**		
Return Period	***10 year***	***100 year***	***200 year***	***10 year***	***100 year***	***200 year***
Peak Discharge (m^3/s)	26.90	46.51	53.10	47.78	83.77	95.04
Total Precipitation (mm)	66.81	94.56	102.75	66.81	94.54	102.75
Total Loss (mm)	39.46	46.07	47.59	39.46	46.06	47.59
Total Excess (mm)	27.35	48.49	55.16	27.35	48.47	55.16
Direct Runoff (mm)	27.35	48.49	55.16	27.35	48.46	55.15
Base flow (mm)	0.0	0.0	0.0	0.0	0.0	0.0
Discharge (mm)	27.35	48.49	55.16	27.35	48.46	55.15

As seen from the results when the return period increased (exceedance probability of the storm decreased), larger peaks and flow depth were obtained. The minimum flow depth for the study subbasin was 36.58 mm and obtained from 10 year frequency and the maximum flow depth was 68.73 mm obtained from 200 years frequency for both 6 hours and 24 hours rainfall durations.

The minimum peak flow for the study subbasin was 26.90 m^3/sec and obtained from 24 hour storm with 10 year frequency and the maximum peak flow was 95.04 m^3/sec obtained from 6 hour storm with 200 years frequency. For 6 hour storm, average time to peak was found out to be 6 hours with 67% intensity position.

Stream flow rates were determined by HEC-HMS at the confluence of Gololo Kore and Akaki rivers. In these modeling results, flows steadily increased to peak flows, remained at near the peak flows for a short period and steadily decreased. Fluid transport analyses considered introduction of leachate volumes into the Akaki River.

The release volume of leachate was considered together with stream flow to consider the dilution of leachate at the potential point of exposure. From water balance calculations, maximum leachate volume of 2160.6 m^3\day, 3039 m^3\day and 3297.2 m^3\day will be generated under 10 year, 100 year and 200 year storm events respectively while the maximum design capacity of the leachate collection system at Sendafa landfill is 1336 m^3\day. Maximum runoff along Gololo Kore watercourse was found out to be 668.8 m^3\day, 1185.43 m^3\day and 1349.06 m^3\day volume for both 6 hour and 24 hour storm with 10 year, 100 year and 200 year frequency.

4.1.6 Future Risks of Contamination on Surface Water Resources near the Landfill Site

The identification of endangered surface water bodies in the vicinity of landfill site and estimate of volume of leachate from the landfill site and peak discharge at the confluent point of Gololo Kore watercourse and Akaki river allow to get a general picture of surface water resources on which impacts of landfill leachate may represent a major concern in terms of the risk associated with contamination. However, as the landfill site has a leachate collection system, the threat and future risk also highly depends on the performance of the leachate collection system.

Analysis results on the impact of landfill leachate on the surrounding surface water bodies under different storm events shows that surface water resources will be subjected to increased risks as a result of spilling of contaminants from the landfill. Consequently, surface water bodies in the vicinity would experience potential risk of being contaminated which would cause significant loss on the environment. Waste solution migration could cause significant contamination risk to the surrounding designated habitat. The potential impact of a storm event on landfill site was directly related to volume of leachate from the landfill site. Analysis using Digital Elevation Model (DEM) and different storm events permit to estimate the dilution potential of Gololo Kore watercourse. This can be interpreted as the potential for waste solution from the landfill to contaminate surface water bodies.

In consideration of the risks associated with long residence time of landfill, even flood events of low probability of occurrence (e.g. 200 - year return interval) need to be considered (Laner et al., 2009). In this study, surface runoff from 1-in-10 year, 1-in-100 year and 1-in-200 year storm events were considered to illustrate their potential impacts on initiating landfill leachate and possible risk of contamination to the surrounding surface water bodies. For this purpose, the impact of landfill leachate was estimated using water balance calculations and the dilution potential of Gololo Kore watercourse was predicted using HEC models based on the DEM and 1-in-10 year, 1-in-100 year, 1-in-200 year storm events for the area.

Results show that, leachate flow from the landfill will be above the capacity of the leachate collection system under 1- in-10 year, 1- in-100 year, 1- in-200 year storm event respectively. As a result, leachate will be discharged through Gololo Kore (watercourse originating from the landfill) and joins the Akaki River at the confluence of Gololo Kore and Akaki River. Under 1-in-10 year, 1- in-100 year, 1- in-200 year storm events leachate volume of 824.6 m^3/day, 1703 m^3/day and 1961.2 m^3/day will be above the capacity of the leachate collection system and be discharged to the surrounding stream network respectively.

4.1.7 Extreme Storm Event - Landfill - Surface Water Resources Interactions

Extreme storm events will lead to more leachate generation from landfill endangering the surrounding surface water bodies. Analysis results in the previous sections showed that, landfill site in the vicinity of surface water resources has greater implications on the risk of accidental release of leachate from the landfill under extreme storm events. It was estimated that under 1 - in - 10 year, 1 - in - 100 year and 1 - in - 200 year storm events, maximum flow of 824.6 m^3/day 1703 m^3/day and 1961.2 m^3/day respectively, will be discharged to the Gololo Kore watercourse and joins the Akaki river at the confluent point of Akaki river and Gololo Kore watercourse. As seen from the analysis results, the extent of impact is directly relate to the storm event.

Surface water bodies in the vicinity of landfill site are referred to as endangered when situated within a potential risk zone. This study aims at determining surface water bodies endangered by accidental release from the landfill site in the study area during the storm event. The new Sendafa landfill is located in the Akaki catchment. For this site, the potential emission during a storm event estimated assuming the worst case by taking 1 - in - 10 year, 1 - in - 100 year and 1 - in - 200 year storm events reveals that surface water bodies in the vicinity are endangered.

In assessing the vulnerability of surface water bodies, the frequency of occurrence of storm event was assessed and expected rainfall that can cause a significant amount of leachate from the landfill was calculated and pollution that would be caused on the Akaki River was drawn. The possible future consequential effects may then possibly be waste solution migration and the extent would relate directly to the amount of storm event. Surface water bodies are vulnerable to waste solution migration from Sendafa landfill due to storm event that may result in increased leachate production. Therefore, the interaction of extreme storm events, landfill and surface water bodies will be a challenge in the future.

4.1.8 **Risk from Landfill with Time**

The investigation of exposure of surface water resources to landfill leachate and their associated risks were carried out on the basis of waste site location with respect to vulnerable surface water bodies and available rainfall data. The change in surface coverage of the waste with time will also contribute to the amount of leachate generated from the landfill. In addition, excessive rainfall caused by extreme events can have a significant impact for the possible waste solution migration.

It was predicted that, depending on the waste composition and future climate conditions, the duration of aftercare period until their impact become environmentally compatible may extend even up to 200-500 years (Belevu et al., 1989; Ehrig et al., 2001). This implies that the long term residence of risks associated with landfills have an implication on the scale similar with the impact of storm event. This indicates that future risks can be affected by impacts of storm events.

5 CHAPTER FIVE

5.1 CONCLUSION AND RECOMMENDATIONS

The methods used to identify surface water bodies that are prone to leachate contamination and to assess associated risks of potential release of pollutants via surface runoff from the landfill as a pathway are mainly based on available data and current knowledge. Therefore, proposed mitigation methods are discussed and recommendations for further studies are described.

5.1.1 Conclusion

The main goal of this research was to better understand the interaction of landfill sites located within water catchment area, runoff driven by extreme storm events and surface water resources, and to investigate their associated future risks. Analysis results, based on waste site location and predicted storm event with a return interval of 10 years, 100 years and 200 years showed that maximum leachate volume of 2160.6 m^3/day, 3039 m^3/day and 3297.2 m^3/day would be generated from the landfill site for 6 hour duration storm where as the design maximum flow is 1336 m^3/day. This implies that leachate flow of 824.6 m^3/day, 1703 m^3/day and 1961.2 m^3/day which is above the capacity of the leachate collection system will be generated under 10 year, 100 year and 200 year storm events respectively and released through Gololo Kore water course and drawn to the Akaki river at the confluence of Akaki river and Gololo Kore. In order to consider the dilution of leachate at the potential point of exposure, maximum runoff along Gololo Kore watercourse was found out to be 668.8 m^3/day, 1185.43 m^3/day and 1349.06 m^3/day for10 year, 100 year and 200 year return period storm event respectively.

As explained earlier, leachate volume for maximum monthly rainfall using 10, 100 and 200 years return periods was analyzed for the risk assessments, which were 2160.6 m^3/day, 3039 m^3/day and 3297.2 m^3/day. Therefore, this happens to be of a major concern in the future as surface water bodies in the vicinity of the landfill are not sufficiently protected. Potential risk during the storm event was considered in terms of worst case scenario assuming that the entire storm infiltrating through the landfill is contaminated. It was determined that the pollutant release potential of the landfill under storm event could be a potential source of contamination of the surrounding surface water bodies.

The general observation of the study reveal that, the presence of the landfill waste sites in such sensitive river catchment area could present a complex future environmental issue in the context of extreme storm event.

In this research, the risk associated with excess waste solution from the landfill site appeared most relevant and analyses were mainly focused on this. In long term conditions, it is important to have a good understanding of potential impacts of the landfill site under extreme storm events and hence, minimize the adverse effects.

5.1.2 Recommendation

5.1.2.1 Proposed Mitigation Measures/ Possible Alternative Options

One of the objectives of the study was to recommend appropriate mitigation measures and suitable options based on analysis result of the future risks of landfill leachate on surface water bodies.

To minimize the impact of leachate on the surface water resources the following four mitigation measures have been recommended on the Final ESIA Report for Sendafa Sanitary Landfill and three Transfer Stations Project of Addis Ababa City Administration (ZTS & MTS, 2014): (1) cover the daily disposal of waste by soil layer to prevent rain from infiltrating the waste deposit (2) immediately after decommissioning of the sanitary landfill, cover the cells by 20 cms thick soil to minimize infiltration of rain water into the waste deposit underneath (3) capture the runoff from and around the cells by providing appropriate drainage system around the landfill site and discharge the runoff to the lowest point of the landfill and the nearby stream located in the south west (4) treat the leachate by providing appropriately designed aerobic and anaerobic ponds and wetlands to reduce the organic waste load and level of heavy metals.

This section provides a brief discussion of suitable measures that could be used taking the future risks into account. For the purpose of this study, five options were identified in terms of addressing the issues of impacts of landfill leachate and the associated risk on the surrounding surface water bodies.

In view of the location of the landfill site which is located within water catchment area, the weather, hydrological conditions, geological conditions and several special conditions have to be taken into serious consideration in the designing of the landfill. In particular, the impact of leachate on the watershed has to be clearly mitigated. Run-off from the active face of the landfill is to be collected and introduced into the leachate collection system and managed as leachate. Therefore, the first option involves upgrading the level of protection provided by the leachate management system. This has to prevent the spilling of excess leachate from the landfill and draining into the surrounding surface water resources. Long term monitoring of water quality should be carried out, so as the potential environmental impacts resulting from the landfill site is kept to the acceptable or tolerable level.

As mentioned in Chapter 2 based on international guidelines establishment of buffer zone that is a minimum distance of 500 m from any surface water resource to avoid impacts on the resource is a necessity. In addition, based on analysis results from 1-in-10 year, 1-in-100 and year1-in-200 year storm events it is noted that surface water bodies in the vicinity would be at potential risk of contamination. Therefore, relocating the waste material facility outside the risk zone is another option.

The third option is risk acceptance. This implies accepting the degree of loss perceived during accidental release of contaminants from the landfill to the surrounding water bodies in short and long term. This would be carried out through emergency response systems. The use of emergency response systems refers that the local, regional and national authorities are aware that surface water bodies in the landfill area are prone to contamination. Therefore, risk will be dealt according to the mission statements established in the emergency plan.

Another alternative is to utilize the leachate as fertilizer. Many tree species naturally absorb metals from soil and store them in their tissues (Balsbrg, 1989, Kukaszewiski et al., 1993). Woody plants species seem to have a lower degree of immobilization to heavy metals than grasses and other herbaceous species. Trees immobilize toxic compounds. Organic compounds can be degraded by enzymes expressed in the membranes of popular trees. These plants may also stimulate the growth of chemical-degrading bacteria around their roots (Harrison, 1996). Popular tree immobilize leachate that waste landfill produces and since the trees utilize a large amount of water in the respiration processes, the moisture is extracted from the soil before it percolates beyond the root zone. Populars grow dense, root into the landfill cover soil, thus acting as a pump that transpires the soil water back to the atmosphere. The plant uptakes, removes water and harmful compounds from root zones (Schnoor et al., 1992). Therefore, popular plantation in landfill can provide an environmentally friendly ecosystem between landfill and its neighbors including surface water resources.

Organic waste constitutes larger portion of landfills. The process of using microorganisms to break down organic matter is another choice for reducing organic waste from the landfill. It is a controlled biological process that uses natural aerobic processes to increase the rate of biological decomposition of organic materials. It is carried out by successive microbial populations that breakdown organic materials into carbon dioxide, water, minerals and stabilized organic matter. The product from organic waste breakdown can be used by farmers and landscapers.

Cost analysis based on the storm events and other environmental and practicality issues are factors that need to be considered to choose the suitable mitigation measures.

5.1.2.2 Recommendation for Further Studies

This section describes recommendations for further studies for a better quantification of risks which may arise and manage them.

The study was performed on the basis of currently available information, data and knowledge about the site. Results of the study showed a general picture of the possible future risks associated with the presence of landfill site in river catchment area and due to its possible interaction with extreme storm events. However, the depth of the study to cover a broader consideration, and to conduct an in-depth analysis of the risks that may be arise in terms of the issues involved based on environmental, social and economic scenarios were limited by lack of knowledge and access to available information and data.

In the context of the study area, the risks associated with landfill leachate appeared to be the most relevant and was considered in the analysis. However, it should be bear in mind that further studies need to be carried on the determination of the risk associated with erosion and rising groundwater table. In addition, risk analysis should consider future uncertainties related to the prediction of impacts of climate change and the possible changes of land use and their impact on the issue. The proposed mitigation options should also consider the possible evolution of the risks with time.

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7 APPENDICES

Appendix 1: Rainfall Data

Table A-1: Addis Ababa (Bole) Station Monthly Rainfall (Source: National Meteorological Agency)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	0.0	1.0	97.5	25.5	132.6	126.6	146.6	283.0	219.3	60.2	0.0	0.0
1965	0.0	0.0	42.5	58.7	6.2	16.8	168.9	231.9	45.7	64.2	6.4	0.5
1966	12.4	73.0	6.9	72.9	0.4	139.4	165.2	287.9	111.6	41.9	0.0	0.0
1967	0.0	6.2	75.8	107.1	145.6	134.7	263.9	208.9	232.9	20.1	38.9	0.0
1968	1.0	149.9	37.8	302.1	15.0	110.5	180.5	155.4	128.6	4.9	0.8	0.0
1969	67.5	109.2	153.5	95.8	123.5	128.2	226.0	300.0	109.3	0.0	0.3	0.1
1970	0.0	52.3	176.4	39.5	31.5	61.7	340.6	311.3	165.5	2.9	0.0	0.0
1971	7.2	0.0	36.8	67.9	154.1	123.1	303.4	300.7	161.3	8.4	4.2	16.0
1972	7.7	103.4	82.4	162.8	83.3	91.4	268.9	152.0	134.1	3.2	6.4	0.0
1973	0.0	0.0	0.0	25.3	68.8	117.6	266.3	333.7	130.8	31.1	0.0	74.6
1974	0.0	15.7	6.4	5.0	142.2	140.3	269.8	237.4	203.3	10.0	0.0	0.0
1975	5.7	0.0	26.7	79.2	8.6	112.9	292.7	155.2	128.8	29.5	0.0	0.0
1976	23.6	9.2	50.4	99.1	129.2	106.3	249.7	236.9	102.3	0.0	78.3	3.4
1977	64.0	46.8	95.2	76.5	104.8	151.7	222.8	300.3	168.5	227.1	9.3	0.0
1978	0.0	71.6	28.9	92.0	46.2	101.6	162.3	244.5	195.8	44.8	0.0	0.0
1979	91.0	7.2	91.0	31.4	139.5	119.9	249.2	164.2	85.0	15.2	0.0	5.8
1980	23.6	26.8	64.3	74.3	44.4	129.1	268.1	214.8	118.6	0.0	0.0	0.0
1981	0.0	42.6	217.5	79.0	18.4	56.9	273.9	256.1	162.5	24.7	0.0	2.7
1982	26.6	96.4	90.2	48.1	73.5	63.6	220.3	221.6	142.8	19.0	40.7	4.9
1983	12.4	41.2	28.9	113.7	186.9	56.1	217.9	213.7	202.2	35.9	0.0	1.5
1984	0.0	0.4	11.6	11.6	135.0	334.2	313.7	180.4	98.8	0.0	0.0	7.0
1985	35.1	0.0	49.1	130.3	92.8	110.9	209.8	260.8	168.6	29.8	0.0	0.4
1986	0.0	37.6	56.2	216.6	37.7	175.2	167.9	222.3	107.4	31.6	0.0	2.5
1987	0.0	49.1	180.1	85.7	154.6	71.9	155.9	98.1	57.0	16.6	0.0	0.4
1988	4.7	33.4	6.7	157.9	34.7	93.2	181.4	265.3	187.3	57.3	0.0	0.0
1989	3.4	33.7	58.4	143.3	0.0	88.1	218.1	318.6	150.0	36.8	0.0	7.9
1990	3.2	161.1	60.4	144.5	25.2	48.3	204.2	413.4	143.0	46.1	2.1	0.0

1991	0.2	29.6	134.1	15.0	7.7	107.5	279.4	287.9	123.1	4.4	2.1	0.0
1992	14.5	28.0	35.0	58.6	55.0	82.2	254.2	223.3	157.0	64.4	2.2	0.4
1993	11.7	52.1	11.6	168.3	91.5	157.2	209.5	291.7	190.1	24.1	0.0	0.0
1994	0.0	0.0	52.9	70.0	31.7	112.9	242.2	199.3	100.9	0.5	11.0	0.0
1995	0.0	81.3	73.3	140.3	95.9	78.2	165.1	256.9	97.0	0.0	0.0	28.6
1996	20.5	5.8	176.2	95.4	128.1	289.7	346.3	312.7	211.4	0.2	0.4	0.0
1997	29.1	0.0	22.1	66.8	44.8	128.0	257.0	160.7	94.7	58.6	15.3	0.0
1998	63.1	40.0	43.8	87.8	193.1	111.6	257.8	236.8	185.2	139.5	0.0	0.0
1999	4.4	0.0	35.0	17.8	30.5	104.6	194.0	270.5	62.8	227.1	0.0	0.0
2000	0.0	0.0	17.6	109.9	95.2	102.1	192.9	221.9	157.5	19.6	13.5	0.0
2001	0.0	10.3	165.3	14.8	106.7	163.0	274.4	179.1	107.3	10.6	0.0	0.0
2002	30.6	25.9	79.4	36.6	49.6	109.0	213.9	233.6	72.6	0.5	0.0	32.8
2003	4.8	34.1	48.9	121.9	33.0	128.0	226.4	238.4	30.2	4.6	0.0	33.8
2004	26.1	11.7	32.4	104.2	7.0	120.6	240.6	230.1	122.1	50.0	0.0	0.0
2005	34.2	56.4	56.2	96.6	94.3	141.3	241.6	243.1	105.5	8.8	0.6	15.2
2006	45.3	21.2	81.0	88.0	62.1	167.1	241.0	232.3	110.9	25.8	1.2	0.0
2007	0.0	22.5	113.8	111.8	34.9	56.1	366.5	258.1	188.8	3.6	0.5	15.4
2008	43.4	58.7	84.7	120.1	53.7	84.9	250.9	284.5	124.6	42.2	46.7	30.3
2009	19.9	49.9	120.4	126.1	219.1	87.5	241.2	284.1	101.9	23.9	3.9	22.7
2010	0.0	0.0	41.8	8.5	141.6	178.5	258.3	221.8	106.1	0.0	0.6	13.1
2011	15.2	0.0	47.7	49.1	48.5	45.6	257.3	281.9	105.1	21.1	4.1	0.0
2012	0.0	51.2	88.0	133.5	89.0	157.9	243.9	279.4	144.0	11.9	0.0	0.0
2013	2.4	77.3	112.1	92.4	137.0	86.2	182.0	261.8	112.9	19.0	1.4	21.4

Table A1-2: Debre Zeit Station Monthly Rainfall (Source: National Meteorological Agency)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	0	0	0	184	42.3	56	434.5	365.3	187.1	22.6	0	11
1965	19.8	0	58.5	29.5	0	38.2	408.5	246.8	125.6	76.9	6.7	0
1966	0	256.2	27.5	135.2	25.1	122.5	251.4	409.6	168.5	40	0	0
1967	0	0	100	73.9	164.8	62.1	314.2	259.6	136	16	79.1	0
1968	0	190.1	12.6	102	4	60.1	277.3	135.2	203	0	17.8	0

1969	11	0	56.7	109	24.9	137.1	125.1	278.6	64.6	7.5	3.2	0
1970	44.1	31.1	7.5	71.4	45.3	46	250.7	290.1	112	5.9	0	0
1971	0.7	0	16.5	63	107.6	121.3	215.8	281	123.1	2.9	0.3	14.4
1972	0	95.2	53.7	136	47.7	102.1	214.4	124.6	66	2.6	0	0
1973	0	0	0	2.7	28	90.31	138.5	241.9	130.4	42.1	0	2
1974	0	12.5	104.2	7.6	98.1	114.4	307.3	199	160.3	3	0	0
1975	0	0	19.5	72.1	54.5	149.7	382.1	223.4	154.4	7	0	0
1976	0	0	71.1	107.2	80.7	102.9	241.9	232.2	42.2	3.8	35.2	0.8
1977	43.1	1	87.7	90.2	57.6	101.6	272.8	202.7	82.2	187.6	3.4	0
1978	1.4	69	34.4	47.4	28.5	133.7	132.3	191.1	122.3	25.1	0	0.1
1979	77.7	0	54.7	13.5	76	110.9	224.9	187.6	83.8	12.6	0	0
1980	20	10.1	32.3	24.2	69.4	76.1	242.4	212.5	58.1	40.7	0	1.2
1981	0	14.2	164.2	62.1	7.1	35.8	284.6	151.8	162.8	4.2	0	0
1982	20.8	75.4	34.5	47.3	57.7	91	123.9	233.6	46.1	25.5	9.4	0
1983	0	10.2	62.8	105.2	209.5	149.4	128.8	344.8	88.6	23.4	0	0
1984	0	0	19.3	0	108.7	81.5	220.5	85	147.5	0	0	3.6
1985	3.5	0	14.5	63.6	115.5	74	307.3	272.7	130	1.1	0	0
1986	0	23.6	51.7	141.6	72.4	166.8	178.8	162.5	90.2	3.2	0	0
1987	0	61.4	138.2	90.1	164	65.5	83.3	155.9	80.9	4.6	0	0
1988	8	14.9	6	44.6	36.8	100.6	145.9	236.8	121.4	16.6	0	0
1989	0.9	12.2	35.1	47	0.4	59	183.7	171.7	135.2	21.2	0	3.3
1990	0	98.3	46.2	48.7	73.4	49.1	203.7	130.1	68.5	1.2	0	0
1991	7.4	25.4	126.8	8.3	7.7	107.5	279.4	256.3	128.3	4.4	1.1	2.6
1992	12.8	36.5	19.4	45.1	44.7	76.4	256	285.0	154.4	60.3	1.1	0.2
1993	8.3	76.4	6.3	145.6	91.5	157.2	323.0	319.8	175.6	19.3	0	0
1994	0	0	29.2	19.5	19.6	74.5	232.8	187.3	86.6	0	10.2	0
1995	0	2.4	7.8	33.9	5.5	92.5	188.4	169.6	75.1	0	0	11.9
1996	16.4	0	103.1	55.3	105.4	261.5	164.1	275.6	90	0.1	5.9	0
1997	27.8	0	26.7	74.8	13.6	121.7	235.8	171.8	71.4	99.9	10.9	0
1998	32	51.4	13.9	77.2	41.8	77.7	206.3	293.5	97.6	93.3	0	0

1999	0.5	0	36.6	0	10	176.8	298.7	258.6	47.2	159.5	0	0
2000	0	0	8.6	50.4	65.4	77.4	244.3	181.4	139.4	40	23.6	3.4
2001	0	4.6	165.6	21.8	104	79.5	252.3	142.8	64.3	37.2	0	0
2002	8.6	0.0	48.2	34.6	11.0	102.3	194.3	181.0	58.4	0.0	0.0	21.3
2003	38.3	55.4	61.6	100.3	21.1	81.4	277.9	285.1	119.4	6.0	3.6	35.4
2004	23.8	9.6	68.1	119.9	2.0	133.5	172.5	209.5	209.1	79.6	22.6	10.3
2005	12.2	75.6	19.5	109.3	113.2	57.5	234.1	367.8	72	24	20	3
2006	0	25.6	269	107.1	151.4	36	107.1	270.7	39.9	3.8	0	7.6
2007	23.5	91.1	8.9	80.6	16.9	41.1	339.5	369.6	163.3	10.3	0	0
2008	19.4	45.2	66.8	117.7	29.6	45.6	260	386.1	94.5	33.6	2	30.4
2009	0	106.4	56.5	70	11.2	12.9	398	228.39	216.8	11.8	0	0.6
2010	21.6	53.8	80.5	1.9	32.1	94.7	256.7	365.7	143.4	8.5	0	1.4
2011	0	52.3	45.2	123.2	53	52.6	329.2	331.7	130.1	0	0	35.5
2012	21.4	57.1	20.8	133	94.6	78.2	377.5	285.9	123	14.4	0	0
2013	1.6	2.1	70.2	55.1	18.8	100.4	307.1	324.4	128	0.1	10.6	0

Table A1-3: Sendafa Station Monthly Rainfall (Source: National Meteorological Agency)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	8.2	8.3	37.7	79.3	39.5	117.1	279.3	274.2	134.4	37.4	0.0	36.3
1965	25.3	0.8	18.1	31.3	7.4	27.3	278.7	329.7	72.1	43.9	32.1	0.0
1966	0.0	141.8	52.9	114.8	9.0	121.4	217.5	392.7	64.1	19.7	0.0	0.0
1967	0.0	4.0	82.0	150.1	112.3	171.9	293.5	522.4	60.5	20.0	45.2	0.0
1968	0.0	49.1	0.0	0.0	8.6	33.2	288.6	176.6	186.6	10.1	0.0	0.0
1969	60.7	69.5	93.4	87.6	6.6	84.7	465.0	293.4	89.6	3.1	6.0	0.0
1970	81.3	39.8	77.3	49.0	13.9	48.3	322.8	666.5	207.5	7.3	0.0	0.0
1971	6.0	7.9	173.0	198.3	224.5	490.9	365.5	659	246.7	42.7	8.7	24.4
1972	30.7	0.0	55.0	193.4	134.5	174.4	277.1	208.9	62.0	0.8	12.0	12.0
1973	0.0	0.0	0.0	13.0	61.5	62.3	217.1	455.6	175.8	0.0	0.0	3.0
1974	0.0	0.0	87.5	0.0	93.7	123.4	267.5	209.4	116.1	0.0	0.0	0.0
1975	0.0	0.0	43.2	58.7	22.0	95.0	284.4	296	100.2	6.5	0.0	0.0
1976	0.0	0.0	50.4	115.6	103.9	63.2	234.0	214.8	92.9	10.1	57.6	23.5

1977	76.9	21.4	22.0	42.4	73.4	159.6	384.4	385.1	242.7	147.1	18.0	0.0
1978	0.5	86.7	47.9	43.5	36.7	164.5	265.9	288.4	152.5	63.7	0.0	0.0
1979	133.7	8.6	77.6	56.2	81.1	117.8	380.6	256.9	136.4	9.9	0.0	56.4
1980	27.9	38.5	32.7	64.2	41.2	88.8	325.5	379.4	49.0	28.0	7.1	0.0
1981	0.0	8.9	247.1	94.3	0.0	24.0	413.6	241	125.9	9.3	0.0	5.4
1982	39.4	84.7	54.8	31.7	71.5	31.3	226.1	262.8	77.0	40.7	14.5	14.1
1983	1.4	25.4	43.1	91.6	150.9	272.9	177.7	98.2	197.1	4.7	0.0	0.0
1984	0.0	0	45.2	0.0	78.4	169.1	339.7	184.9	118.3	0.0	0.0	1.2
1985	9.5	0.0	38.6	158.9	157.9	76.4	394.1	451.5	105.9	10.8	0.0	0.0
1986	0.0	28.1	117.3	193.7	32.3	164.7	270.9	244.5	143.2	0.0	0.0	0.0
1987	0.2	33.1	128.9	80.5	110.1	55.7	223.6	143.6	105.3	8.7	0.0	0.0
1988	0.0	32.9	0.9	132.3	22.1	104.6	451.1	360.3	198.4	5.2	0.0	0.0
1989	18.0	10.3	43.3	112.0	21.4	46.3	357.2	339.4	139.9	10.2	0.4	0.6
1990	21.5	190.4	35.7	148.4	38.2	88.5	273.4	470.4	109.3	3.8	0.0	0.0
1991	15.9	20.5	118.1	0.5	7.7	107.5	279.4	218.9	134.5	4.4	0.0	5.6
1992	10.7	46.5	1.0	29.1	32.5	69.6	257.5	357.9	151.4	55.5	0.0	0.0
1993	4.3	105.2	0.0	118.7	91.5	157.2	457.2	353.0	158.4	13.7	0.0	0.0
1994	0.0	0.0	0.0	64.1	11.0	130.7	337.9	184.1	94.4	0.0	6.4	0.0
1995	0.0	11.4	106.2	116.7	42.9	22.5	230.8	338.8	87.1	0.0	0.0	0.0
1996	69.4	5.6	99.3	77.3	117.8	180.4	339.2	338.6	111.4	0.0	0.0	0.0
1997	44.5	0.0	29.4	60.0	44.8	149.7	303.8	251.1	84.7	72.0	34.6	0.0
1998	28.9	23.3	5.8	27.0	38.2	68.8	359.1	289.7	145.6	98.9	0.0	0.0
1999	0.0	1.2	56.3	11.8	25.4	144.7	441.6	365.2	74.8	79.6	0.0	0.0
2000	0.0	0.0	0.0	44.0	87.9	166.0	352.2	373.4	113.9	5.0	10.0	0.0
2001	0.0	35.3	154.1	9.2	135.2	149.5	335.5	276.8	27.4	9.8	0.0	0.0
2002	21.2	3.4	67.2	20.6	60.9	144.4	246.8	289.2	85.4	0.0	0.0	27.4
2003	75.5	0.0	29.7	126.9	1.7	120.6	304.4	373.4	122.4	0.0	0.0	19.7
2004	21.1	7.1	2.2	118.9	0.0	126.4	209.8	220.8	161.4	63.4	10.2	4.7
2005	24.5	22.3	12.3	136.1	150.2	57.7	381.3	282.9	73.3	34.6	0	0
2006	0	23.8	165.8	77.2	31.1	126.2	455.8	398.7	78.9	0	0	0

2007	38	53.48	8.2	92.9	24.2	162	288.8	343.4	114.1	0	0	0
2008	0	0	0	0	0	87.9	290.3	306.2	175.3	24.7	63.7	30.7
2009	10.2	75.6	91.76	100.8	125.55	53.4	311.9	1188.5	153.9	18.91	1.5	12.1
2010	0	12.5	18	205.3	76.4	106.7	316.2	295.8	65.6	1.5	0	7.44
2011	8.494	23.8	45.88	71.5	136.7	86.8	216.8	328.6	116.4	11.78	1.5	16.1
2012	9.672	53.48	57.04	134.1	92.07	122.7	305.0	282.1	134.4	13.33	0	0
2013	7.3	3.4	0	44.7	45.3	274.7	374.6	449	27.5	0	0	5.9
2014	0	0	73.8	204.7	12.5	41.0	81.7	731.3	139	6.4	0	0

Table A1-4: Maximum Rainfall for One Day Rainfall Duration (National Meteorological Agency)

Year	Gauging Station		
	A. A Bole	Debre Ziet	Sendafa
1985	36.8	54.9	75.3
1986	98.1	32.1	60.9
1987	53.0	45.8	28.9
1988	35.8	32.5	102.6
1989	48.4	37.8	72.6
1990	30.1	42.3	50.6
1991	59.6	*30.2*	34.7
1992	44.3	*24.9*	42.4
1993	40.6	*36.8*	48.8
1994	38.2	34.6	31.8
1995	64.7	32.4	77.8
1996	37.5	62.0	47.2
1997	37.3	57.0	44.8
1998	60.1	70.0	69.7
1999	37.8	78.0	48.3
2000	47.0	47.0	63.8
2001	32.4	39.8	40.8
2002	28.6	44.7	39.4
2003	34.6	45.6	*27.6*

2004	29.0	46.2	81.2
2005	44.5	37	50.0
2006	61.7	74.4	35.5
2007	71.2	38.1	57.0
2008	37.2	45.9	31.5
2009	51.2	28.7	*28.1*
2010	54.4	44.6	34.6
2011	36.9	61.0	61.5
2012	64.7	61.0	28.6
2013	42.6	52.2	100.5
2014	27.2	*38.2*	63.2

Table A1-5: Conversion of 10 years, 100 years, 200 years Return Period Daily Maximum Rainfall into 24 hours Incremental Rainfall for AA Bole Station

Time (hr)	10 hours Return Period Rainfall				100 hours Return Period Rainfall				200 hours Return Period Rainfall			
	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricptatn (mm)	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)
1	12.87	12.87	0--1	1.33	18.1	18.1	0--1	1.86	19.64	19.64	0--1	2.03
2	18.21	5.34	1--2	1.39	25.59	7.49	1--2	1.95	27.78	8.14	1--2	2.12
3	22.3	4.09	2--3	1.42	31.34	5.75	2--3	2	34.02	6.24	2--3	2.17
4	25.75	3.45	3--4	1.5	36.19	4.85	3--4	2.11	39.28	5.26	3--4	2.29
5	28.79	3.04	4--5	1.54	40.46	4.27	4--5	2.16	43.92	4.64	4--5	2.34
6	31.53	2.74	5--6	1.63	44.33	3.87	5--6	2.29	48.11	4.19	5--6	2.5
7	34.06	2.53	6--7	1.69	47.88	3.55	6--7	2.38	51.97	3.86	6--7	2.58
8	36.41	2.35	7--8	1.82	51.18	3.3	7--8	2.56	55.56	3.59	7--8	2.78
9	38.62	2.21	8--9	1.9	54.29	3.11	8--9	2.67	58.93	3.37	8--9	2.89
10	40.71	2.09	9--10	2.09	57.22	2.93	9--10	2.93	62.11	3.18	9--10	3.18
11	42.7	1.99	10--11	2.21	60.02	2.8	10--11	3.11	65.15	3.04	10--11	3.37
12	44.6	1.9	11--12	2.53	62.69	2.67	11--12	3.55	68.04	2.89	11--12	3.86
13	46.42	1.82	12--13	2.74	65.25	2.56	12--13	3.87	70.82	2.78	12--13	4.19
14	48.17	1.75	13--14	3.45	67.71	2.46	13--14	4.85	73.49	2.67	13--14	5.26
15	49.86	1.69	14--15	4.09	70.09	2.38	14--15	5.75	76.07	2.58	14--15	6.24
16	51.49	1.63	15--16	12.87	72.38	2.29	15--16	18.1	78.57	2.5	15--16	19.64

17	53.08	1.59	16--17	5.34	74.61	2.23	16--17	7.49	80.99	2.42	16--17	8.14
18	54.62	1.54	17--18	3.04	76.77	2.16	17--18	4.27	83.33	2.34	17--18	4.64
19	56.12	1.5	18--19	2.35	78.88	2.11	18--19	3.3	85.62	2.29	18--19	3.59
20	57.57	1.45	19--20	1.99	80.93	2.05	19--20	2.8	87.84	2.22	19--20	3.04
21	58.99	1.42	20--21	1.75	82.93	2	20--21	2.46	90.01	2.17	20--21	2.67
22	60.38	1.39	21--22	1.59	84.88	1.95	21--22	2.23	92.13	2.12	21--22	2.42
23	61.74	1.36	22--23	1.45	86.79	1.91	22--23	2.05	94.2	2.07	22--23	2.22
24	63.07	1.33	23--24	1.36	88.65	1.86	23--24	1.91	96.23	2.03	23--24	2.07

Table A1-6: Conversion of 10 years, 100 years, 200 years Return Period Daily Maximum Rainfall into 24 hours Incremental Rainfall for Debre Ziet Station

Time (hr)	10 hours Return Period Rainfall				100 hours Return Period Rainfall				200 hours Return Period Rainfall			
	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)
1	13.01	13.01	0--1	***1.35***	18.14	18.14	0--1	***1.87***	19.65	19.65	0--1	***2.03***
2	18.4	5.39	1--2	***1.4***	25.65	7.51	1--2	***1.95***	27.8	8.15	1--2	***2.12***
3	22.53	4.13	2--3	***1.44***	31.42	5.77	2--3	***2.01***	34.04	6.24	2--3	***2.17***
4	26.02	3.49	3--4	***1.51***	36.28	4.86	3--4	***2.11***	39.31	5.27	3--4	***2.28***
5	29.09	3.07	4--5	***1.56***	40.56	4.28	4--5	***2.17***	43.95	4.64	4--5	***2.35***
6	31.87	2.78	5--6	***1.65***	44.43	3.87	5--6	***2.3***	48.14	4.19	5--6	***2.5***
7	34.42	2.55	6--7	***1.71***	47.99	3.56	6--7	***2.39***	52	3.86	6--7	***2.58***
8	36.8	2.38	7--8	***1.84***	51.31	3.32	7--8	***2.56***	55.59	3.59	7--8	***2.78***

9	39.03	2.23	8--9	***1.92***	54.42	3.11	8--9	***2.68***	58.96	3.37	8--9	***2.89***
10	41.14	2.11	9--10	***2.11***	57.36	2.94	9--10	***2.94***	62.15	3.19	9--10	***3.19***
11	43.15	2.01	10--11	***2.23***	60.16	2.8	10--11	***3.11***	65.19	3.04	10--11	***3.37***
12	45.07	1.92	11--12	***2.55***	62.84	2.68	11--12	***3.56***	68.08	2.89	11--12	***3.86***
13	46.91	1.84	12--13	***2.78***	65.4	2.56	12--13	***3.87***	70.86	2.78	12--13	***4.19***
14	48.68	1.77	13--14	***3.49***	67.87	2.47	13--14	***4.86***	73.54	2.68	13--14	***5.27***
15	50.39	1.71	14--15	***4.13***	70.26	2.39	14--15	***5.77***	76.12	2.58	14--15	***6.24***
16	52.04	1.65	15--16	***13.01***	72.56	2.3	15--16	***18.14***	78.62	2.5	15--16	***19.65***
17	53.64	1.6	16--17	***5.39***	74.79	2.23	16--17	***7.51***	81.04	2.42	16--17	***8.15***
18	55.2	1.56	17--18	***3.07***	76.96	2.17	17--18	***4.28***	83.39	2.35	17--18	***4.64***
19	56.71	1.51	18--19	***2.38***	79.07	2.11	18--19	***3.32***	85.67	2.28	18--19	***3.59***
20	58.18	1.47	19--20	***2.01***	81.12	2.05	19--20	***2.8***	87.9	2.23	19--20	***3.04***
21	59.62	1.44	20--21	***1.77***	83.13	2.01	20--21	***2.47***	90.07	2.17	20--21	***2.68***
22	61.02	1.4	21--22	***1.6***	85.08	1.95	21--22	***2.23***	92.19	2.12	21--22	***2.42***
23	62.39	1.37	22--23	***1.47***	87	1.92	22--23	***2.05***	94.26	2.07	22--23	***2.23***
24	63.74	1.35	23--24	***1.37***	88.87	1.87	23--24	***1.92***	96.29	2.03	23--24	***2.07***

Table A1-7: Conversion of 10 years, 100 years, 200 years Return Period Daily Maximum Rainfall into 24 hours Incremental Rainfall for Sendafa Station

Time (hr)	10 hours Return Period Rainfall				100 hours Return Period Rainfall				200 hours Return Period Rainfall			
	Hourly Distributed Cumulative Precp. (mm) $P=M*sqrt(T_i)$	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) $P=M*sqrt(T_i)$	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) $P=M*sqrt(T_i)$	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)
1	16.3	16.3	0--1	***1.68***	24.09	24.09	0--1	***2.49***	26.4	26.4	0--1	***2.72***
2	23.05	6.75	1--2	***1.75***	34.07	9.98	1--2	***2.6***	37.33	10.93	1--2	***2.84***
3	28.23	5.18	2--3	***1.8***	41.73	7.66	2--3	***2.66***	45.72	8.39	2--3	***2.92***
4	32.6	4.37	3--4	***1.89***	48.18	6.45	3--4	***2.8***	52.79	7.07	3--4	***3.07***
5	36.45	3.85	4--5	***1.95***	53.87	5.69	4--5	***2.88***	59.03	6.24	4--5	***3.15***
6	39.93	3.48	5--6	***2.07***	59.01	5.14	5--6	***3.06***	64.66	5.63	5--6	***3.35***
7	43.13	3.2	6--7	***2.14***	63.74	4.73	6--7	***3.16***	69.84	5.18	6--7	***3.47***
8	46.1	2.97	7--8	***2.31***	68.14	4.4	7--8	***3.41***	74.66	4.82	7--8	***3.74***
9	48.9	2.8	8--9	***2.4***	72.27	4.13	8--9	***3.55***	79.19	4.53	8--9	***3.89***
10	51.55	2.65	9--10	***2.65***	76.18	3.91	9--10	***3.91***	83.48	4.29	9--10	***4.29***
11	54.06	2.51	10--11	***2.8***	79.9	3.72	10--11	***4.13***	87.55	4.07	10--11	***4.53***
12	56.46	2.4	11--12	*3.2*	83.45	3.55	11--12	***4.73***	91.44	3.89	11--12	***5.18***
13	58.77	2.31	12--13	*3.48*	86.86	3.41	12--13	***5.14***	95.18	3.74	12--13	***5.63***
14	60.99	2.22	13--14	***4.37***	90.14	3.28	13--14	***6.45***	98.77	3.59	13--14	***7.07***
15	63.13	2.14	14--15	***5.18***	93.3	3.16	14--15	***7.66***	102.24	3.47	14--15	***8.39***
16	65.2	2.07	15--16	***16.3***	96.36	3.06	15--16	***24.09***	105.59	3.35	15--16	***26.4***
17	67.21	2.01	16--17	***6.75***	99.33	2.97	16--17	***9.98***	108.84	3.25	16--17	***10.93***

18	69.16	1.95	17--18	***3.85***	102.21	2.88	17--18	***5.69***	111.99	3.15	17--18	***6.24***
19	71.05	1.89	18--19	***2.97***	105.01	2.8	18--19	***4.4***	115.06	3.07	18--19	***4.82***
20	72.9	1.85	19--20	***2.51***	107.73	2.72	19--20	***3.72***	118.05	2.99	19--20	***4.07***
21	74.7	1.8	20--21	***2.22***	110.39	2.66	20--21	***3.28***	120.97	2.92	20--21	***3.59***
22	76.45	1.75	21--22	***2.01***	112.99	2.6	21--22	***2.97***	123.81	2.84	21--22	***3.25***
23	78.17	1.72	22--23	***1.85***	115.53	2.54	22--23	***2.72***	126.6	2.79	22--23	***2.99***
24	79.85	1.68	23--24	***1.72***	118.02	2.49	23--24	***2.54***	129.32	2.72	23--24	***2.79***

Table A1-8: Conversion of 10 years, 100 years, 200 years Return Period Daily Maximum Rainfall into 6 hours Incremental Rainfall for AA Bole Station

Time (hr)	10 hours Return Period Rainfall				100 hours Return Period Rainfall				200 hours Return Period Rainfall			
	Hourly Distributed Cumulative Precp. (mm) $P=M*sqrt(T_i)$	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) $P=M*sqrt(T_i)$	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) $P=M*sqrt(T_i)$	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)
1	25.75	25.75	0--1	**5.5**	36.19	36.19	0--1	**7.72**	39.28	39.28	0--1	**8.39**
2	36.41	10.66	1--2	**6.89**	51.18	14.99	1--2	**9.69**	55.56	16.28	1--2	**10.53**
3	44.6	8.19	2--3	**8.19**	62.69	11.51	2--3	**11.51**	68.04	12.48	2--3	**12.48**
4	51.49	6.89	3--4	**25.75**	72.38	9.69	3--4	**36.19**	78.57	10.53	3--4	**39.28**
5	57.57	6.08	4--5	**10.66**	80.93	8.55	4--5	**14.99**	87.84	9.27	4--5	**16.28**
6	63.07	5.5	5--6	**6.08**	88.65	7.72	5--6	**8.55**	96.23	8.39	5--6	**9.27**

Table A1-9: Conversion of 10 years, 100 years, 200 years Return Period Daily Maximum Rainfall into 6 hours Incremental Rainfall for DebreZiet Station

Time (hr)	10 hours Return Period Rainfall				100 hours Return Period Rainfall				200 hours Return Period Rainfall			
	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)
1	26.02	26.02	0--1	**5.56**	36.27	36.27	0--1	**7.74**	39.31	39.31	0--1	**8.39**
2	36.8	10.78	1--2	**6.97**	51.29	15.02	1--2	**9.72**	55.59	16.28	1--2	**10.53**
3	45.07	8.27	2--3	**8.27**	62.82	11.53	2--3	**11.53**	68.09	12.5	2--3	**12.5**
4	52.04	6.97	3--4	**26.02**	72.54	9.72	3--4	**36.27**	78.62	10.53	3--4	**39.31**
5	58.18	6.14	4--5	**10.78**	81.1	8.56	4--5	**15.02**	87.9	9.28	4--5	**16.28**
6	63.74	5.56	5--6	**6.14**	88.84	7.74	5--6	**8.56**	96.29	8.39	5--6	**9.28**

Table A1-10: Conversion of 10 years, 100 years, 200 years Return Period Daily Maximum Rainfall into 6 hours Incremental Rainfall for Sendafa Station

Time (hr)	10 hours Return Period Rainfall				100 hours Return Period Rainfall				200 hours Return Period Rainfall			
	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)	Hourly Distributed Cumulative Precp. (mm) P=M*sqrt(T_i)	Incremental Depth (mm)	Time Interval (hr)	Pricipitation (mm)
1	32.59	32.59	0--1	**6.96**	48.18	48.18	0--1	**10.29**	52.79	52.79	0--1	**11.27**
2	46.09	13.5	1--2	**8.73**	68.14	19.96	1--2	**12.91**	74.66	21.87	1--2	**14.15**
3	56.45	10.36	2--3	**10.36**	83.45	15.31	2--3	**15.31**	91.43	16.77	2--3	**16.77**
4	65.18	8.73	3--4	**32.59**	96.36	12.91	3--4	**48.18**	105.58	14.15	3--4	**52.79**
5	72.87	7.69	4--5	**13.5**	107.73	11.37	4--5	**19.96**	118.04	12.46	4--5	**21.87**
6	79.83	6.96	5--6	**7.69**	118.02	10.29	5--6	**11.37**	129.31	11.27	5--6	**12.46**

Appendix 2: Computation Table for Consistency of Precipitation Records

Year	Annual Precipitation for Stations					Cumulative Annual Precipitation for Stations					
	A. A. Bole	*Debre Zeit*	Chancho	*Aleltu*	*Sendafa*	*A. A. Bole*	*Debre Zeit*	Chancho	*Aleltu*	*Sendafa*	*Mean*
1964	13.3	6.57	9.1	10.0	15.2	13.3	6.57	9.1	10.0	15.2	11.69
1965	11.8	11.92	11.9	9.6	11.08	25.1	18.49	21.0	19.6	26.28	23.29
1966	11.2	8.89	9.8	9.8	10.9	36.3	27.38	30.7	29.4	37.18	33.62
1967	11.1	7.11	8.6	6.4	11.0	47.4	34.49	39.3	35.8	48.18	43.36
1968	11.0	9.358	10.0	9.9	21.5	58.4	43.85	49.3	45.7	69.68	57.31
1969	10.8	7.803	8.9	9.5	14.7	69.2	51.65	58.2	55.2	84.38	68.41
1970	10.3	5.93	7.6	6.9	11.5	79.5	57.58	65.8	62.2	95.88	77.65
1971	9.8	9.065	9.3	13.0	21.3	89.3	66.65	75.1	75.2	117.18	91.04
1972	9.7	8.987	8.5	5.2	15.0	99	75.63	83.7	80.4	132.18	102.27
1973	9.7	8.8	10.6	10.5	12.4	108.7	84.43	94.3	90.9	144.58	112.57
1974	9.4	12.3	7.0	7.6	9.5	118.1	96.73	101.2	98.5	154.08	122.97
1975	9.4	10.4	11.3	8.4	14.7	127.5	107.13	112.6	106.9	168.78	134.47
1976	9.3	13.21	9.6	7.6	12.7	136.8	120.34	122.2	114.5	181.48	146.21
1977	9.3	9.01	11.9	7.5	9.0	146.1	129.35	134.0	122.0	190.48	155.31
1978	9.2	12.45	12.6	6.1	9.877	155.3	141.80	146.6	128.2	200.36	165.82
1979	9.2	12.8	8.9	6.6	10.1	164.5	154.60	155.5	134.8	210.46	176.52
1980	9.1	14	14.5	6.4	9.0	173.6	168.60	170.0	141.2	219.46	187.22
1981	9.1	10.7	10.1	9.8	10.6	182.7	179.30	180.1	151.0	230.06	197.35
1982	9.0	12.2	8.9	7.2	9.84	191.7	191.50	189.0	158.2	239.90	207.7
1983	8.9	8.14	4.2	13.2	10.8	200.6	199.64	193.2	171.4	250.70	216.98
1984	8.8	9.18	9.0	9.4	13.3	209.4	208.82	202.2	180.8	264.0	227.41
1985	8.7	6.92	7.6	13.2	8.9	218.1	215.74	209.8	194.0	272.90	235.58
1986	8.7	9.91	9.5	8.8	8.6	226.8	225.65	219.3	202.9	281.50	244.65
1987	8.7	9.64	9.3	7.9	14.2	235.5	235.29	228.6	210.8	295.70	255.5
1988	8.6	7.82	8.1	11.3	12.2	244.1	243.11	236.7	222.0	307.90	265.04

1989	8.6	7.639	8.0	13.8	14.6	252.7	250.75	244.7	235.9	322.50	275.32
1990	8.5	10.1	12.7	10.3	16.9	261.2	260.85	257.3	246.2	339.40	287.15
1991	8.4	9.91	10.9	13.9	14.6	269.6	270.76	268.2	260.1	353.10	298.12
1992	8.4	10.46	10.7	9.1	14.48	278	281.22	279.0	269.2	368.48	309.23
1993	8.3	6.08	13.1	12.4	10.9	286.3	287.30	292.0	281.6	379.38	317.66
1994	8.3	7.61	10.8	12.2	9.8	294.6	294.91	302.8	293.7	389.18	326.23
1995	8.3	9.468	11.9	10.6	11.6	302.9	304.38	314.7	304.3	400.78	336.02
1996	8.3	11.8	11.9	10.1	10.2	311.2	316.18	326.5	314.4	410.98	346.12
1997	8.2	9.193	12.3	9.6	11.5	319.4	325.37	338.8	324.0	422.48	355.75
1998	8.1	7.8	13.3	11.7	7.5	327.5	333.17	352.1	335.7	429.98	363.55
1999	8.0	7.25	12.2	14.3	12.3	335.5	340.42	364.3	350.0	442.28	372.73
2000	7.9	6.165	10.3	15.6	9.3	343.4	346.59	374.6	365.5	451.58	380.52
2001	7.8	7.51	10.9	9.9	10.9	351.2	354.10	385.6	375.4	462.48	389.26
2002	7.8	6.758	23.2	11.0	7.1	359	360.86	408.8	386.4	469.58	396.48
2003	7.8	11.86	27.2	12.0	12.3	366.8	372.72	436.0	398.4	481.88	407.13
2004	7.8	8.732	36.9	10.0	14.7	374.6	381.45	473.0	408.4	496.58	417.54
2005	7.7	9.197	8.3	6.8	12.0	382.3	390.65	481.3	415.2	508.58	427.17
2006	7.5	13.2	8.4	10.6	10.6	389.8	403.85	489.7	425.7	519.18	437.61
2007	7.5	6.27	13.3	6.9	9.3	397.3	410.12	503.0	432.7	528.48	445.3
2008	7.2	5.77	9.4	14.2	8.7	404.5	415.89	512.3	446.8	537.18	452.52
2009	7.2	7.88	8.5	9.2	12.0	411.7	423.76	520.9	456.0	549.18	461.55
2010	7.1	7.535	10.6	9.0	8.5	418.8	431.3	531.5	465.0	557.68	469.26
2011	7.0	11.12	9.1	12.3	9.1	425.8	442.42	540.6	477.3	566.78	478.33
2012	5.8	8.95	14.4	6.6	9.3	431.6	451.37	554.9	483.9	576.08	486.35
2013	5.8	5.029	7.6	6.2	7.2	437.4	456.40	562.6	490.2	583.28	492.36

Appendix 3: Runoff Curve Numbers for Small Watershed

Table 2-2b Runoff curve numbers for cultivated agricultural lands [1]

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment [2]	Hydrologic condition [3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

1 Average runoff condition, and I_a=0.2S
2 Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.
3 Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Table 2-2c Runoff curve numbers for other agricultural lands [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.

2 *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.

3 *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

4 Actual curve number is less than 30; use CN = 30 for runoff computations.

5 CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

6 *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Table 2-2d Runoff curve numbers for arid and semiarid rangelands [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition [2]	A [3]	B	C	D
Herbaceous—mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

1 Average runoff condition, and $I_a = 0.2S$. For range in humid regions, use table 2-2c.

2 Poor: <30% ground cover (litter, grass, and brush overstory).
Fair: 30 to 70% ground cover.
Good: > 70% ground cover.

3 Curve numbers for group A have been developed only for desert shrub.