

ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL SCIENCES
SCHOOL OF GRADUATE STUDIES

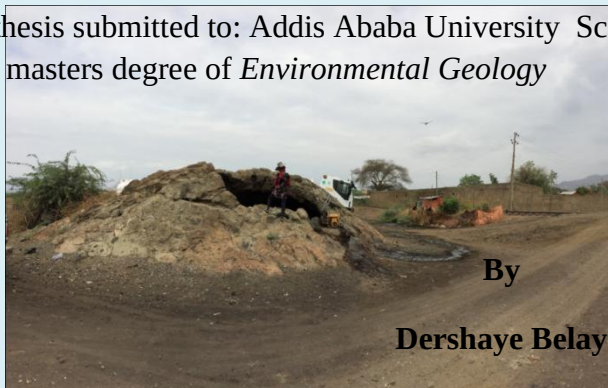
SCHOOL OF EARTH SCIENCES



Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion on the Integrity of Fentale-Metehara Blister Caves in the Main Ethiopian Rift



A thesis submitted to: Addis Ababa University School of Graduate Studies in the partial fulfillment for masters degree of *Environmental Geology*



By

Dershaye Belay



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ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL SCIENCES
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCE

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of Fentale-Metehara Blister Caves in the Main Ethiopian Rift***

By

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Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of
Science in Environmental Geology

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Declaration

I hereby declare that work which is being presented in this thesis entitled "Environmental impact analysis of infrastructures development and the Lake Beseka expansion on the integrity of the Fentale-Metehara blister caves" is performed under the supervision of my research advisor Prof. Asfawossen Asrat and co-advisor Dr. Binyam Tesfaw. It is my original work, has not been presented for a degree or diploma in any other university and that all source of the material used for the thesis have been duly acknowledged.

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ABSTRACT

This study deals with the analysis of environmental impact of the Lake Beseka expansion and the infrastructures development on the Fentale-Metehara blisters and blister caves in the Main Ethiopian Rift. The Fentale-Metehara blisters and blister caves are unique and spectacular geological features found in such number and extent in this area only. The aerial extent of the blistered region is about 54 km². However, the area of the individual blisters and blister caves ranges from about 7m² to 24000m². Decadal landuse and land cover (LU/LC) change of the area analyzed using supervised classification system of Landsat images have been processed in ERDAS IMAGINE 2014 version. In addition, 161 blister caves and 478 blisters were mapped and documented in a geo-database schema using Google Earth accompanied by detailed field investigation. Susceptibility to destruction of these features has been analyzed based on the frequency ratio technique and non-hierarchical cluster analysis of natural (topographical factors, drainage systems, Lake Beseka expansion and lava flows) and human induced (urbanization, irrigation activities and infrastructure lines) triggering factors. For the susceptibility mapping of these blister fields 119 blisters and blister caves were selected and categorized as affected/threatened blister fields. Most of the blister fields fall on the high to very high susceptibility zones. These techniques revealed that the Lake, irrigation fields and the rapid expansion of the urban settlements led to a destruction of some of the blister fields during the past four decades. It was found out that further expansion of Lake Beseka, as well as the human induced factors including the infrastructure development could lead to further destruction of the remaining blister fields. The LULC analysis further corroborates this conclusion as it has been observed that the Lake Beseka, farmlands and settlements expanded at about 46.2 km², 46.6 km² and 3.3 km² area during the last four decades. In conclusion, proper and well-organized documentation of the blister fields in a geo-database schema and also the high quality susceptibility zonation map, which were produced in this study will help in the preservation efforts of these unique geoheritage resources.

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I would like to thank both Samson Workaye and Eshetu Gebre from Ethiopian Mapping Agency who helped me on using the *Raster Calculator tool* in the Arc GIS environment which was used for the susceptibility mapping and to assess the accuracy of the classified image for the LU/LC change analysis, respectively. I am also grateful to my beloved family for their appreciation and encouragement during my study.

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ACRONYMS

AOI	Area of Interest
EARS	East African Rift System
EIGS	Ethiopian Institute of Geological Survey
EMA	Ethiopian Meteorological Agency
ETM+	Enhanced Thematic Mapper
FCC	False Color Composite
Fig	Figure
GCPs	Ground control points
GIS	Geographic Information System
GPS	Global Positioning System
LS	Lacustrine sediments
LU/LC	Landuse/Land Cover
MER	Main Ethiopian Rift
MLC	Maximum Likelihood Classification
MSEP	Metehara Sugar Estate Plantation
MSS	Multi Spectral Scanner
OLI	Operational Land Image
OWWDSE	Oromia Water Works Design and Supervision Enterprise
RGB	Red Green Blue
Sq. Km (Km ²)	Square Kilometer

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TIRS	Thermal Infrared Sensor
TM	Landsat Thematic Mapper
UTM	Mercator Universal Transverse
WWDSE	Water Works Design and Supervision Enterprise

CHAPTER ONE

INTRODUCTION

1.1. Background

The Main Ethiopian Rift (MER), which belongs to the northern most branch of the East African Rift System (EARS) is characterized by active extensional tectonics. It has been seismically, tectonically and volcanically active since early Miocene (Berihu Abadi, 2007). Ash-flow tuffs constitute some of the major volcanic products in the MER. These are pyroclastic deposits, often of enormous volume and extent, which appear to have been deposited from very dense incandescent gas clouds rich in fragmental material. The critical feature of these clouds is their ability to flow for great distances and thus to disperse the entrapped fragmental material widely over the low-lying areas surrounding the source vent(s). This high fluidity is apparently the result of the cloud of fragmental material being fluidized; that is, the cloud has a gaseous continuum and although richly charged with fragmental material it behaves as a single, rather dense fluid phase (Gibson, 1974).

Such fluid rich pyroclastic flows in the Fentale-Metehara area form a unique geological feature called blistering, which is the up-doming of the flowing pyroclastic flow due to gases entrapped in the progressing flow. Some of these could remain closed while others are subsequently breached to form what is generally called “Blister caves”. The Blister caves in the Fentale-Metehara area constitute the biggest and most abundant blister caves in the world, distributed in an area of about 80 square km, mostly on the southwestern side of the Fentale volcano and north and northeast of the Beseka Lake and Metehara town. The main route from Addis to Djibouti and the Addis Ababa to Djibouti railway cross this field of Blister caves in the Metehara area. The distribution of blisters in the Fantale area is of particular significance as this information constrains theories as to their origin (Gibson, 1974).

However, the unprecedented expansion of Lake Beseka has resulted in flooding and salinization of the area and endangers the routes (road and railway) from Addis Ababa to Djibouti. The expansion of Lake Beseka has necessitated the relocation of the road and railway lines. The Lake to date has inundated fully and partially about 150ha of the Sugar cane plantation to the

Southeast and over 2000ha of grazing land (MWR, 1999; Berihu Abadi, 2007). This rapid expansion of the lake, and the rapid infrastructure development in the area (road networks, railway lines, urbanization, industrialization) and irrigations are serious environmental impacts which threaten not only the natural blister caves but also the whole environmental-anthropogenic system, calling for an integrated environmental impact analysis of all these developments on the natural environment and on each other. Hence, the current study is aiming at conducting this.

1.2. Statement of the Problem

Blister caves are unusual kind of caves formed by gas pressure (Gibson, 1974; Grimes, 2002). The biggest and most spectacular blister caves in the world are found in the Metahara area, in the Main Ethiopian Rift. More than 600 blister caves ranging in diameter from a few meters to more than 100 m are identified and distributed in an area of about 80 sq. km, mostly at the southwestern foot of the Fantale volcano, and generally north of Lake Beseka. These blister caves, which have been associated to the ash flow tuff from the Fantale volcano (Gibson, 1974; Williams et al., 2004) form hollow domes, seen on the ground as small, rounded hillocks. Some of these are partially collapsed, permitting access to the interior. In some other cases the side of the blister is open while in other cases they are perforated at the apex of the dome, often with a very small aperture opening into a bell-shaped cavity below. The biggest concentration of such caves in the world is located and widely available only in the Fantale-Metahara, Ethiopia; however, except a cursory description of these caves by Gibson (1974), there has not been any systematic study conducted on these caves.

Against this background, the rapid and unprecedented expansion of Lake Beseka causes serious environmental problems: infrastructure (road networks, railways) damage and relocation, risk and actual damage to the blister caves (potential geotouristic sites and potential archaeological evidences, which are found in some of the blister caves), limits the urban and irrigation expansion, and also it affects Abadir Farm, a sugar cane plantation and sugar cane factory nearby. Similarly, the infrastructures development and urban expansion in the Fantale-Metehara area pose significant risks to the caves and to their contents unless the caves are properly mapped and documented and the impact of these environmental interactions is properly analysed. In general, the study area is exposed to serious, inter-related and complex environmental problems.

Therefore, in order to preserve the blister caves and their potential archaeological contents, to conduct an integrated urban-infrastructure and development planning of the area, an integrated temporal and spatial environmental impact analysis is required, hence this study.

1.3. Objective of the Study

1.3.1. General Objective

The main objective of this study is to conduct an integrated spatio-temporal environmental impact analysis (susceptibility mapping) in order to investigate the impact of Lake Beseka expansion, infrastructures development (railway, road networks, urbanization, industrialization), and the expansion of irrigations (Abadir Farm and the Metehara Sugar Estate Plantation) on the integrity of the blister caves.

1.3.2. Specific Objectives

The specific objectives for this study are to:

- map the land use /land cover change of the study area during the last four decades (from 1973 to 2015);
- map the individual gas blisters and blister caves;
- document all the gas blisters and blister caves in the area and prepare a well organized Geo-database;
- map the geology of gas blisters and blister caves; and
- produce susceptibility map of blisters and blister caves.

1.4. Data and Methodology

1.4.1. Data

To achieve the objectives of this research numerous GIS (Geographic Information System), RS (Remote Sensing), in situ field and some auxiliary/secondary data sets have been used. These data sets have been used to analyze the last four decades (from 1973 to 2015) land use/land cover changes, to map the individual blisters and blister caves, to prepare the geological map of the area, and finally for the preparation of the susceptibility map of the blisters and blister caves.

1.4.1.1. GIS Data

The mapping of the 639 blisters and blister caves identified in the field were organized as 639 GIS data layers, where one GIS data layer represents one blister or blister cave. Furthermore, eleven GIS data layers each representing the triggering factors for the susceptibility of blisters and blister caves, and one GIS data layer for affected/threatened blisters and blister caves were used for the frequency ratio modeling and *K-means (non-hierarchical) cluster analysis*, in order to produce the expected susceptibility map of the study area. GIS data layers of the susceptibility and all the 119 (one hundred nineteen) affected gas blisters and blister caves maps were used for the validation of the susceptibility map.

The eleven GIS data layers of triggering factors used for preparation of the susceptibility map were: seven distance maps (lineament, drainage, settlement, road networks, railways, irrigations and Beseka Lake), three topographic factor maps (elevation, slope and slope aspect) and lithological map of the study area.

1.4.1.2. RS Data

The 1973, 1985, 1995, 2002 and 2015 remotely sensed data sets were used for the 1973 to 2015 landuse and land cover change analysis of the study area. All the Landsat images are cloud cover free and level one products. The Path and Row for all the Landsat imageries is 168/54 (Path=168 and Row=054), except the 1973 Landsat imagery, which is 180/54. Moreover, The spatial resolution or pixel/cell size (x, y) for the 1985, 1995, 2002 and 2015 imageries is 30m x 30m, but 60m x 60m for the 1973 imagery. The detail information for each Landsat imagery is given in Table 1.1.

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Table 1.1. The 1973, 1985, 1995, 2005 and 2015 Landsat imagery detail information.

<i>Landsat Archive</i>	<i>Entity ID</i>	<i>Path/ Row</i>	<i>Cloud cover (%)</i>	<i>Pixel size (meter)</i>	<i>Date of acquisition</i>	<i>Product</i>
L1-5 MSS	LM11800541973030AAA04	180/54	0	60, 60	Jan 30, 1973	Level one (27.0MB)
L4-5 TM	LT51680541985002XXX02	168/54	0	30, 30	Jan 02, 1985	Level one (162.6MB)
L4-5 TM	LT51680541995030XXX00	168/54	0	30, 30	Jan 30, 1995	Level one (922.7MB)
L7ETM+ SLC-on (1999-2003)	LE71680542005353ASN00	168/54	0	30, 30	Dec 25, 2000	Level one (283.0MB)
L8 OLI/TIRS	LC81680542015357LGN00	168/54	0	30, 30	Dec 23, 2011	Level one (155.4MB)

1.4.1.2. In-situ and Ancillary Data

Several in-situ or primary data sets were collected in addition to GIS and RS data. In-situ data were collected during field survey using GPS (Global Positioning System) points. The GPS point data include : Individual blister or blister caves (identification, mapping); level and cause of damage of blister caves (for susceptibility mapping); ground truth points for land use and land cover mapping, and for geological mapping; and structural measurements at point locations.

The ancillary layers include:

- 1975 topographic map of Metehara sheet at a scale of 1:50,000
- Geological map of the Nazareth sheet (1:250,000 Scale)
- DEM (Digital Elevation Map) of the study area with 30m x 30m spatial resolution

- Metrological data (Mean monthly rain fall (mm), mean monthly temperature (°C), mean monthly relative humidity (%), mean monthly wind speed (km/day), mean monthly sunshine hours (hr) and mean monthly evaporation (mm))
- Published and unpublished papers, reports related to this study

1.4.1.3. Softwares used

The following were the softwares used to accomplish this study:

Google Earth

- To identify and digitize the blisters and blister caves
- To digitize the recent area of Beseka lake, towns (Metehara, Addis Ketema and Metehara Sugar Factory), irrigations (Abadir town and Metehara Sugar Estate) as a polygon feature; and new main Road and railways as poly-line features

Erdas Imagine 2014

- To do the pre-image processing activities (import/export, image correction, layer stack, image sub-setting (AOI), geo-referencing, band combination) and image classification for the four decadal landuse and land cover during image processing stage.

Arc Map 10.3

- To digitize roads, railways, drainage systems from the 1975 Metehara sheet topographic map
- To convert Kml/Kmz data to layers, and then layer datasets to shape-files
- To convert raster layers to vector data sets and vector to raster layers
- To extract images by masking
- To clip, edit and merge class features (poly-line and polygons)
- To geo-reference non-geo-referenced images
- To export class features to shape-files, and raster datasets to tiff format
- To do *k-means* cluster analysis in the spatial statistics tools

Global Mapper 10.3

- For image geo-referencing

1.4.2. Methodology

All the five representative Landsat imageries (1973, 1985, 1995, 2002 and 2015) for the four decadal landuse and land cover change analysis were downloaded from USGS (United States Geological Survey) Earth explorer at different acquisition dates. The imageries were processed using Erdas Imagine 2014. The pre-processing procedures are import/export/ image correction (radiometric correction)/ Layer stacking/image subset/ color composite band combination and finally image geo-referencing. Image classification was done during image processing. The classification algorithm used for those five imageries was supervised classification. All the five classified images were opened and mapped in Arc Map 10.3. Lastly, accuracy assessment for the 2015 classified image was done using the collected GPS points from field survey and Google Earth. Then, the spatial and temporal landuse/land cover change analysis for all the landuse land cover classes were conducted using Arc GIS 10.3.

All the six hundred thirty nine individual gas blisters and blister caves identified either during the field investigation and/or from Google Earth were digitized in polygon format at the scale of 1:2,000 to 1: 100 from the Google Earth and saved as KML/KMZ files. Then all the saved 639 KML/KMZ files converted to layer files in Arc GIS 10.3, were converted to shape files in this software using KML to layer conversion tool. Finally, all these blisters and blister caves were mapped. All the individual 119 affected/threatened blisters/blister caves identified during the field survey and using Google Earth were mapped using Arc Map 10.3 separately.

Geological map of the study area was prepared by extracting the study area from the 1978 geological map of Nazareth sheet and then digitized in Arc Map 10.3, and then updated during a detailed field investigation.

To produce the susceptibility map of gas blisters and blister caves there were several stages (Fig.1.1) to accomplish. The first step for this susceptibility mapping was to identify and map all the affected blisters and blister caves. Next, all the eleven triggering factors for the susceptibility of these threatened features were identified and selected and then eleven triggering factor maps were prepared at the same scale and grid properties. For the preparation of a susceptibility map, a Frequency Ratio Model (Yilmaz, 2007; Fell, 2008) was utilized. It is the ratio of the area where

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collapse/destruction in the total study area; if the ratio is greater unity it indicates stronger relationship between collapse/ destruction and the given factor's attribute (Yilmaz, 2007).

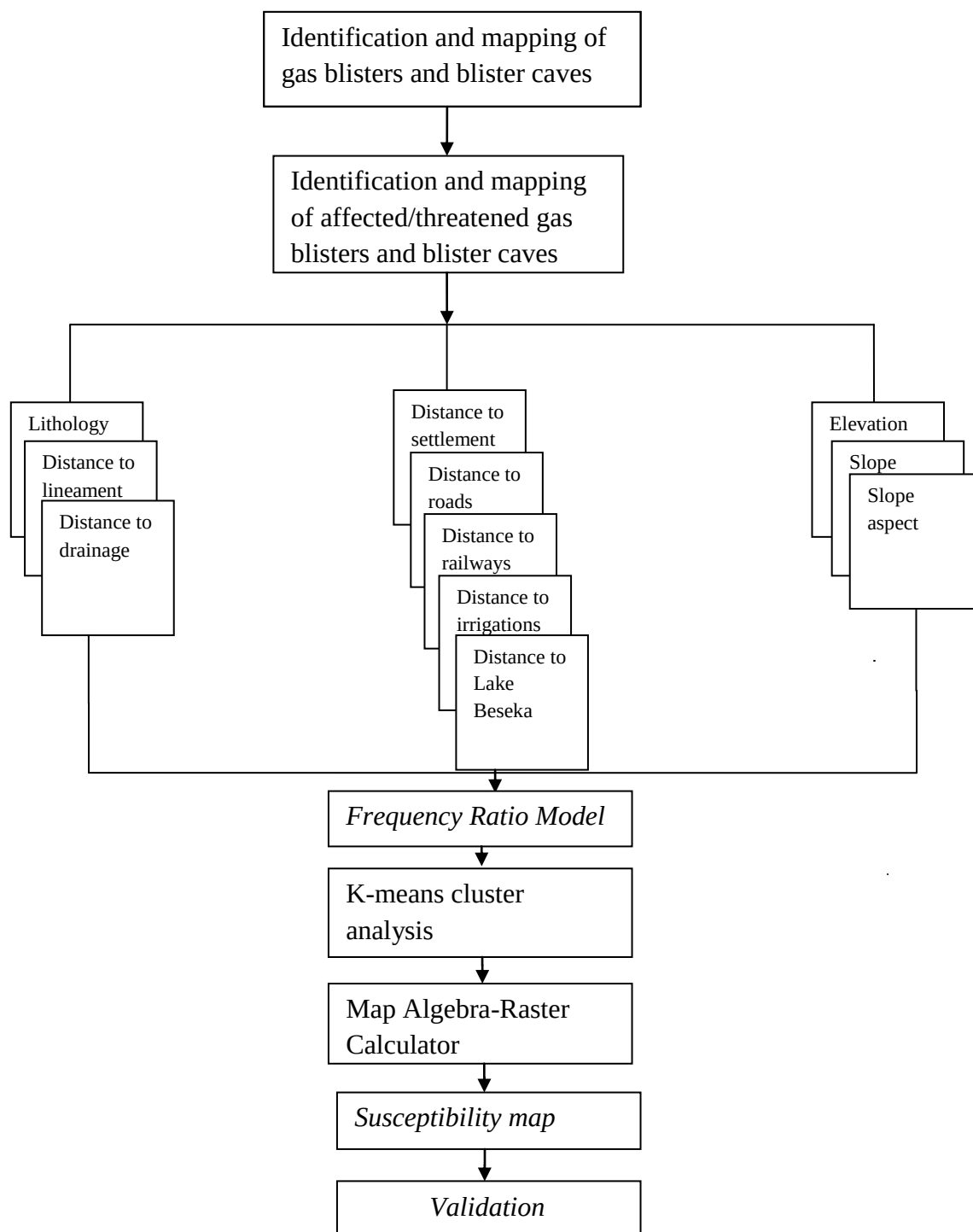


Fig.1.1. General flow chart for the gas blisters and blister caves susceptibility mapping procedure.

1.5. Significance of the Study

The gas blister caves are located close to the Awash National Park. In fact some of them are within the park. These spectacular caves will be ideal sites for establishing a geopark, which will provide tourists more opportunities and options to visit. At the same time the local community will be provided with employment opportunities (guiding to and protecting the caves) if the caves are assigned into a geopark. However, these caves are currently poorly documented and investigated which hinders advancing this plan. Therefore, this research will lay the foundation for establishing the geopark, which preserves and protects these spectacular caves.

In addition, some of the blister caves have been naturally collapsed from the top and subsequent occupation by early humans is a strong possibility, as the general area was occupied by early humans (e.g., Clark and Williams, 1976). Investigation of these caves for any sedimentary deposits in their interiors will provide data to archaeologists who might be interested in excavating the sediments for human and archaeological remains.

The rapidly ever-expanding Beseka Lake borders the blister caves to the south. Expansion of the lake might have some relation to the volcanic activity of the Fantale volcano and the ash flow tuff deposition. Therefore, investigation of the blister caves possibly gives some insights into this environmental problem. On the other hand, expansion of the lake is threatening some of the blister caves and documenting these caves will be the first step in defining preservation and mitigation mechanisms.

Furthermore, the Fentale-Metehara area is now under a very rapid expansion in terms of infrastructures development (rail, road network), urbanization, and large-scale irrigation. Conducting environmental analysis using land use/land cover changes as well as other geological approaches will therefore be of great significance for planning the integrated development of the area.

1.6. Outcome of the Study

The outputs of this research work are:

- Detailed Landuse/Land cover maps of the study area detailing the spatial and temporal evolution of lake Beseka expansion and infrastructures development;
- Detailed map of the field of blisters and blister caves;
- Complete and well organized Geodatabase of blister caves;
- Geological map of blisters and blister caves;
- Susceptibility map of blisters and blister caves;

1.7. Scope of the Study

This research mainly deals with the blisters and blister caves which are widely available only in Fentale-Metehara, Ethiopia, and have been threatened by Lake Beseka expansion, irrigation activities (Metehara Sugar Estate Plantation (MSEP) and Abadir Farm), expanding railways and road networks, Metehara Sugar Factory, Addis Ketema and Metehara towns expansion. The study analyzes the spatial and temporal change during the last four decades. Moreover, this study focuses on the impact of unusual Lake Beseka expansion on infrastructures development (urbanization, railway and road networks), irrigation activities and the whole natural ecosystem; and also the impact of irrigation activities in turn. This research provides detailed distribution map of individual blisters and blister caves with a complete geo-database as well as their detailed geological and susceptibility map, and detailed landuse and land cover and geological map of the study area.

CHAPTER TWO

LITERATURE REVIEW

2.1. Background

In order to provide a conceptual framework of the research problem a systematic and extensive literature review has been carried out. As the study is focused mainly on the environmental impact analysis of infrastructures development and the Lake Beseka expansion on the integrity of Fentale-Metehara blister caves, literature related to this topic were reviewed from different sources including journals, text books, conference papers, technical reports, published and unpublished papers. Thus, based on the observations made from different and relevant literatures a systematic methodology was prepared for this study. A summary of previous studies relevant to the current study is presented below.

2.2. Geological Setting and Structures

The Fantale volcano is a Quaternary volcano situated along the Wonji Fault Belt (Mohr, 1960; Gibson, 1974; Williams et al., 2004). The main volcanic edifice rises approximately 600 m from the floor of the Rift Valley and its lavas, excluding the welded tuff, cover a roughly oval area of some 100 km² (Fig. 2.1). The upper part of the volcano is dominated by a large elliptical caldera approximately 3.5 km in diameter and 300 m deep. The majority of lavas were apparently erupted from a centre, or centres, close to the pre-collapse summit of the volcano. They consist largely of trachytes and pantelleritic rhyolites. A trachyte flow about 3 km north of the caldera has been dated at 1.86 ± 0.1 Ma by K/Ar dating (Williams et al., 2004). A younger group of trachytes and rhyolites was erupted from a satellite centre about 3.5 km from the centre of the main caldera. About 8 km northeast of the main Fantale caldera is an older, eroded caldera (Tinishu Fantale), which appears to have had a similar but earlier geological history to that of Fantale. Caldera collapse of both Tinishu Fantale and Fantale was accompanied by the eruption of voluminous ash flows, which solidified to welded tuffs. The older welded tuff from Tinishu Fantale covers the plains to the east and south east of the complex, and the plains to the south, west and north are covered by the lavas and tuffs of Fantale itself. The Fantale tuff has also entered the eroded caldera of the older volcano. The welded tuff from Tinishu Fantale has been dated at 1.51 Ma (K/Ar dating of feldspar; Kazmin et al., 1980) in a section in the Awash Gorge

near Karayu Lodge (Fig. 2.1), and the Fantale welded tuff at $168,000 \pm 8,000$ years (Williams et al., 2004). Following the eruption of the younger welded tuff a group of pitchstones and rhyolites was erupted from vents on the west, south, southeast and northeast slopes of the mountain, and within the caldera itself. At least two episodes of recent basaltic volcanism are visible immediately south of Fantale. The earlier resulted in the formation of the tuff ring of Tinishu Sabober. The later was in the form of two small flows, the first originating from a locality about 1 km north of the tuff ring, and the second from a point close to its southern rim. The loci of the eruptions are aligned in the direction of the Wonji Fault Belt. The lava from both eruptions flowed southwards, covering a combined area of some 3 km^2 . The most recent flow is dated from historical report (Harris, 1844; Buxton, 1949) and local oral tradition at about 1810 AD.

The rock unit of interest to this research is the Fantale welded tuff. This unit covers the plains to the south and west of Fantale and much of the lower slopes of the mountain, then thins and becomes less extensive on the higher slopes where it is confined to valley fillings. It clearly predates the tuff ring of Tinishu Sabober. On the plains the tuff is about 30 m thick and possibly 50 m in places. It consists of a collapsed pumice matrix with flattened vesicles and elongated stringers or fiamme of black pitchstone, which would have been plastic at the time of deposition and compressed on cooling. The tuff has undergone very little weathering and has only a thin veneer of sediment cover. A unique feature of the tuff is the occurrence of numerous circular, hollow hummocks (blisters) a metre or more high and ranging from about 2 m to over 100 m in diameter.

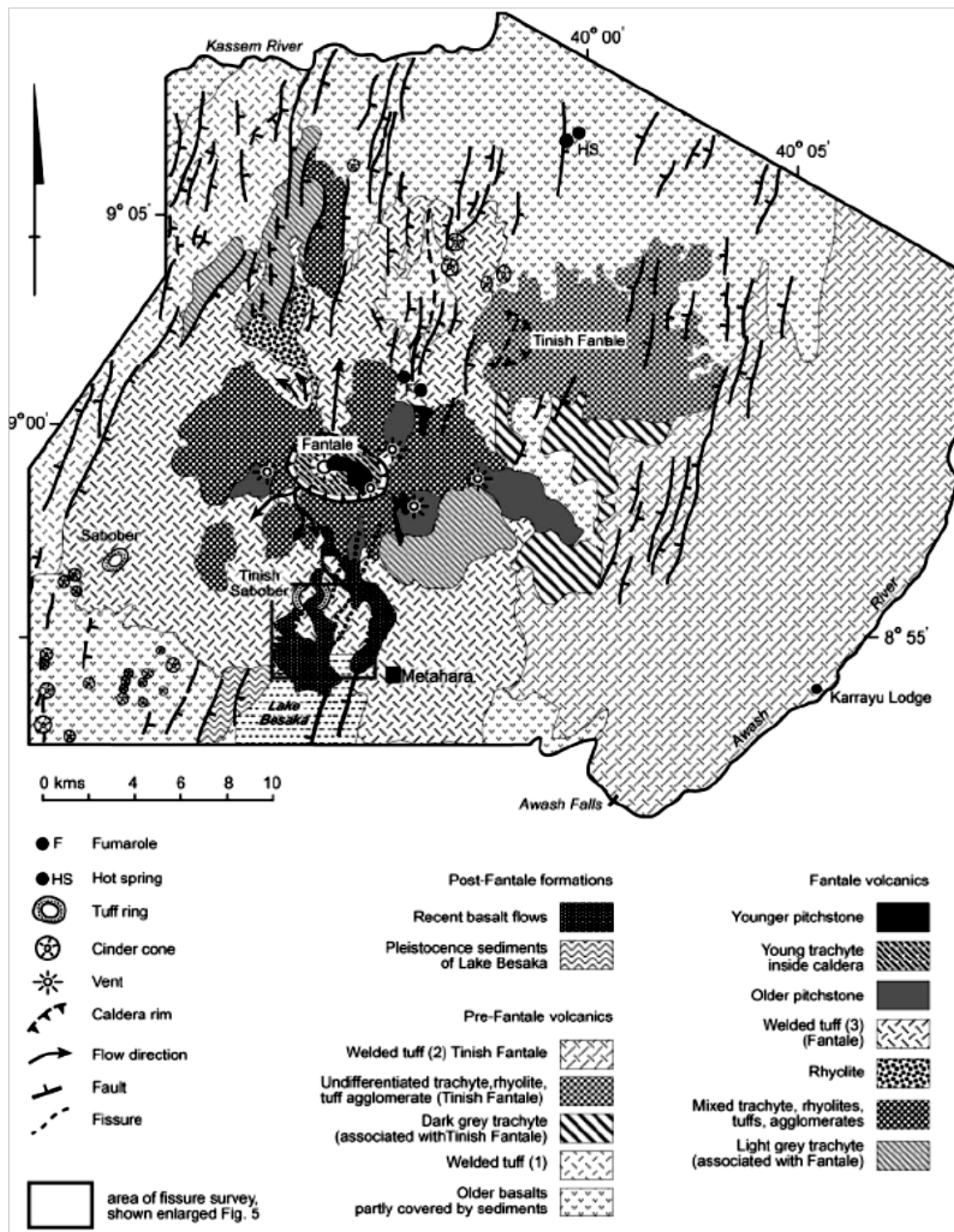


Fig. 2.1. Geological Map of the Fantale Caldera (after Williams et al., 2004).

2.3. Impact of Beseka Lake Level Rise

According to WWDSE (2011) the negative and positive Beseka Lake level rise impacts on the environment are as follows:

2.3.1. Potential Positive Environmental Impacts

Two major social benefits: job opportunity creation and aquatic resources promotion, were identified as positive impacts due to Lake Beseka level rise and expansion.

2.3.1.1. Aquatic Resources Promotion

Lake Beseka level rise and expansion promoted considerable number of crocodiles, fish populations and other saline aquatic lives. Tilapia (*Oreochromis niloticus*) and Catfish (*Clarias gariepinus*) are the two fish species of the lake. This provides opportunities for fisheries development and fish farming in the project area that can supplement to nutrition of the people. Lake area expansion created more habitats for aquatic lives. This created job opportunities and enhances economic benefits to the communities of the area.

2.3.2. Potential Adverse Impacts on the Physical Environment

2.3.2.1. Impact on Water Balance and Downstream Release

The hydrology and hydrogeology studies related to lake balance and groundwater modeling indicate increasing trend for both the lake volume and groundwater discharge. This trend can aggravate influence of the saline lake water on entering into Awash River that can affect the water quality and downstream ecological balance of the aquatic environment.

2.3.2.2. Impact on Water Supply

As a result of the Lake level rise and expansion, Metahara Town water supply has faced complete damage of pipelines by the flooding and loss of water supply services of five household customers of the town before 2011 (WWDSE, 2011). The saline Lake water is also damaging the lines and imposing psychological pressure on community members and resulted on financial losses for spare parts purchase, maintenance and rehabilitation activities of water supply lines.

The immediate downstream district, *Awash 7 kilo Town* has faced problems on water supply as a result of the saline lake water discharge during the flooding. The identified major problems are:

- Intermittent close of mobile water pump intake on Awash River,
- Decrease in the river water clarifying efficiency to the needed chemical and bacteriological quality standard,
- Rusting of water pumps and other metals used in the town's water treatment plant,
- Change in treated water color, taste and formation of jelly like floating substances in treated water and
- Financial losses due to pump damage and additional treatment chemicals purchase.

2.3.2.3. Water quality deterioration

The surrounding fresh water quality is continuously decreasing by flooding of the saline lake water. Physical changes can also resulted in chemical impacts on the river system, e.g., inundation of grazing areas and other vegetation may lead to an increase in nitrate and phosphate inputs that may initiate eutrophication. Eutrophication may ultimately lead to depletion of dissolved oxygen and hence formation of anoxia in the periphery of the lake, where production of hydrogen sulfide (H₂S) is inevitable. The phenomena of anoxia would have an immediate effect on the invertebrates present in the lake and downstream. The surface runoff may carry nutrients mainly nitrates and phosphates into the lake and River Awash. This may cause excessive growth of aquatic plants and algae resulting in eutrophication. The water quality can also be affected by residuals of agro-chemicals (chemical fertilizers and biocides) used in the irrigation farms of the area. The actual effects of the chemicals are dependent on several factors such as the nature of the chemicals (pollutants) themselves, the physico-chemical characteristics of the recipient soils, the general climatic conditions prevailing in the area, the dilution capacity of the water body in question, etc.

2.3.2.4. Soil Quality Change

The saline lake water completely changes the color of the soil on which the lake flooded. Soils color changes into black. At some areas whitish color is observed on areas on which the lake water is flooded.

2.3.2.5. Drainage Systems Impacts

Drainage systems are creating serious problems in directing water from different sources. From the southern part, especially between Lake Beseka and Abadir Farm the flooding protection dike

collects all the runoff from western and northwestern catchments and drain into the lake, which is as big as stream flow.

2.3.2.6. Surface Runoff and Sediment Transportation Impacts

High runoffs enter into Lake Beseka in almost all directions of the lake by natural and artificial drainages. In the northern part, runoff from mountains, hills and plains enter into the lake. Rill erosion, sheet erosion, gully erosion and wind erosion are types of erosions identified in the lake area, from Meti, Fentale and Birant Mountains. These types of erosions are accelerated and induced by interference of human beings on natural environment. Previous study indicated future occurrences of serious soil degradation that is currently observed due to accelerated depletion of natural resources of the area (WWDSE, 2011). The major causes for the depletion problems are heavy demand due to rapid population growth of the area, while irrigation farms expansion and cultivation lands needs are the leading problems for environmental degradation of the area.

Especially, these days, destruction of natural vegetation covers for house construction, fire wood including charcoal production and lands clearing for cultivation were tremendously increased that aggravated erosion problems of the catchment. As in most parts of the country, and specific to the area, charcoal and fire wood markets are serious as the area is on the main import and export route of the country that can aggravate deforestation for charcoal production and exposed the area to serious erosion problems.

2.3.3. Negative Impacts on Biological Environment

2.3.3.1. Impacts on Natural Vegetation

The lake water level rise damages indigenous plant species around the lake. Deforestation also aggravated by expansion of different development activities, population growth and pressure, adapting of the indigenous community members to farming practices and increase need for farming lands by displaced community members due to the lake expansion and clearing for construction, charcoal production and fire woods are imposing pressures on existing vegetation covers of the area.

2.3.3. 2. Proliferation of New Plant Species

Thorny and very dangerous plant for man, domestic and wild animals called “*prosopise Julifera species*” was identified invading the areas. The communities have indicated the problems of the plant on domestic animals and themselves.

2.3.3. 3. Impacts on Wildlife

Human activities affected the habitats of the lake area and thus currently the areas do not support significant wildlife resources. Most of the wild animals that used to inhabit the area now left. In addition, the flooding of lake water aggravated problems on wildlife. Thanks to Awash National Park at near distance, at present many of the wildlife of the area migrate to the park. However, some of the animals are still found in the area. Therefore, the lake level rise and expansion is expected to aggravate the problems.

In terms of impacts on birdlife, the lake water may not disturb the aquatic birds unless for terrestrial bird species. The flooding can disturb and limit the breeding success of the terrestrial bird species. The only chances of such birds are to migrate to other areas where probably their habitat is threatened.

Over-flooding of Lake Beseka affects ecological conditions of wildlife that are depending on water sources of the area. Major impacts imposed by the lake water on wildlife restricting migratory corridors, creating unpleasant odor to pale arctic migrants (birds from North Africa, Europe and Asia) and large mammals like the locally endangered Hippopotamus because of the lake water alkaline nature and impeding effects on their breathing system, etc.

2.3.3. 4. Impacts on Aquatic Ecology

The inundation problem of the lake created barriers to movement of aquatic fauna. As fish are sensitive to the chemicals of water body, the effects of high sediment loads and residual agricultural chemicals related to irrigation projects of the area can adversely affect the aquatic fauna.

2.3.4. Negative Impact on the Social Environment

2.3.4.1. Waterborne and Water Related Health Impacts

The major negative impacts of the lake level rise and expansion on the Lake area communities include social, economical and health impacts. It can aggravate bone and teeth decay problems, which are known as blue baby syndrome. It also aggravates problems on safe water provision as the saline lake water imposes pressure on water treatment. It also enhances water treatment chemicals needs that have economic implications. Lack of safe water promotes social and economic impacts and affects community livelihoods. As a result of the saline lake water, waterborne disease can be aggravated. During the field survey; it was identified that expansion of abnormal waterborne disease cases in Awash Sebat Kilo town and also increase in the disease cases in Fentale district were identified (WWDSE, 2011). Change in color and taste of treated water of Awash Sebat kilo town was identified.

Typhoid, typhus, amoeba, jardia and other waterborne and related diseases such as trachoma, malaria, etc. were found to be prevalent human health problems of Lake Beseka area. It was indicated that these diseases could be aggravated by the flooding problems.

The Lake level rise and expansion will likely increase number of breeding sites for vectors through creation of ponds, stagnant or slow moving water bodies that can enhance various disease vectors which can aggravate public health problems of the area.

2.3.4.2. Malaria Intensification Impacts

Malaria is the first of ten top diseases, which have been prevailing in the area. The lake expansion and flooding aggravates the problem by creating pool of stagnant water that promotes vectors breeding sites.

2.3.4.3. Lake Beseka Overflow and Downstream impacts

Construction of overflow canal may create obstruction to free movements of the town communities, livestock and traffic conditions. Beside this, vegetation and trapped sediments can clutter the proposed canal and can create canal path chocking. As the planned discharge canal from the lake up to Awash River is about 6 kilometers if open system can be exposed to choking and traffic problems.

2.3.4.4. Loss of Land under Various Uses

Community displacement was not significant key problem as only five residences were displaced (reference?). But if the communities of the town were settled on the residence proposed areas, which were flooded, community displacement would have been serious. The area was identified for residences by the town administration but were not provided for the communities. Different infrastructures such as a high school, health center, youth center, an office and others were affected by the lake flooding.

From these, one can see that lands under various uses were flooded by the lake water. More than 3,500ha of valuable rural farmlands, about 36.45km² valuable grazing and woodland were lost or over flooded during the last three decades. At present, a total of 234 hectares of Metahara Town Administration land was is flooded by Lake Beseka water.

2.3.4.5. Impact on Community Displacement

As a result of Lake Beseka level rise and expansion, 5 households with about 25 members were completely displaced and 9 households in Kebele 01 of Metehara Town Administration were slightly affected. The town administration is seeking solutions on how to resettle these community members.

2.3.4.6. Impacts on Tourist Attractions and Recreational Sites

Overflowing of the lake water together with Awash River at Campsite or tourist accommodation site can affect the recreational value of the park. The Lake water level rise and expansion resulted in overflowing of a modern recreational site which is completely covered by lake water.

2.3.5. Negative Impacts on the Economic Environment

Under this title, financial losses of different institutions as a result of the lake level rise, expansion and flooding are addressed.

2.3.5.1. Impacts on Metehara Sugar Factory

The Lake level rise and flooding created problems on the factory activities. The total commutative flooded and damaged area is identified to be 178.4 hectares by November 2010 (WWDSE, 2011).

2.3.5.2. Impacts on Ethio-Djibouti Railway Services

Ethio-Djibouti Railway line is one of the social services affected by Lake Beseka water level rise and expansion. The railway crosses the Lake on stretch of nearly 3.3km. It has become a barrier against the lake water expansion to east side in which both the embankment and the track materials have always been rocked by strong waves leaving the entire section vulnerable to any possible danger. This has been interrupting the railway operations (passengers and freight traffic) for couple of months every year, especially, during rainy seasons.

2.3.5.3. Impacts on Ethiopian Road Authority Services

The problems and damages posed on the organizational activities due to Lake Beseka water level rise and expansion are road embankment damages, narrowed the road width, traffic flow interruption and accidents and resulted in financial demand to rehabilitate the road.

The authority has been taking remedial measures repeatedly to overcome the problems. It raised the road level in 2005 by Keangnam Enterprise Ltd of which the specific cost for the Lake site was not obtained. Due to the current lake water level rise and expansion the Alemgena DRMP constructed detour or diversion road of 7.3km in 2010 to make access for traffic flow in its short-term plan.

Depending on available data, the Authority had spent about 2.5million Ethiopian Birr for Lake Beseka Site asphalt road maintenance before year 1999 and Birr 14,230,974.78 for the diversion road construction in 2010. Without including the cost incurred for raising the road level in 2005 and designing and future new route construction cost, the authority had lost Birr 16,730,974.78 so far due to Lake Beseka water level rise and expansion.

2.3.5.4. Impacts on Electric Services

At present Lake Beseka water covered part of electric line distribution of Metehara town. As a result, the lake water created problems on line maintenance and supervision activities. As the lake water contains high fluoride contents and alkaline characteristics, it damages electric poles within short period of time and minimizes its service durability that is creating serious effects on the district electric light and distribution.

The financial losses of the district office indicate:

- The estimated damage cost due to the Lake flooding so far is estimated at about 254,927.46 Birr.
- It needs Birr 14,203.40 to rehabilitate the lines.
- The office has a long-term plan to relocate the lines or distribute on other directions. To re-distribute the line through other optional route, it was reported that the office requires about 214,203.40 Birr for material, labour and transport costs.

2.3.5.5. Impacts on Metahara Town Administration Development Activities

The report of Metehara Town Administration indicates similar problems. The town administration has faced serious damages that is discouraging the investment activities of the town and different social services. Few of them are complete damages of Gudina Tumsa Foundation Office, students dormitory and high school. Investors such as Anino Trading, Mofti Nuredin, Saf Trading, Adey Abeba Textile has left the area. 122.68 hectaers of investment areas was covered by the lake water. Animals fattening has also flooded by the lake. Generally, the investment and development activities of the town was discouradged by the Lake level rise and expansion.

The 1999 study EIA Study document, indicated that Metehara Town Council had incurred:

- Birr 90,000 for assessing water supply sources free of fluoride contamination and
- Birr 11,400 for excavating an intercepting drain to protect Metehara Sugar Factory sugarcane farm from flooding by the lake.

The town administration has expressed its worry in that the lake water is currently expanding from time to time that is creating more and more psychological threats for the inhabitants and also on the development of the town. Therefore, the council recommended that all stakes should give due attentions on how to manage water entering into the lake and find immediate and sustainable solutions for the area.

Furthermore, Lake Beseka has attractive landscape and important biodiversity; the lake lands two commercially important fish species (Cat fish and Nile tilapia), Crocodiles, alligators, different birds and hot springs. The fish resource of the lake was estimated to be about 205 tonnes per year whereas current production does not exceed 17 tonnes per year. For its high salinity, the lake water is not used for drinking purpose both for human and domestic animals although it is in area where water scarcity is much prominent (Senbete, 2015).

In addition to (WWDSE, 2011) and (Senbete, 2015); according to Megersa Olumana et al. (2009) the Beseka Lake expansion affects the surface and groundwater dynamics and soil properties of the region and the condition is specifically dangerous for the sustainability of MSE and Metehara town in particular and the Awash basin irrigation in general. And also the rapid expansion of the Lake has several implications: Since 1993 Lake Beseka has partially flooded and Stalinized the Abadir Farm (Goerner et al., 2008). According to Mercier et al. (2002) as cited in Goerner et al. (2008) Lake level rise may be due to: (i) changes in surface pressure; (ii) wind-driven events (i.e. seiches) and tides; (iii) fluctuations in the volume of this column due to an alternating temperature or composition; or (iv) modifications of the hydrologic cycle (i.e. recharge, outflow, evaporation). Items (iii) and (iv) will ultimately result in lake water volume changes. The first three factors may be relevant for larger rift lakes, but cannot explain a water level increase of more than 4 m within less than three decades (Ayenew, 2004) of the comparatively small Lake Beseka. Cause (iv) can be directly triggered by non-climatic factors, for example tectonically induced alteration of flow patterns, changes in the heat budget due to geothermal effects, and artificial regulation.

However, regarding the impact of Lake Beseka expansion on the blisters and blister caves was not yet well studied. Therefore, this research was conducted to address this issue.

2.4. Impact of Irrigation Activities

It is evident that Metehara Sugar Estate (MSE) is experiencing signs of a rising groundwater table, salinity and alkalinity (Olumana et al., 2009). Based on a hydro chemical analysis by Tessema (1998) some studies (e.g., Ayenew, 2004; Alemayehu et al., 2006) argue that poor irrigation efficiency is an important contribution to Lake Beseka's level rise as cited by (Goerner et al., 2008).

2.5. Landuse and Land Cover Change

The spatial and temporal variation of Lake Beseka's extension was analyzed during the last three decades, from 1973 to 2002 by Goerner et al. (2008), from 1973 to 2003 by Fassika Abebe (2007) and from 1973 to 2008 by Olumana et al. (2009). But, there was no any study on the gas blisters and blister caves area (landuse land cover) change analysis. Thus, this study was aimed to conduct this change analysis associated with Beseka Lake expansion, roads and railways, irrigations and Metehara and Addis Ketema towns during the last four decades, from 1973 to 2015.

2.6. Gas Blisters and Blister Caves

According to Grimes (2002) the usage of lava blister for those inflated by liquid lava (and later drained), gas blister for those generated by gas pressure, and a "blister" should only be used on its own where the genesis is *uncertain*.

Volcanic caves are widespread in the world and are actively explored by cavers (Forti, 2005). They are formed only in zones where a distention type of volcanism occurs and basic lavas are the final volcanic products (Licitra, 1975). According to Forti (2005) these caves host up to six active minerogenetic mechanisms: Sublimation and deposition from aerosols and vapors at high and low temperature degassing processes, respectively, evaporation, oxidation, hydration-dehydration, ionic exchange, from biogenic activities (diffusion, digestion, dissolution-precipitation, double exchange, and guano combustion).

According to Licitra (1982) there are two typical volcanic factors controlling cave formations:

1. The shifting of coherent volcanic material, more or less fluid, moved by gravity and/or by hydrostatic pressure and/or by endogenetic pushes (originated by the steam pressure of the engulfed gas);
2. The action of gases, when their volume and steam pressure reach such a power that irreversible deformations are caused in the engulfing molten lava or volcanic deposit or rock.

Licitra (1982) classified volcanic caves into two classes based on their genesis:

1. Caves generated by lava flow are classified as *rheogenetic* (from ancient Greek "rheo" = flow), whether the flow occurs on the surface, in an active lava flow (rh. surface cave) or

through pre-existing rocks, when lava flows to the surface through an eruptive fissure and next flows downwards (rh. fissure cave);

2. *Pneumatogenetic caves* (from Greek "pneuma" = blow, breath) action of gases, whether they are volcanic gases released by lava, or induced ones, generated by masses of water, snow or ice containing hot volcanic gas or lava.

Moreover, according to Licitra (1975 and 1982) there are three main types of volcanic caves considered in the classification, and described as follows:

i. Rheogenetic Surface Caves: this group includes the most widespread, best known and most studied volcanic caves on a world scale. They are reported as lava tube caves or lava tunnels or galleries.

ii. Pneumatogenetic Explosive Caves: these are caves engendered by gas explosions, whether the exploding gases are volcanic or phreatic. In addition to diatreams, which are of limited importance from a speleological angle, hornitos are included in this group. They are tall welded spatter cones, with a hollow core, built up by spatters of molten lava splashed by gurgling gas bubbles, around a rootless vent from which very fluid and partially degassed pahoehoe lava emerges. Rheogenetic surface or fissure caves are frequently found beneath hornitos or at their base.

iii. Pneumatogenetic Expansion Caves: this type of cave is not very widespread and is generally associated with rheogenetic surface caves. Furthermore, this is the only type of volcanic cave, which has been noticed in volcanic rocks other than basic lava flows. Pneumatogenetic expansion cave occurs when two different factors are interacting: (i) presence of abundant gases, the steam pressure of which is incapable of completely overcoming the resistance of the engulfing material; and (ii) volcanic products (basic lava, or ignimbrites) too viscous to allow the engulfed gases to be released, yet plastic enough to be warped by the gas pressure before the stiffness of the solid state has been attained. Caves of this type are called blister caves by English authors, or cavidades cutaneas by the Spanish Montoriol- Pous and De Mier (1970), and may be formed when a lava flow enters a large quantity of water (lake, sea) or buries a marshy ground (such as Myvatn, Iceland).

The most remarkable type of Pneumatogenetic expansion cave has been surveyed and studied in a pre historic ignimbritic deposit at Fentale Volcano, Ethiopia. Gibson (1974) ascribes the

formation of such blister caves to expanding gases and steam held beneath wrappings of ashes and viscous rhyolitic lava scrubs, at very high temperature, after red-ho ash flow has halted. However, the gas blisters and blister caves at Fentale volcano were not well studied and documented, and their susceptibility destruction due to any triggering factor was not conducted. Thus, this study tries to document the caves in detail and to assess their degree of susceptibility to destruction due to natural and man-made factors.

CHAPTER THREE

GENERAL OVERVIEW OF THE STUDY AREA

3.1. Location and Accessibility

The study area (Fig. 3.1) is located at about 195 km Southeast of the capital city of Ethiopia, Addis Ababa, in the Oromia National Regional State, East Shoa Zone, Fentale and Merti weredas in the Middle Awash Basin within northern part of the Main Ethiopian Rift (MER). The study area covers the area between south and southwest of the Fentale volcano and north and northeast of Lake Beseka (Fig. 3.1). It straddles Lake Beseka, Metehara and Addis Ketema towns, Metehara Sugar Factory, Abadir Farm and Metehara Sugar Estate Plantation (MSEP), the infrastructure lines (railway and road networks), and some part of the Fentale Mount. Moreover, it is situated along the Addis-Dire Dawa-Djibouti or Addis-Harar-Jigjjiga highway road. Fentale Mount, Tinishu Sabober and the infrastructure lines are situated north of Beseka Lake and the two towns (northeast of the Lake and northwest of the Sugar Estate). Abadir Farm is located immediately south of the Lake and adjacent to the MSEP to the east, while the Sugar Factory is located east of Beseka Lake, west of MSEP and directly south of the two towns. Location map of the study area (Fig. 3.1) was mapped at the scale of 1:130,000. Geographically, the study area is bounded between 39°49'31"E - 40°01'45"E longitude and 8°45'22"N - 8°58'40"N latitude, and has an aerial extent of about 502.8 Km².

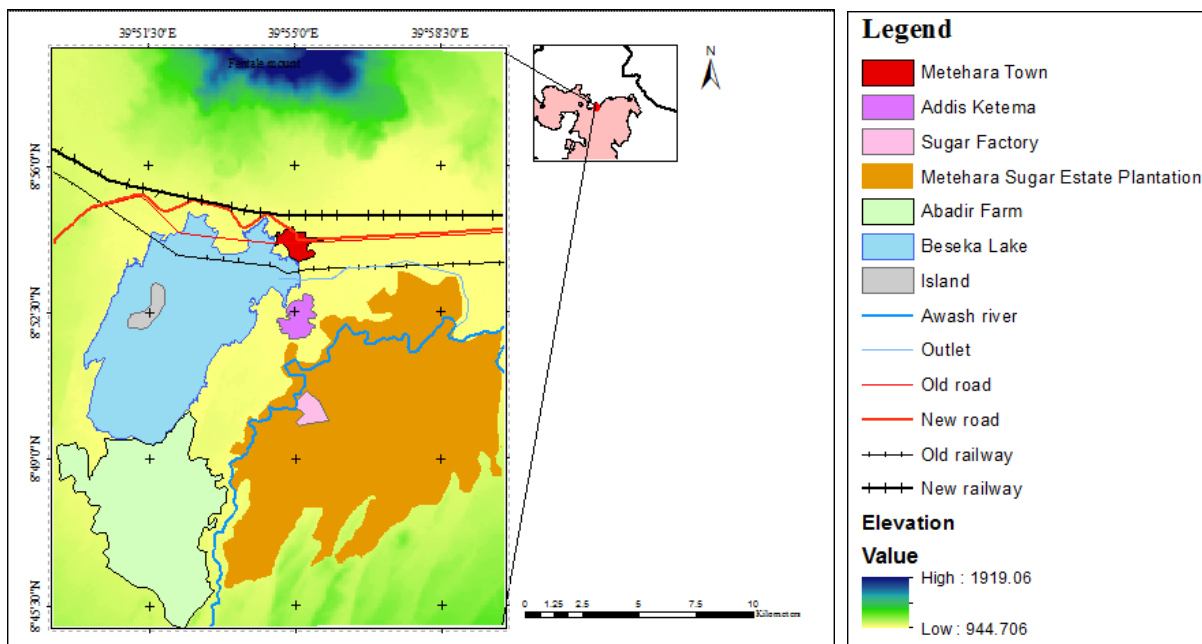


Fig. 3.1. Location map of the study area.

3.2. Topography

The topography of the study area ranges from 944m (flat plains) to 1919m above mean sea level (some part of Fentale Mount) (see Figs. 3.1 and 3.2), but at the center of the volcano it reaches to 2007m. Lake Beseka is situated at low elevation, and the two towns: Metehara and Addis Ketema towns are also characterized by flat plains. Metehara Sugar Factory and the irrigations (Abadir Farm and Metehara Sugar Estate) are characterized by flat to undulating plains as compared to Lake Beseka. Undulating plain of the area is located at south and southern parts of Abadir Farm and Metehara Sugar Estate Plantation (MSEP), and north of the infrastructure lines and Tinishu Sabober. The intermediate and high slopes are situated in the Mount Fentale at the northern part of the study area. Some volcanic cones are concentrated at the northwest and southeast of the Lake Beseka, and within the MSEP.

3.3. Drainage

The study area is found within the middle Awash drainage basin. The drainage pattern surrounding the Fentale Mount is both radial, where streamlines radiate from the summit of the volcano, and dendritic in the lower reaches of the area. The remaining part of the study area has flat to dendritic drainage pattern.

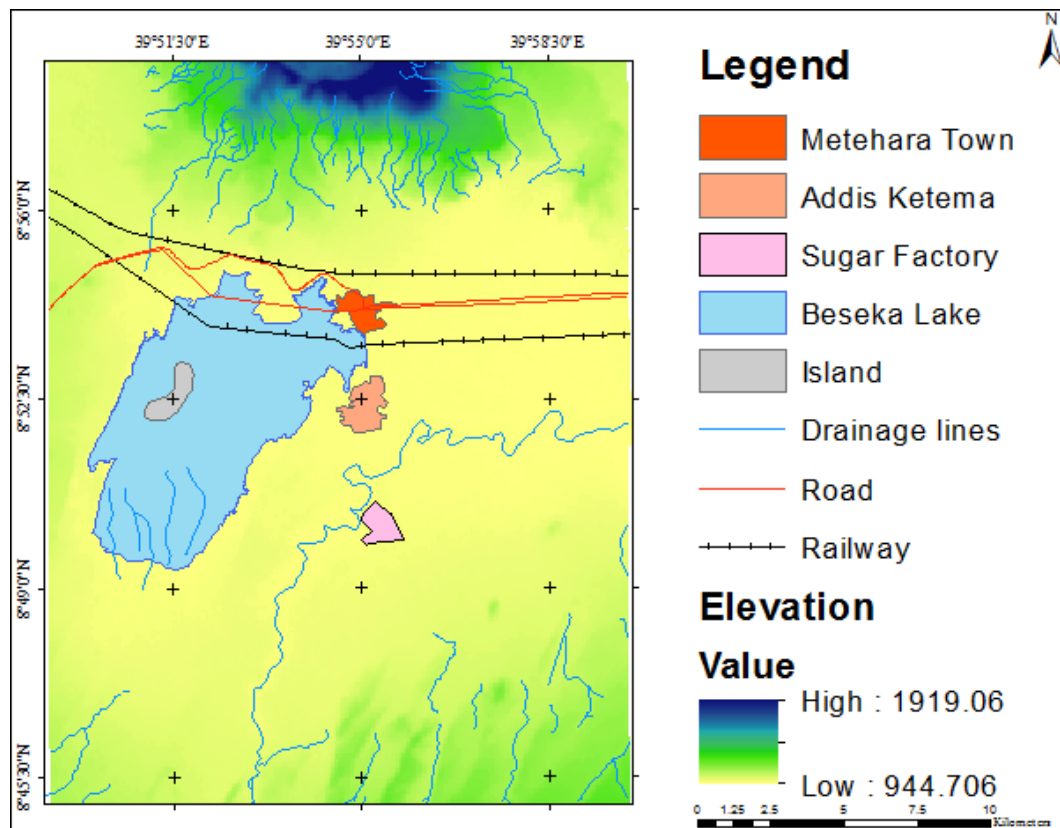


Fig. 3.3. Drainage map of the study area (drainage lines were digitized from 1975 topographic map of Metehara Sheet with a scale of 1:50,000).

3.4. Weather and climate

According to Goerner A. et al (2008) the study area is characterized by semi- arid climatic condition. For the sake of understanding the Beseka Lake level change causing serious environmental problems in the study area; rainfall, temperature, relative humidity, wind speed, sunshine hours and pitche evaporation meteorological data of Metehara station from Water Works Design and Supervision Enterprise (WWDSE) and Ethiopian Meteorological Agency (EMA) were used for climate analysis of the area during the last four decades.

3.4.1. Rainfall

Based on WWDSE (2011) and EMA rainfall recorded data, the study area gets its smallest and highest rainfalls in November and July months respectively from the period of 1970 to 2015 (Fig. 3. 3). The minimum, mean and maximum annual precipitations during this period are 308.7 mm, 522.7mm and 863.5mm respectively. Furthermore, the maximum annual precipitation was observed in 1982 and its minimum was in 2002.

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Table 3.1 Mean monthly rain fall (mm) (1970-2015).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean. RF	15.1	24.2	47	38.7	37.3	24.9	125	121.9	47.6	26.6	5.9	8

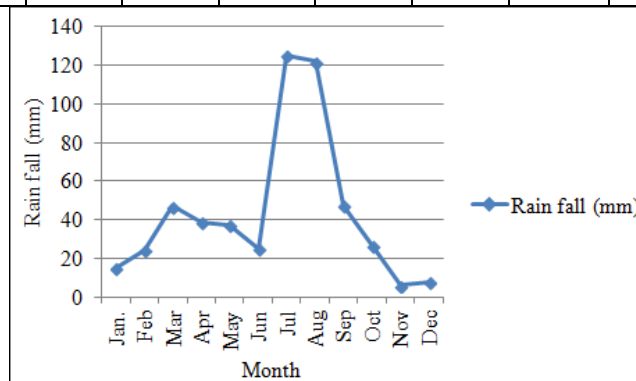


Fig. 3.3. Mean monthly rain fall (mm) from 1970 to 2015.

3.4.2. Temperature

The minimum and maximum mean monthly temperature values recorded at Metehara station are 21.8°C in December and 28.9°C in June respectively (Table 3.2 and Fig 3.4). The mean annual temperature of the study area is 304.7°C. The minimum and maximum annual temperatures in the area were recorded in the 1971 and 2015. Unlike rainfall, annual temperature of the study area is characterized by an increasing rate and it shows that it reaches at climax in 2015.

Table 3.2. Monthly temperature (°C) (1970-2015).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min Temp	14.6	16.2	17.9	19	19.4	21.4	20.3	19.8	19.2	16.2	14	13.2
Mean Temp	22.7	24.2	25.9	26.9	27.5	28.9	26.7	26.1	26.4	24.7	22.8	21.8
Max Temp	30.9	32.2	33.9	34.7	35.7	36.3	33.2	32.3	33.7	33.2	31.7	30.4

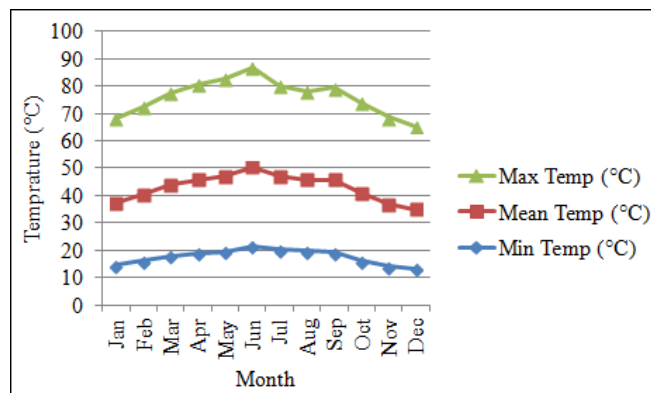


Fig. 3. 4. Monthly temperature (°C) from 1970 to 2015.

3.4.3. Relative humidity

In the study area, the lowest and highest mean monthly relative humidity values from 1970 to 2010 are 52% and 62% respectively (Table 3.3). The lowest values were recorded in June while its highest was in January (Fig. 3.5).

Table 3.3. Mean monthly relative humidity(%) (1970-2010).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min RH	34.4	32.9	31.0	29.0	26.9	26.8	32.3	34.6	30.2	27.4	30.1	31.9
Mean RH	62	60	59	58	55	52	58	61	59	58	60	61
Max RH	89	88	86	86	84	77	85	87	88	89	90	91

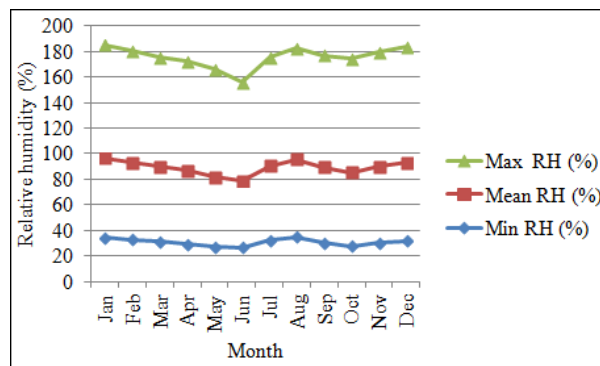


Fig. 3. 5. Monthly relative humidity (%) from 1970 to 2010.

3.4.4. Wind speed (WS)

The daily wind speed of the area varies from 3.2km/hr to 5.5km/hrs with a minimum value was observed in September, and the maximum value was observed in July month from 1973 to 2010.

Table 3.4. Mean monthly wind speed (km/hr) (1973-2010).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
WS (day)	4.2	4.1	3.9	3.7	3.7	5.0	5.5	4.4	3.2	3.7	4.2	4.4
WS (night)	0.9	1.2	1.3	1.1	1.1	3.1	3.1	2.2	1.3	2.3	2.2	2.2

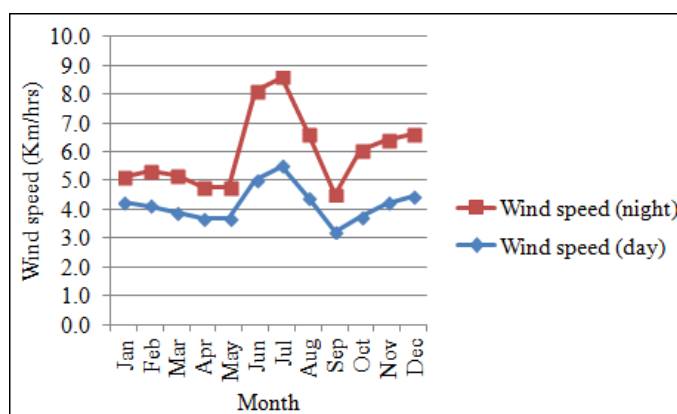


Fig. 3. 6. Mean monthly wind speed (km/hrs) from 1973 to 2010.

3.4.5. Sunshine

The mean monthly sunshine hours ranging from 1970 to 2010 in the study area varies from 7.3 hours to 10.3 hours (Table 3.5). The lowest and highest values were observed in July and December months respectively.

Table 3.5. Mean monthly sunshine hours (hr) (1970-2010).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sunshine(hrs)	8.8	8.7	8.4	8.3	8.8	8.7	7.3	7.4	7.7	8.3	9.2	10.3

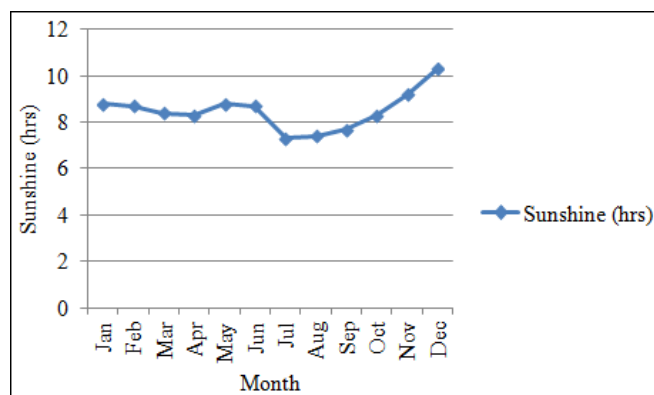


Fig. 3.7. Mean monthly sunshine hours (hr) from 1970 to 2010.

3.4.6. Pan Evaporation (PE)

The maximum and minimum mean monthly pan evaporation values recorded in Metehara station occurred in June and December months respectively.

Table 3.6. Mean monthly pan evaporation (mm) (1970-2010).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PE(mm)	6.2	6.8	7.2	7.2	7.6	8	6.8	6.1	6.3	6.7	6.5	6.1

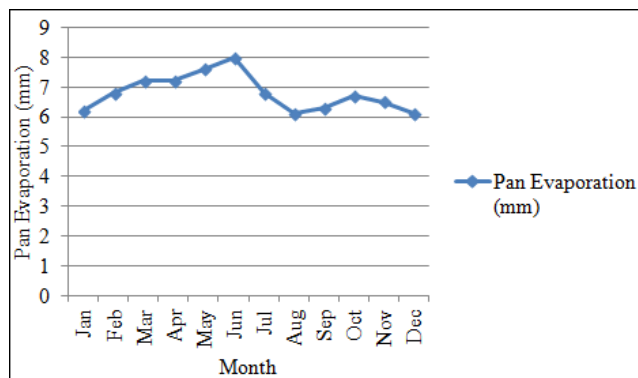


Fig. 3.8. Mean monthly pan Evaporation (mm) from 1970 to 2010.

3.5. Vegetation cover

Majority of the study area is covered by scrubs. However, northwest and east of Lake Beseka, north and northeast of Metehara town along the infrastructure lines, east of Tinishu Sabober and north of Metehara Sugar Estate is covered by scattered trees. According to Addis Geo-systems (2007) vegetation cover is dense on the younger volcanic and less on the ignimbrites and ash flow tuffs in general.

3.6. Geology

3.6.1. Regional lithological units

Most of the geologic sections exposed along the rift margins are dominated by Tertiary volcanic rocks except for a few locations where crystalline basement is uncomfortably overlain by Mesozoic sedimentary and /or Tertiary volcanic rocks (Woldegabriel et al., 1990). A thick succession of ignimbrites, unwelded tuffs, ash flows, rhyolites and trachytes collectively known as the Nazareth Group constitute the larger part of the rift floor and also outcrop in the escarpments and on the adjacent plateau margins (Habtamu et al., 2012).

Lacustrine sediments in the rift proper comprise clay, silt, tuff, travertine, and diatomite with intercalation of pumice (Habtamu et al., 2012).

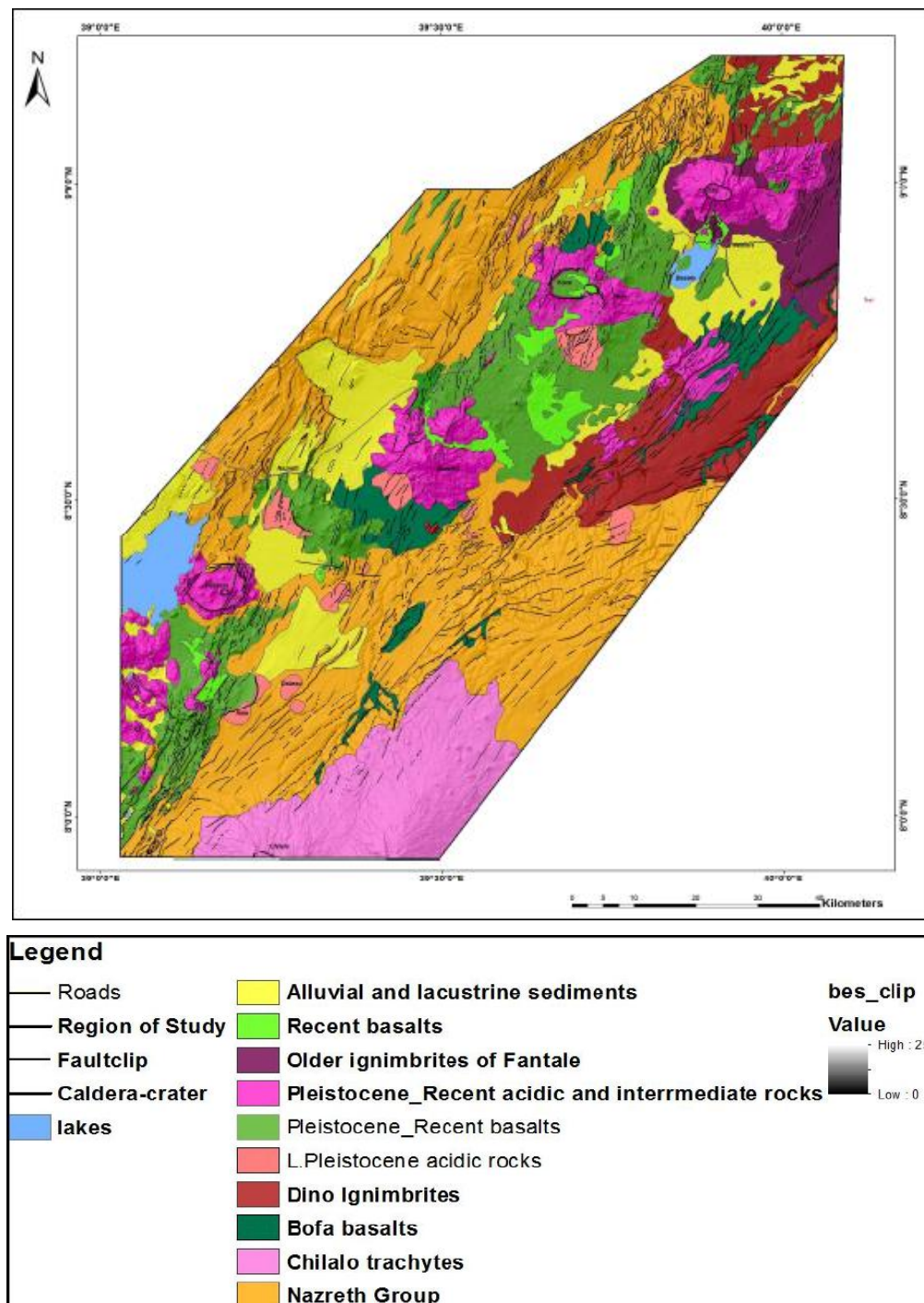


Fig. 3.9. Geological map of the Main Ethiopian rift between Chhialo and Fentale volcanoes (after MOWIE/OWWDSE, 2014).

3.6.2. Lithological units of the study area

Basically, the rock units in the study area are basalt, rhyolite, trachyte and obsidian flows of the two groups: Nazareth Group (oldest) and Wonji Group (youngest) of the Fentale and post-Fentale volcanics. According to the Geological Map of Nazareth Sheet (EIGS, 1978) the oldest and youngest rock units in this study area are Bofa Basalts and Recent pantelleritic and comenditic obsidian flows and domes, respectively. There are eleven mappable lithological units in the study area. However, the most prevalent unit in the study area is Young ignimbrites of Fentale.

3.6.2.1. Bofa basalts

Bofa Basalts, Pliocene in age, forming the topmost part of the Nazareth Group are the only lithological unit exposed in the study area from this Group. This unit is exposed between Abadir Farm and Metehara Sugar Estate, along the Awash River, and mainly south of the Sugar Estate Plantation (Fig. 3.10); and they are highly affected by faults. Bofa Basalts are overlain by the oldest Pleistocene volcanics. These basalts are generally flood basalts, mostly aphyric, locally vesicular, with several flows separated by scoracious horizons (Berihu, 2007); and they are compositionally alkaline (Yared, 2008). In Bofa Basalts, columnar jointing is very well developed (Getahun, 1987).

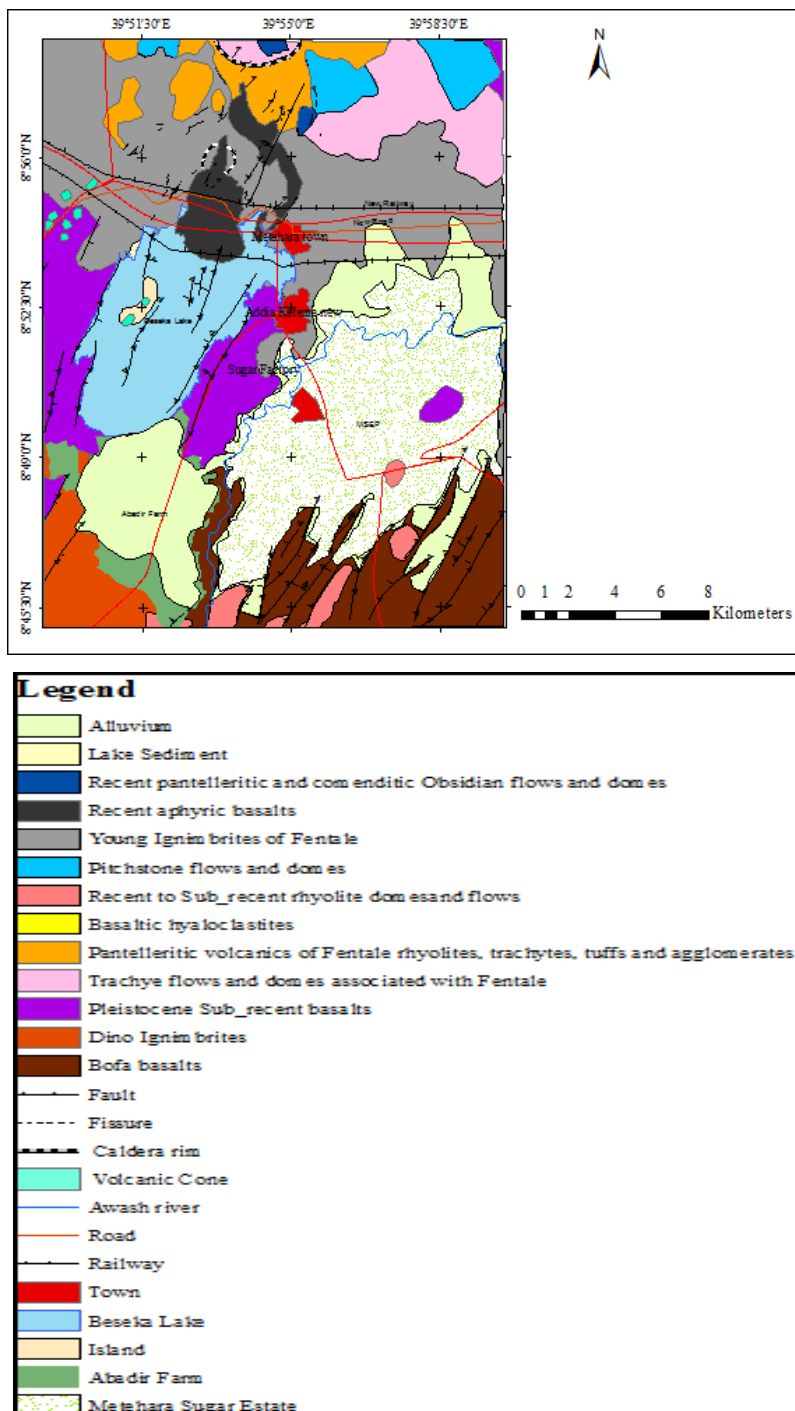


Fig. 3.10. Geological map of the study area (modified after EIGS, 1978), and shorelines of the Beseka Lake and boundaries of Abadir Farm and Methara Sugar Estate were digitized from the Google Earth.

3.6.2.2. Dino ignimbrites

Dino Ignimbrites are exposed west and southwest of Abadir Farm and also south of Lake Beseka. These rocks are light grey to greenish in color; however, south of Abadir Farm they are highly weathered. Dino ignimbrites are the oldest rocks of the Wonji Group. These rocks underlie Pleistocene sub recent basalts of the same Group. According to Habtamu et al. (2012) Dino ignimbrites, in some cases, are intercalated with aphyric basalts and unwelded pyroclastics, and they are dated at 1.5 million years by K-Ar dating.

3.6.2.3. Pleistocene to sub recent basalts

Pleistocene sub recent basalts are widely distributed west and southeast of Lake Beseka. In addition, they are exposed directly east of Fentale caldera and eastern part of Metehara Sugar Estate Plantation (MSEP), and are characterized by black color and having high fractured zones. They are vertically and horizontally jointed rocks (Getahun, 1987). These rocks are Pleistocene in age, and NNE-SSW trending normal faults and are common in this unit. Contemporaneous cinder and scoria cones are found on this unit, aligned parallel to the local NNE-SSW fault trend showing structural control of their emplacement (OWWDSE, 2014). Moreover, in the study area, there are five cinder and scoria cones northwest of Lake Beseka, and two cones on the island.

3.6.2.4. Trachyte flows and domes associated with Fentale

These rocks occur within the main caldera, southeast of the caldera and north of the main road and railway. They are overlain by the mixed Fentale rhyolite, trachyte, tuffs and agglomerates. In the study area trachyte flows and domes are originated from Fentale volcano. According to Williams et al. (2004) trachyte flows from Tinishu Fentale (Pre-Fentale volcanism), at the northeast of Fentale caldera, are older than the Fentale associated flows.

However, compositionally, both of them are similar. These rocks contain large grains of anorthoclase and plagioclase and minor olivine, pyroxene, quartz and amphibole (hornblende) (Addis Geosystems PLC, 2007).

3.6.2.5. Pantelleritic Volcanics of Fentale Rhyolites, Trachytes, Tuffs and Agglomerates

In the study area, Pantelleritic volcanics of Fentale are exposed in the southern and western slopes of the mount. Major products of pantelleritic volcanic eruptions comprises peralkaline rhyolites and trachytes with some pumice, pitchstone and obsidian (Habtamu et al., 2012).

However, a few thin welded tuffs have been observed within these Pantelleritic rocks of a varied series of silica lavas and intercalated tuffs succession but the majority of the pyroclastic units are unwelded and consist of thin pumice beds between the lavas (Gibson, 1967). These mixed rocks cover trachytes associated with the Fentale volcano. According to Williams et al. (2004) younger group of trachytes and rhyolites was erupted from a satellite centre about 3.5 km from the centre of the main caldera.

3.6.2.6. Basaltic hyaloclastites

Hyaloclastites are one of the most commonly sampled volcanic rock types from the ocean floor; and they are glassy fragmental materials associated with pillow lavas and bedded deposits (Heiken and Wohletz, 1985). These rocks are exposed north of Beseka Lake and within Tinishu Sabober caldera embedding the recent aphyric basalt in the central part of this caldera. In the study area, these rocks have the smallest areal coverage. Basaltic hyaloclastites are volcanic eruptions under water and they are loosely cemented and medium grained (Getahun, 1987).

3.6. 2.7. Recent to sub recent rhyolite dome sand flows

Trachyte flows are exposed at the south of Metehara Sugar Estate Plantation, and they overlie basaltic hyaloclastites. These are acidic and intermediate flows and domes inter finger with one another and have limited areal extent owing to the high viscosity of the parent magma (OWWDSE, 2014).

3.6.2.8. Pitchstone flows and domes

In the study area, Pitchstones are exposed west and southeast of the Fentale volcano. According to Gibson (1967) these acidic lava extrusions, pitchstones, are extruded from vents both within the caldera and on the southeastern flank are all cossyrite pitchstones and the source vents for these flows lie along a fracture zone running from NW to SE, diagonally across the caldera.

3.6.2.9. Young ignimbrites of Fentale

According to Williams et al. (2004) the welded tuff from Tinishu Fantale has been dated at 1.51 Ma (K/Ar dating of feldspar: Kazmin et al., 1980; Williams et al., 2004) in a section in the Awash Gorge near Karayu Lodge, and the Fantale welded tuff at 168,000 $\pm$ 38,000 years. Therefore, Fentale ignimbrites (Fig. 3.11) are younger than ignimbrites of Tinishu Fentale.

At the southern side of the volcano, a very recent basalt fissure eruption has given rise to two discreet flows, which now cover part of the blister region of the Fentale tuff (Gibson, 1974).

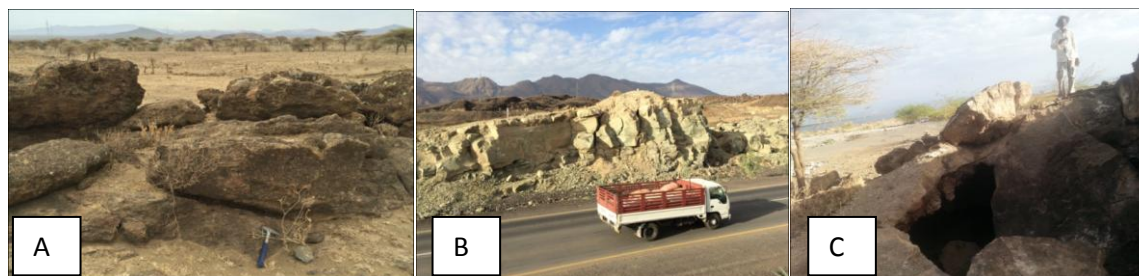


Fig. 3.11. Young ignimbrite rocks: A) East of Fentale Basaltic flow and south of Fentale caldera, B) along the Addis-Dire Dawa-Djibouti new road and north of Lake Beseka, and C) Blister cave breached at the top, north of Lake Beseka.

3.6.2.10. Recent aphyric basalts

Quaternary - Holocene basaltic rock which is found between the northern shore of the Lake Beseka and the Fentale caldera. These rocks have a jacked surface with a black color. However, the most recent flow is dated from historical report (Harris, 1844; Buxton, 1949; Williams et al., 2004) and local oral tradition at about 1810 AD.

According to Gibson (1974) basalt flows are generally absent from Fentale itself, and the eruption is clearly related to the Wonji Fault Belt and not directly to the Fentale. These basalts are porphyritic, containing plagioclase phenocrysts set in a fine-grained groundmass composed of pyroxene and plagioclase lathes (MOWIE/OWWDSE, 2014).

3.6.2.11. Recent Pantelleritic and comenditic obsidian flows and domes

Obsidian flows and domes in the study area are associated with the Fentale Volcano. They occur within the central part of the main Fentale caldera and at the southern rim of the volcano.

These rocks have a black lustrous color and characterized by conchoidal fracture (Habtamu et al., 2012).

3.6.2.12. Alluvial and lacustrine sediments

In the study area, alluvial sediments appear in the Metehara sugar plantation and Abadir areas. These sediments are exposed in the south, east and southeast of Lake Beseka. According to

Getahun (1987) alluvial sediments are Holocene in age and their thickness reaches 40m in Metehara and Abadir areas Table 3.3. Mean monthly relative humidity (%) (1970-2010).

Lacustrine sediments are deposited from extensive Lakes during Pleistocene pluvial phases, and are Pleistocene to Holocene in age (Habtamu et al., 2012). These sediments are exposed NNW of Beseka Lake shore, and they cover the smallest areal coverage in the study area.

3.6.2. Geological structures

The MER is the northern segment of the African Rift System and it runs approximately NNE-SSW through Ethiopia (Williams et al., 2004). The eastern margin of the MER is characterized by high-angle border faults striking NNE-SSW south of Chlialo and NE-SW to the north (OWWDSE, 2014).

The NNE-SSW striking normal faults and fissures system, which are mostly determining the Lake Beseka shape, can be observed at the present eastern and western shoreline of the north and south of Lake (Berihu, 2007). Extensive fissures are found in the young ignimbrite of Fentale, particularly north of the Lake. In this fissured area, Most of the blister caves and blisters are widely distributed. These blister fields are spectacular geological structures. In the world, they are only found in the Fentale-Metehara area. Moreover, there are five volcanic cones northwest of Lake Beseka, and two cones on the island (Fig. 3.12). There are two caldera rims embedding the Fentale volcano (Larger caldera rim in the area) and Tinishu Sabober.

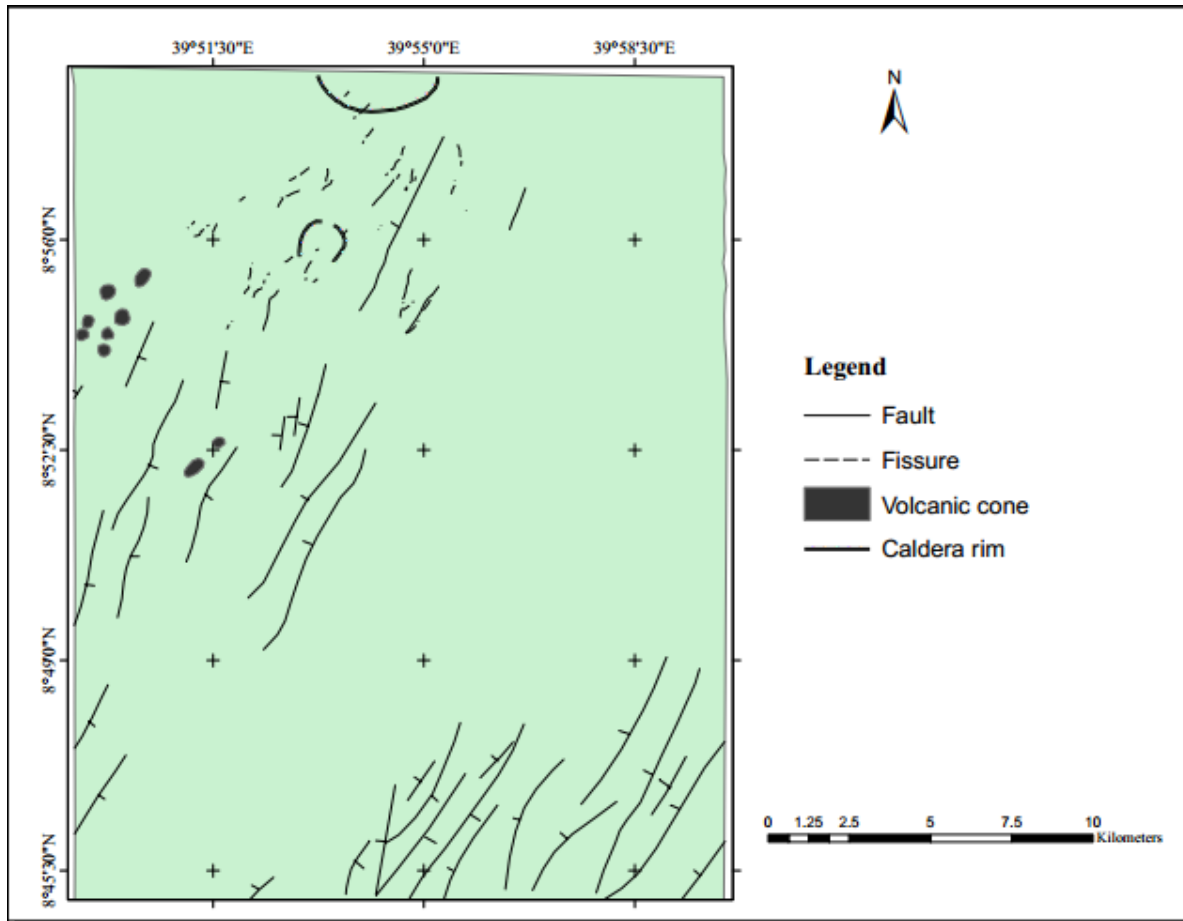


Fig. 3.12. Structural map of the study area (modified after EIGS, 1978).

CHAPTER FOUR

DECADAL LAND USE AND LAND COVER CHANGE ANALYSIS

4.1. Introduction

Landuse refers to the way in which land has been used by human beings and their habitat, usually with accent on the functional role of land for economic activities; while land cover refers to the physical characteristics of earth's surface, captured in the distribution of vegetation, water, soil and other physical features of the land, including those created solely by human activities e.g., settlements (Rawat and Kumar, 2015). Landuse and/or land cover change is an important aspect of global warming studies since it is a major factor for global environmental changes (Weng, 2002; Xiao et al., 2006; Dewan and Yamaguchi, 2009). For instance, change in urban areas pose habitat destruction, loss of arable land and decline in natural vegetation cover; and urbanization leads to serious local and environmental problems (Dewan and Yamaguchi, 2009). In the study area, the change in surface area of the Beseka Lake (lake level change) has been causing damage and relocation of infrastructure lines, socio-economic problems to indigenous peoples; inundation of houses, schools and hospitals (Fassika, 2007; Megersa, 2012). Thus to study the changes in landuse and land cover is crucial for the protection of spectacular places, blisters and blister caves, and the overall analysis of environmental changes in the study area.

This study was conducted on landuse and land cover changes over four time series periods: 1973-1985, 1985-1995, 1995-2002 and 2002-2015 in the Fentale, Metehara area. The change analysis was executed using remote sensing and GIS techniques with ancillary data for extracting landuse and land cover features of the study area from the time series Landsat satellite images.

4.2. Satellite image processing

In this study, Multi Spectral Scanner (MSS), Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and OLI/TIRS Landsat data were used to analyze decadal time series landuse land cover changes of the area. MSS image was acquired on 30 January 1973. There are two TM images, which were acquired on January 02/1985 and January 30/1995. The acquisition dates of ETM+ and Operational Land Image (OLI) and Thermal Infrared Sensor (TIRS) images were on December 25/2002 and December 23/2015.

Among all the Landsat images, only the 1973 MSS image has a spatial resolution (cell size) of 60 m x 60 m with 180/54 (Path/Row) but the others have 30 m x 30 m cell size and 168/54 (Path/Row). Moreover, all the Landsat images used in this study are cloud free.

There are three stages in processing a remotely sensed data in order to evaluate landuse and land cover changes. The first stage is preprocessing, which is a preliminary activity before classifying a satellite image. The second stage is the actual classification of an image into landuse and land cover classes based on the decision rules and visual interpretation of an image. The final stage is evaluating the accuracy of the classified image.

4.2.1. Image preprocessing

4.2.1.1. Import/export

Importing data is the first stage in satellite image processing using ERDAS IMAGINE. It is a way of managing data, which converts raster and vector datasets from external formats to internal formats directly usable by ERDAS IMAGINE. Whereas exporting data is a process that converts raster and vector datasets from the internal formats directly usable by ERDAS IMAGINE into external formats suitable for use in other software packages. Therefore all the Landsat satellite images at different years with raster datasets were imported into IMG format in Erdas Imagine 2014 version. Then the imported satellite images with an IMG format were exported into TIFF format for further processing.

4.2.1.2. Geometric correction

From 2013 ERDAS Field GuideTM, geometric correction is applied to raw sensor data to correct errors of perspective due to the Earth's curvature and sensor motion. Geometric correction was performed on all images using a Landsat OLI/TIRS image from 2015 as a reference.

4.2.1.3. Layer stacking

This is a process of stacking multiple spectral bands/layers into a single output multi-band raster image file. Multi Spectral Scanner (MSS), Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and OLI/TIRS sensors have four, five, seven and eight spectral bands, respectively.

4.2.1.4. Geo-referencing

This is one of the satellite image pre-classification processes, and it is done with geoprocessing toolbar in Arc GIS, which allows referencing a raster dataset and image service layers spatially. Raster data is obtained by scanning a map or collecting satellite images or aerial photographs. The MSS, TM, ETM and OLI/TIRS Landsat satellite images of the study area were georeferenced using the georeferenced 1975 Topographic Map of Metehara Sheet raster data and that gives the desired map coordinate system. The coordinate system used in georeferencing these images was Universal Transverse Mercator (UTM). In geo-referencing the images, a series of ground control points (GCPs) known (x, y) coordinates have been identified. The GCPs are accurately identified locations, which link the satellite images to be referenced with a spatially referenced topographic Map of Metehara Sheet raster data.

4.2.1.5. Sub-setting

This refers to breaking out a portion of a large file into one or more files, and it is helpful to reduce the size of the image file to include only the area of interest (AOI) (Pouncey et al., 1999). Sub-setting or resizing of different sense satellite images of the study area was done by masking using Extract by Mask from Spatial Analyst Tools in Arc GIS 10.3. Extract by Mask is an extraction tool, which extracts the cells of a raster that correspond to the area of interest defined by a mask. In masking or resizing of the study area (area of interest), the polygon feature of the study area was an input feature mask data for each input raster satellite image (1973, 1985, 1995, 2002 and 2015).

4.2.2. Image classification

Generally there are two digital satellite image classification methods, namely supervised and unsupervised. Supervised classification is usually appropriate when relatively few classes are to be identified, and when training sites that can be verified with ground truth data are selected, or when distinct, homogenous regions that represent each class can be identified; while unsupervised classification is applied based on the natural grouping of pixels in image data when they are plotted in feature space (Pouncey et al., 1999). Maximum likelihood classification (MLC) algorithm is one of the most popular supervised classification methods used with remote sensing image data, and this method is based on the probability that a pixel belongs to a

particular class (Rawat and Kumar, 2015). It is also parametric, meaning that it relies heavily on a normal distribution of the data in each input band (ERDAS Field GuideTM, 2013). Supervised classification was applied in this study because adequate GCPs were collected in the field and digital topographic map of Metehara sheet was available for verification.

Through visual interpretation, an appropriate 453 and 432 False Color Composite (FCC) band combination in Red, Green and Blue (RGB) order was used for identifying the feature classes of each Landsat images. The 432 FCC in RGB order, red, light grey to grey and dark red to brown colors represents irrigation or farm, scrub and vegetated areas, respectively. In both band combinations, black and light colors are representative features for water body and barren areas, respectively. But in 453 band combination scrub areas appear light purple to purple in color.

Based on visual interpretation of the different time series Landsat images with different band combinations, each image was categorized into two landuse (farm land and settlement) and four land cover (water body, vegetation, scrub land and bare land) classes (Table 4.1). For each of the land use and land cover type, training samples (samples) were selected by delineating polygons around representative landuse/cover sites from each satellite image. To train the decadal time series Landsat images, 3127 to 13179 training sites were selected by the software based on the training sample identified by the user. Training samples were included in 4 to 14 sub-classes for each landuse and land cover classes. Then, the training samples of each image were distinguished, deleted, renamed and merged.

Table 4.1. Description of different land use and land cover classes of the study area.

Class	Description
<i>A. Landuse classes</i>	
Farmland	Cultivated land where irrigation activities take place
Settlement	Built up area
<i>B. Land cover classes</i>	
Water body	The area which is covered by water
Vegetation	A vegetated area covered with riverine trees and shrubs
Scrubland	An area which is covered by scrubs, small scattered trees with some grasses; It also includes degraded areas in between the scrubs
Bare land	An area of exposed soil, and rock surface

4.3. Landuse and land cover mapping

The Landuse/cover maps of the study area (Figs. 4.1 - 4.5) were produced from the time series classified images in Arc Map 10.3 software verified by detailed field checking. First the classified raster datasets were exported to Tiff images. Then each Tiff image was converted to polygon feature using class-name as a field value. By using editor toolbar, features were deleted, merged and renamed from the same layer attribute table. All Farmland (Abadir Farm and Metehara Sugar Estate), settlement (Metehara and Addis Ketema towns) and water body (Lake Beseka) landuse/ cover class features at different periods were digitized from the different Landsat images of the study area, and using Metehara sheet topographic map as well as Google Earth images. Finally each digitized polygon was merged with the classified polygon at the same period, and then the digitized polygons were clipped. These merged and edited polygons were converted to raster in order to produce the LU/LC maps (Figs. 4.1 - 4.5) and for the time series change analysis. All LU/LC maps were mapped at 1:130,000 scale and WGS-1984-UTM-Zone-37N map projection system with Landscape map page size.

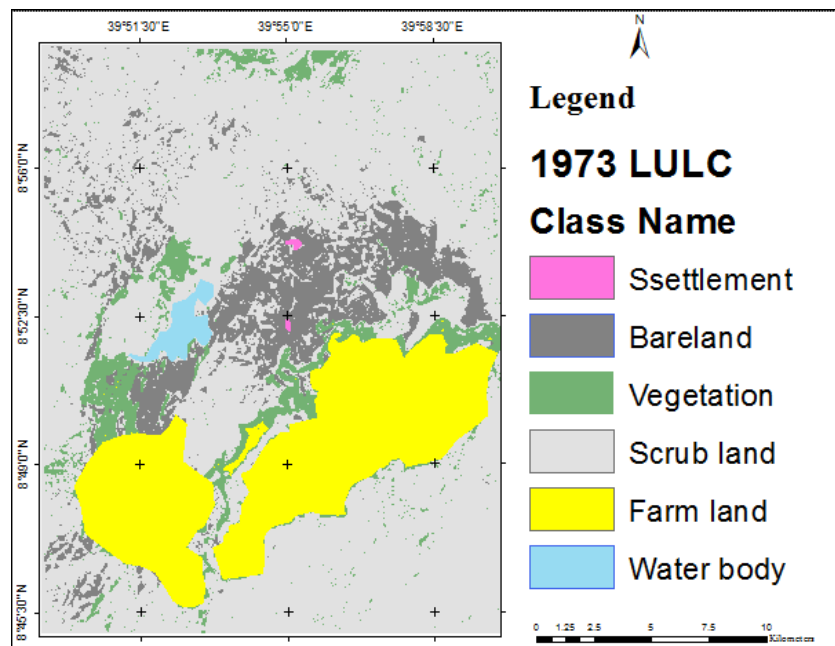


Fig. 4.1. The 1973 LU/LC map of the study area.

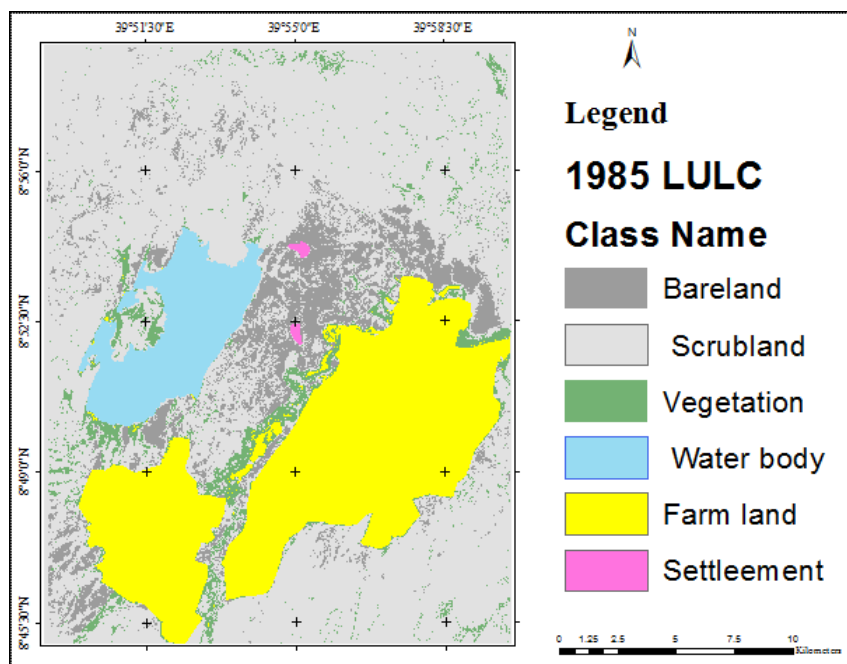


Fig. 4.2. The 1985 LU/LC map of the study area.

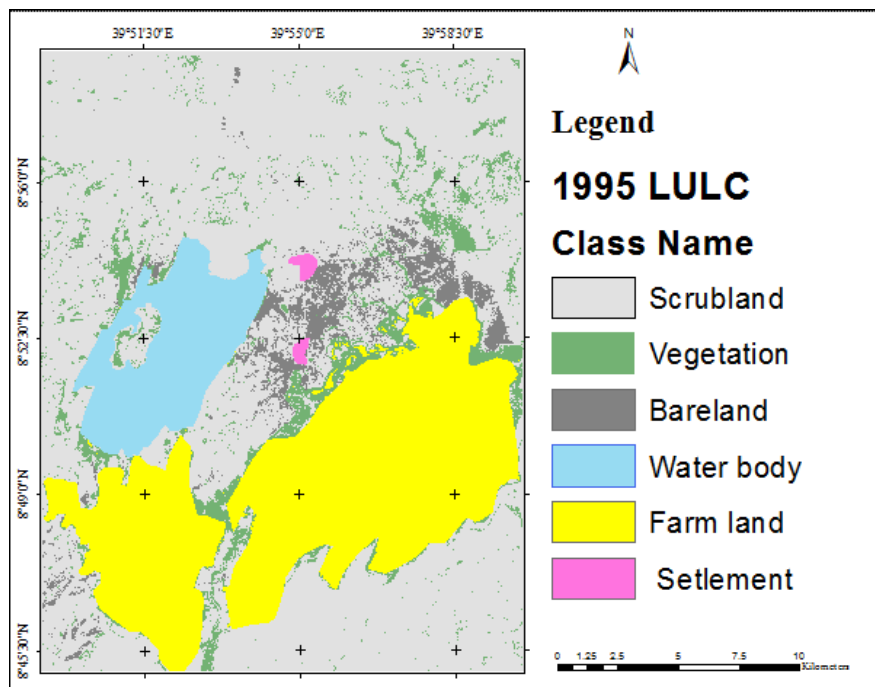


Fig. 4.3. The 1995 LU/LC map of the study area.

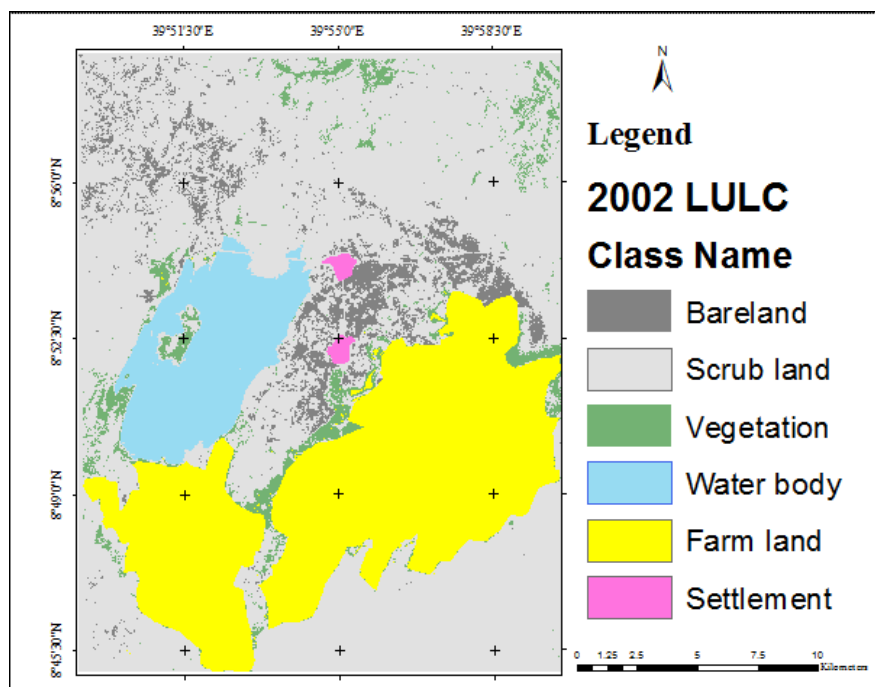


Fig. 4.4. The 2002 LU/LC map of the study area.

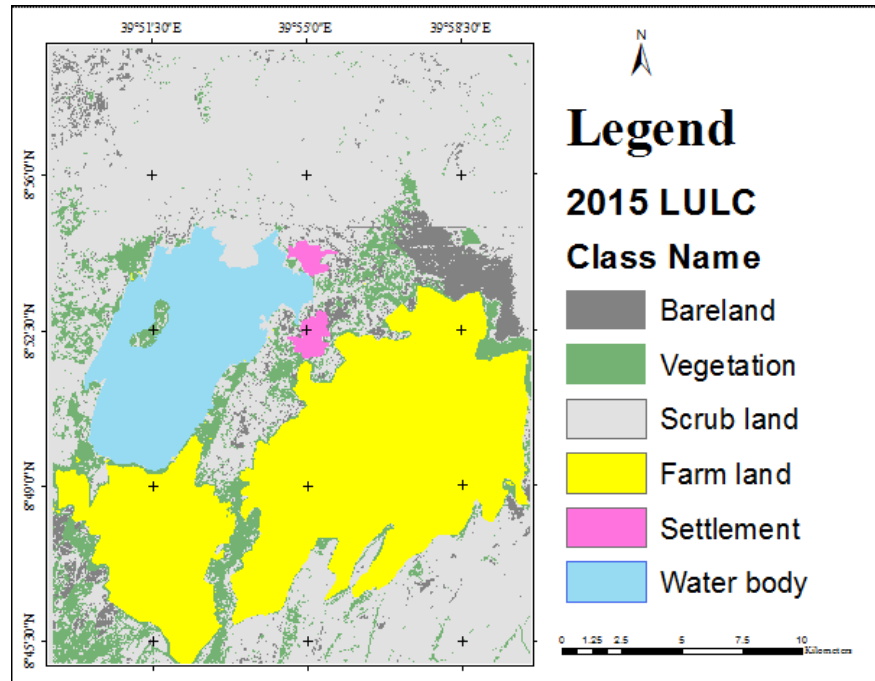


Fig. 4.5. The 2015 LU/LC map of the study area.

4.4. Accuracy assessment

Accuracy assessment is a post classification technique in evaluating the classified landuse and land cover units of a remotely sensed imagery. Validation of the 2015 LU/LC or classified image was carried out in order to determine its quality for the analysis of land use and land cover changes. Using 220 GCPs which were collected during the field survey; Google Earth and through visual interpretation an assessment of classification accuracy was carried out.

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Table 4.2. Confusion matrix summarized for OLI/TIRS Landsat image.

No	Class name	Reference Totals	Classified Total	Number of correct	Producers Accuracy%	User Accuracy %
1	Bare land	60	48	44	73.3	91.8
2	Vegetation	30	35	27	90	77.1
3	Scrub land	98	105	96	98	91.4
4	Farm land	15	14	13	93	87
5	Settlement	8	10	7	70	87.5
6	Water body	9	8	7	78	87.5
Total	220	220	194	194	502.3	522.3

Overall Classification Accuracy=88.18%

Kappa coefficient= 0.88

4.5. Land use and land cover change analysis

The land use and land cover areal coverage and relative changes statistical data during the 1973 to 2015 is summarized in Tables 4.3 to 4.6. Unlike the others, the Lake Beseka, farmland and settlement land cover/use units experienced similar trends (Fig. 4.6). The Lake and farmland experienced a closer relationship during the period 1973 to 2015; the lake was expanded at about 46.2 Km² while the farmland increased at 46.6Km² area. Moreover, the urban area or settlement area expanded by about 3.3Km² (0.6%). Even if vegetation did not have a linear trend like the farmland, the Lake and settlement, it had 14.2Km² (2.7%) decadal area change. The scrubland and barren land units decreased at about 78.8Km² (15.4%) and 31Km² (6.1%) respectively, during this decade. In the study area, the highest LU/LC change is obtained from the Lake and irrigations.

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Table 4.3. Area (in Km²) of the different landuse and land cover classes data from 1973 to 2015.

Class	Area (Km ²)				
	1973	1985	1995	2002	2015
Farmland	88.2	112.1	124.5	129.0	134.8
Settlement	0.3	0.7	1.4	1.8	3.6
Water body	4.8	30.8	39.4	43.4	51
Vegetation	32.2	22.7	31.2	19.9	46.4
Scrubland	332.1	298.8	300.5	292.6	253.3
Bare land	55.7	47.6	18.7	28.9	24.7

Table 4.4. Area (in %) of the different landuse and land cover classes data from 1973 to 2015.

Class	Area (%)				
	1973	1985	1995	2002	2015
Farmland	17.2	21.7	24.1	25	26.2
Settlement	0.1	0.1	0.3	0.3	0.7
Water body	0.9	6.0	7.6	8.4	9.9
Vegetation	6.3	4.4	6.1	3.8	9.0
Scrubland	64.7	58.3	58.3	56.7	49.3
Bare land	10.9	9.3	3.6	5.6	4.8

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Table 4.5. Relative change in area (Km²) of the different landuse and land cover classes data from 1973 to 2015.

Class	Areal change (Km ²)				
	1973-1985	1985-1995	1995-2002	2002-2015	1973-2015
Farmland	23.9	12.4	4.5	5.8	46.6
Settlement	0.4	0.7	0.4	1.8	3.3
Water body	26.0	8.6	4.0	7.6	46.2
Vegetation	- 9.5	8.5	-11.3	26.5	14.2
Scrubland	-33.3	1.7	-7.9	-39.3	-78.8
Bare land	-8.1	-28.9	10.2	-4.2	-31.0

Table 4.6. Relative change in area (%) of the different landuse and land cover classes data from 1973 to 2015.

Class	Areal change (%)				
	1973-1985	1985-1995	1995-2002	2002-2015	1973-2015
Farmland	4.5	2.4	0.9	1.2	9.0
Settlement	0	0.2	0	0.4	0.6
Water body	5.1	1.6	0.8	1.5	9.0
Vegetation	-1.9	1.7	-2.3	5.2	2.7
Scrubland	-6.4	0	-1.6	-7.4	-15.4
Bare land	-1.6	-5.7	2	-0.8	-6.1

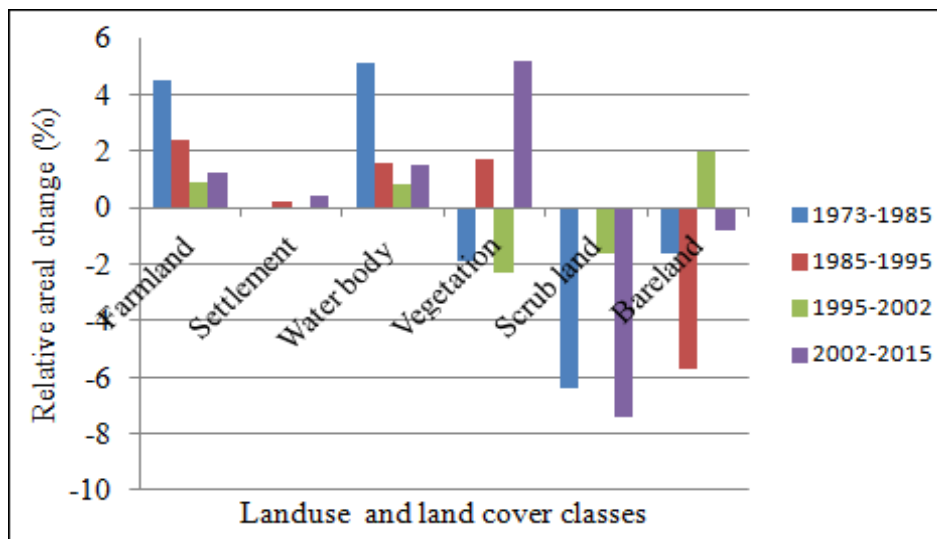


Fig. 4.6. Relative landuse and land cover changes in the study area during different periods.

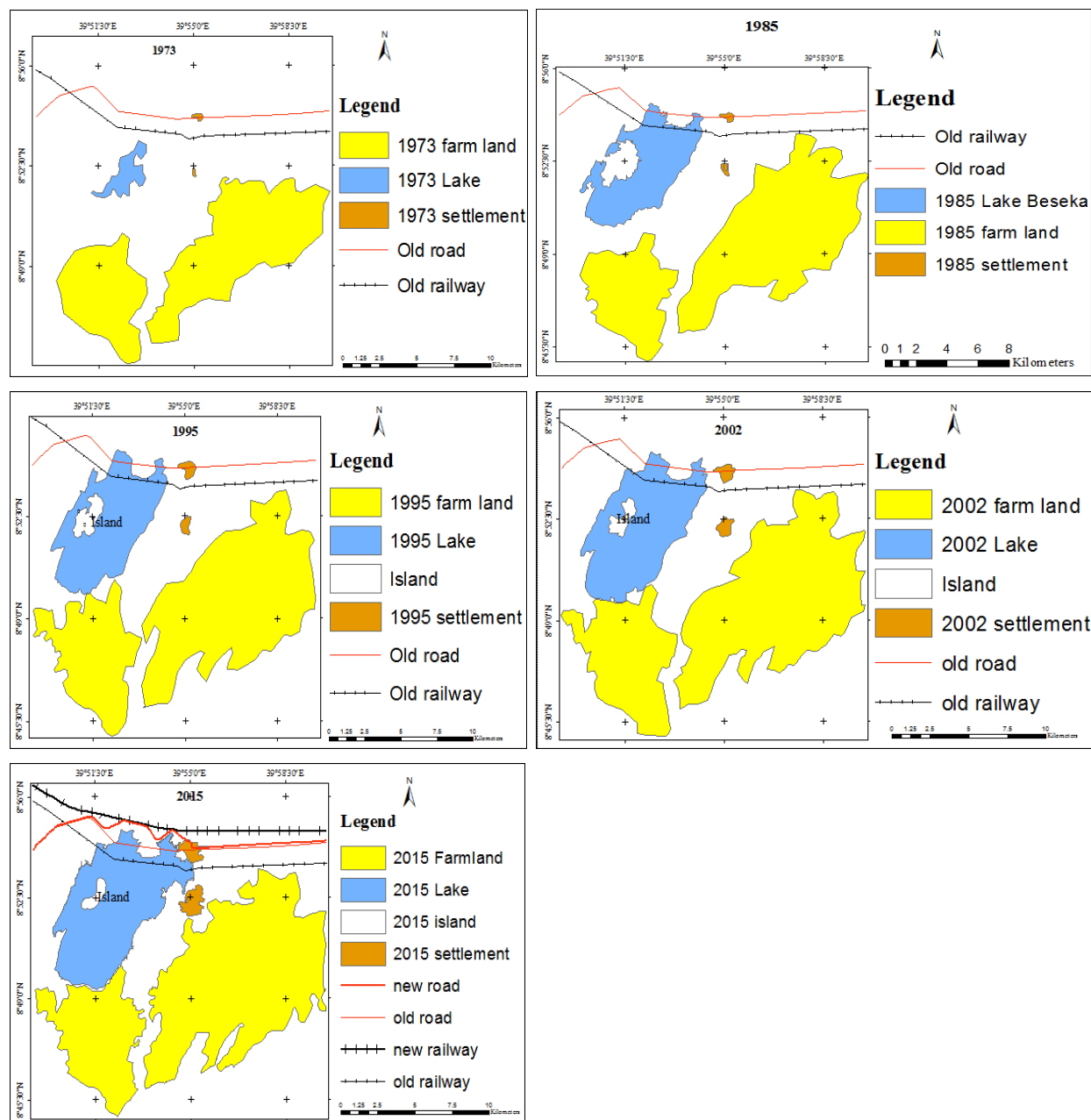


Fig. 4.7. Spatial and temporal land use (farmland and settlement) and land cover (Lake Beseka) change from the year 1973 to 2015.

Period I (1973-1985)

During this period, Beseka Lake and irrigated lands (farmland) show the highest areal expansion than during the other periods (Tables 4.5 and 4.6). Their areal expansion was 26Km² (5.1%) for the Lake and 23.9Km² (4.5 %) for the irrigated lands. About 56.7% of the total surface areal expansion of the Lake occurred during this period. The urban area (the two towns) had increased by 0.4Km². Due to over expansion of the Lake and irrigations in this period, the other land cover units had drastically declined. About 9.5Km² (1.9%) vegetated area, 33.3Km² (6.4%) scrubland and 8.1Km² (1.6%) barren area was changed into either an irrigated area, settlement (urban area) or has been inundated by the Lake water. Furthermore, in the period 1973 to 1985, the Lake totally inundated the Ethiopia-Djibouti railway and main asphalt road.

The Lake Beseka spatial/lateral expansion during the 1973 to 1985 period (Figs. 4.7 and 4.8) was mainly towards north (where the Ethio-Djibouti main road and railway, and Metehara town are located), northwest, south (Abadir Farm) and southwest. Similarly, the irrigations spatial extension direction was mostly towards north (only Metehara Sugar Estate Plantation) and south (Abadir Farm and Metehara Sugar Estate Plantation) (Fig. 4.9). Metehara town expanded during the same period towards the south and southwest (Fig. 4.10), i.e, towards the Lake Beseka. While Addis Ketema expanded toward the south.

Period II (1985-1995)

The farmland expansion rate during the period 1985-1995 decreased by almost half from that of period I (1973 to 1985) (Tables 4.5 and 4.6). This results in the relative decline in the surface area of the Lake from 26Km² (period I expansion rate) to 8.6Km² (period II expansion rate). However, the urban area expanded at 0.7Km² (0.2%) rate. Consequently about 8.5Km² vegetation cover and 1.7Km² scrubland has been gained. About 28.9Km² barren area was changed to either urban area (settlement), vegetated and scrublands.

The Lake Beseka expansion direction during the period 1985 to 1995 was towards north, northwest, south (Abadir Farm) and west (Fig. 4.8). During the Lake expansion towards the west an island was formed. The urban area expanded towards north and south (Fig. 4.10); while farmland extension direction was towards north (Abadir Farm), southeast and southwest (Metehara Sugar Estate) (Fig. 4. 9).

Period III (1995-2002)

The Lake and farmland rate of expansion during this period (1995-2002) was less than during the other periods. The highest vegetation loss of the last four decades has also occurred during this period. About 11.3Km² (2.3%) vegetated area and 7.9Km² (1.6%) scrubland was changed to about 4.5Km² (0.9%) farmland, while 4.0Km² (0.8%) area was covered by the Lake; 0.4Km² urban area and 10.2Km² (2%) barren area (Tables 4.5 and 4.6). During this period, about 4.0Km².

Lake Beseka expanded mostly towards the Abadir Farm and to a lesser extent to the northeast and northwest directions (Fig. 4.8). Along the northeast and northwest Lake expansion directions, the Ethio-Djibouti main road and railway were covered by the Lake water (Fig. 4.7). About 4.5Km² farm area expansion direction was towards southern part of the Abadir Farm and western part of Metehara Sugar Estate Plantation (Fig. 4.9). Metehara and Addis Ketema towns expanded about 0.4Km² area towards the west (Beseka Lake) and along East-West directions, respectively.

Period IV (2002-2015)

During the last four decades, the highest relative loss of scrubland and the lowest barren land change happened during this period (2002-2015). The highest vegetation cover was also gained in this period. This could possibly be related to the high propagation of the *Prosipis juliflora* in the area during the last two decades. About 39.3Km² (7.4%) of the scrubland and 4.2Km² (0.8%) barren land was changed into 5.8Km² (1.2%) irrigation area, 7.6Km² (1.5%) covered by the Lake water, 1.8Km² (0.4%) urban area and 26.5Km² (5.2%) vegetated area (Tables 4.5 and 4.6).

The Lake expansion direction, during this period, was to the south (Abadir Farm), northwest and northeast (Figs. 4.7 and 4.8). The Lake expansion direction was mostly towards the Metehara and Addis Ketema towns and to the old and new Ethio-Djibouti roads and railways. There was no significant expansion of Abadir Farm but Metehara Sugar Estate plantation expanded towards the northwest (the two towns) and southeast directions (Figs. 4.7 and 4.9). Both Metehara and Addis Ketema towns expanded along East-West directions. However, Addis Ketema town also expanded towards the north (Metehara town), showing its major expansion extent during this period. Metehara town's expansion was mostly towards the Lake Beseka.

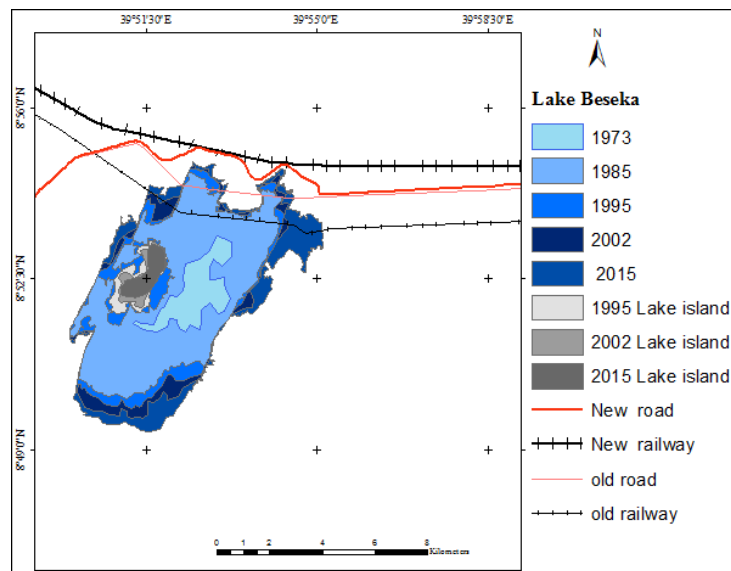


Fig. 4.8. Lake Beseka spatial expansion and its extent during the 1973-2015 period. The old main road and railway were digitized from the topographic map of Metehara sheet but the new road and railway, constructed after the year 2000, were digitized from the Google Earth on screen digitization; it was mapped at 1:100,000 scale.

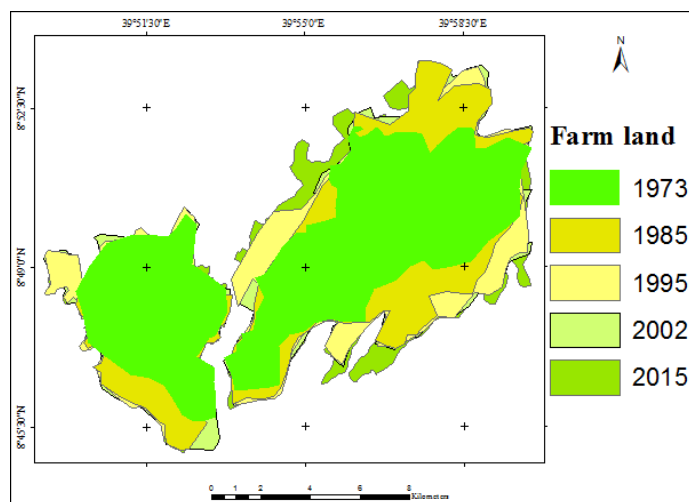


Fig. 4.9. Farmland (Abadir Farm and Metehara Sugar Estate Plantation) spatial expansion and their extent in the 1973-2015 period, mapped at 1:100,000 scale.

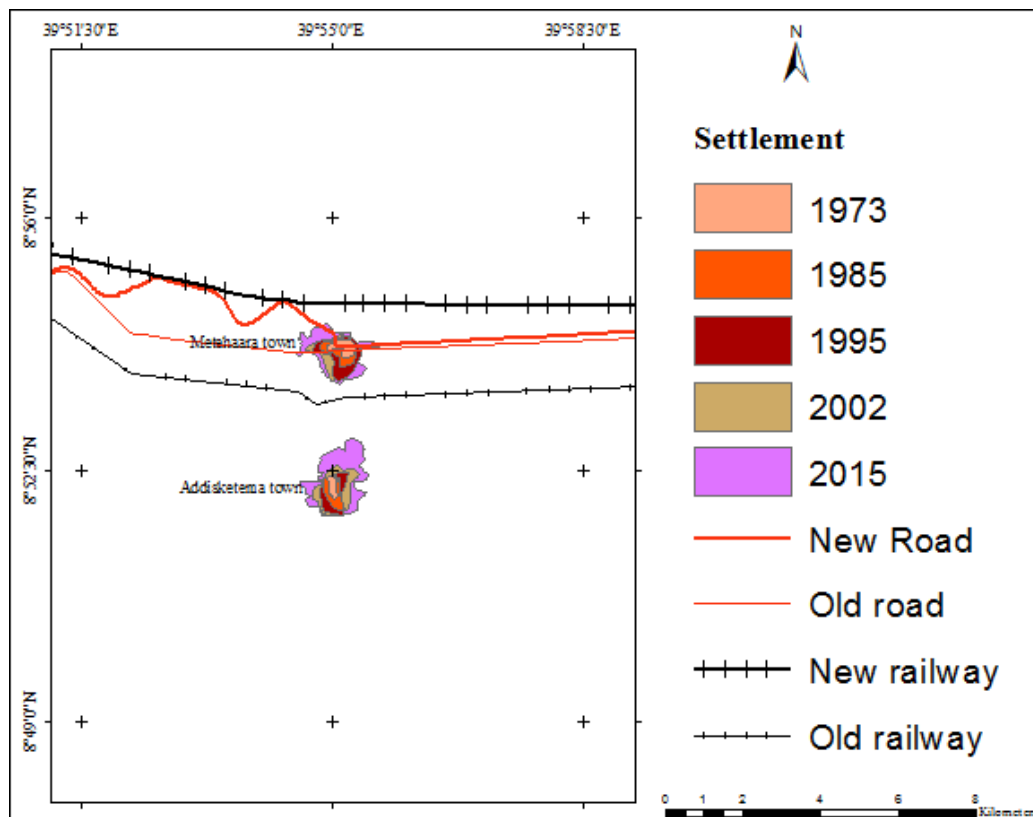


Fig. 4.10. Settlement/urban area (Metehara and Addis Ketema towns) expansion and its extent in the 1973-2015 period, mapped at 1:100,000 scale.

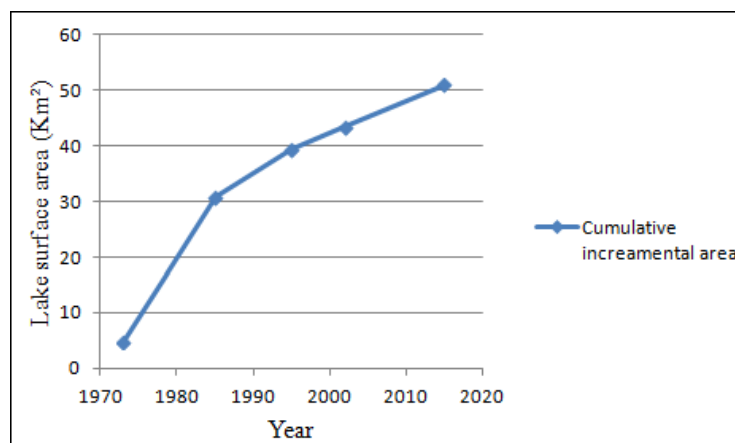


Fig. 4.11. Beseka Lake surface area in the 1973 to 2015 period.

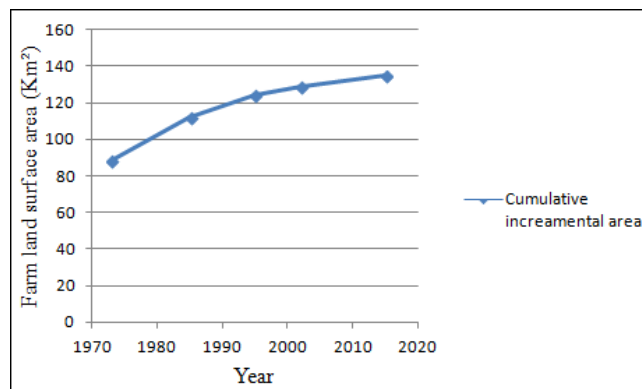


Fig. 4.12. Farmland surface area in the 1973 to 2015 period.

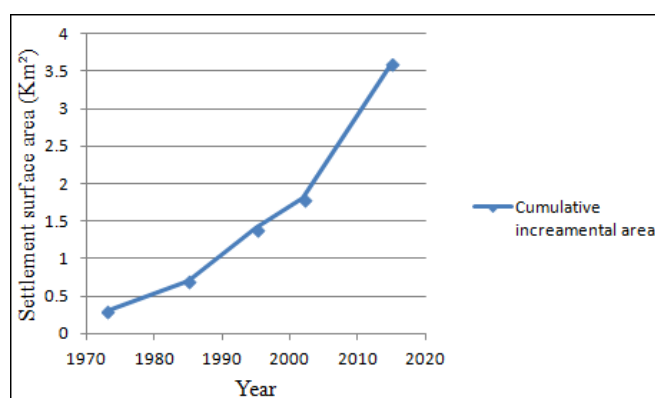


Fig. 4.13. Settlement surface area in the 1973 to 2015 period.

The Fentale-Metehara blisters and blister caves are associated with ignimbrite ash flow tuffs from the Fentale volcano (Gibson, 1974). The blistered areal coverage by the Lake Beseka expansion has been started since the period 1973-1985 (Fig. 4.14).

Since Metehara town is settled on the blistered region and the town had a linear trend areal expansion, there are so many blisters and blister caves destructed due to this urban expansion. Moreover, the rapid expansion of the irrigations and the Lake led to the damage and relocation of the Ethio-Djibouti road and railway. The road and railway crossed some of the blisters and blister caves and its relocation and the construction of new road and railway lines destructed numerous blistered features since these features are situated along and very close to the infrastructure lines.

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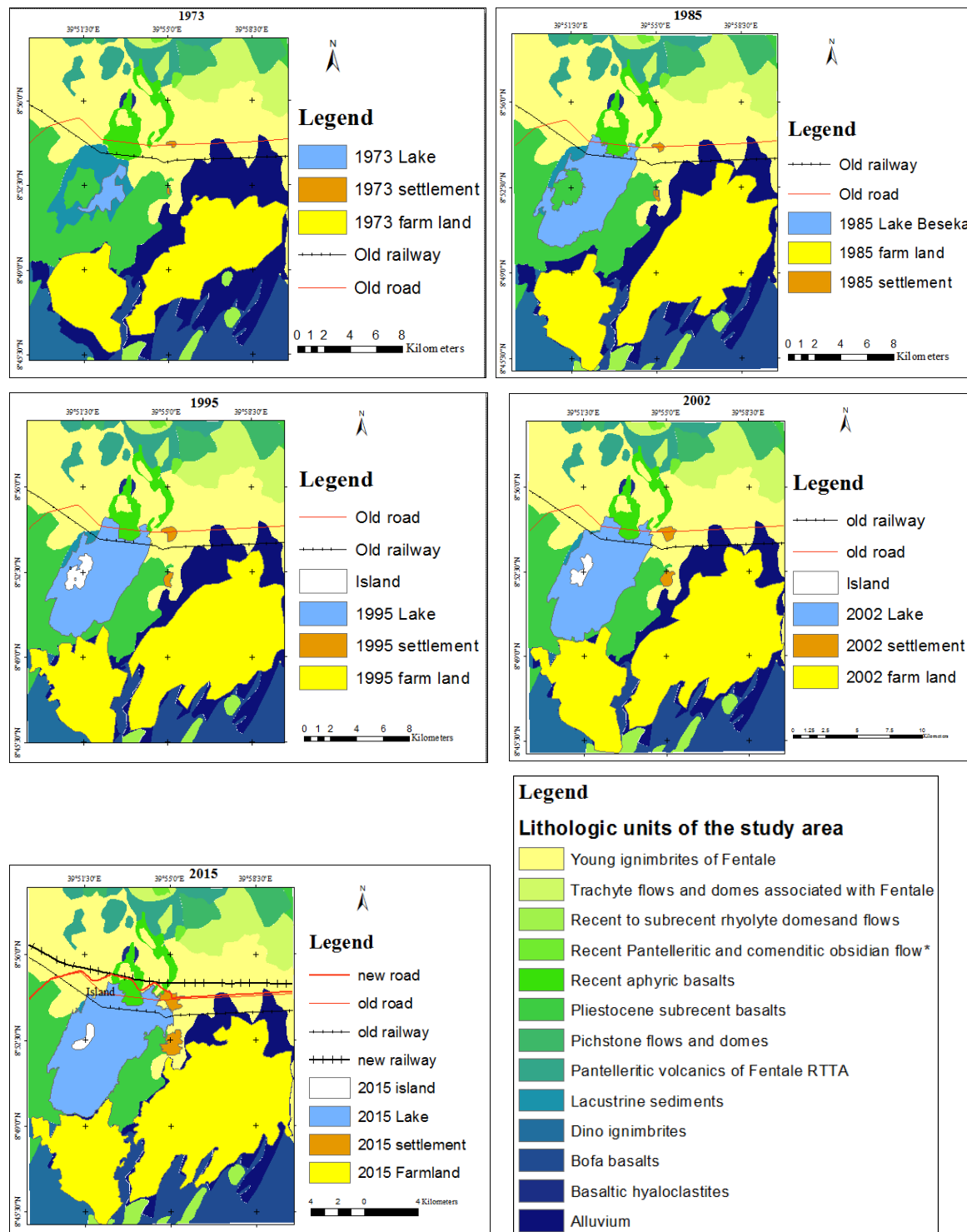


Fig. 4.14. Spatial and temporal land use (Settlement and irrigation) and land cover (Lake Beseka) change on the Fentale-Metehara blistered area from the year 1973 to 2015.

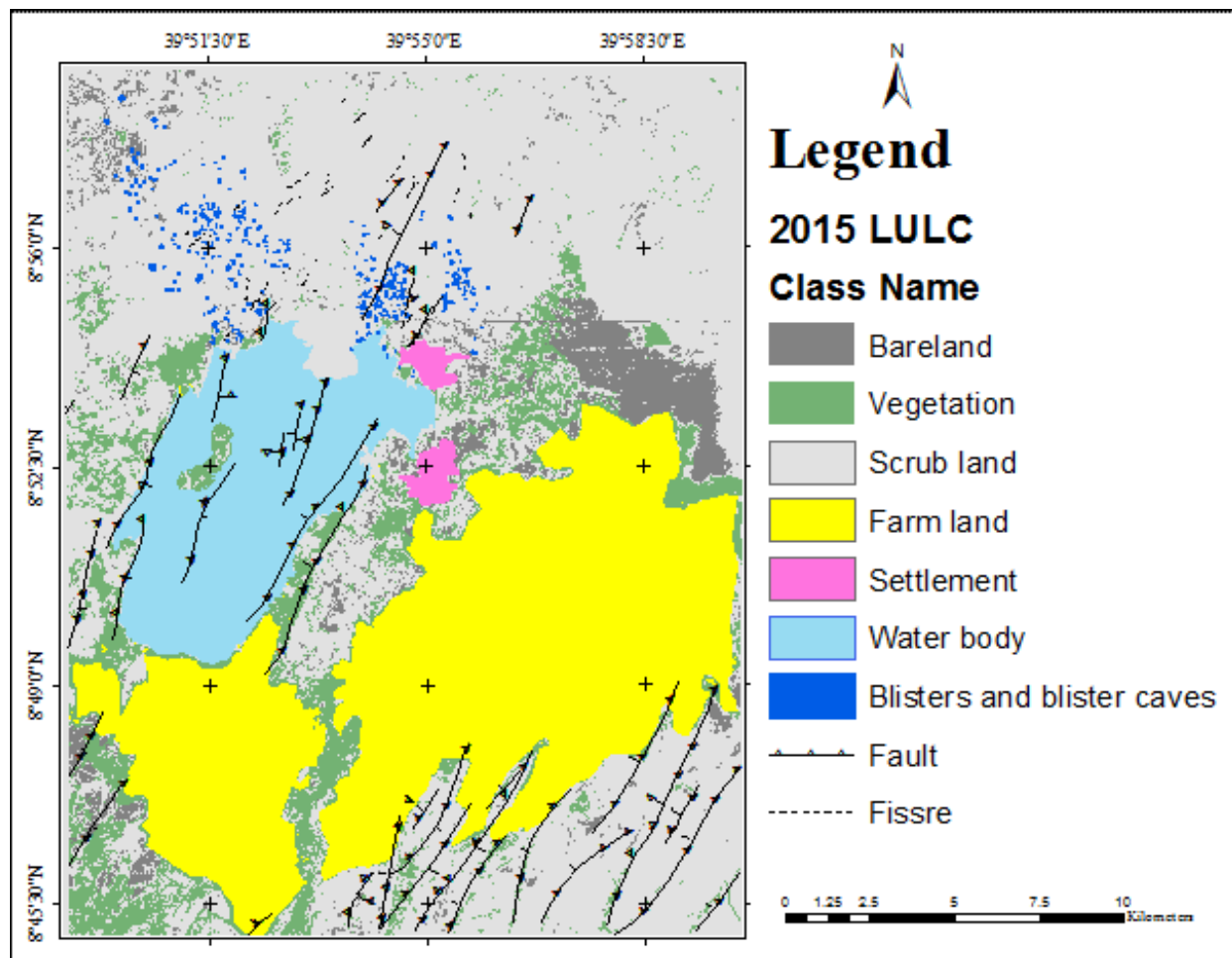


Fig. 4.15. The Fentale-Metehara blisters and blister caves crossed by faults and fissures and mostly they are distributed in scrub areas. Note that the fault traces on this map are imported from the geological map of 1978 when the Beseka Lake was smaller in size at the time of the geological mapping when the faults were exposed on the surface (not covered by the Lake water) while the LULC map is from 2015, hence the appearance of the fault traces on the lake surface.

CHAPTER FIVE

FENTALE-METEHARA BLISTERS AND BLISTER CAVES

5.1. Location and areal coverage

The Fentale-Metehara blisters and blister caves are widely distributed at the south and southwest sides of the Fentale mount and north and northern part of the towns (Metehara and Addis Ketema) and Lake Beseka (Fig. 5.1). The area of these features is bounded between 39.83 to 39.94 and 8.89 to 8.97 longitude and latitude in decimal degrees (Table 5.1) respectively. The aerial extent of the blistered region in the study area is about 53.57 Km². However, the area of the individual blisters and blister caves ranges from 6.78m² to 23810.05m² (Table 5.1). In addition, the perimeter of these individual features ranges from 9.81m to 553.83m.

Table 5.1. Minimum and maximum area, perimeter, longitude and latitude of the all blisters and blister caves.

Parameter	Minimum	Maximum
Longitude (decimal degree)	39.83	39.94
Latitude (decimal degree)	8.89	8.97
Area (m ²)	6.78	23810.05
Perimeter (m)	9.81	553.83

5.2. Blisters

In the study area, the total number of blisters is 478 (Table 5.4). They are located at about 39.83 to 39.94 longitude and 8.89 to 8.97 latitude in decimal degrees. The minimum and maximum areas of the individual blisters are 6.78m² and 12627.50m² respectively (Table 5.2). Generally, the area of the individual blisters, as compared to the blister caves, is relatively small. The smallest areal coverage is observed from these blisters. Similarly, their perimeter is also small.

Table 5.2. Minimum and maximum area, perimeter, longitude and latitude of all the blisters.

Parameter	Minimum	Maximum
Longitude (decimal degree)	39.83	39.94
Latitude (decimal degree)	8.89	8.97
Area (m ²)	6.78	12627.50
Perimeter (m)	9.81	421.70

5.3. Blister caves

There are 161 blister caves in the Fentale-Metehara area (Table 5.4). They are located between 8.90 and 8.97 latitude in decimal degrees, but their longitude is similar to the blisters (Tables 5.2 and 5.3). The area of these blister caves ranges from 14.92m² to 23810.06m². Moreover, the largest perimeter is obtained from the blister caves rather than the blisters. This large diameter of most of the blister caves make them collapsed.

Table 5.3. Minimum and maximum area, perimeter, longitude and latitude of all the blister caves.

Parameter	Minimum	Maximum
Longitude (decimal degree)	39.83	39.94
Latitude (decimal degree)	8.90	8.97
Area (m ²)	14.92	23810.06
Perimeter (m)	15.54	553.83

Table 5.4. Total number of blisters and blister caves.

Name of the blister field	Total number
Blister	478
Blister cave	161
Blister and blister cave	639

5.4. Mapping the individual blisters and blister caves

All the 478 blisters and 161 blister caves identified during the field survey and from the Google Earth (Fig. 5.1). They were digitized in polygon format using the Google Earth 2014 version at 1:2,000 to 1: 100 scale. They are semi-circular to circular in shape. The detail procedure how these digitized KMZ/KML files were converted to shape files is explained in chapter one. All the 478 blister and 161 blister cave shape files were merged into one blister and one blister cave respectively using *merge geo-processing tool* in Arc GIS 10.3. Then, the blisters and blister caves map (Fig. 5.2) was mapped at 1:45,000 scale with 3' and 30,000,000" x and y axis intervals; only top and left label axes with major division ticks; degree, minutes and seconds label style map grid properties; WGS-1984-UTM-Zone-37N map projection system with Landscape map page size.



Fig. 5.1. GeoEye (Google Earth) image of some blisters and blister caves of the Fantale - Metahara area.

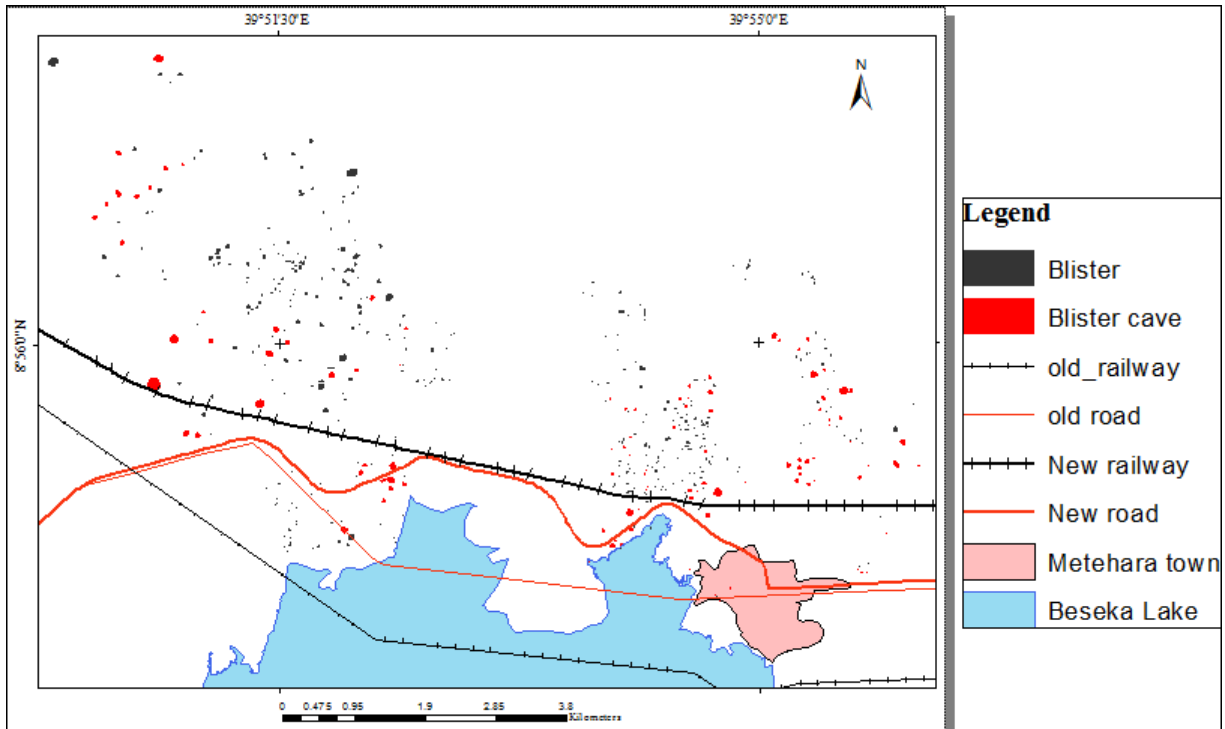


Fig. 5.2. Fentale-Metehara blisters and blister caves map.

5.5. Lithology of the Fentale -Metehara blisters and blister caves

As it can be seen from Fig. 5.3, all the blisters and blister caves fall on the young ignimbrite of Fentale (extracted from the lithological map of the study area). Therefore, the source rock of the Fentale-Metehara blisters and blister caves is young ignimbrite from the Fentale volcano.

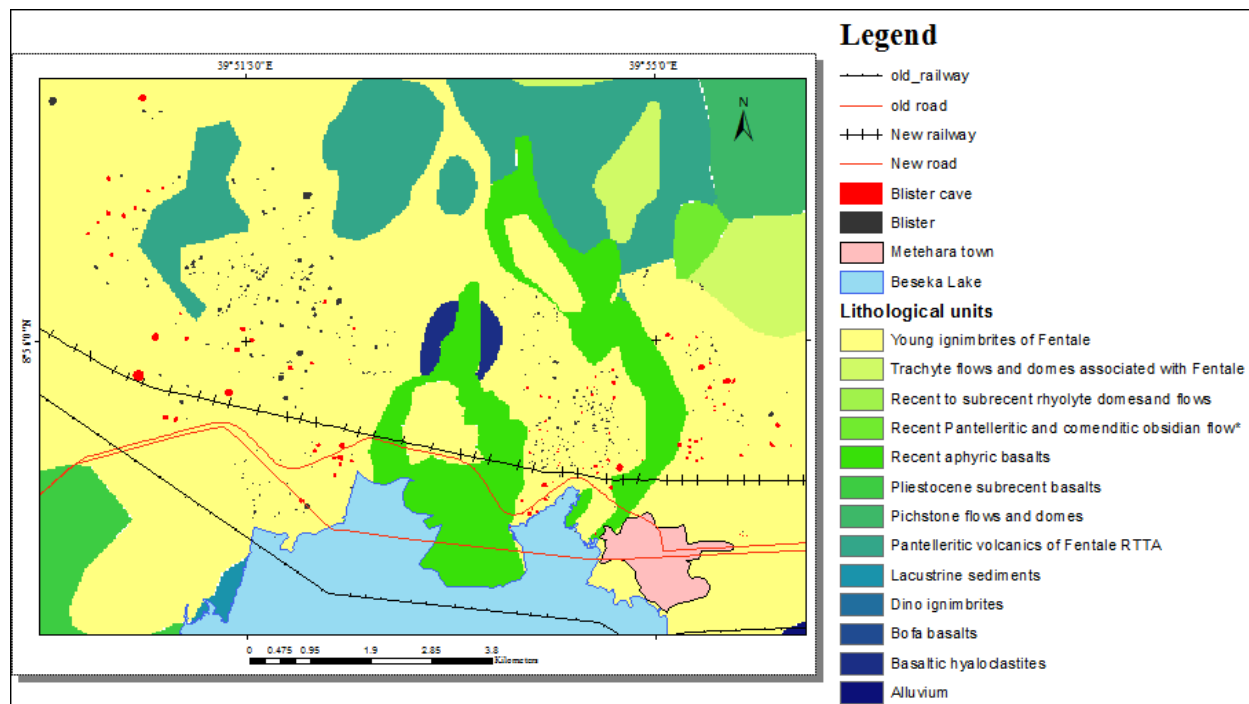


Fig. 5.3. A map of Fentale-Metehara blisters and blister caves overlies the lithology of the blistered area (young Fentale ignimbrite).

5.6. Description of some selected blisters and blister caves identified from the field survey

The topography of the study area ranges from 944m to 1919m above mean sea level. Generally, all 478 blisters and 161 blister caves are situated at lower elevations in the area. About one blister cave and 14 blisters are within the Lake Beseka; and six blister caves are found in Metehara town. From the field investigation, the blisters and blister caves range from 0.5m to 6m height (Table 5.5).

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Table 5.5. Longitude, latitude, elevation, height and rock characteristic (intact/collapsed) of some blisters and blister caves collected during the field survey.

No.	Name of the blister field	Longitude (decimal degree)	Latitude (decimal degree)	Elevation (meter)	Height (meter)	Rock characteristic of the blister field
1	Blister cave	039.85440°	08.92372°	971	2	intact
2	Blister cave	039.85615°	08.92600°	977	3	collapsed
3	Blister cave	039.85497°	08.92509°	975	1	collapsed
4	Blister cave	039.85529°	08.92478°	973	2	collapsed
5	Blister	039.85453°	08.92274°	971	0.75	collapsed
6	Blister	039.85452°	08.92229°	969	0.5	collapsed
7	Blister	039.85731°	08.92893°	985	4	intact
8	Blister	039.85607°	08.92952°	985	2	intact
9	Blister	039.85610°	08.92963°	985	0.5	intact
10	Blister	039.85470°	08.93030°	987	0.5	intact
11	Blister	039.85485°	08.93041°	986	2.5	intact
12	Blister	039.85500°	08.93231°	993	5	intact
13	Blister	039.85573°	08.93290°	994	5	Definitely intact
14	Blister	039.85653	08.93081°	987	0.5	intact
15	Blister cave	039.85733°	08.93193°	993	5	collapsed
16	Blister cave	039.85904°	08.93128°	991	6	intact
17	Blister	039.86785°	08.92999°	987	4	collapsed

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	cave					
18	Blister cave	039.91047°	08.91213°	993	3	collapsed
19	Blister	039.90351°	08.91259°	965	2.5	intact
20	Blister	039.92212°	08.92332°	977	4	intact
21	Blister cave	039.92279°	08.92357°	974	2.5	intact
22	Blister cave	039.92361°	08.92390°	971	2.5	collapsed
23	Blister cave	039.92427°	08.92380°	969	0.75	Strongly collapsed
24	Blister cave	039.92343°	08.92443°	971	0.5	collapsed
25	Blister	039.92408°	08.92511°	977	6	intact
26	Blister	039.92408°	08.92511°	974	3	collapsed
27	Blister cave	039.92746°	08.92441°	966	1.5	Strongly collapsed
28	Blister	039.92746°	08.92441°	970	0.75	intact
29	Blister cave	039.91123°	08.90281°	957	5	intact
30	Blister cave	039.91180°	08.90200°	961	5	intact
31	Blister cave	039.90810°	08.90577°	958	5.5	collapsed

For the susceptibility map of blisters and blister caves presented in the next chapter (chapter six), an inventory map of these features (Fig. 5.5) was prepared by identifying the affected/threatened blisters and blister caves during the field survey and from the aerial photos and Google Earth. Among the 639 blisters and blister caves, 78 blisters and 41 blister caves are considered to be affected blister fields.

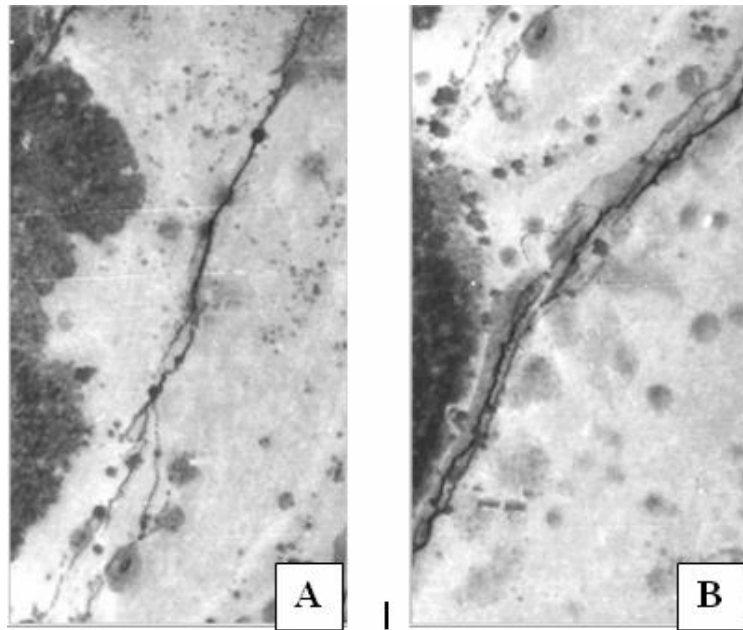


Fig.5.4. Some of the Fentale-Metehara blisters and blister caves crossed by faults and fissures northeast of Lake Beseka, from the 1975 aerial photograph (after Berihu, 2007).

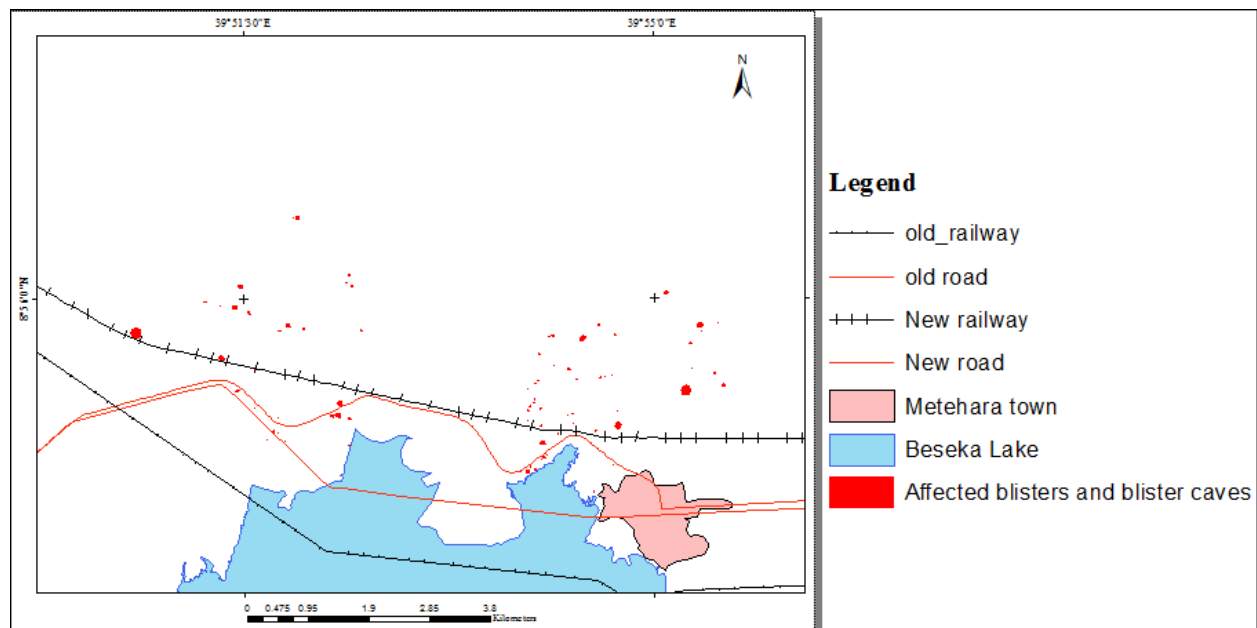


Fig. 5.5. Affected blisters and blister caves map.

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Table 5.6. Total number of affected and non-affected blisters and blister caves.

Name of the blister field	Total number
Affected blister and blister cave	119
Non- affected blister and blister cave	520
Affected blister	78
Non- affected blister	400
Affected blister cave	41
Non- affected blister cave	120

CHAPTER SIX

SUSCEPTIBILITY OF FENTALE-METEHARA BLISTERS AND BLISTER CAVES

6.1. Introduction

Generally, there are two groups of triggering factors for the susceptibility of blister caves and blisters namely natural and human induced factors. Natural factors include: drainage systems, lineaments and topographical parameters (elevation, slope and slope aspect); while roads, railways are considered to be human induced factors.

Non-hierarchical or k-means clustering has been considered an essential technique for grouping features in producing susceptibility maps (Yilmaz, 2007; Fell et al., 2008). It is applied based on the frequency ratio values from a given triggering factor attribute table and analyzed using frequency ratio as an analysis field in the Arc GIS software. An Euclidian distance method is applied for clustering features at equal areas in a particular study area. Degree of fitness, on the other hand, is a method that is used to evaluate the quality of susceptibility map expressed in terms of ratio. The ratio is between areas of the endangered susceptibility class to the corresponding susceptibility class in the total study area. It can be also expressed in percentage.

6.2. Triggering factors

The blister caves and blisters are under continuous threat of destruction due to various factors. Their susceptibility to destruction is therefore a result of a combination of factors whose individual relative impact may vary. In order to determine the susceptibility, eleven factors have been considered. All the distance factor raster datasets: distance to roads, railways, drainage systems, Lake Beseka, irrigations, lineaments and settlements were derived using Euclidean Distance Spatial Analyst Tool from the Arc Toolbox window. The input features source data were the new and merged polygon features (irrigations, Lake Beseka and settlements) and poly-line features (roads, railways, drainages and lineaments) of the corresponding output triggering raster dataset. For topographic factors (elevation, slope and slope aspect) Surface Spatial Analyst Tool was used to perform these factors raster data sets. Then each factor raster dataset including lithology factor was exported to TIFF format raster layer for further analysis.

All the raster layers have the same properties: 30 m x 30 m (x, y) cell size, processing extent same as database boundary shape of the study area (8.98° top, 8.75° bottom, 39.82° left and 40.0° right), WGS-1984-UTM-Zone-37N spatial reference.

For this study frequency ratio (FR) model was used. According to Yilmaz (2007) frequency ratio is the ratio of the probabilities of a collapse occurrence to a non-occurrence for a given attribute, and if the ratio is greater than unity it indicates a stronger relationship between collapse occurrence and the given factors attribute while if the ratio is lower, lesser relationship is obtained. Accordingly, it is assumed the probability of collapse occurrence of Yilmaz (2007) represents probability of destruction of blisters in the current study. To calculate the areas of each classes of a given factor, the raster dataset was reclassified into reversed integer values using Reclassify Spatial Analyst Tool in the Arc Map 10.3. The reclassified raster layer was converted to a polygon feature and this feature was edited using merge editing tool from the editor menu. Then the area in square meter of each class of a given triggering factor was calculated by adding area field in the attribute table of the given factor polygon feature and using calculate geometry tool.

Moreover, each class area of the affected or threatened blisters and blister caves of each triggering factor (Table 6.1- 6.11) was calculated from the corresponding triggering factor affected polygon feature. The affected polygon feature of each factor was performed using clip geoprocessing tool with processing extent same as layer area of affected blister fields and the corresponding total study area polygon feature of each factor as an input feature dataset. The areas of each factor classes and the corresponding affected blister field classes were changed to percentage in order to do the frequency ratio. Finally, the frequency ratio was calculated by dividing the affected blister fields class area in percentage of a given factor to the corresponding total study area (area in domain) of a given factor class in percentage (Table 6.1- 6.11).

All the factor maps were prepared at 1:130,000 scale with: 3' and 30,000,000" x and y axis intervals, only top and left label axes with major division ticks; degree, minutes and seconds label style format and graticule map grid properties.

6.2.1. Distance to roads

Roads are considered to be important factors determining the susceptibility to destruction of the blisters and blister caves, because of their direct impact on the blister caves. When a road is aligned across or close to a blister cave, there will be physical destruction by excavation. Moreover, blister caves close to a road will be relatively more exposed to destruction as they will be easily accessible.

Road lines were digitized from the 1975 topographic map of Metehara Sheet at 1:50,000 scale and from Google Earth 2014 version. The old Addis Ababa to Djibouti main road and other accessory road networks were digitized from topographic map of Metehara Sheet in Arc Map 10.3, and then these poly-line features were exported to a new shape file. The new Addis Ababa to Djibouti main road and new accessory road networks (constructed since?) were digitized on screen from the Google Earth and saved as KMZ and KML files. These saved files were imported in to Arc Map 10.3. Then, using KML to layer conversion tool the new main and accessory roads KML and KMZ files were converted to dataset layers. Finally, new road dataset layers were exported to shape file and all the new and old road poly-line features were merged using "Merge" geoprocessing tool for further analysis. The merged road poly-line was used as an input feature class in mapping the distance to roads map with classes in meter from the roads. The distance to roads raster image was reclassified (Fig. 6.1) into ten classes ranging from 1 to 10 integer values using "Reclass" spatial analyst tool from the Arc Toolbox window. The integer reclassified class values are reversed with respect to the old class values in meter.

All the affected blisters and blister caves ("affected" means the blisters in one way or the other have been fully or partly destroyed) fall in the 9th and 10th reclassified distance to road classes (Table 6.1 and Fig. 6.2) that is within 1,324.4m distance from roads in the study area. This implies that there is a strong threat to the blisters and blister caves along and close to the roads especially along the main Addis Ababa to Djibouti old and new roads (i.e., there is higher susceptibility to destruction of the blister caves and blisters). Frequency ratio value is high only within 662.2m distance from the roads while it is low farther than 662.2m. Generally, the impact of the roads on the blisters and blister caves decreases with increasing distance from the roads.

Within 662.2 m distance from the roads, about 98.1% of the affected blistered area is threatened at a very high rate.

Most of the threatened blisters and blister caves are crossed by the main and other accessory roads while some others are found very close to these roads and are devastated by the traffic loads and road construction and relocation activities.

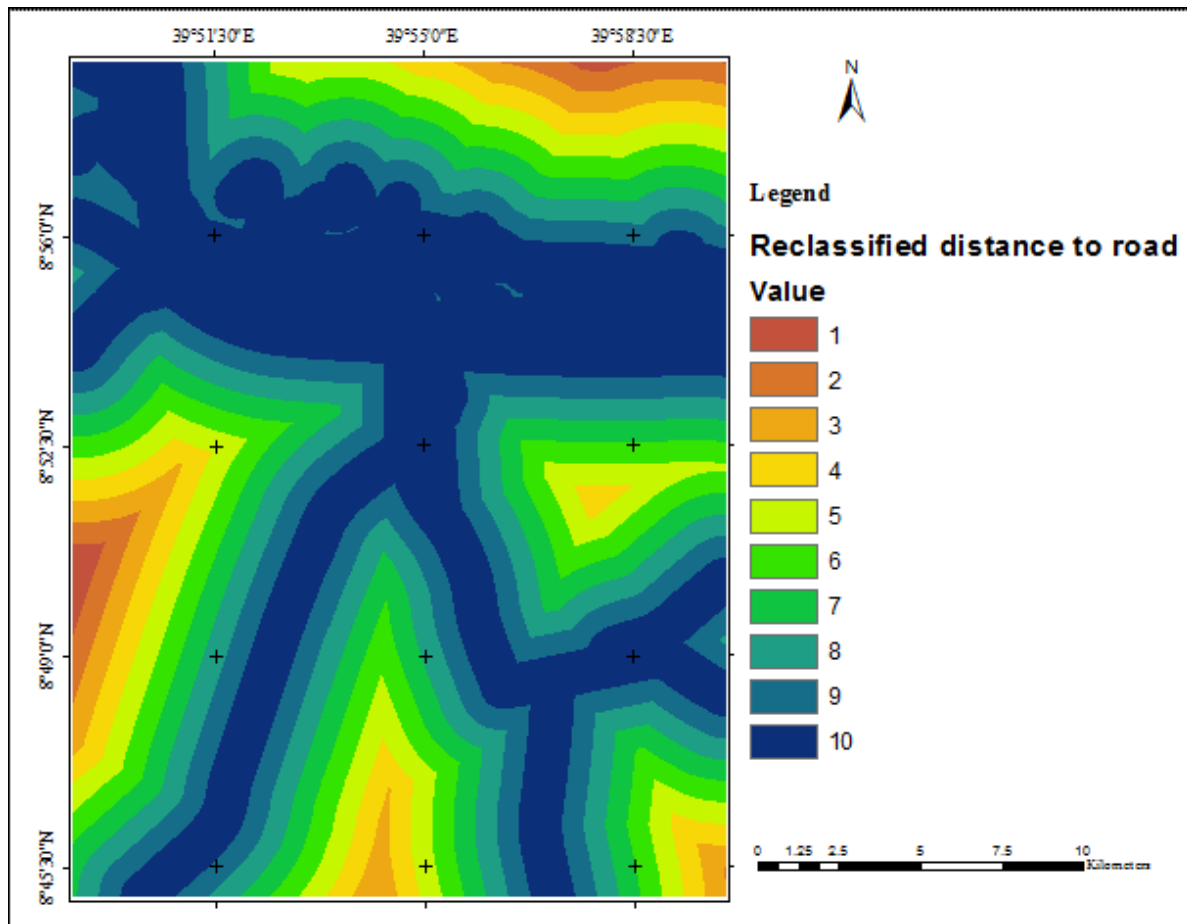


Fig. 6.1. Reclassified distance to roads map of the study area.

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Table 6.1. Frequency ratio of reclassified distance to roads.

Old value/class (m)	Reclassified value/class	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
0 - 662.2	10	19030747.3	98.1	164807538.6	32.1	3.1
662.2 - 1,324.4	9	371881.7	1.9	81072259.6	15.8	0.1
1,324.4 - 1,986.6	8	0	0	67707590.6	13.2	0
1,986.6 - 2,648.8	7	0	0	59761085.9	11.7	0
2,648.8 - 3,311.0	6	0	0	49950846.2	9.7	0
3,311.0 - 3,973.2	5	0	0	38592838.7	7.5	0
3,973.2 - 4,635.3	4	0	0	25382076.9	4.9	0
4,635.3 - 5,297.5	3	0	0	15646096.3	3.1	0
5,297.5 - 5,959.7	2	0	0	7961847.1	1.6	0
5,959.7 - 6,621.9	1	0	0	1774019.9	0.3	0

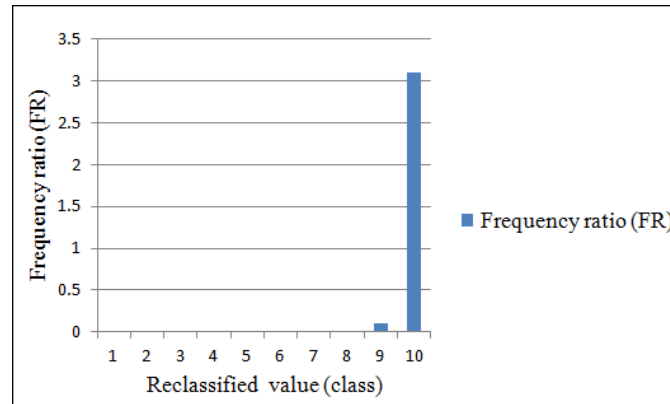


Fig. 6.2. Reclassified distance to roads frequency ratio model.

6.2.2. Distance to lineaments

Lineaments, including faults and fissures are very common phenomena in the study area. All the lineaments in the study area were digitized on screen from the 1978 Geological Map of Nazareth Sheet (1:250,000 scale) and in Arc Map 10.3. Numerous, parallel to sub-parallel, active tension fractures and high-angle, small-throw normal faults generally oriented NNE-SSW cross most parts of the study area, hence affecting the formation, alignment and stability of the blisters and blister caves. The faults, many of which are very recent, and some significantly deep fissures provide excellent cross-sections through the blistered portions of the Fentale tuff (Gibson, 1974).

A significant number of blisters and blister caves are threatened by the active and recent rift faults and fissures in the area between Lake Beseka and Fantale volcano, suggesting that these lineaments could be important triggering factors to the destruction (susceptibility) of the blister caves and blisters as they can physically affect the blisters and at the same time act as reasons for the lake Expansion. Accordingly, most of the affected blistered area falls within 831m distance from the lineaments, and it accounts for 85.9% of the total area of this blistered region (Table 6.2 and Figs. 6.3 and 6.4). The higher frequency ratio value is also obtained within 831m distance from lineaments, implying that lineaments significantly threaten the blisters and blister caves. Moreover, the frequency ratio values decrease as distance increases farther away from lineaments.

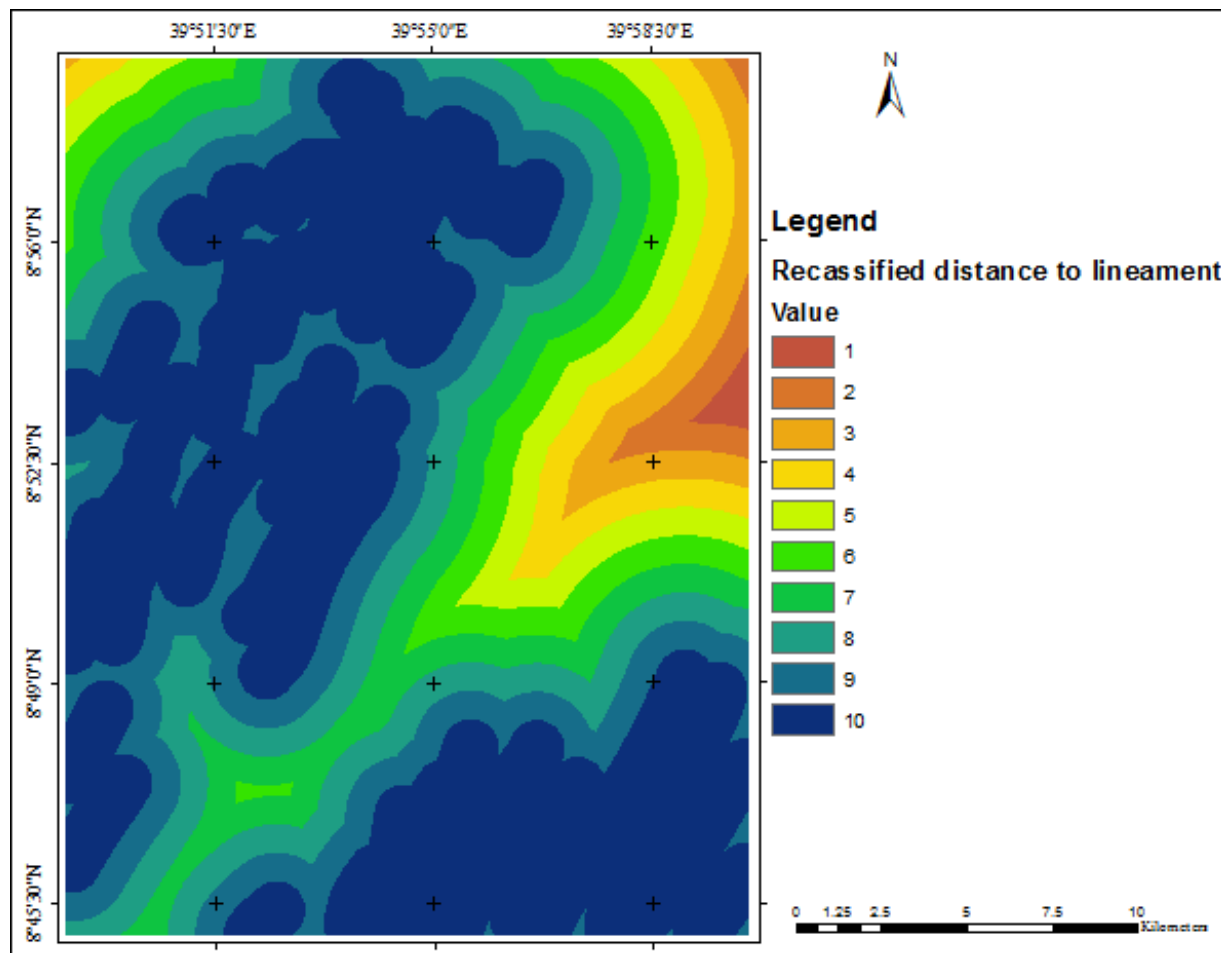


Fig. 6.3. Reclassified distance to lineaments map of the study area.

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Table 6.2. Frequency ratio of reclassified distance to lineaments.

Old value/class (m)	Reclassified value/class	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
0 - 831.0	10	16668767.7	85.9	212372195	41.4	2.1
831.0 - 1,662.0	9	2733861.3	14.1	87339931.8	17.0	0.2
1,662.0 - 2,493.0	8	0	0	62587197.1	12.2	0
2,493.0 - 3,324.0	7	0	0	49037642.5	9.6	0
3,324.0 - 4,155.0	6	0	0	31436098.5	6.1	0
4,155.0 - 4,986.0	5	0	0	25167505.9	4.9	0
4,986.0 - 5,817.0	4	0	0	20933899.5	4.1	0
5,817.0 - 6,648.0	3	0	0	14867138.4	2.9	0
6,648.0 - 7,479.0	2	0	0	7075965.6	1.4	0
7,479.0 - 8,310.1	1	0	0	1838625.7	0.4	0

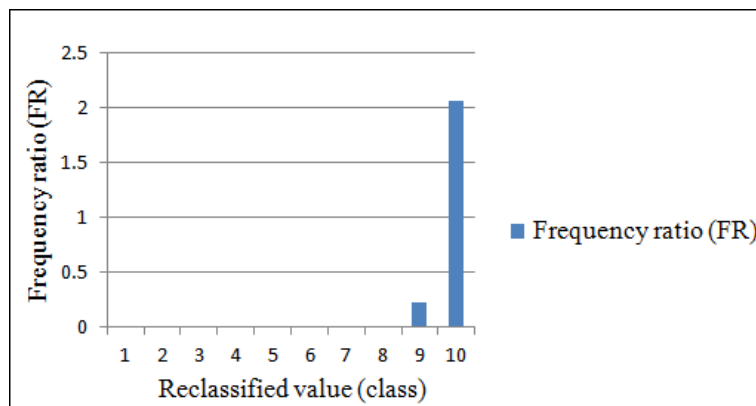


Fig. 6.4. Reclassified distance to lineaments frequency ratio model.

6.2.3. Distance to drainage systems

Drainage lines in the study area were digitized on screen in Arc Map 10.3 from the 1975 topographic map of Metehara Sheet at 1:50,000 scale. In this triggering factor, except the distance ranging from 4,219.7m to 4,688.5m, all the affected blisters and blister caves are distributed in all classes but their areal coverage decreases with increasing distance away from drainages (Table 6.3 and Figs. 6.5 and 6.6). High frequency ratio values are obtained between 468.9m and 1,875.4m distance from drainage systems, and in this distance range about 58.9% of the area of blisters and blister caves is highly threatened. Generally as distance increases from the drainage lines, the impact on the blisters and blister caves becomes lower because it is assumed that the drainage systems act as conduits for water flow which might carry debris and boulders as well as floods which might physically destroy the blisters and inundate the blister caves.

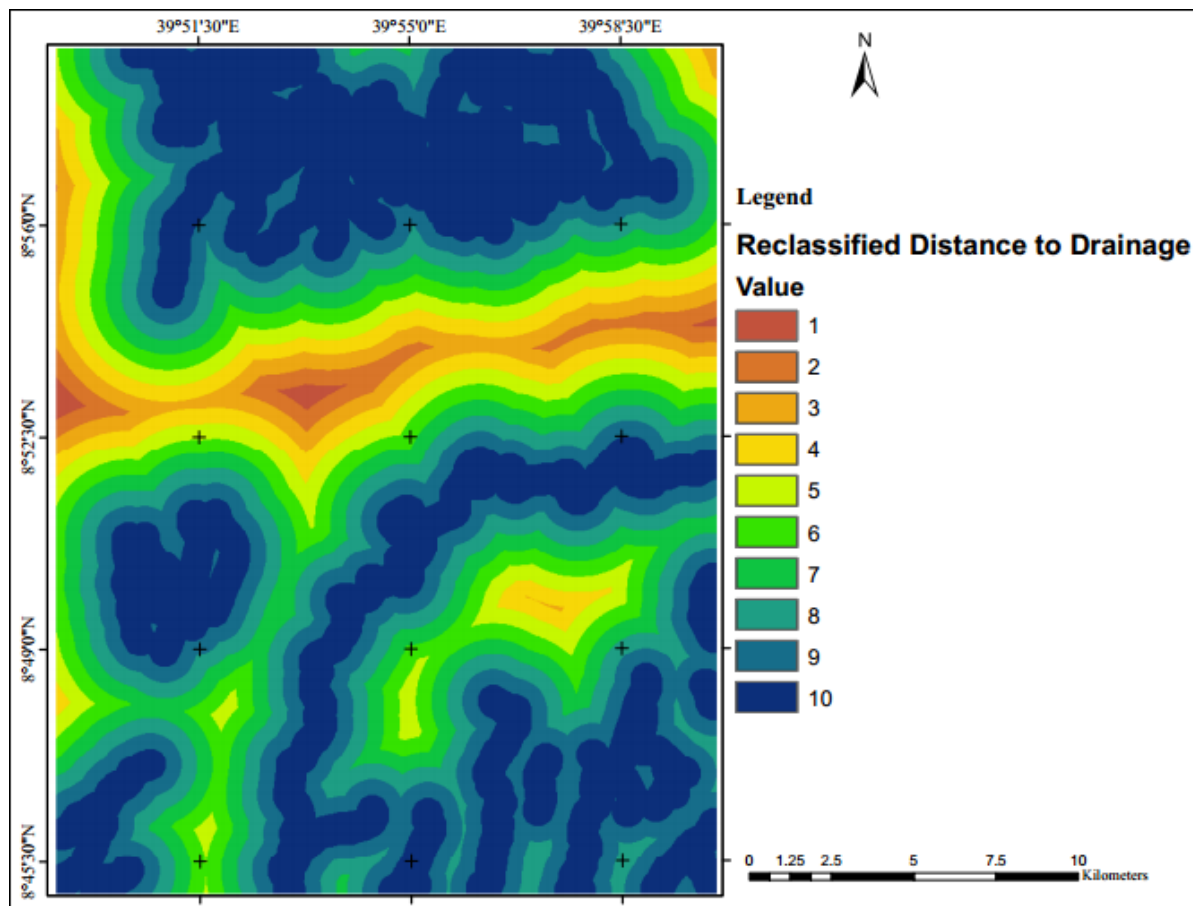


Fig. 6.5. Reclassified distance to drainage systems map of the study area.

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Table 6.3. Frequency ratio of reclassified distance to drainage systems.

Old value/class (m)	Reclassified value/class	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
0 - 468.9	10	5050842.1	26.0	156827299.5	30.6	0.9
468.9 - 937.7	9	4992851.4	25.7	89025492.7	17.4	1.5
937.7 - 1,406.6	8	3673441.3	18.9	67731374.6	13.2	1.4
1,406.6 - 1,875.4	7	2779906.5	14.3	58812529.7	11.5	1.3
1,875.4 - 2,344.3	6	1344783.9	6.9	48378487.1	9.4	0.7
2,344.3 - 2,813.1	5	709311.5	3.7	34063907.7	6.6	0.6
2,813.1 - 3,281.9	4	445721.7	2.3	27267491.1	5.3	0.4
3,281.9 - 3,750.8	3	342558.4	1.8	20055417.5	3.9	0.5
3,750.8 - 4,219.7	2	63212.3	0.3	9096595.6	1.8	0.2
4,219.7 - 4,688.5	1	0	0	1397604.4	0.3	0

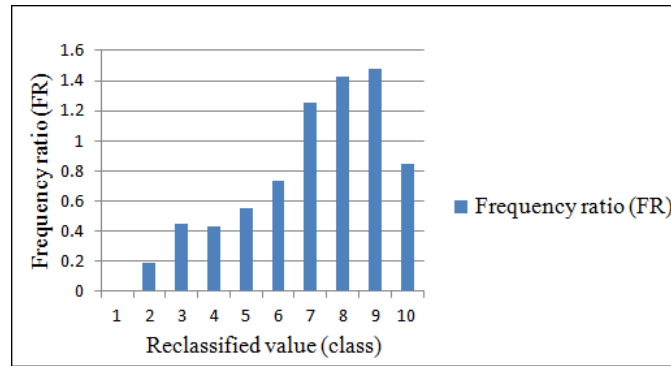


Fig. 6.6. Reclassified distance to drainage systems frequency ratio model.

6.2.4. Distance to Lake Beseka

Lake Beseka has been expanding rapidly since the last 40 years (MWR, 1999; Fasika, 2007; Eleni, 2009; WWDSE, 2011; Megersa, 2012). Its expansion threatens many natural (e.g. the blisters and blister caves) and man-made structures (roads, railway line, etc.). It can be considered as the single most significant threat to the future of the blister caves and blisters especially those located along the expansion direction of the Lake, as it eventually will cover them.

The Beseka Lake shoreline was digitized as a polygon feature from the 2015 satellite image with a 30 m x 30 m spatial resolution of the study area, and it was exported to a new shape file. This Beseka Lake polygon feature was used as an input feature class in mapping distance to Lake Beseka map. Then the distance to Lake Beseka map was reclassified (Fig. 6.7) with a reversed integer value classes ranging from 1 to 10. The high value has a high probability to endanger the blisters and blister caves, and the reverse is also true. Among the 119 endangered blisters and blister caves mapped, 14 blisters and one blister cave are found in the northern part of Lake Beseka and they are very much threatened by the Lake. As indicated in Table 6.4, as distance from the Lake increases, the area of all the affected blisters and blister caves in the study area decreases. All the affected blisters and blister caves in the study area are found within the lake and 5,047.5m distances from the Lake. About 98.3% of the area of all these 119 features is categorized as a high to very high rate of probability to be destroyed by the Lake within 3,364.9m distance from the Lake.

The area between 3,364.9m and 5,047.5m distance from the Lake, which covers 1.7% of the blistered area, has a relatively low probability of threat because its value of frequency ratio is low.

As indicated in the frequency ratio analysis, the impact of the Lake expansion is not only on the blisters and blister caves, but also on the infrastructure development (roads, railways, the Metehara town, power lines and stations, etc.), which further leads to relocation of these infrastructures aggravating the destruction of the blisters and blister caves, as has been observed during the recent relocation of the main Addis Ababa – Djibouti highway.

Furthermore, since Metehara town is situated close to and along the expansion direction of the Lake, its expansion is mostly possibly towards the north where most of the blisters and blister caves are found, leading to their destruction due to construction related excavations and eventual covering by man-made features. It could be concluded that distance to Lake Beseka is the number one triggering factor for the susceptibility of the blisters and blister caves, because its expansion does not only directly threaten the blisters and blister caves but it also determines the effect of three other triggering factors (distance from roads, railways and settlement).

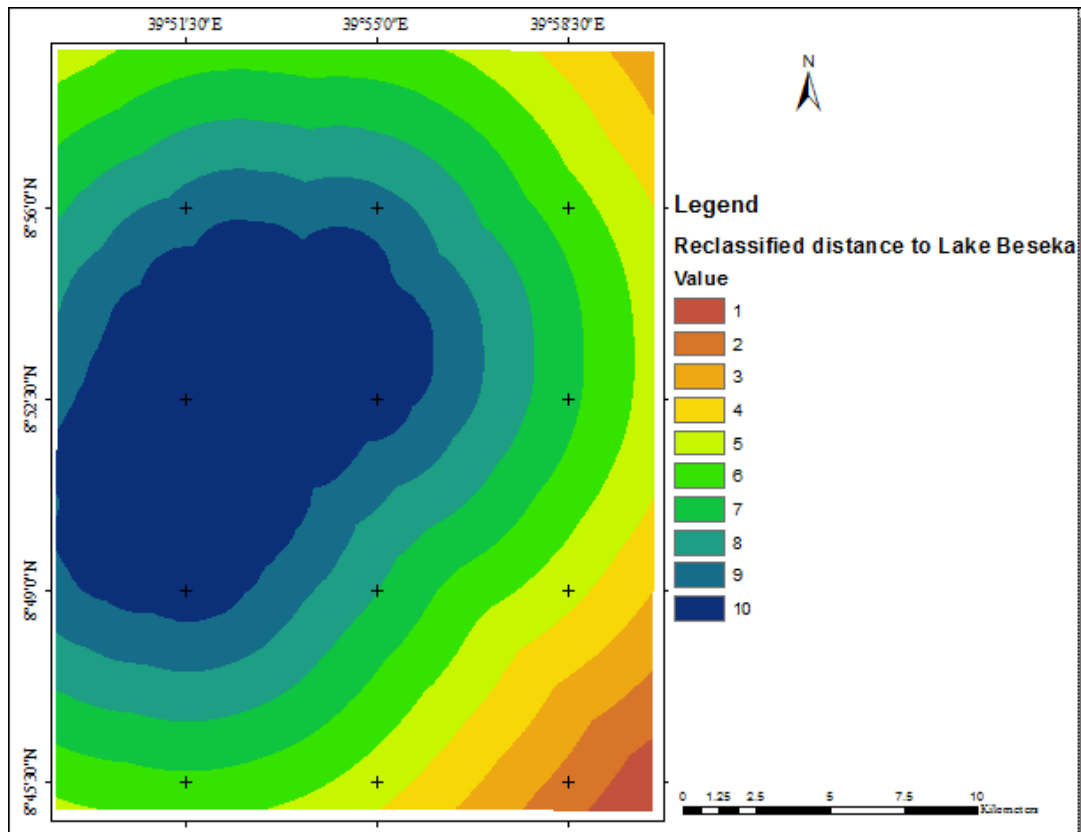


Fig. 6.7. Reclassified distance to Lake Beseka map of the study area.

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Table 6.4. Frequency ratio of reclassified distance to Lake Beseka.

Old value/class (m)	Reclassified value/class	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
0 - 1,682.5	10	9586866.8	49.4	117744375.7	23	2.2
1,682.5 - 3,364.9	9	9487607.1	48.9	65586363.0	12.8	3.8
3,364.9 - 5,047.5	8	328155.1	1.7	70621853.8	13.8	0.1
5,047.5 - 6,729.9	7	0	0	78376070.1	15.3	0
6,729.9 - 8,412.4	6	0	0	77681790.7	15.2	0
8,412.4 - 10,094.9	5	0	0	48026519.5	9.4	0
10,094.9 - 11,777.4	4	0	0	27938231.7	5.5	0
11,777.4 - 13,459.9	3	0	0	15505756.5	3.0	0
13,459.9 - 15,142.4	2	0	0	8251459.3	1.6	0
15,142.4 - 16,824.8	1	0	0	2923779.7	0.6	0

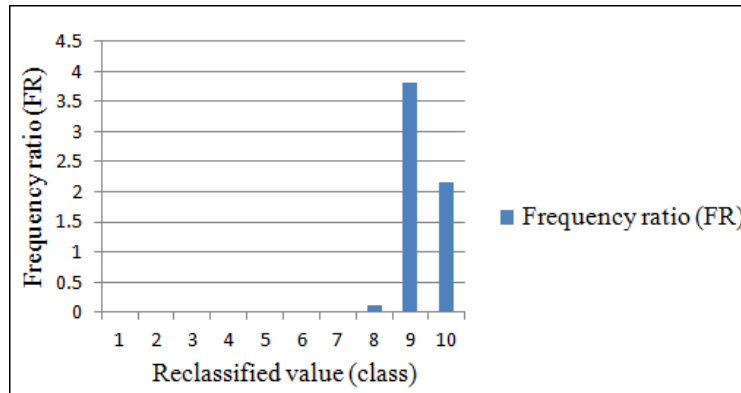


Fig. 6.8. Reclassified distance to Lake Beseka frequency ratio model.

6.2.5. Distance to irrigation fields

Metehara Sugar Estate Plantation (MSEP) and Abadir Farm are the main irrigation lands in the study area. Abadir Farm is smaller than MSEP in area coverage and it is found directly south of Beseka Lake and west of MSEP while MSEP is found southeast of the Lake. Both irrigation fields are situated south of the blisters and blister caves. A single shape file for distance to irrigation fields was created by first digitizing these two irrigation fields on screen from the Google Earth 2014 as a polygon feature classes and saved as a KML files in the current workspace, and then the KML files were converted to layer files using KML to Layer conversion tool from the Arc Toolbox window in order to maintain the symbology found within the original KML file. The individual irrigation layer file was exported to a new polygon feature class. Lastly, both irrigation fields' (Abadir Farm and Metehara Sugar Estate Plantation) polygon feature classes were merged using "Merge" geoprocessing tool. This merged polygon feature is used as an input feature class in distance to irrigations mapping process.

After mapping the distance to irrigations map in Arc Map 10.3, the map was reclassified (Fig. 6.9) with 10 classes ranging from 1 to 10 integer values at equal interval. The higher the value the higher the impact on the blisters and blister caves. Within distances between 11,764.2m and 16,806m and up to 1,680.6m from the irrigation fields, endangered blisters and blister caves are absent (Table 6.5). About 99.8% of the area of affected blisters and blister caves falls in between 4th to 8th from the irrigations reclassified classes having a high frequency ratio values with a high impact on them.

But the highest frequency ratio (Fig. 6.10) is obtained from 5,041.8m to 6,722.4m distance (in the 7th distance to irrigations reclassified class) from the irrigation fields, and it indicates that 30% of the endangered blisters and blister caves in the study area are threatened at a very high rate. Thus, irrigations could be important factors for the susceptibility of the caves because Beseka Lake level rise and expansion is also related to the expansion of the irrigation activities.

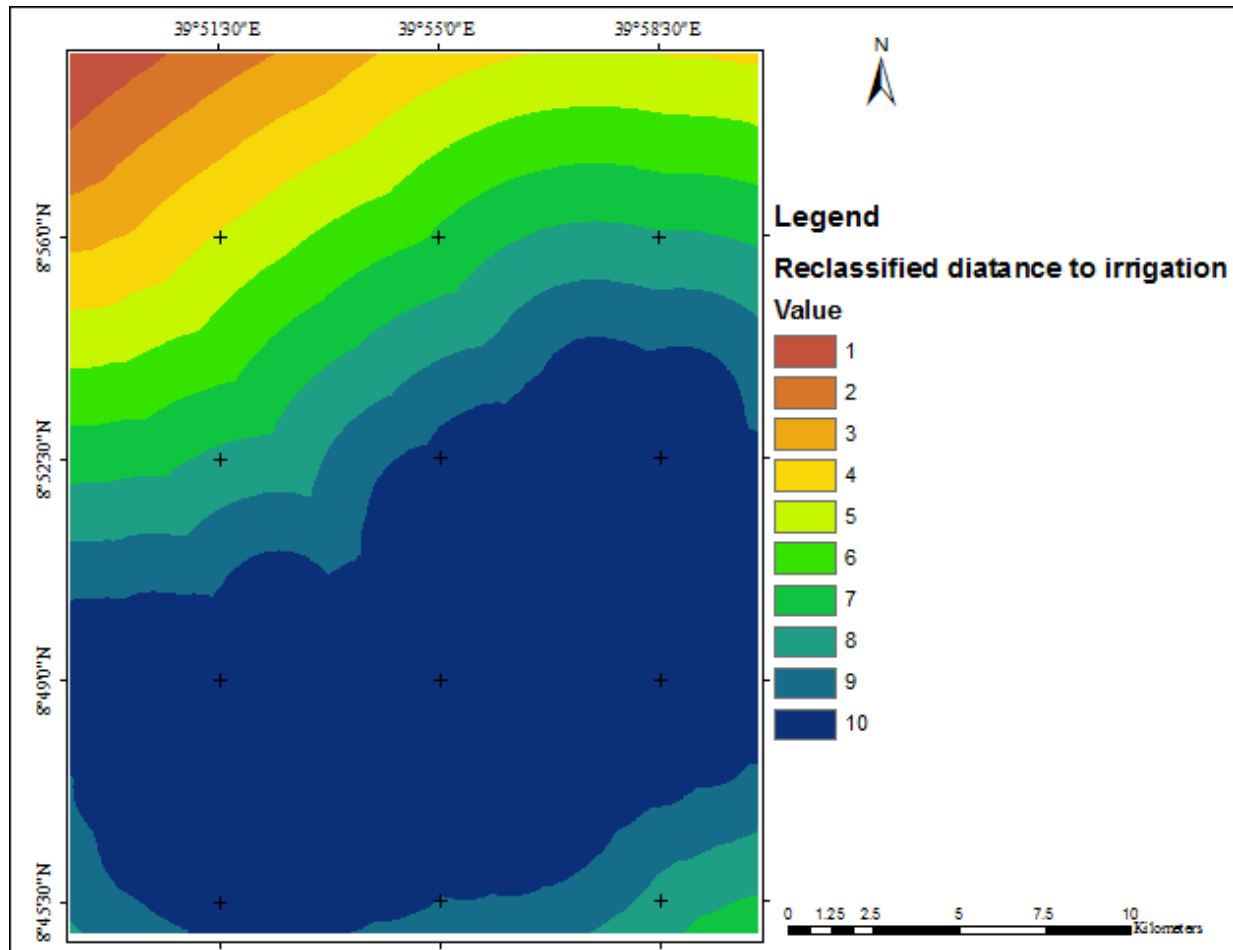


Fig. 6.9. Reclassified distance to irrigations map of the study area.

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Table 6.5. Frequency ratio of reclassified distance to irrigations.

Old values /classes (m)	Reclassified values/classes	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
0 - 1,680.6	10	0	0	240386378.3	46.9	0
1,680.6 - 3,361.2	9	50755.6	0.3	62700459.1	12.2	0
3,361.2 - 5,041.8	8	2522061.1	13	45538547.2	8.9	1.5
5,041.8 - 6,722.4	7	5801795.8	30	39391698.9	7.7	3.9
6,722.4 - 8,403.0	6	3595473.9	18.5	37606794.1	7.3	2.5
8,403.0 - 10,083.6	5	5100589.2	26.3	37134274.4	7.2	3.6
10,083.6 - 11,764.2	4	2331953.3	12.0	22313658.8	4.4	2.8
11,764.2 - 13,444.8	3	0	0	15343719.3	3.0	0
13,444.8 - 15,125.4	2	0	0	9168367.1	1.8	0
15,125.4 - 16,806.0	1	0	0	3072302.8	0.6	0

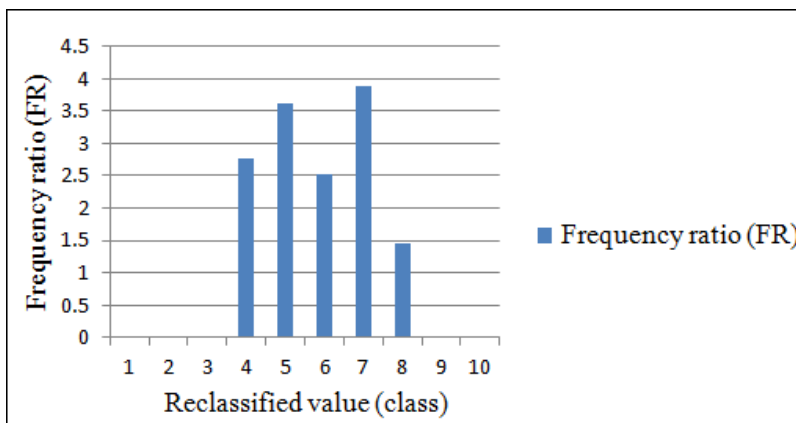


Fig. 6.10. Reclassified distance to irrigations frequency ratio model.

6.2.6. Distance to railways

One old and one new railway lines connecting Addis Ababa to Djibouti cross the study area. The old railway, which has been partly submerged under the Lake since 2002 is not functional, while the new railway line currently under construction is located very close to the northern shoreline of the Lake. The old railway line was digitized as a poly-line in Arc Map 10.3 from the 1975 Topographic Map of Metehara Sheet at 1:50,000 scale, The new railway line was digitized from the Google Earth 2014 as a poly-line feature and saved as KML file. The KML file is converted to layer file using KML to Layer conversion tool and then the layer file again converted to shape file using Layer to Shape file conversion tool in the Arc Toolbox window. From the geoprocessing tool using Merge tool the old and new railways were merged and saved as a new shape file, which is used for further analysis. Then, using this new railways shape as an input feature class the distance to railways was mapped and this map was reclassified (Fig. 6.11) with integer reclassified classes ranging from 1 to 10 at equal intervals (Table 6.6 and Fig. 6.12).

Generally, distance from the railways increases with decreasing area of affected blisters and blister caves. All the 119 threatened blisters and blister caves in this distance to railways triggering factor of susceptibility are found up to 3,443.8m distance from the railways and all are threatened at a high to very high rate (Fig. 6.12). About 85.6% of the area of these endangered features is threatened at a very high rate.

Each reclassified distance to railways class from 8 to 1 (Table 6.6), above 3,443.8m distance from railways, has a zero frequency ratio value because there is no blister and/or blister cave in these classes and all the threatened features are classified under a high to very high rate of devastation. Thus, distance to railways, similar to distance to roads is another main triggering factor for the susceptibility of the blisters and blister caves.

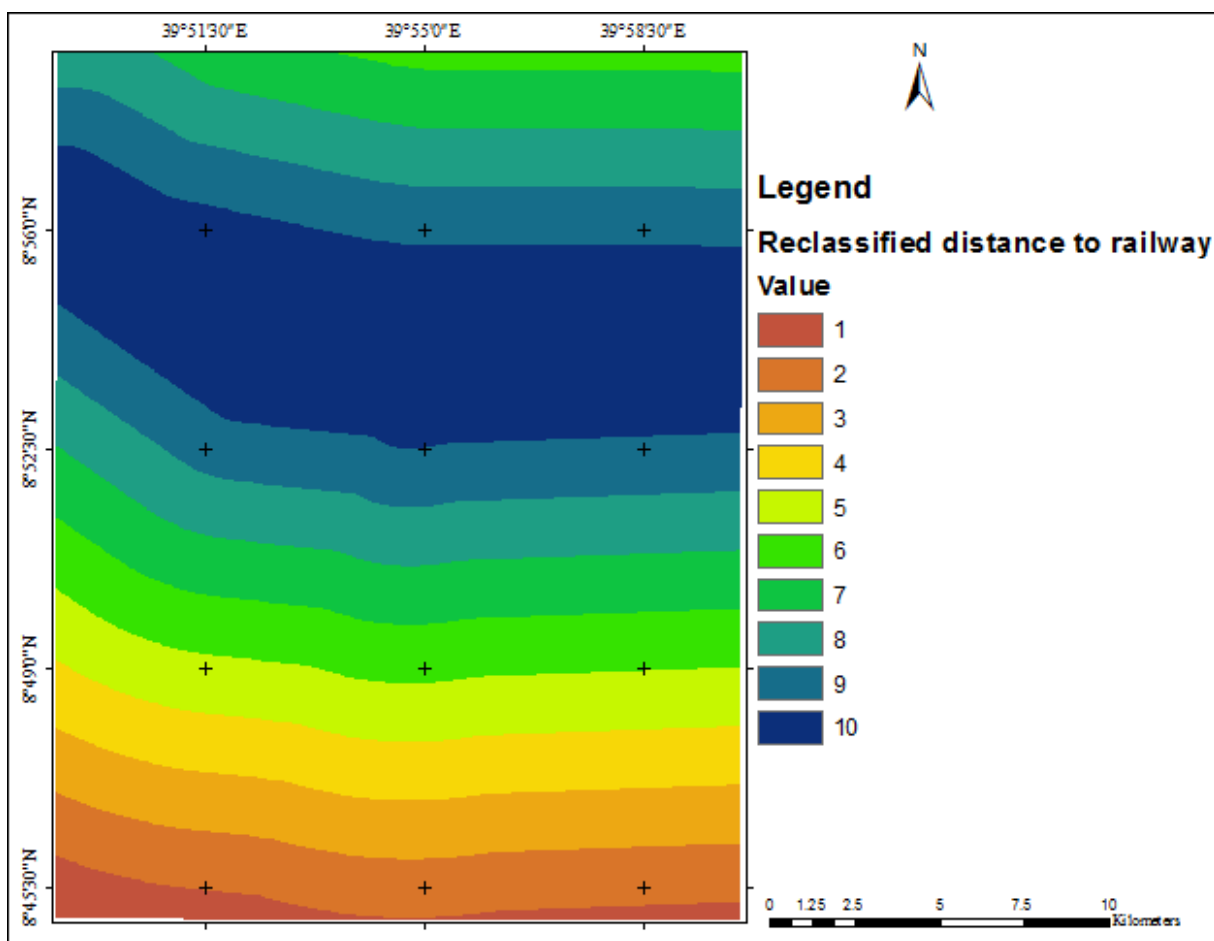


Fig. 6.11. Reclassified distance to railways map of the study area.

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Table 6.6. Frequency ratio of reclassified distance to railways.

Old values /classes (m)	Reclassified values/classes	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
0 - 1,721.9	10	16613631.3	85.6	113893322.1	22.2	3.9
1,721.9 - 3,443.8	9	2788997.7	14.4	71560528.9	14	1.0
3,443.8 - 5,165.8	8	0	0	70724270.5	13.8	0
5,165.8 - 6,887.7	7	0	0	62773921.4	12.2	0
6,887.7 - 8,609.6	6	0	0	42480102.5	8.3	0
6,887.7 - 8,609.6	5	0	0	35356813.6	6.9	0
10,331.5 - 12,053.4	4	0	0	35037775.9	6.8	0
12,053.4 - 13,775.4	3	0	0	34958201.2	6.8	0
13,775.4 - 15,497.3	2	0	0	34853553.6	6.8	0
15,497.3 - 17,219.2	1	0	0	11017710.3	2.2	0

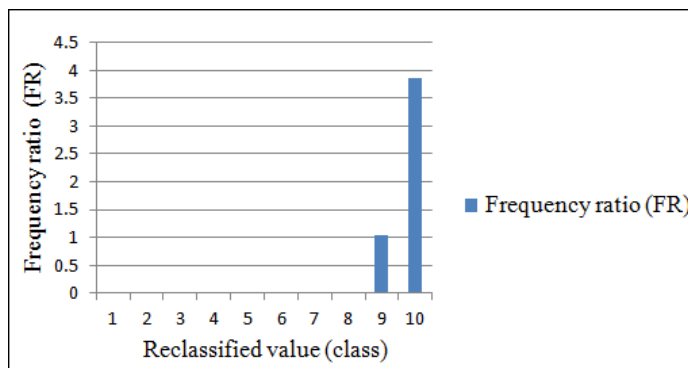


Fig. 6.12. Reclassified distance to railways frequency ratio model.

6.2.7. Distance to settlement

The two towns namely Metehara and Addis Ketema, and the Metehara Sugar Factory are considered as settlement features. Addis Ketema town is situated between Metehara town to the north and the Sugar Factory to the south, and all are found northeast of Beseka Lake. The two towns were digitized on screen from the 2014 version Google Earth as polygon features and saved as KML files in the current workspace. The KML files were imported to Arc Map 10.3 version and they were converted to layer files using KML to Layer conversion tool. Then both layer files were converted to shape files. The Sugar Factory was digitized as a polygon from the 1975 topographic map of Metehara sheet at 1:50,000 scale in Arc Map 10.3 and it was exported to a new shape file for further analysis. In order to do the distance to settlements analysis, first, all the three polygon features (Metehara, Addis Ketema and Metehara Sugar Factory polygon features) were merged. Then using this merged polygon feature as an input feature class the distance to settlements map was produced. Finally the distance to settlements raster image was reclassified (Fig. 6.13) with a reversed 1 to 10 integer values at equal intervals. The higher value (10) indicates a high probability to threaten the blisters and blister caves by the settlement.

Generally as indicated in Table 6.7 and Fig. 6.14, as distance from the settlement increases, the probability of susceptibility of the blisters and blister caves to destruction by settlement decreases. The endangered blisters and blister caves are found within 8,423.6m distance from the settlements. Frequency ratios of distance to settlements are higher in distances lower than 2,807.9m and between 4,211.8m and 7,019.6m distances from settlements. Farther than

8,423.6m distance from settlements, the frequency ratio values are zero since there is no a blister and /or blister cave in these regions.

About 91.2% of the area of endangered blisters and blister caves is threatened at a higher rate. This is because most of the 119 endangered blisters and blister caves are found very close to Metehara town and along its expansion, while some are already located within the town perimeters.

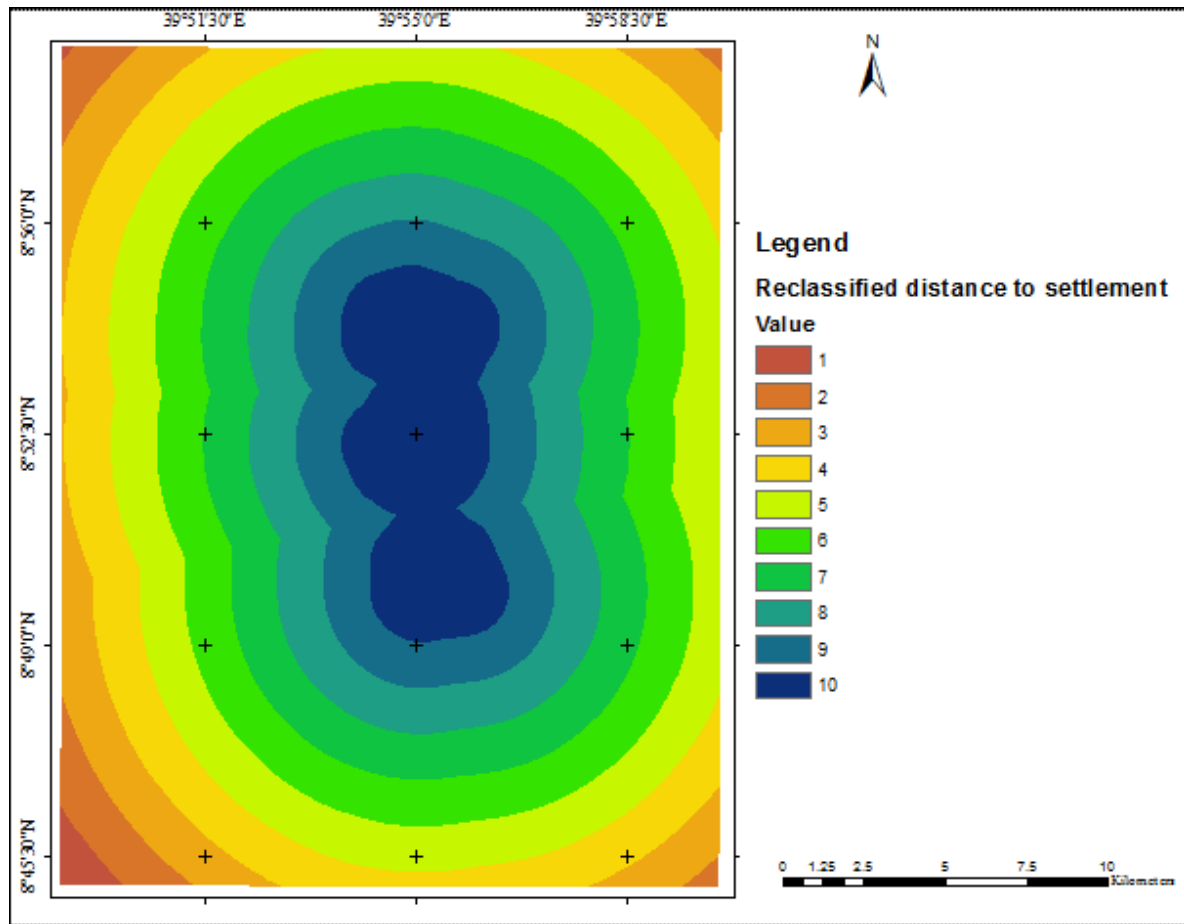


Fig. 6.13. Reclassified distance to settlement map of the study area.

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Table 6.7. Frequency ratio of reclassified distance to settlement.

Old values /classes (m)	Reclassified values/ classes	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
0 - 1,403.9	10	3822940.7	19.7	43399322.4	8.5	2.3
1,403.9 - 2,807.9	9	4751258.4	24.5	49190384.0	9.6	2.6
2,807.9 - 4,211.8	8	878920.4	4.5	60063791.9	11.7	0.4
4,211.8 - 5,615.7	7	5113058.9	26.4	72088178.4	14.1	1.9
5,615.7 - 7,019.6	6	4000161.7	20.6	84237268.0	16.4	1.3
7,019.6 - 8,423.6	5	836288.8	4.3	91682908.5	17.9	0.2
8,423.6 - 9,827.5	4	0	0	65536469.7	12.8	0
9,827.5 - 11,231.4	3	0	0	33346835.0	6.5	0
11,231.4 - 12,635.3	2	0	0	10868748.7	2.1	0
12,635.3 - 14,039.3	1	0	0	2242293.4	0.4	0

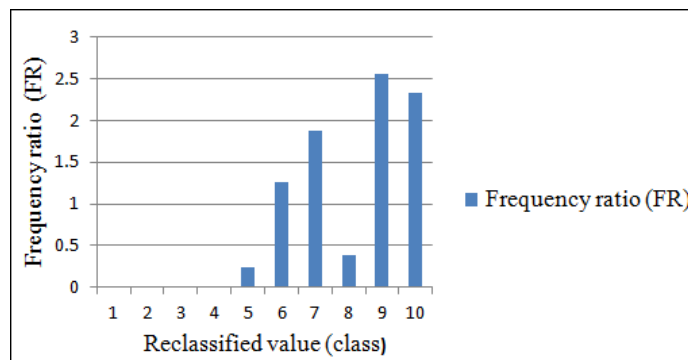


Fig. 6.14. Reclassified distance to settlement frequency ratio model.

6.2.8. Lithology

Eleven volcanic rock units, as well as an alluvial and a lacustrine unit are exposed in the study area. The lithological units were outlined from the 1978 Geological Map of Nazareth Sheet at 1: 250, 000 scale through on screen digitizing in Arc MAP 10.3 and through intensive field checking. An auto complete polygon tool, an essential construction tool, which creates a common boundary between features has been used to create lithological and sediment features.. Then, all the lithological and sediment feature data layers were exported to geo-database feature classes. These polygon features were converted to raster using polygon to raster conversion tool accessed from Arc Toolbox window. In the conversion, the value field was the name of lithology and sediments from the input feature dataset's attribute table. The converted raster dataset was exported to TIFF format, and then using the common map layout properties lithological factor map was created.

The lithological factor image was reclassified (Fig. 6.15) using "Reclass" spatial analyst tool in Arc Toolbox window. It was reclassified reversely with "Value" reclassified field. The values are integers ranging from 1-13. The highest value is given to young ignimbrites of Fentale (Table 6.8), which is the most prevalent unit on which most of the blister caves have developed. On the contrary, lowest value is given to alluvial sediments with low priority. Thus, the highest value for lithology corresponds to the affected blistered region.

According to Gibson (1974) the blisters are features of the tuff itself. In the study area, most of the threatened or affected blistered area is observed in the young ignimbrites of Fentale (QWi₂). This rock unit covers about 89.5% of the affected blistered region. However, recent Aphyric

basalts (QWb₃) and Pantelleritic volcanics of Fentale rhyolites, trachytes, tuffs and agglomerates (QWPo) covers 10.5% and 0.01% of the affected blistered area, respectively (Table 6.8). This is because of the following reasons: (i) since the recent aphyric basalts are younger than the Fentale young ignimbrites, these basalt flows cover some parts of the blistered area; (ii) even if the tuff in the Pantelleritic volcanics of Fentale rhyolites, trachytes, tuffs and agglomerates is unwelded tuff, sometimes it can form a blister since these rocks are exposed at the contact with the young ignimbrites of Fentale. With respect to this triggering factor of susceptibility of blisters and blister caves, high rate of frequency ratio is observed in recent aphyric basalts (Table 6.8 and Fig. 6.16). In other words, the recent aphyric basalts could be potentially disastrous to the blisters and blister caves if they were to erupt in the same region in the future. The frequency ratio values are higher in the recent aphyric basalts and young ignimbrites of Fentale. But the highest frequency ratio value is obtained in the recent aphyric basalts even if the area of the endangered blisters and blister caves is 10.5%. Therefore, recent aphyric basalt flow has a great impact on the blisters and blister caves.

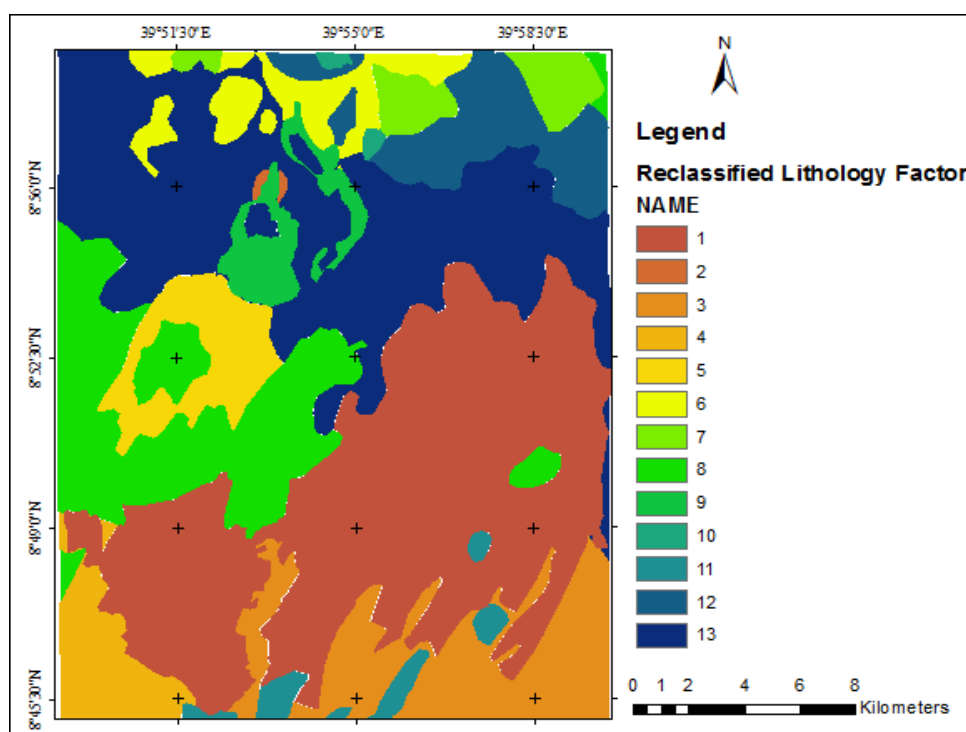


Fig. 6.15. Reclassified lithological map of the study area.

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Table 6.8. Reclassified lithology frequency ratio.

Lithology	Reclassified Lithology	Reclassified value/class	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
QWi ₂	Alluvium	1	0	0	160159745.5	31.9	0
QWt	QWh	2	0	0	659554.2	0.1	0
QWr	N ₂ Qb	3	0	0	43637552.54	8.7	0
QWo	QWi	4	0	0	17033053.5	3.4	0
QWb ₃	LS	5	0	0	20153734.9	4.0	0
QWb ₁	QWPo	6	2666.5	0.01	18439760.6	3.7	0.003
QWp	QWp	7	0	0	13191272.4	2.6	0
QWPo	QWb ₁	8	0	0	63042927.2	12.6	0
LS	QWb ₃	9	2042987.4	10.5	12951491.8	2.6	4.1
QWi	QWo	10	0	0	1348046.6	0.3	0
N ₂ Qb	QWr	11	0	0	7764982.9	1.6	0
QWh	QWt	12	0	0	27751812.7	5.5	0
Alluvium	QWi ₂	13	17356975.1	89.5	114732575.9	22.9	3.9

Where;

QWi - Dino ignimbrites

QWb₁ - Pleistocene sub-recent basalts

QWb₃ - Recent aphyric basalts

QWi₂ - Young ignimbrites of Fentale

QWo - Recent pantelleritic and comenditic obsidian flows and domes

QWp - Pitchstone flows and domes

QWPo - Pantelleritic volcanics of Fentale rhyolites, trachytes, tuffs and agglomerates

QWr - Recent to sub recent dome sand flows

QWt - Trachyte flows and domes

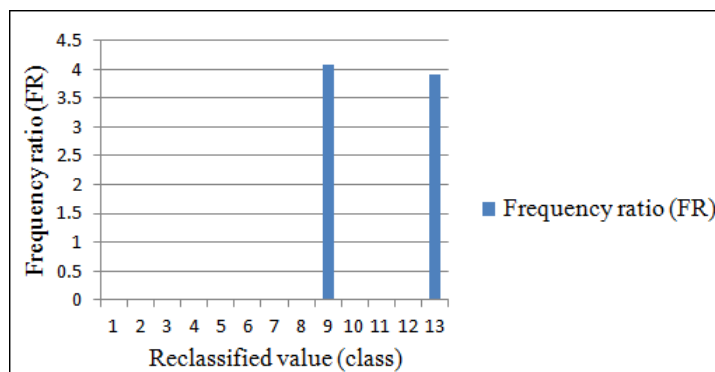


Fig. 6.16. Reclassified lithology frequency ratio model.

6.2.9. Elevation

Digital Elevation Mode (DEM) is a surface representation derived from irregularly spaced sample points and break line features (Dagnachew and Esayiyas, 2008). DEM of the study area is downloaded from USGS Earth explorer with a spatial resolution (cell size) of 30m x 30m. DEM of the study area with a spatial resolution (cell size) of 30m x 30m was downloaded from USGS Earth explorer. In the study area, the highest elevation is 1,919.1m at the Fentale Mount while the lowest elevation is 944.7m at the Lake Beseka. DEM raster dataset having stretched values in meter along a color map was reclassified into a new and reversed integer values ranging from 1 to 9 at equal intervals. The reclassified elevation map of the study area (Fig. 6.17) and Table 6.9 indicate that the lower elevations are observed in the Lake Beseka and surrounding settlements (Metehara and Addis Ketema towns and Metehara Sugar Factory).

All the affected blisters and blister caves are found between 944.7m and 1,082.3m elevations (Table 6.9). The frequency ratio value is higher only in elevations between 975.3m to 1,021.1m. In this range of elevation about 49.4% of the area of affected blisters and blister caves is threatened at a higher rate. Generally, the impact of elevation on these threatened blisters and blister caves is higher at lower elevations, because almost all of the most triggering factors (Lake Beseka, roads, railways, settlements, lithology, lineaments and irrigations) for the susceptibility of these features are found at lower elevations.

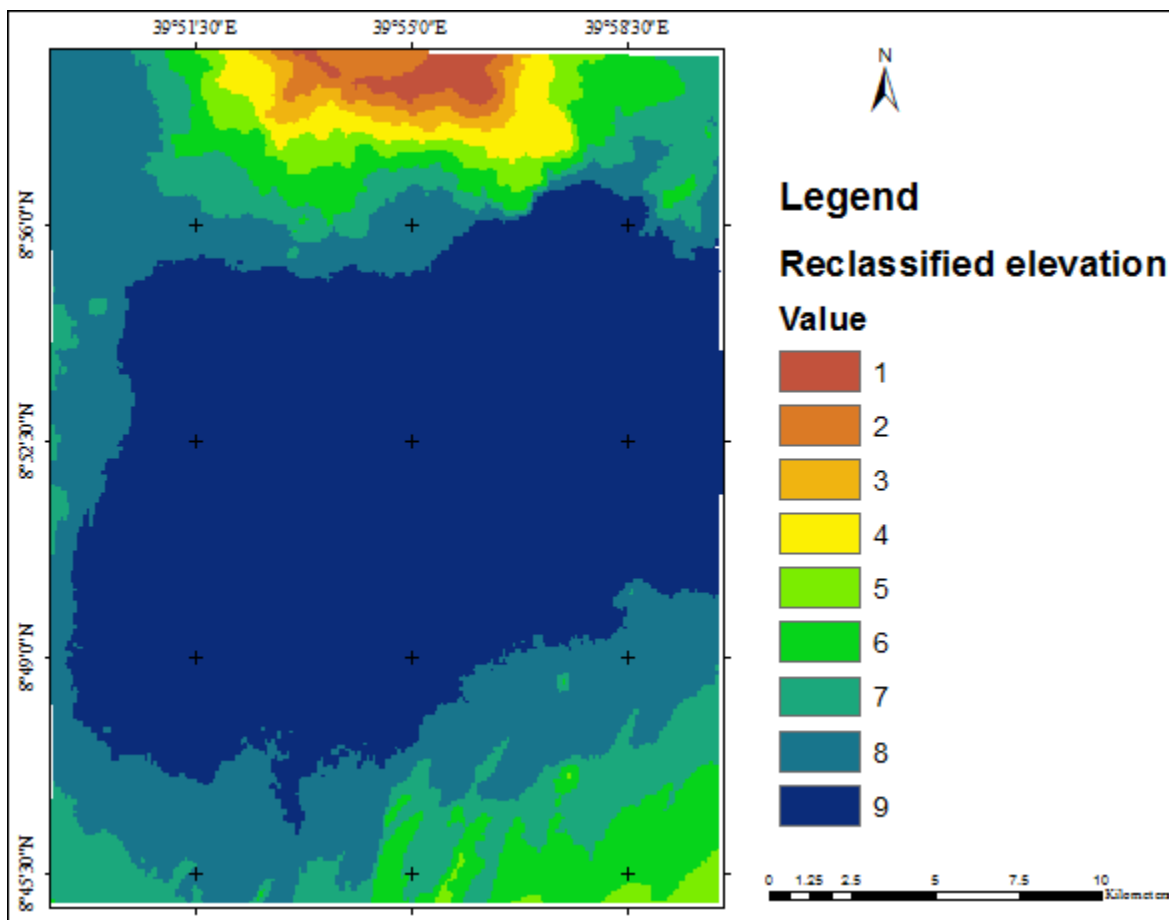


Fig. 6.17. Reclassified elevation (DEM) map of the study area.

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Table 6.9. Reclassified elevation frequency ratio.

Old values /classes (m)	Reclassified values/ classes	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
944.7 - 975.3	9	7927114.9	40.9	251485278.6	50.0	0.8
975.3 - 1,021.1	8	9576862.7	49.4	121014009.6	24.0	2.1
1,021.1 - 1,082.3	7	1898651.4	9.8	55125350.9	11.0	0.9
1,082.3 - 1,177.8	6	0	0	37718717.4	7.5	0
1,177.8 - 1,303.9	5	0	0	12272688.8	2.4	0
1,303.9 - 1,449.1	4	0	0	10404212.3	2.1	0
1,449.1 - 1,594.3	3	0	0	4943487.7	1.0	0
1,594.3 - 1,728.0	2	0	0	6209100.0	1.2	0
1,728.0 - 1,919.1	1	0	0	4113900.0	0.8	0

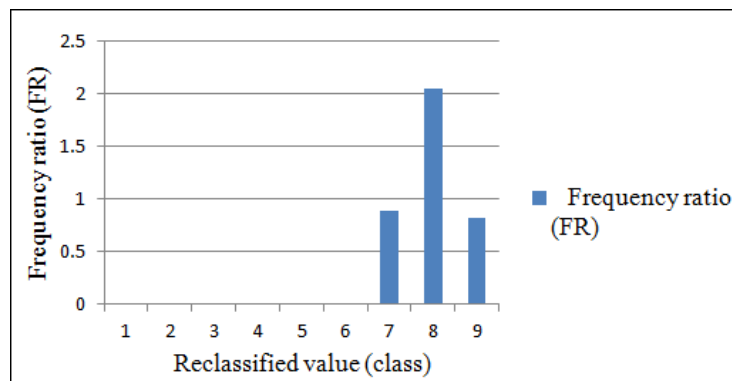


Fig. 6.18. Reclassified elevation frequency ratio model.

6.2.10. Slope aspect

Slope aspect of the study area was constructed from DEM of the study area at 30m x 30m spatial resolution using "Aspect" surface spatial analyst tool from Arc Toolbox widow in Arc Map 10.3. The slope aspect raster classified values are in degrees and this raster dataset was reclassified to a new and reversed integer values ranging from 1 to 10 at equal intervals for further analysis. Using this reclassified dataset the reclassified slope aspect map of the study area (Fig. 6.19) was produced. As can be seen from Table 6.10, all the affected blisters and blister caves fall in all slope aspect ranges. However, the higher frequency ratio values are obtained between 67.5° and 247.5° in the east, southeast, south and southwest of the affected blisters and blister caves. Among those high frequency values, the highest value is to the south of the blistered region from 157.5° to 202.5°, that is along the roads and railways and at the northern part of the Lake, settlements and the recent aphyric basalts. Thus, the blisters and blister caves are threatened strongly in this part of the study area by the roads, railways, the Lake, settlements and recent basalts. Slope aspect can therefore be considered as an important triggering factor because those blisters and blister caves located at a slope facing the northern and northeaster shore of the Beseka Lake are susceptible to the inundation of the lake.

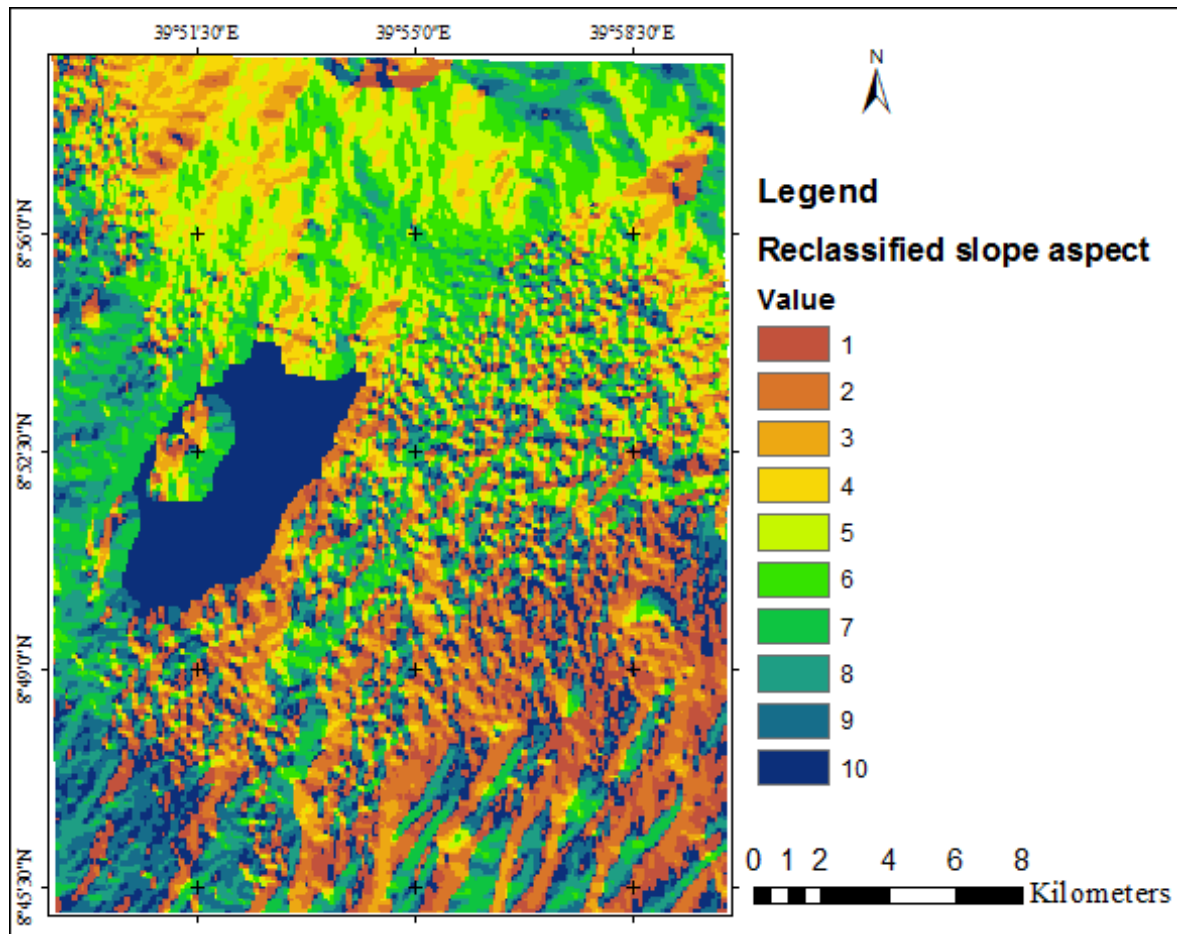


Fig. 6.19. Reclassified slope aspect map of the study area.

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Table 6.10. Reclassified slope aspect frequency ratio.

Old values /classes (degree)	Reclassified values/ classes	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
Flat (-1)	10	59340.4	0.3	62024400	12.3	0
North (0- 22.5)	9	140113.5	0.7	49327200	9.8	0.1
Northeast (22.5-67.5)	8	423287.1	2.2	50246100	10.0	0.2
East (67.5- 112.5)	7	2476277.2	12.8	551654100	10.9	1.2
Southeast (112.5- 157.5)	6	5649980.8	29.1	51355800	10.2	2.9
South (157.5- 202.5)	5	6177303.7	31.8	46936800	9.3	3.4
Southwest (202.5- 247.5)	4	3086480.7	15.9	40625100	8.1	2.0
West (247.5- 292.5)	3	1015916.5	5.2	41928300	8.3	0.6
Northwest (292.5- 337.5)	2	311582.9	1.6	548540100	10.9	0.2
North (337.5-360)	1	62346.1	0.32	52007400	10.3	0

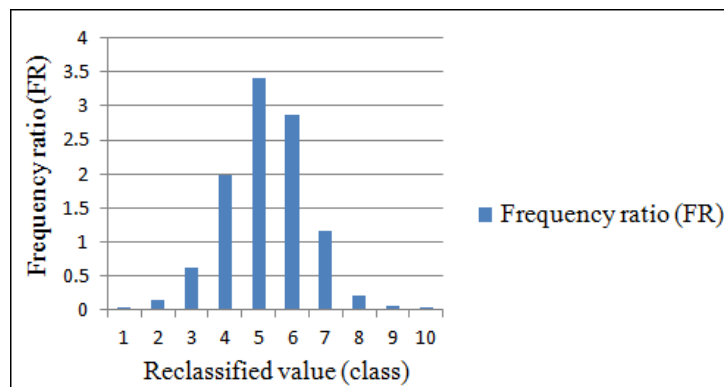


Fig. 6.20. Reclassified slope aspect frequency ratio model.

6.2.11. Slope

Slope of the study area was also constructed from DEM of the study area using "Slope" surface spatial analyst tool from Arc Toolbox window in Arc Map 10.3. Then, slope raster dataset with class values in degrees was reclassified to a new and reversed integer values ranging from 10 to 1 at equal intervals. The endangered blisters and blister caves are found within 2.1° in the study area. However, the higher frequency ratio is obtained in the 9th reclassified class, 0.4° to 1.1° (Table 6.11 and Fig. 6.22). About 39.4% of the affected features are threatened at a high rate. Slightly sloping to non-sloping areas are susceptible to inundation by the Lake, hence directly affecting the susceptibility of the blister caves.

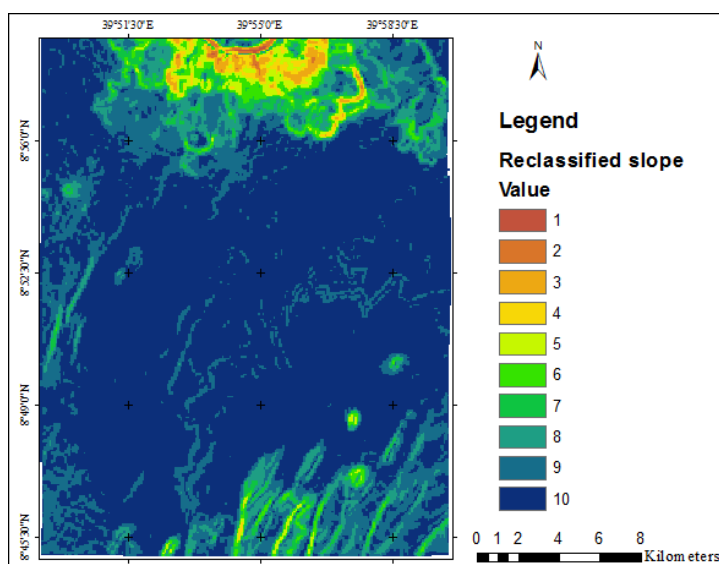


Fig. 6.21. Reclassified slope map of the study area.

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Table 6.11. Reclassified slope frequency ratio.

Old values /classes (degree)	Reclassified values/ classes	Affected grids (Sq. m)	Affected grids (%)	Grids in domain (Sq. m)	Grids (%)	Frequency ratio (FR)
0 - 0.4	10	11399609.7	58.8	325975500	64.6	0.9
0.4- 1.1	9	7636239.9	39.4	975851100	19.3	2.0
1.1 - 2.1	8	364644.1	1.9	36085500	7.2	0.3
2.1 - 3.3	7	2135.3	0	17356500	3.4	0
3.3 - 4.7	6	0	0	10818900	2.1	0
4.7 - 6.2	5	0	0	72440100	1.4	0
6.2 - 7.7	4	0	0	4542300	0.9	0
7.9 - 9.7	3	0	0	3739500	0.7	0
9.7 - 12.9	2	0	0	9260100	0.2	0
12.9 - 16.2	1	0	0	1970100	0.04	0

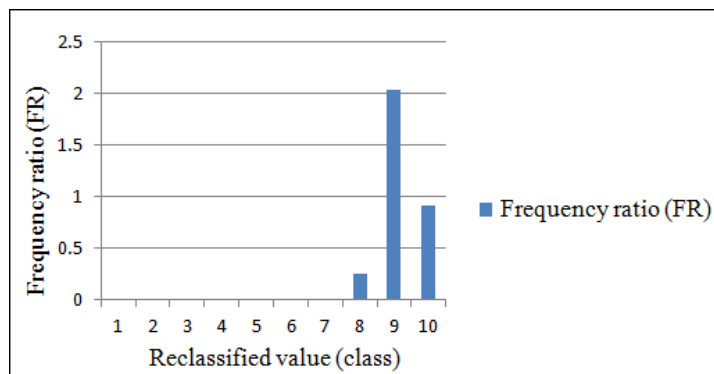


Fig. 6. 22. Reclassified slope frequency ratio model.

6.3. Cluster analysis and susceptibility mapping

6.3.1. Cluster analysis

For this study non - hierarchical (K - means) cluster analysis was applied which is used to group features based on feature attributes and optional spatial constraints. In order to do the analysis, first, the reclassified raster data sets of each triggering factor having the same: 30 m x 30 m cell size (x, y), WGS-1984-UTM-Zone-37N output coordinate system with processing extent the same as layer boundary of the study area must be converted to polygon feature. Then, frequency ratio (FR) field was added in to each polygon feature attribute table and all the frequency ratio values of each triggering factor polygon feature were added in FR field with the corresponding GRIDCODE. To group all the polygon features mapping clusters grouping analysis from the spatial statistical tools was used in the Arc Tool box window. In this grouping analysis the input feature was each polygon triggering feature and its analysis field value was FR. Each polygon feature was classified into five groups or classes using EUCLIDEAN distance method with K - Means - Nearest - Neighbors spatial constraint.

6.3.2. Susceptibility mapping

To map the susceptibility of the Fentale - Metehara blisters and blister caves, each grouped triggering factor polygon feature having FR field value should be converted to a raster with the same cell size using to raster conversion tool and FR as a field value. Then, all the raster datasets of triggering factors were imported to TIFF format for further analysis.

From the spatial analyst tools, map algebra raster calculator was used for mapping the susceptibility of blisters and blister caves in the study area. All the triggering factors' raster TIFF images with FR raster class values were summed using raster calculator analysis tool in order to produce the final susceptibility map of the study area. The susceptibility map has five classes with susceptibility values/indices (SI) at equal areal distribution. The susceptibility class values/indices (Fig. 6.23) are ranging from 0.9 to 31.72. The higher the susceptibility indices (SI), the more susceptible is corresponding combination of factors to destruction (Yilmaz, 2007). very low (SI = 0.9-7.1), low (SI = 7.1-13.2), moderate (SI = 13.2-19.4), high (SI = 19.4-25.6) and very high (SI = 25.6-31.72) susceptibilities.

The susceptibility map (Fig. 6. 23) mapped at 1: 130,000 scale, shows that all the affected blisters and blister caves have a high to very high degree of susceptibility.

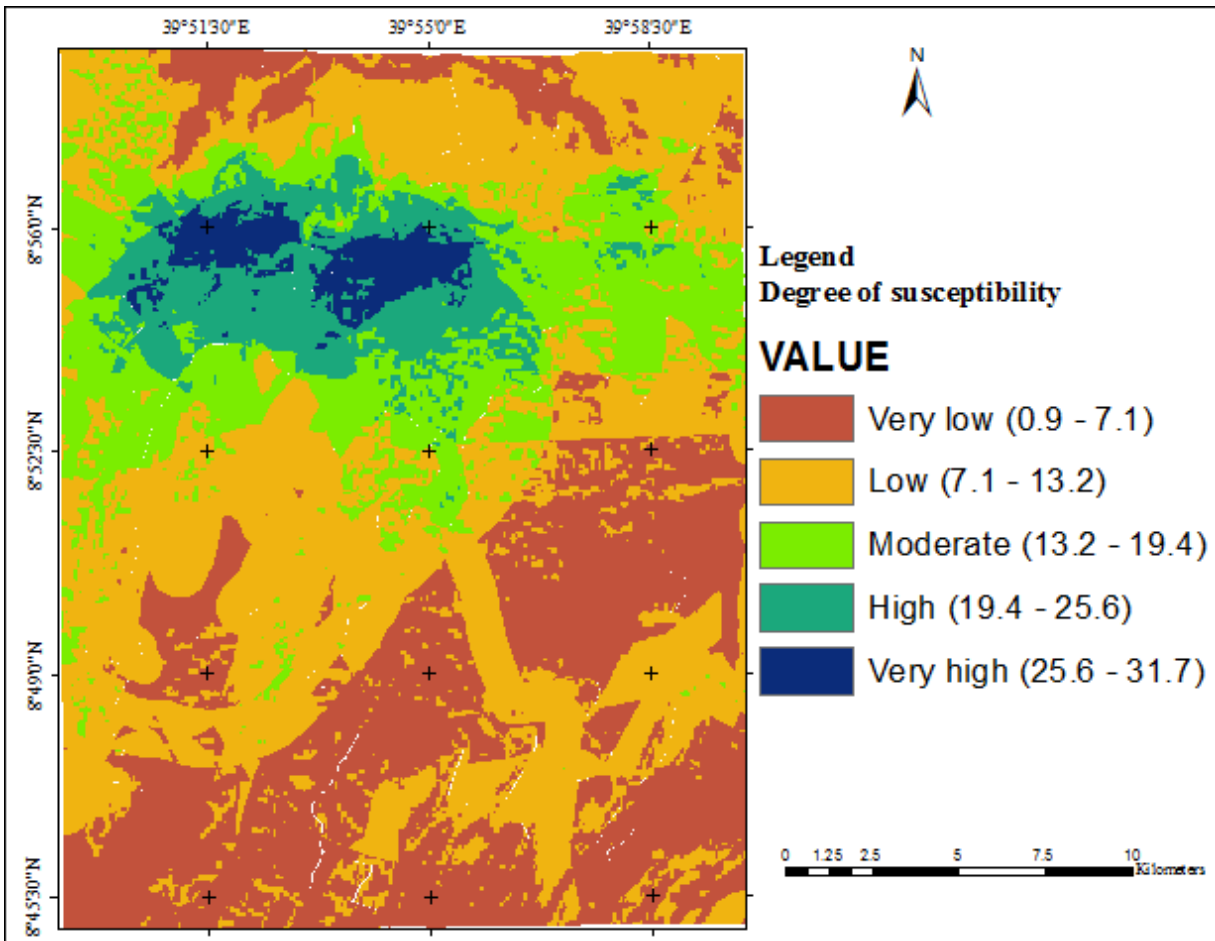


Fig. 6. 23. Susceptibility map of the study area.

6.3.2.1. Map Validation

According to Yilmaz (2007) susceptibility map of the area is validated by means of area of affected features corresponding to the susceptibility classes (very low to very high). In order to calculate the area of susceptibility classes, susceptibility raster image of the study area was reclassified (Fig. 6. 24) with new integer values (classes) ranging from one to five representing very low to very high susceptibility classes (degree of susceptibilities).

According to Irigaray (1995) as cited in Yilmaz (2007) validation of susceptibility map of the study area is determined by the degree of fitness (DF) using the following formula.

$$DF = (Bi/Si)/\sum(Bi/Si)$$

where

Bi = Area of affected terrain (in this case the blister fields) in the i class of susceptibility

Si = Area of the i class of susceptibility

The reclassified susceptibility raster image was converted to polygon in order to calculate the area of susceptibility classes and to clip the area of affected blister fields using *clip geoprocessing tool* same as layer affected blister fields processing extent. The area of all the susceptibility classes of the study area and the affected blister fields was calculated using *calculate geometry* in the polygon attribute table. It can be seen from Figs. 6.25 and 26 and Table 6.12, the area of all the 119 affected blisters and blister caves is threatened at a high to very high rate, at about 99.75%. Only 0.25% of the area of these features is threatened at moderate rate. There is no affected blister and/or a blister cave, which is susceptible at a low and/or very low rate. Furthermore, the reclassified susceptibility map of the area of affected blister fields with the overlaid 119 affected and 520 non affected blisters and blister caves (Fig. 6.25) shows that most of the relatively non affected blisters and blister caves in the study area are also threatened at a very high and high rate of susceptibility. Thus the degree of fitness for the affected blister fields' degree of susceptibility/susceptibility classes (Table 6.12), the area of affected blister fields with the corresponding susceptibility classes (Fig. 6. 26), degree of fitness of the susceptibility classes (Fig. 6.27) and the reclassified susceptibility map of the area of affected blister fields with the overlaid 119 affected and 520 non affected blisters and blister caves (Fig. 6.25), clearly illustrate the susceptibility map of the study area is validated as a high quality. Therefore there must be a special protection mechanism for these affected and non-affected spectacular blisters and blister caves because these features are very unique geo-heritages and their protection is crucial as they can contribute to the country's economy through geo-tourism.

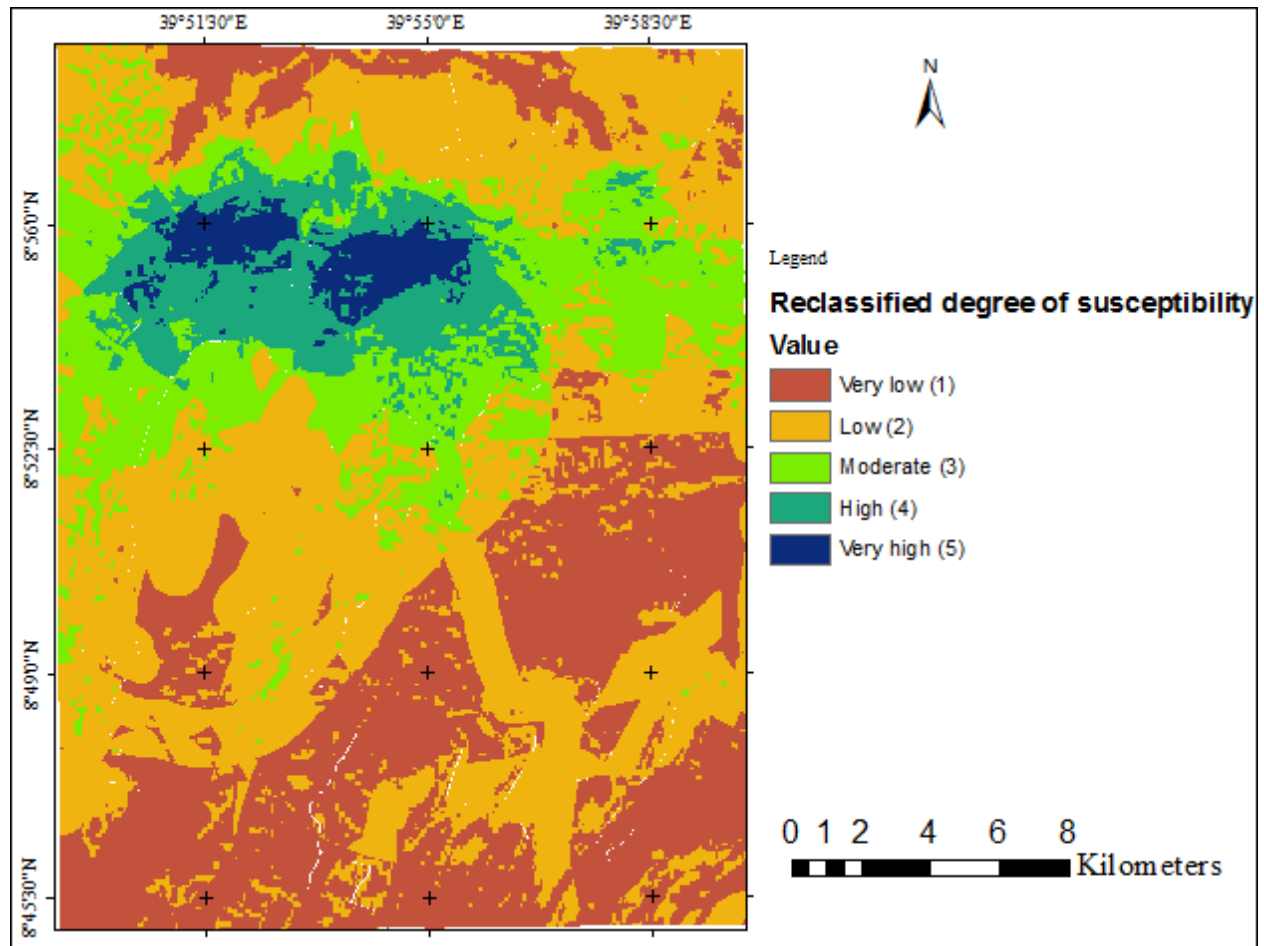


Fig. 6. 24. Reclassified susceptibility map of the study area.

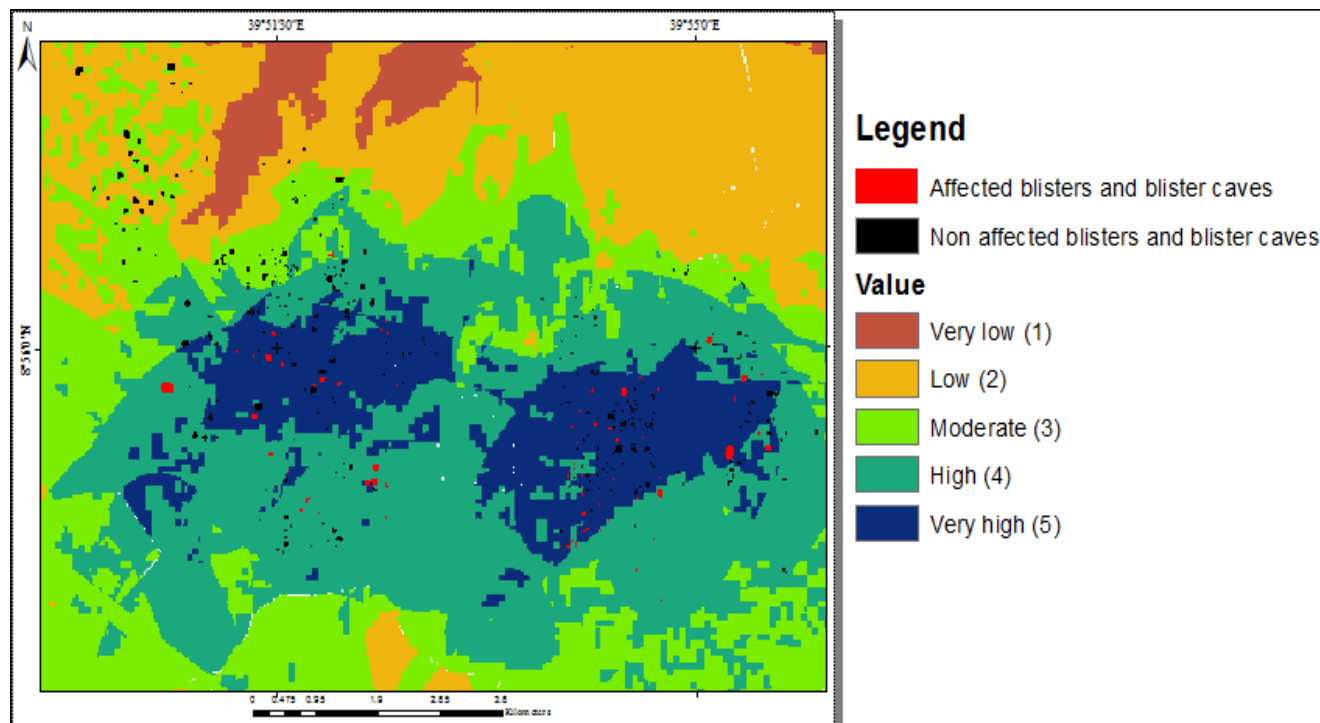


Fig. 6.25. Reclassified susceptibility map of the area of affected blister fields with the overlaid 119 affected and 520 non affected blisters and blister caves at 1: 45,000 scale.

Table 6.12. Degree of fitness for the affected blister fields degree of susceptibility.

Degree of susceptibility	Area of affected blister fields (Bi) (Sq. m)	Affected area in domain (Si) (Sq. m)	Bi/Si	Degree of fitness (DF) = (Bi/Si)/ Σ (Bi/Si)	Degree of fitness (DF) (%)
Very low	0	153645552.5	0	0	0
Low	0	206545067.8	0	0	0
Moderate	199536.0	84089142.52	0.0024	0.0025	0.25
High	9260711.6	41394162.9	0.2237	0.238	23.8
Very high	9941765.1	13945099.7	0.7129	0.759	75.9

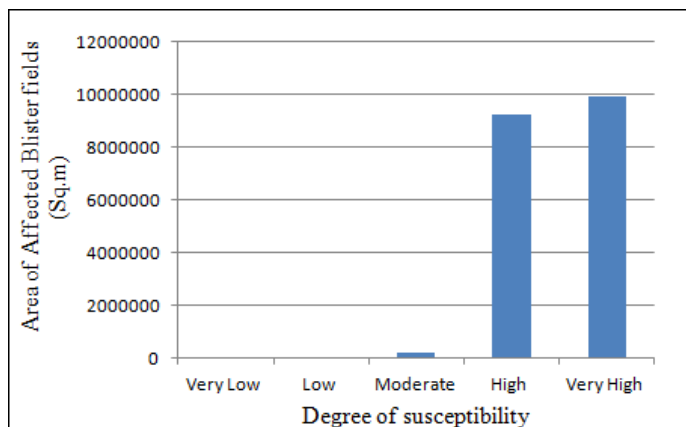


Fig. 6.26. Area of affected blister fields with the corresponding susceptibility classes.

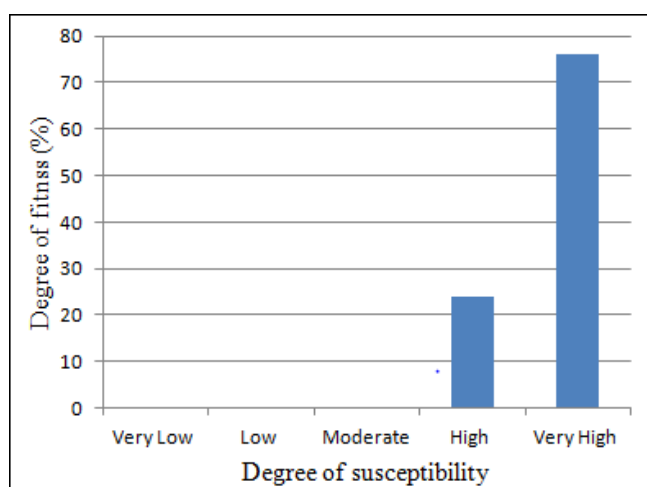


Fig. 6. 27. Degree of fitness of the susceptibility classes.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1. Conclusion

The spatio-temporal land use and land cover change over the last four decades was carried out using Landsat images, topographic map of Metehara sheet and detailed field survey. The result indicated that Lake Beseka, irrigated areas and the two towns revealed a rapid expansion over the past four decades. Due to the rapid expansion the lake about 46.2 Km² Lake surface area has resulted flooding of settlements, scrublands, irrigated and barren areas; and also destruction of blisters and blister caves has been occurred. The spatio-temporal Lake Beseka change overlies lithology of the area map indicated Lake water impact on these blisters and blister caves has been started since the period 1973-1985. The Lake expansion direction was mostly towards the blistered and irrigated areas. Furthermore, about 3.3Km² urban expansion during the year 1973-2015 has resulted the destruction of those blister fields.

There are 478 blisters and 161 blister caves identified and put in a geo-database schema. They are bounded between 39.83 to 39.94 longitude and 8.89 to 8.97 latitude in decimal degrees. Their area ranges from 6.78m² to 23810.05m².

Generally, there are natural and human induced factors for the susceptibility of blisters and blister caves. Human induced factors are the most triggering factors which aggravate the devastation of these blister fields. Frequency ratio model is an essential technique for the susceptibility of blisters and blister caves. Non-hierarchical (K-means) clustering was utilized in order to group the features in susceptibility mapping. The produced susceptibility map indicated that most of the blisters and blister caves fall on the high to very high degree of susceptibility.

7.2. Recommendations

- For the LULC change analysis for the susceptibility of blisters and blister caves, it is possible to perform using Landsat images. In order to achieve interesting results from the time series change, it is recommended to use the higher resolution satellite images with aerial photos.
- Even though the well documented blisters and blister caves have longitude, latitude, area, perimeter and affected/non-affected parameters, their geo-database schema might be better if the height is included as one of the parameters. This is important for the 3D modeling of these blister fields.
- Additional research work is needed to include other triggering factors, such as power lines, for the susceptibility of blisters and blister caves.

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Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift

Annex 1. Mean monthly and annual rainfall (mm).

Year	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Avg.
1970	24.0	24.0	89.0	9.5	6.0	1.0	127.0	171.0	39.2	32.0	0.0	0.0	522.7	43.6
1971	0.0	0.0	1.5	21.5	27.5	39.0	159.5	186.0	22.5	0.0	24.0	16.5	498.0	41.5
1972	0.0	75.0	45.0	19.5	59.0	31.0	57.0	82.5	25.5	10.0	0.0	0.0	404.5	33.7
1973	0.0	0.0	0.0	7.2	22.4	25.4	112.6	95.8	52.0	9.1	0.0	0.0	324.5	27.0
1974	0.0	0.0	70.8	4.2	46.9	35.9	52.5	52.1	100.9	1.1	0.0	0.0	364.4	30.4
1975	0.5	31.9	52.1	49.8	51.0	58.1	186.4	195.4	49.6	2.8	0.0	0.0	677.6	56.5
1976	0.0	0.0	57.2	53.5	52.3	8.9	122.5	146.6	30.5	7.9	30.3	2.7	512.4	42.7
1977	110.0	46.4	6.7	68.4	87.6	102.5	74.8	70.0	18.2	223.4	18.2	0.3	826.5	68.9
1978	0.0	105.9	0.0	5.9	16.1	3.7	98.7	89.6	51.5	33.7	5.0	29.8	439.9	36.7
1979	75.9	0.0	51.4	4.5	59.0	42.0	135.0	74.7	53.2	13.5	0.0	3.0	512.2	42.7
1980	9.8	0.0	4.9	46.7	15.4	29.7	131.9	182.9	33.5	6.9	12.0	0.0	473.7	39.5
1981	0.0	1.4	129.9	72.1	2.7	0.0	173.6	189.5	61.8	11.1	0.0	0.0	642.1	53.5
1982	32.0	67.1	68.1	21.2	101.4	3.1	101.2	304.3	35.9	92.2	36.0	1.0	863.5	72.0
1983	6.2	49.2	63.5	49.4	93.0	21.2	139.1	142.6	18.2	8.2	0.0	0.0	590.6	49.2
1984	0.0	0.0	13.4	0.0	62.6	33.0	66.3	69.4	70.8	0.0	0.0	7.7	323.2	26.9
1985	5.7	0.0	19.5	89.7	71.8	4.6	173.4	131.2	44.2	8.6	0.0	0.0	548.7	45.7
1986	0.0	55.9	49.2	26.1	4.7	78.3	75.2	85.4	52.6	5.4	0.0	4.0	436.8	36.4
1987	0.0	11.1	70.4	45.5	75.0	0.0	35.6	123.7	9.5	5.0	0.0	0.0	375.8	31.3

1988	19.9	19.3	19.1	41.4	7.1	10.9	158.6	131.2	83.6	36.6	0.0	11.2	538.9	44.9
1989	0.0	27.9	89.0	102.3	2.6	62.7	54.8	163.3	24.7	0.0	0.0	18.8	546.1	45.5
1990	0.5	221.7	97.7	67.9	3.8	1.9	181.6	82.2	73.6	3.5	0.0	1.6	736.0	61.3
1991	0.0	54.2	64.6	27.0	51.7	13.8	171.1	108.7	80.7	0.0	0.0	0.0	571.8	47.7
1992	22.1	0.0	1.7	77.9	17.3	41.4	97.7	163.7	79.6	49.7	1.9	2.6	555.6	46.3
1993	39.9	38.3	0.0	142.1	99.9	24.9	93.9	94.4	46.2	31.3	0.0	49.6	660.5	55.0
1994	0.0	0.0	3.0	33.1	44.0	41.1	246.9	115.4	60.6	0.0	11.1	1.5	556.7	46.4
1995	0.0	43.6	66.0	42.0	10.9	17.9	74.2	129.9	72.7	0.9	0.0	0.0	458.1	38.2
1996	25.3	0.8	92.3	41.0	112.4	30.9	137.5	105.8	69.0	11.9	13.7	0.0	640.6	53.4
1997	35.5	0.0	16.0	27.3	12.5	37.6	167.9	49.4	49.0	114.6	9.8	0.0	519.6	43.3
1998	39.9	44.5	56.5	34.3	12.5	7.8	77.8	138.6	37.0	79.7	0.0	0.0	522.0	44.1
1999	1.0	0.0	76.3	16.0	24.0	47.8	121.9	137.7	16.4	86.9	2.3	0.0	530.3	44.2
2000	0.0	0.0	9.0	22.9	41.7	26.7	116.8	166.7	34.2	49.0	5.0	9.7	481.7	40.1
2001	0.0	7.6	106.3	19.1	12.2	13.8	152.4	66.7	30.5	7.0	0.0	0.0	415.6	34.6
2002	0.0	0.0	61.1	17.5	8.5	18.0	44.9	105.1	25.5	1.3	0.0	26.8	308.7	25.7
2003	30.0	12.8	68.7	31.4	0.8	28.8	157.3	232.9	33.4	0.0	1.9	17.2	615.2	51.3
2004	42.4	3.5	112.4	116.8	0.0	14.9	95.2	108.3	33.0	7.3	2.3	0.0	536.1	44.7
2005	24.7	0.0	44.0	39.1	63.1	34.8	128.1	119.9	28.1	0.0	0.0	0.0	481.8	40.2
2006	0.0	69.8	64.1	35.0	8.1	5.4	160.1	100.3	20.9	37.1	0.0	65.7	566.5	47.2
2007	8.0	38.6	142.8	36.1	12.2	11.0	131.1	156.0	50.0	4.2	17.1	0.0	607.1	50.6
2008	0.0	0.0	0.0	22.6	43.3	13.5	222.7	84.0	10.7	40.4	44.4	0.0	481.6	40.1

2009	83.5	0.0	9.0	25.4	11.6	16.9	65.2	79.9	42.2	56.1	2.7	30.1	422.6	35.2
2010	0.0	49.0	67.1	42.0	90.2	19.8	167.5	95.1	42.8	37.1	0.0	65.7	676.3	56.4
2011	0.0	0.0	28.0	0.0	29.8	13.4	164.6	198.2	80.2	0.0	5.3	0.0	519.5	43.3
2012	0.0	0.0	32.6	27.6	47.0	6.9	161.7	98.6	31.4	0.0	0.0	0.0	405.8	33.8
2013	57.2	4.3	18.7	21.0	24.2	3.6	272.0	38.6	100.9	24.3	26.0	0.0	590.8	49.2
2014	0.0	8.6	23.6	38.9	34.6	0.3	89.9	67.5	80.8	73.1	2.2	0.0	419.5	35.0
2015	0	17.7	0	39.65	36.15	62.6	16.2	79.4	82	0	4	4.45	342.15	28.5
AVG	15.1	24.6	47.0	38.7	37.3	24.9	125.0	122.0	47.6	26.6	6.0	8.0	522.7	

Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift

Annex 2. Mean monthly and annual minimum temperature (°C).

Year	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Annual
1970	16.7	16.2	18.6	18.8	19.8	22.9	20.9	19.8	18.4	16.2	10.2	10.7	17.4	209.2
1971	13.4	11.4	15.9	17.9	19.4	21.2	19.5	18.5	17.9	14.9	14.9	12.3	16.4	197.2
1972	14.1	16.4	16.3	19.3	17.2	19.7	21.0	19.6	18.5	16.0	15.6	15.0	17.4	208.7
1973	14.7	13.9	17.8	20.5	20.2	21.7	21.1	21.0	20.1	15.4	13.1	9.5	17.4	209.0
1974	13.4	16.3	18.5	15.9	18.6	21.0	20.2	20.3	19.3	15.8	11.1	11.9	16.9	202.3
1975	11.9	16.3	18.1	19.0	19.3	20.7	19.3	19.6	19.0	14.4	11.4	10.0	16.6	199.0
1976	12.3	17.1	17.9	18.6	19.7	21.4	20.1	18.6	18.4	15.3	14.1	13.6	17.3	207.1
1977	18.4	14.3	17.7	18.6	19.3	21.4	21.0	19.8	19.3	18.8	15.2	14.2	18.2	218.0
1978	12.9	16.0	18.7	18.5	20.4	21.7	19.6	19.1	18.5	16.5	13.7	14.1	17.5	209.7
1979	16.9	13.6	16.9	17.8	18.8	20.8	19.8	19.5	19.2	15.7	11.2	14.0	17.0	204.2
1980	14.1	16.8	19.8	19.4	19.2	22.7	20.6	19.6	19.4	16.5	14.7	11.3	17.8	214.1
1981	13.3	13.1	17.7	17.7	17.5	20.8	20.5	19.0	18.6	15.0	12.5	11.3	16.4	197.0
1982	16.6	18.1	17.3	18.2	18.2	20.4	20.3	19.1	18.4	15.1	15.6	15.4	17.7	212.7
1983	13.5	18.1	20.2	19.8	20.1	20.0	20.7	20.2	19.5	15.1	12.8	12.8	17.7	212.8
1984	11.1	11.2	15.9	18.0	19.3	20.6	19.4	20.1	18.3	13.9	15.5	14.4	16.5	197.7
1985	13.8	14.4	18.2	19.4	18.7	20.9	19.4	18.7	17.8	15.1	13.5	12.7	16.9	202.6
1986	10.8	18.2	17.1	19.8	19.4	21.9	19.8	19.4	18.6	15.7	14.0	14.6	17.4	209.3
1987	14.0	15.9	20.0	18.1	19.6	22.7	21.0	20.3	19.5	17.4	12.8	13.8	17.9	215.1

1988	16.8	18.8	17.4	19.5	18.7	21.9	21.1	19.8	19.4	16.5	10.6	12.7	17.8	213.2
1989	13.8	16.1	18.0	19.0	16.2	20.4	20.5	19.6	19.3	15.2	14.4	18.9	17.6	211.4
1990	14.9	18.8	17.8	17.5	19.4	22.1	19.7	19.9	19.7	15.1	14.8	12.5	17.7	212.2
1991	16.4	17.5	19.1	18.5	18.9	21.0	20.8	20.0	19.0	16.1	14.8	7.5	17.5	209.6
1992	15.9	17.9	19.8	20.1	19.2	20.8	20.1	19.7	18.1	16.0	14.9	16.4	18.2	218.9
1993	17.1	16.4	15.3	19.5	19.0	21.3	20.4	19.9	19.7	17.4	13.9	12.4	17.7	212.3
1994	11.9	14.8	19.8	20.4	19.6	21.6	19.6	19.7	18.3	14.7	14.4	12.6	17.3	207.4
1995	12.3	16.0	18.7	19.7	19.4	20.4	21.0	19.9	18.6	16.7	13.0	16.8	17.7	212.5
1996	17.5	14.9	19.7	19.3	19.2	20.9	20.1	19.9	19.2	14.8	13.7	11.8	17.6	211.0
1997	16.0	13.6	18.8	19.2	19.1	20.2	20.4	20.0	19.2	18.7	18.4	14.5	18.2	218.1
1998	18.3	19.6	20.0	20.3	20.9	22.6	21.6	20.2	19.8	17.6	12.2	10.0	18.6	223.1
1999	13.7	14.6	19.3	18.0	18.9	20.2	19.4	19.2	18.8	17.4	12.0	11.9	17.0	203.4
2000	13.1	12.3	15.9	18.8	20.1	21.9	19.9	19.8	19.9	17.0	14.8	13.5	17.3	207.0
2001	13.6	15.0	18.9	18.5	20.6	21.9	19.8	19.9	17.9	17.3	13.4	14.1	17.6	210.9
2002	15.9	15.0	19.5	19.4	20.3	22.4	21.2	19.9	18.8	17.0	14.1	18.0	18.5	221.5
2003	15.6	17.0	19.0	20.5	18.5	21.4	20.0	19.6	20.0	15.7	15.9	13.9	18.1	217.1
2004	17.8	15.0	15.6	19.0	17.7	21.5	19.8	20.1	19.4	16.3	15.0	15.4	17.7	212.6
2005	15.2	15.5	18.1	18.3	20.3	21.4	20.2	19.8	20.3	16.0	14.3	10.9	17.5	210.3
2006	15.9	18.6	20.0	18.5	18.6	21.9	20.0	20.1	19.5	17.6	14.9	15.7	18.4	221.3
2007	16.1	17.0	16.8	18.0	20.6	21.5	20.1	19.1	19.3	15.4	13.4	10.5	17.3	207.8
2008	13.3	30.0	11.8	18.5	19.9	21.1	19.8	19.4	20.1	15.3	13.3	10.5	17.8	213.0

2009	13.5	14.8	17.3	18.1	18.3	21.8	20.8	20.2	19.9	17.5	13.9	17.7	17.8	213.8
2010	15.2	18.4	18.0	20.2	21.4	22.3	20.8	20.3	19.4	17.6	14.9	15.7	18.7	224.3
2011	14.6	15.9	16.3	20.6	20.8	21.2	20.9	20	20.4	14.7	16.9	11.5	17.82	213.8
2012	13.2	14	16.2	20.7	19.3	22.2	19.8	19.6	19.9	14.5	14.3	13.8	17.29	207.5
2013	14	16.8	19.6	20.4	21.5	20.55	19.6	20.4	18.7	16.6	15.5	11	17.89	214.7
2014	14.6	18.3	18.3	19.7	20.5	20.9	21.4	20.4	19.9	16.3	15.3	11.6	18.1	217.2
2015	12.4	15.25	18.1	19.3	20.85	22.4	22.3	21	20.5	19.2	15.9	12.5	18.3	219.6
Avg.	14.6	16.2	18.0	19.0	19.4	21.4	20.3	19.8	19.2	16.2	14.0	13.2	17.6	

Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift

Annex 3. Mean monthly and annual maximum temperature (°C).

Year	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Avg.
1970	30.0	32.1	30.6	34.1	36.2	36.5	33.7	30.7	32.2	32.3	30.3	28.8	387.5	32.3
1971	28.6	31.4	32.9	34.0	33.8	34.7	31.7	30.1	31.5	31.7	29.5	28.1	378.0	31.5
1972	30.6	28.6	33.6	34.4	34.4	34.2	32.9	32.2	32.8	32.2	31.1	30.1	387.1	32.3
1973	30.7	32.8	35.0	35.8	35.2	35.8	32.7	32.3	33.9	33.8	32.2	30.0	400.2	33.4
1974	31.1	32.4	31.7	35.0	34.6	35.3	33.0	33.2	33.7	35.1	31.6	30.9	397.6	33.1
1975	30.9	32.1	34.6	34.3	35.3	34.6	31.3	30.7	32.0	33.1	30.5	29.2	388.6	32.4
1976	30.7	33.1	34.8	34.6	34.4	37.2	32.8	30.8	33.2	33.3	30.5	31.0	396.4	33.0
1977	29.7	29.1	33.6	34.4	34.9	35.5	33.4	32.6	34.7	32.5	29.5	30.5	390.4	32.5
1978	30.9	31.3	33.3	36.5	36.7	37.1	31.4	31.9	32.9	32.2	31.2	29.2	394.6	32.9
1979	27.8	30.9	33.0	33.9	33.7	34.4	33.1	32.6	34.1	33.1	32.3	30.6	389.5	32.5
1980	30.1	33.2	35.1	34.2	35.6	37.2	31.9	32.3	34.2	33.9	32.4	30.5	400.6	33.4
1981	31.9	32.0	29.8	30.5	34.1	36.3	32.4	30.7	31.6	32.2	31.1	29.6	382.2	31.9
1982	30.2	31.0	33.4	32.4	32.9	36.0	33.4	30.1	32.7	30.1	29.9	29.3	381.4	31.8
1983	29.2	30.2	32.7	33.7	34.2	35.3	34.2	31.1	33.2	32.9	30.9	28.9	386.5	32.2
1984	29.3	30.7	34.7	35.8	34.7	34.2	33.8	33.8	32.9	33.1	31.9	29.7	394.6	32.9
1985	31.1	30.8	34.4	32.1	33.2	35.8	31.6	30.4	32.9	32.8	31.5	29.9	386.5	32.2
1986	29.9	32.2	32.8	33.5	35.5	34.4	32.0	32.8	33.6	32.9	31.9	29.9	391.4	32.6
1987	29.5	32.7	32.1	32.9	33.1	36.2	36.0	33.3	35.4	33.7	32.0	31.0	397.9	33.2
1988	30.0	32.8	34.5	34.8	36.4	36.9	31.8	31.8	32.7	32.4	30.9	30.0	395.0	32.9
1989	29.4	30.2	32.7	31.0	34.8	36.0	32.2	32.9	33.4	33.2	31.6	29.8	387.2	32.3
1990	30.7	29.8	30.7	32.6	36.4	37.4	32.8	32.8	33.7	32.2	32.1	30.1	391.3	32.6
1991	31.9	32.0	34.3	33.9	34.5	36.6	32.5	31.8	33.6	33.8	31.7	30.3	396.9	33.1
1992	30.2	29.5	33.0	34.8	35.5	36.4	32.6	31.1	32.2	32.1	31.9	31.3	390.6	32.6
1993	29.8	29.5	34.9	33.5	33.1	36.0	32.8	33.2	34.5	33.5	32.7	31.1	394.6	32.9
1994	31.2	32.0	35.3	36.1	35.8	35.9	31.4	31.3	32.0	32.3	30.2	29.5	393.0	32.8
1995	30.8	30.6	32.0	34.2	36.4	37.3	33.3	32.6	33.4	34.0	32.4	31.8	398.8	33.2
1996	30.8	33.5	33.9	34.3	33.5	34.2	32.4	32.6	33.5	33.2	31.2	30.5	393.6	32.8
1997	30.7	31.6	34.8	33.4	36.1	35.7	33.4	34.3	36.1	32.2	30.2	30.1	398.6	33.2
1998	31.4	32.9	33.9	36.8	36.7	37.9	34.4	32.1	34.5	32.9	31.9	31.0	406.4	33.9
1999	31.7	34.7	33.6	35.9	37.4	37.5	32.6	33.4	34.1	31.9	31.2	30.4	404.4	33.7
2000	32.2	33.1	35.2	35.8	37.3	38.1	33.4	32.5	34.4	32.5	31.9	30.8	407.2	33.9
2001	30.0	32.8	33.4	35.5	37.5	36.9	33.5	31.9	34.2	34.2	31.8	29.9	401.6	33.5
2002	30.4	33.3	34.1	35.5	37.8	37.8	36.5	33.4	34.8	34.1	32.7	30.2	410.6	34.2
2003	30.6	33.8	35.0	35.0	37.1	36.4	32.5	31.5	33.9	33.8	32.2	30.3	402.1	33.5
2004	31.9	31.7	33.7	33.4	37.1	36.9	33.7	33.6	34.9	33.2	32.3	31.2	403.6	33.6
2005	31.5	34.8	34.8	36.3	35.0	36.7	32.3	34.4	35.4	34.2	32.8	32.1	410.3	34.2
2006	34.3	32.3	35.0	36.1	38.5	37.7	33.9	32.1	34.5	34.1	32.4	30.2	411.1	34.3
2007	31.6	34.4	36.0	35.0	38.1	37.2	33.4	32.2	33.1	34.6	32.5	31.5	409.6	34.1
2008	33.3	31.9	35.4	39.0	36.6	36.8	34.6	32.4	35.5	34.7	30.6	31.0	411.8	34.3
2009	31.7	34.3	36.3	35.6	37.2	37.9	34.5	33.4	35.4	33.2	32.7	30.6	412.8	34.4
2010	30.9	31.8	32.0	35.0	36.8	36.3	32.8	33.0	33.0	34.1	32.4	30.2	398.1	33.2
2011	32.7	34.7	34.3	37.2	36.6	37.3	35	32.8	33.1	34.6	32.8	31.3	412.4	34.4
2012	32.5	33.9	36.1	36.3	37.4	37.2	32.8	31.8	33.7	34.1	33.6	31.9	411.3	34.3
2013	31.5	33.85	36.2	36.9	37.3	34.65	32	32.2	33.8	33.7	32.3	30.9	405.3	33.8
2014	32	33.4	35.3	36.1	36.5	38	35.9	33.8	34	32.3	33	31.5	411.8	34.3
2015	31.4	34.15	36.9	35.3	36.05	36.8	36.5	35.2	35.2	36	33.5	30.9	417.9	34.8
Avg.	30.9	32.2	33.9	34.7	35.7	36.3	33.2	32.3	33.7	33.2	31.7	30.4		

Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift

Annex 4. Mean monthly and annual minimum relative humidity (%).

Year	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Annual
1970	42.0	34.0	41.0	32.0	27.0	22.0	22.0	31.0	26.0	23.0	21.0	25.0	28.8	346.0
1971	30.0	23.0	24.0	22.0	24.0	22.0	27.0	30.0	25.0	23.0	28.0	29.0	25.6	307.0
1972	25.0	36.0	22.0	25.0	25.0	27.0	31.0	33.0	30.0	27.0	30.0	35.0	28.8	346.0
1973	34.0	28.0	16.0	14.0	13.0	21.0	31.0	34.0	29.0	21.0	21.0	21.0	23.6	283.0
1974	31.0	31.0	34.0	21.0	31.0	28.0	31.0	33.0	30.0	24.0	22.0	27.0	28.6	343.0
1975	25.0	28.0	25.0	24.0	22.0	25.0	34.0	38.0	33.0	22.0	30.0	33.0	28.3	339.0
1976	34.0	36.0	29.0	31.0	33.0	29.0	36.0	40.0	34.0	29.0	34.0	32.0	33.1	397.0
1977	44.0	36.0	33.0	31.0	30.0	30.0	36.0	34.0	25.0	29.0	28.0	26.0	31.8	382.0
1978	22.0	30.0	29.0	23.0	26.0	27.0	38.0	34.0	29.0	27.0	29.0	35.0	29.1	349.0
1979	46.0	37.0	33.0	26.0	26.0	26.0	28.0	29.0	27.0	24.0	21.0	30.0	29.4	353.0
1980	34.0	27.0	26.0	25.0	18.0	21.0	29.0	31.0	28.0	23.0	26.0	27.0	26.3	315.0
1981	28.0	29.0	37.0	33.0	25.0	22.0	27.0	34.0	30.0	20.0	23.0	25.0	27.8	333.0
1982	34.0	31.0	26.0	26.0	26.0	21.0	24.0	35.0	26.0	26.0	29.0	33.0	28.1	337.0
1983	30.0	34.0	29.0	23.0	24.0	19.0	23.0	34.0	22.0	20.0	23.0	29.0	25.8	310.0
1984	24.0	19.0	16.0	20.0	21.0	18.0	18.0	18.0	20.0	17.0	27.0	25.0	20.3	243.0
1985	22.0	25.0	21.0	25.0	19.0	18.0	x	x	x	x	x	33.0	23.3	163.0
1986	30.0	33.0	31.0	32.0	27.0	31.0	32.0	32.0	28.0	26.0	31.0	38.0	30.9	371.0
1987	37.0	35.0	43.0	37.0	39.0	32.0	32.0	36.0	32.0	32.0	31.0	35.0	35.1	421.0
1988	41.0	36.0	24.0	26.0	21.0	22.0	33.0	33.0	30.0	25.0	24.0	28.0	28.6	343.0
1989	31.0	34.0	33.0	35.0	24.0	-	34.0	34.0	32.0	26.0	32.0	44.0	32.6	359.0
1990	35.0	50.0	42.0	33.0	24.0	26.0	34.0	33.0	28.0	24.0	31.0	28.0	32.3	388.0
1991	33.0	35.0	29.0	28.0	28.0	24.0	33.0	35.0	28.0	23.0		22.0	28.9	318.0
1992	38.0	39.0	32.0	26.0	25.0	23.0	x	x	x	x	x	x	30.5	183.0
1993	x	x	x	x	x	x	x	x	x	x	x	x	x	0.0
1994	x	x	34.0	31.0	32.0	32.0	39.0	43.0	38.0	30.0	36.0	36.0	35.1	351.0
1995	37.0	37.0	37.0	33.0	30.0	29.0	38.0	34.0	31.0	31.0	31.0	33.0	33.4	401.0
1996	30.0	27.0	34.0	33.0	31.0	30.0	31.0	32.0	30.0	26.0	39.0	33.0	31.3	376.0
1997	44.0	36.0	39.0	40.0	34.0	31.0	32.0	x	x	34.0	39.0	34.0	36.3	363.0
1998	41.0	37.0	35.0	30.0	31.0	31.0	35.0	43.0	37.0	x	x	34.0	35.4	354.0
1999	40.0	x	x	x	x	x	x	x	x	x	x	34.0	37.0	74.0
2000	35.0	36.0	35.0	34.0	32.0	35.0	40.0	37.0	30.0	34.0	39.0	37.0	35.3	424.0
2001	45.0	37.0	37.0	32.0	29.0	34.0	36.0	42.0	35.0	38.0	38.0	39.1	36.8	442.1
2002	43.0	35.0	35.0	31.0	29.0	30.0	41.0	39.0	36.0	35.0	37.0	46.0	33.4	437.0
2003	37.0	36.0	35.0	35.0	32.0	34.0	40.0	44.0	35.0	31.0	34.0	34.0	35.6	427.0
2004	40.0	35.0	33.0	35.0	29.0	28.7	32.0	34.0	28.0	28.0	29.0	36.0	32.3	387.7
2005	33.0	28.0	29.0	29.0	28.0	30.0	35.0	29.0	28.0	28.0	30.0	28.0	29.6	355.0
2006	33.0	32.0	26.0	30.0	26.0	26.0	30.0	35.0	29.0	28.0	27.0	33.0	29.6	355.0
2007	32.0	26.0	26.0	26.0	25.0	25.0	27.0	32.0	30.0	23.0	24.0	24.0	26.7	320.0
2008	27.0	30.0	26.0	26.0	25.0	24.0	30.0	39.0	55.0	53.0	51.0	39.0	35.4	425.0
2010	32.6	34.1	30.2	26.9	25.2	19.5	28.1	30.8	27.9	x	x	x	28.4	255.3
Avg	34.4	33.0	31.0	29.0	27.0	26.8	32.3	34.6	30.2	27.4	30.1	32.0		

Annex 5. Mean monthly and annual maximum relative humidity (%).

**Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
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Year	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Avg.
1970	93	84	93	86	79	62	77	82	88	85	90	91.0	1010	84
1971	85	87	82	81	80	73	84	90	84	87	89	92.0	1014	85
1972	93	94	90	87	96	90	91	95	96	95	94	98.0	1119	93
1973	97	93	75	67	70	71	85	89	94	94	92	94.0	1021	85
1974	95	93	93	91	93	87	91	90	93	92	96	93.0	1107	92
1975	92	89	83	86	83	84	91	90	90	94	97	96.0	1075	90
1976	94	90	90	89	89	78	84	89	88	89	93	90.0	1063	89
1977	87	87	84	85	85	78	82	82	88	92	94	90.0	1034	86
1978	93	93	92	87	85	83	83	84	83	85	84	87.0	1039	87
1979	86	85	85	85	83	82	82	82	84	85	83	84.0	1006	84
1980	83	82	82	82	82	80	79	80	81	82	83	82.0	978	82
1981	81	81	80	80	83	80	81	82	82	81	81	81.0	973	81
1982	82	81	80	79	79	80	78	79	80	79	81	80.0	958	80
1983	80	79	80	79	80	78	78	78	79	80	79	80.0	950	79
1984	80	80	77	78	78	77	78	77	79	77	77	78.0	936	78
1985	77	76	78	79	78	76	84	85	87	85	86	92.0	983	82
1986	92	92	95	92	90	82	89	93	95	93	95	96.0	1104	92
1987	95	96	97	95	95	80	90	95	94	95	96	97.0	1125	94
1988	95	96	79	86	77	71	82	88	90	92	94	91.0	1041	87

Annex 6. Mean monthly and annual wind speed (day) Km/hr.

Year	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Annual
1973	x	x	x	x	x	x	x	x	x	7.2	8.0	7.9	7.7	30.8
1974	7.7	8.8	6.5	8.2	7.2	8.9	9.0	7.9	5.8	6.8	7.8	7.7	7.7	92.3
1975	7.3	7.4	6.6	5.2	6.5	8.0	9.7	7.1	5.0	6.0	7.1	7.1	6.9	83.0
1976	7.1	2.5	5.9	5.7	5.1	8.3	8.3	7.4	5.6	6.4	5.7	6.4	6.2	74.4
1977	6.1	6.3	6.8	5.5	4.5	6.5	8.7	7.1	5.6	5.4	5.8	6.2	6.2	74.5
1978	6.2	5.3	6.2	6.3	6.0	7.2	7.8	5.7	4.6	5.4	6.9	6.1	6.1	73.7
1979	5.5	6.1	5.7	6.1	6.4	6.8	7.5	5.3	4.5	5.4	6.4	5.9	6.0	71.6
1980	6.6	5.9	6.6	5.7	6.3	6.9	7.3	6.2	4.8	4.8	5.8	6.0	6.1	72.9
1981	5.5	5.9	4.1	4.3	5.3	6.1	6.5	5.5	3.9	4.3	5.8	5.7	5.2	62.9
1982	5.3	4.2	4.8	4.1	4.1	5.0	7.1	4.1	2.2	3.2	4.0	4.8	4.4	52.9
1983	5.2	4.3	4.0	3.7	3.1	3.9	6.0	4.8	3.4	3.4	4.0	4.7	4.2	50.5
1984	4.9	5.4	4.2	6.0	3.8	5.6	5.9	4.0	2.9	4.7	4.7	4.8	4.7	56.9
1985	4.6	6.0	5.1	3.2	3.0	4.5	5.2	6.0	3.4	3.8	3.5	4.2	4.4	52.5
1986	3.6	3.5	3.8	4.2	4.6	6.0	5.5	5.0	3.7	4.3	4.7	5.1	4.5	54.0
1987	5.3	4.2	4.0	4.2	4.5	5.4	5.5	4.4	3.3	4.1	4.4	4.7	4.5	54.0
1988	4.9	4.0	5.3	3.9	5.0	6.1	6.7	4.3	3.2	3.7	4.8	4.9	4.7	56.8
1989	5.6	6.5	4.6	3.5	2.2	5.3	6.9	5.5	3.9	4.4	5.5	5.6	5.0	59.5
1990	5.5	3.6	4.6	3.6	4.6	6.2	6.8	6.0	4.0	4.2	4.4	4.6	4.8	58.1
1991	4.2	3.8	4.3	3.9	4.0	4.5	6.4	5.0	3.2	3.6	3.7	4.3	4.2	50.9

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1992	4.1	4.3	4.5	3.5	2.9	4.5	5.6	4.6	2.9	2.6	3.0	3.7	3.9	46.2
1993	4.2	3.9	2.7	3.2	2.8	5.0	6.6	5.5	3.9	3.5	4.1	4.2	4.1	49.6
1994	4.4	5.3	4.6	4.3	4.0	5.6	5.5	4.2	2.6	3.5	3.5	3.9	4.3	51.4
1995	3.7	3.1	2.4	1.5	2.3	2.7	4.1	2.9	1.5	3.2	2.6	2.6	2.7	32.6
1996	2.4	2.6	1.8	1.5	1.0	2.0	1.4	1.0	1.1	1.4	1.3	1.3	1.6	18.8
1997	1.1	2.4	1.3	1.7	1.7	1.8	1.8	1.6	1.0	1.2	1.5	2.4	1.6	19.5
1998	1.7	1.5	1.6	1.8	1.8	2.3	2.2	1.8	1.3	1.2	1.7	2.7	1.8	21.6
1999	2.1	2.4	1.6	2.5	1.9	1.8	3.0	1.9	1.8	1.4	2.0	3.2	2.1	25.6
2000	3.6	4.0	4.1	3.3	3.1	4.2	4.5	3.2	2.1	1.9	3.0	3.3	3.4	40.3
2001	3.7	3.9	2.0	3.1	3.6	4.9	4.0	3.6	2.6	3.7	4.5	4.8	3.7	44.1
2002	4.4	4.2	3.2	3.6	3.3	4.3	4.6	4.2	2.7	3.1	3.7	3.7	3.7	44.9
2003	3.6	3.4	4.1	3.0	3.4	4.9	5.5	3.7	3.1	2.9	3.9	3.2	3.7	44.5
2004	3.0	3.9	3.0	2.4	3.7	4.5	5.1	4.1	2.9	2.8	3.8	3.8	3.6	43.0
2005	3.1	3.5	3.7	3.7	3.1	4.5	4.1	3.4	3.1	2.9	3.0	3.2	3.5	41.4
2006	3.3	3.2	2.2	2.7	3.0	4.8	3.9	3.5	2.4	3	2.2	2.0	3.0	35.6
2007	2.4	1.7	1.9	1.6	2.1	3.6	3.4	2.71	2.45	1.4	2.0	2.1	2.3	27.4
2008	1.9	3.0	2.0	2.3	1.5	2.5	3.6	2.33	1.44	1.0	1.0	1.6	2.0	24.1
2009	1.0	0.9	2.0	1.8	3.3	7.9	5.6	5.7	6.3	7.3	7.4	7.0	4.7	56.2
2010	2.31	1.67	1.67	1.67	1.78	2.36	2.28	1.94	1.47	3.1	3.2	3.2	2.2	
Avg	4.2	4.1	3.9	3.7	3.7	5.0	5.5	4.4	3.2	3.7	4.2	4.4		

Annex 7. Mean monthly and annual wind speed (night) Km/hr.

Year	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.	Annual
1973	x	x	x	x	x	x	x	x	x	2.3	2.2	2.2	2.2	8.9
1974	2.9	4.1	3.9	2.2	3.3	4.4	6.7	5.3	3.9	2.3	2.2	2.2	3.6	43.4
1975	2.5	2.9	2.7	2.8	2.9	5.4	6.3	4.4	3.2	2.3	2.2	2.2	3.3	39.8
1976	1.6	2.5	2.8	2.3	2.3	8.9	6.3	4.9	2.6	2.3	2.2	2.2	3.4	40.9
1977	2.6	1.6	2.6	1.8	2.0	4.6	6.1	3.9	3.1	2.3	2.2	2.2	2.9	35.0
1978	1.4	3.0	1.3	2.4	2.3	5.9	4.9	3.0	2.1	2.3	2.2	2.2	2.8	33.0
1979	2.0	1.1	1.9	1.6	1.6	4.2	4.8	3.1	1.7	2.3	2.2	2.2	2.4	28.7
1980	1.1	2.3	2.5	1.7	1.6	4.6	4.2	2.8	1.5	2.3	2.2	2.2	2.4	29.0
1981	0.8	2.2	2.2	0.7	1.1	3.1	4.8	2.5	1.6	2.3	2.2	2.2	2.1	25.7
1982	1.2	1.5	1.2	0.7	0.6	2.7	4.0	1.7	0.6	2.3	2.2	2.2	1.7	20.9
1983	1.3	1.0	0.8	1.0	1.1	2.4	3.3	2.3	0.9	2.3	2.2	2.2	1.7	20.8
1984	0.4	0.6	1.3	1.1	1.2	2.9	2.1	1.2	1.1	2.3	2.2	2.2	1.6	18.6
1985	1.0	0.9	1.6	0.8	0.6	1.9	2.6	2.2	0.4	2.3	2.2	2.2	1.6	18.7
1986	0.2	1.2	1.0	1.9	1.3	5.1	3.4	2.6	1.4	2.3	2.2	2.2	2.1	24.8
1987	0.8	1.5	1.4	0.7	1.5	3.6	3.2	2.6	1.3	2.3	2.2	2.2	1.9	23.3
1988	0.9	1.1	1.1	1.6	1.4	4.1	4.7	2.1	1.1	2.3	2.2	2.2	2.1	24.8
1989	0.7	1.0	1.8	1.3	0.8	3.2	4.2	2.9	1.7	2.3	2.2	2.2	2.0	24.3
1990	1.8	1.7	0.9	1.1	1.9	4.1	3.6	3.2	2.0	2.3	2.2	2.2	2.3	27.0

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1991	1.5	1.5	1.4	0.6	0.8	2.9	3.9	2.7	1.6	2.3	2.2	2.2	2.0	23.6
1992	1.2	1.3	1.6	1.2	0.7	2.2	3.4	2.3	1.1	2.3	2.2	2.2	1.8	21.7
1993	1.3	0.9	0.5	1.4	1.0	3.1	3.9	2.6	2.1	2.3	2.2	2.2	2.0	23.5
1994	0.4	0.9	1.7	1.0	1.0	4.1	2.6	1.4	0.5	2.3	2.2	2.2	1.7	20.3
1995	0.2	0.7	0.5	0.1	0.4	1.1	1.8	1.9	0.4	2.3	2.2	2.2	1.2	13.8
1996	0.3	0.2	0.4	0.2	0.2	0.7	0.5	0.2	0.3	2.3	2.2	2.2	0.8	9.7
1997	0.1	0.5	0.5	0.2	0.2	0.5	0.6	0.4	0.2	2.3	2.2	2.2	0.8	9.9
1998	0.2	0.3	0.1	0.2	0.3	0.6	0.6	0.4	0.1	2.3	2.2	2.2	0.8	9.5
1999	0.1	0.2	0.1	0.3	0.2	0.3	0.6	0.3	0.1	2.3	2.2	2.2	0.7	8.9
2000	0.2	0.3	0.5	0.6	0.5	2.2	1.8	1.5	0.6	2.3	2.2	2.2	1.2	14.8
2001	0.3	0.7	0.7	0.5	1.6	2.9	1.8	1.4	0.6	2.3	2.2	2.2	1.4	17.2
2002	0.8	1.1	0.9	1.2	0.8	2.1	1.9	1.8	0.5	2.3	2.2	2.2	1.5	17.8
2003	0.5	0.8	1.0	1.0	0.7	2.3	3.0	1.4	1.1	2.3	2.2	2.2	1.5	18.6
2004	0.5	0.5	0.5	0.5	0.4	2.3	3.0	1.8	0.8	2.3	2.2	2.2	1.4	16.9
2005	0.8	0.8	1.1	1.1	0.9	2.0	2.4	1.4	1.6	2.3	2.2	2.2	1.6	18.7
2006	1.2	1.0	0.5	0.5	0.9	2.6	2.0	1.5	1.03	2.3	2.2	2.2	1.5	17.9
2007	0.8	0.6	0.8	0.2	0.9	2.6	2.2	1.1	1.3	2.3	2.2	2.2	1.4	17.3
2008	0.4	1.0	0.6	1.0	0.5	2.1	2.4	1.6	0.8	2.3	2.2	2.2	1.4	17.3
2009	0.3	0.4	1.0	1.0	1.0	4.0	1.0	3.5	2.2	2.3	2.2	2.2	1.8	21.1
2010	1.1	1.1	1.1	0.9	0.9	1.4	1.4	1.0	0.4					
Avg	1.0	1.2	1.3	1.1	1.1	3.1	3.1	2.2	1.3	2.3	2.2	2.2		

Annex 8. Pan Evaporation (mm).

Year	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	AVG
1970	6.2	8.2	6.9	9.2	10.0	10.8	8.8	6.4	7.5	8.6	8.2	7.8	98.6	8.2
1971	7.8	9.4	9.3	8.4	9.6	10.8	9.7	7.8	7.1	8.0	7.4	6.1	101.4	8.5
1972	7.2	6.1	8.6	8.2	8.8	8.7	7.5	7.0	7.1	7.9	7.2	6.6	90.9	7.6
1973	7.0	8.4	9.5	9.9	8.4	9.4	8.3	7.0	6.9	7.8	7.9	6.9	97.4	8.1
1974	6.7	7.9	6.4	8.7	7.4	8.0	7.5	6.9	6.3	7.5	7.2	7.1	87.6	7.3
1975	7.3	6.7	7.6	6.3	7.4	7.5	6.7	5.7	5.5	6.9	7.0	6.1	80.7	6.7
1976	6.6	7.4	7.5	7.2	6.5	8.7	6.5	5.6	6.2	6.8	5.9	6.0	80.9	6.7
1977	5.0	6.0	7.6	6.6	6.3	7.6	7.1	6.6	6.6	6.6	5.3	5.6	76.9	6.4
1978	6.4	5.6	6.6	8.1	7.9	8.9	6.4	6.4	6.0	6.9	6.6	6.2	82.0	6.8
1979	4.7	6.4	6.7	7.5	6.3	7.9	7.5	6.2	6.3	6.5	6.9	6.2	79.1	6.6
1980	6.2	7.5	8.5	7.1	7.9	8.2	6.2	6.4	7.4	6.6	6.6	6.5	85.1	7.1
1981	6.3	7.0	5.8	5.7	7.2	7.7	6.7	5.8	5.4	6.0	6.4	6.7	76.7	6.4
1982	6.0	5.5	6.9	6.5	7.3	7.5	7.0	5.5	6.4	6.2	5.3	5.4	75.5	6.3
1983	6.5	6.0	6.4	6.1	7.0	7.9	7.4	5.6	5.8	6.7	6.4	5.8	77.6	6.5
1984	6.2	7.7	8.2	8.9	7.9	7.7	7.5	7.6	6.9	8.5	8.4	7.0	92.5	7.7
1985	7.4	8.7	9.3	6.7	7.9	7.6	6.4	6.2	6.1	6.6	7.0	6.5	86.4	7.2
1986	7.0	6.7	6.8	7.7	8.6	8.0	6.5	6.6	7.1	7.5	7.8	7.0	87.3	7.3
1987	6.8	7.4	6.8	8.1	6.9	8.5	8.3	7.0	7.6	8.0	7.9	6.3	89.6	7.5
1988	6.0	7.0	7.7	6.9	8.6	8.5	6.7	6.6	5.6	6.0	7.1	6.2	82.9	6.9
1989	6.6	6.6	7.3	5.3	7.5	7.8	7.1	5.5	5.4	7.2	7.2	5.8	79.3	6.6

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1990	7.2	5.1	6.0	6.9	8.0	8.6	6.5	7.1	6.2	6.8	6.7	6.5	81.6	6.8
1991	7.1	6.1	7.2	7.0	6.8	7.7	7.0	6.4	5.8	6.5	5.7	5.7	79.0	6.6
1992	5.4	5.5	7.9	7.7	8.0	7.9	6.2	5.6	5.3	5.8	5.8	5.3	76.4	6.4
1993	4.9	5.5	8.1	6.7	6.3	6.9	6.7	6.2	5.9	6.2	6.1	5.8	75.3	6.3
1994	6.0	6.9	7.1	7.9	7.2	7.7	5.5	6.1	5.8	6.4	5.5	6.0	78.1	6.5
1995	6.5	6.1	5.7	6.5	8.4	7.7	6.9	5.7	5.9	7.4	6.3	6.1	79.2	6.6
1996	5.9	6.6	6.4	6.5	5.5	6.7	5.2	6.0	6.5	6.5	5.8	6.3	73.9	6.2
1997	5.6	7.2	7.3	6.0	7.8	6.9	6.1	6.3	6.1	5.3	4.7	5.4	74.7	6.2
1998	4.7	6.1	6.0	6.9	7.6	7.7	6.3	5.5	5.7	6.0	6.2	5.7	74.4	6.2
1999	6.1	7.4	5.5	7.7	7.5	7.0	6.0	6.2	6.6	5.7	5.6	6.0	77.3	6.4
2000	6.0	6.3	7.2	6.6	7.3	8.2	6.0	5.9	5.9	6.3	6.2	5.8	77.7	6.5
2001	5.7	7.0	6.1	7.0	7.9	7.8	6.1	5.2	5.9	6.7	6.9	6.1	78.4	6.5
2002	5.9	7.4	6.8	7.1	7.8	8.0	7.4	6.1	6.3	6.7	6.8	5.1	81.4	6.8
2003	5.7	6.6	7.3	6.5	7.9	7.4	5.5	4.7	5.8	6.8	6.4	5.2	75.8	6.3
2004	5.3	6.4	6.4	5.9	7.4	6.1	5.8	6.3	5.9	5.8	6.1	6.3	73.7	6.1
2005	6.2	7.7	7.9	8.3	7.0	8.5	6.2	6.8	7.2	7.4	7.2	7.1	87.5	7.3
2006	6.9	7.1	7	7.3	7.7	8.3	5.8	4.9	5.7	5.8	5.9	4.8	77.2	6.4
2007	5.3	6.2	7.2	6.3	8.4	7.6	5.5	4.5	4.8	5.9	5.9	5.6	73.2	6.1
2008	5.9	6.1	7.1	6.7	6.3	7.0	6.3	5.2	5.9	6	5	5.4	72.9	6.1
2009	4.8	6.2	7.0	6.2	7.8	9.8	7.5	6.9	8.5	7.5	7.2	5.8	85.2	7.1
2010	7.0	6.3	6.9	7.6	7.2	8.4	6.5	6.1	7.2	5.8	5.9	4.8	79.9	6.7
AVG	6.2	6.8	7.2	7.2	7.6	8.0	6.8	6.1	6.3	6.7	6.5	6.1		

Annex 9. The Fentale-Metehara blister caves and blisters geo-database schema.

No.	Name of the blister field	Type of the blister field	Area (m ²)	Longitude (degree)	Latitude (degree)	Perimeter (m)
1	Blister	Affected	1029.385266	39.87301	8.935553	116.602243
2	Blister	Affected	473.47071	39.922136	8.923328	80.44921
3	Blister	Affected	492.572194	39.925803	8.929824	81.312211
4	Blister	Affected	99.115759	39.923499	8.928605	38.333833
5	Blister	Affected	621.548481	39.901472	8.911083	91.92264
6	Blister	Affected	540.337973	39.900643	8.910377	84.896325
7	Blister	Affected	1072.146321	39.90065	8.915212	118.084454
8	Blister	Affected	982.141497	39.903041	8.914097	118.017725
9	Blister	Affected	218.564173	39.905248	8.915579	56.723337
10	Blister	Affected	140.758128	39.86038	8.913454	44.673825
11	Blister	Affected	279.625428	39.904388	8.91673	60.721747
12	Blister	Affected	835.681133	39.900595	8.9176	106.263926
13	Blister	Affected	332.929877	39.898808	8.91591	67.102022

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14	Blister	Affected	324.028085	39.859771	8.913954	66.013858
15	Blister	Affected	1349.696678	39.899114	8.917995	136.840348
16	Blister	Affected	374.713045	39.861594	8.913338	72.449443
17	Blister	Affected	952.656919	39.899624	8.918465	112.745425
18	Blister	Affected	753.993636	39.899704	8.918943	99.25904
19	Blister	Affected	481.301968	39.899687	8.921256	79.927131
20	Blister	Affected	784.605291	39.9	8.92124	101.569836
21	Blister	Affected	1272.799305	39.901829	8.927851	131.242345
22	Blister	Affected	2651.67443	39.862568	8.91452	194.161991
23	Blister	Affected	21.342594	39.869616	8.917778	17.074034
24	Blister	Affected	2567.180027	39.866906	8.928955	186.737281
25	Blister	Affected	541.322607	39.865526	8.944645	85.553806
26	Blister	Affected	1833.792494	39.902328	8.927998	154.958316
27	Blister	Affected	311.367116	39.902561	8.923771	65.240063
28	Blister	Affected	1002.222296	39.875126	8.928764	115.564228
29	Blister	Affected	193.58642	39.909229	8.922875	51.216663
30	Blister	Affected	155.833771	39.906177	8.916236	47.780064
31	Blister	Affected	1077.351404	39.909054	8.922035	119.237038
32	Blister	Affected	1387.468565	39.873391	8.936638	139.964428
33	Blister	Affected	2346.748702	39.863477	8.928706	198.908051
34	Blister	Affected	355.217104	39.863203	8.916404	69.451959
35	Blister	Affected	318.822252	39.86417	8.913039	65.966251
36	Blister	Affected	292.696828	39.910828	8.90966	61.642359
37	Blister	Affected	579.256148	39.859829	8.917774	90.104741
38	Blister	Affected	359.143397	39.85994	8.923236	68.805608
39	Blister	Affected	710.164909	39.87329	8.912489	96.627759
40	Blister	Affected	34.368914	39.869787	8.918415	22.452914
41	Blister	Affected	187.254384	39.910696	8.922346	49.82211
42	Blister	Affected	304.863924	39.909825	8.922222	63.945512

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43	Blister	Affected	621.387759	39.905136	8.916895	91.145758
44	Blister	Affected	43.89305	39.872439	8.921945	24.850415
45	Blister	Affected	2774.87931	39.859093	8.931267	197.497836
46	Blister	Affected	2139.814427	39.90466	8.923217	168.487909
47	Blister	Affected	859.895172	39.905698	8.921748	106.675704
48	Blister	Affected	1208.244502	39.911236	8.928155	129.445128
49	Blister	Affected	3472.173771	39.866026	8.944729	217.246558
50	Blister	Affected	279.897249	39.90296	8.914888	61.512325
51	Blister	Affected	217.346372	39.911518	8.917224	55.543292
52	Blister	Affected	1589.014671	39.852833	8.932833	152.637939
53	Blister	Affected	650.501217	39.855035	8.932273	93.045396
54	Blister	Affected	1105.78338	39.900177	8.921583	120.61579
55	Blister	Affected	174.190845	39.899355	8.923473	49.129217
56	Blister	Affected	142.061272	39.902767	8.916128	43.406769
57	Blister	Non-affected	636.203696	39.848024	8.95573	92.329356
58	Blister	Non-affected	684.401081	39.845051	8.964923	95.913131
59	Blister	Non-affected	2260.529838	39.846258	8.965855	189.498065
60	Blister	Non-affected	194.664477	39.860094	8.93255	51.222496
61	Blister	Non-affected	339.274953	39.856999	8.938869	67.129375
62	Blister	Non-affected	1419.870047	39.855203	8.937785	140.218647
63	Blister	Non-affected	894.765946	39.856495	8.93526	110.165949
64	Blister	Non-affected	32.745775	39.868995	8.918182	21.512706

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65	Blister	Non-affected	19.136184	39.880299	8.932425	16.430892
66	Blister	Non-affected	2091.435871	39.863803	8.937243	167.173315
67	Blister	Non-affected	408.544224	39.908704	8.928828	75.339471
68	Blister	Non-affected	584.452306	39.902712	8.936704	88.468557
69	Blister	Non-affected	169.866261	39.900008	8.93379	47.924213
70	Blister	Non-affected	1831.876714	39.843832	8.965922	160.550444
71	Blister	Non-affected	656.397457	39.89962	8.937066	96.331214
72	Blister	Non-affected	2001.51636	39.90004	8.937103	163.6332
73	Blister	Non-affected	2693.033298	39.870353	8.940776	190.667019
74	Blister	Non-affected	1101.613701	39.90274	8.937144	121.433046
75	Blister	Non-affected	2385.787694	39.876891	8.932455	179.003021
76	Blister	Non-affected	580.277884	39.896482	8.940561	89.303652
77	Blister	Non-affected	422.273376	39.877117	8.928985	76.198924
78	Blister	Non-affected	1416.454079	39.907689	8.923739	141.514727
79	Blister	Non-affected	134.01413	39.877354	8.930125	42.626136

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80	Blister	Non-affected	834.941735	39.925402	8.931775	105.440908
81	Blister	Non-affected	41.134135	39.854275	8.926344	23.661609
82	Blister	Non-affected	1865.686586	39.907971	8.921201	159.677803
83	Blister	Non-affected	1776.37069	39.907889	8.920782	155.999546
84	Blister	Non-affected	636.203696	39.848024	8.95573	92.329356
85	Blister	Non-affected	552.06326	39.852231	8.942977	85.611785
86	Blister	Non-affected	534.400264	39.855946	8.944738	85.420876
87	Blister	Non-affected	914.938452	39.859926	8.942304	110.327926
88	Blister	Non-affected	679.265828	39.859589	8.943313	94.900544
89	Blister	Non-affected	283.416626	39.85656	8.9417	62.667736
90	Blister	Non-affected	204.90428	39.858113	8.942042	52.696857
91	Blister	Non-affected	2170.376224	39.861614	8.93929	170.359232
92	Blister	Non-affected	1371.204309	39.865742	8.938786	133.947204
93	Blister	Non-affected	312.76636	39.90821	8.917525	64.750505
94	Blister	Non-affected	268.609737	39.878424	8.934742	60.43197

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95	Blister	Non-affected	258.991747	39.879553	8.934524	60.118222
96	Blister	Non-affected	70.849364	39.880548	8.932474	31.257989
97	Blister	Non-affected	118.941512	39.879174	8.934278	41.966218
98	Blister	Non-affected	48.198963	39.879563	8.935642	26.064483
99	Blister	Non-affected	49.353183	39.879281	8.935399	26.02219
100	Blister	Non-affected	360.99647	39.922496	8.931917	69.993322
101	Blister	Non-affected	105.177271	39.909037	8.918021	37.787616
102	Blister	Non-affected	360.403954	39.878558	8.93267	69.343651
103	Blister	Non-affected	432.254227	39.857709	8.945291	76.233037
104	Blister	Non-affected	1324.608172	39.862355	8.951992	134.918034
105	Blister	Non-affected	937.403765	39.861273	8.951408	113.424612
106	Blister	Non-affected	1632.033169	39.860846	8.951723	157.324604
107	Blister	Non-affected	1462.975635	39.860945	8.951279	138.926374
108	Blister	Non-affected	534.156491	39.863667	8.949141	86.000423
109	Blister	Non-affected	941.600525	39.861087	8.954626	111.95095

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

110	Blister	Non-affected	196.546345	39.860665	8.953746	51.354804
111	Blister	Non-affected	2054.069333	39.862216	8.957797	166.331284
112	Blister	Non-affected	317.179802	39.922799	8.932093	66.266186
113	Blister	Non-affected	27.465567	39.909758	8.918251	19.043209
114	Blister	Non-affected	2346.748702	39.863477	8.928706	198.908051
115	Blister	Non-affected	779.144535	39.860301	8.942737	101.639086
116	Blister	Non-affected	1236.486477	39.859894	8.943072	128.603438
117	Blister	Non-affected	800.535003	39.860888	8.943109	104.131402
118	Blister	Non-affected	607.860275	39.857013	8.947329	89.841089
119	Blister	Non-affected	848.541746	39.854473	8.941277	108.772545
120	Blister	Non-affected	658.480609	39.864568	8.947151	93.668491
121	Blister	Non-affected	1037.458327	39.866782	8.948079	117.621289
122	Blister	Non-affected	1484.023261	39.860045	8.956255	147.966603
123	Blister	Non-affected	831.305183	39.921959	8.941576	106.5884
124	Blister	Non-affected	244.363612	39.908598	8.920122	57.047569

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

125	Blister	Non-affected	693.462397	39.867894	8.952229	96.430841
126	Blister	Non-affected	1149.374954	39.867293	8.951453	124.028056
127	Blister	Non-affected	1146.35242	39.856678	8.955768	123.901319
128	Blister	Non-affected	447.60196	39.866045	8.950404	76.961414
129	Blister	Non-affected	729.265292	39.866179	8.950995	99.115819
130	Blister	Non-affected	1406.066015	39.855608	8.937669	138.051705
131	Blister	Non-affected	1755.84128	39.855906	8.938281	155.976154
132	Blister	Non-affected	556.688045	39.922709	8.94176	87.368917
133	Blister	Non-affected	1686.863184	39.838619	8.941525	150.258409
134	Blister	Non-affected	1623.676086	39.848788	8.956574	147.30723
135	Blister	Non-affected	1034.55914	39.863018	8.908834	121.163135
136	Blister	Non-affected	65.423367	39.858356	8.908433	31.760024
137	Blister	Non-affected	129.372806	39.859485	8.909994	42.167962
138	Blister	Non-affected	118.983261	39.85954	8.90982	39.859154
139	Blister	Non-affected	901.57446	39.859418	8.910777	110.473248

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

140	Blister	Non-affected	260.605069	39.85887	8.909908	59.821544
141	Blister	Non-affected	1257.008106	39.923175	8.941134	129.843622
142	Blister	Non-affected	350.335908	39.909468	8.920547	69.093708
143	Blister	Non-affected	227.227912	39.860363	8.911823	55.998145
144	Blister	Non-affected	411.471069	39.859334	8.913117	74.274499
145	Blister	Non-affected	3899.226607	39.867675	8.943854	237.641833
146	Blister	Non-affected	938.624939	39.850337	8.942846	113.943008
147	Blister	Non-affected	792.288551	39.850966	8.943017	103.599833
148	Blister	Non-affected	2076.759108	39.850738	8.944241	165.400181
149	Blister	Non-affected	1985.768081	39.850863	8.943783	164.204234
150	Blister	Non-affected	730.910812	39.923431	8.940464	100.246799
151	Blister	Non-affected	784.535677	39.909677	8.920738	101.340272
152	Blister	Non-affected	24.258143	39.872696	8.919735	18.202052
153	Blister	Non-affected	3204.752717	39.851967	8.945103	205.85804
154	Blister	Non-affected	2462.532948	39.850884	8.944669	182.651964

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

155	Blister	Non-affected	407.422394	39.855811	8.942372	78.526657
156	Blister	Non-affected	2157.265525	39.856435	8.94377	173.530058
157	Blister	Non-affected	1414.994646	39.854417	8.943002	144.260705
158	Blister	Non-affected	310.914198	39.854584	8.942709	64.630093
159	Blister	Non-affected	1772.490838	39.859562	8.909097	167.687431
160	Blister	Non-affected	617.507069	39.923436	8.940884	91.616475
161	Blister	Non-affected	255.816836	39.858771	8.9087	58.622505
162	Blister	Non-affected	763.614344	39.860311	8.911437	100.940801
163	Blister	Non-affected	121.923995	39.858517	8.912313	40.681687
164	Blister	Non-affected	405.881666	39.935504	8.92575	73.244027
165	Blister	Non-affected	47.908281	39.910522	8.920348	25.334381
166	Blister	Non-affected	571.65182	39.857834	8.91392	88.601133
167	Blister	Non-affected	16.032184	39.910955	8.919488	14.908969
168	Blister	Non-affected	18.93008	39.911194	8.920157	15.929325
169	Blister	Non-affected	761.415755	39.909741	8.917618	106.334621

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

170	Blister	Non-affected	729.109452	39.910011	8.92075	97.630699
171	Blister	Non-affected	37.471886	39.869445	8.918695	23.44806
172	Blister	Non-affected	535.376225	39.910069	8.921708	87.082766
173	Blister	Non-affected	40.118203	39.866597	8.917855	23.144316
174	Blister	Non-affected	357.387405	39.909788	8.921684	68.791081
175	Blister	Non-affected	140.858468	39.907769	8.919753	43.655761
176	Blister	Non-affected	149.995121	39.907655	8.92015	44.919184
177	Blister	Non-affected	133.041849	39.906862	8.919733	42.028812
178	Blister	Non-affected	85.316497	39.906888	8.919847	33.827352
179	Blister	Non-affected	132.983257	39.90731	8.920447	43.489485
180	Blister	Non-affected	320.456153	39.904967	8.920255	65.71637
181	Blister	Non-affected	153.667151	39.903574	8.920067	45.30405
182	Blister	Non-affected	75.143301	39.858732	8.93424	31.759767
183	Blister	Non-affected	294.196739	39.857474	8.934194	62.70394
184	Blister	Non-affected	380.879864	39.915058	8.941	71.900686

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

185	Blister	Non-affected	282.67378	39.858958	8.934923	61.270633
186	Blister	Non-affected	244.494055	39.907006	8.923316	58.521634
187	Blister	Non-affected	3575.217747	39.863964	8.925211	219.530946
188	Blister	Non-affected	362.680744	39.866081	8.927167	70.228302
189	Blister	Non-affected	277.359995	39.905317	8.924325	61.093748
190	Blister	Non-affected	924.841417	39.908914	8.924189	111.859294
191	Blister	Non-affected	733.297789	39.866302	8.926519	99.727625
192	Blister	Non-affected	799.724708	39.910512	8.924247	103.267245
193	Blister	Non-affected	1437.846789	39.910376	8.923648	140.681578
194	Blister	Non-affected	1139.245399	39.864746	8.930374	136.147072
195	Blister	Non-affected	655.093306	39.864307	8.930314	101.364998
196	Blister	Non-affected	1243.969253	39.915249	8.942342	131.397545
197	Blister	Non-affected	1197.065514	39.909843	8.923359	127.696345
198	Blister	Non-affected	1247.007416	39.909066	8.928823	131.10123
199	Blister	Non-affected	39.296611	39.872217	8.914896	23.03589

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

200	Blister	Non-affected	427.137388	39.908377	8.926285	75.561988
201	Blister	Non-affected	3472.173771	39.866026	8.944729	217.246558
202	Blister	Non-affected	557.232406	39.906508	8.925301	87.612757
203	Blister	Non-affected	982.713593	39.866334	8.94201	115.631878
204	Blister	Non-affected	614.219111	39.90758	8.925968	90.312053
205	Blister	Non-affected	2437.67034	39.867181	8.942091	180.637717
206	Blister	Non-affected	839.922793	39.8667	8.942269	108.291908
207	Blister	Non-affected	783.569546	39.906807	8.924719	104.078895
208	Blister	Non-affected	1023.10741	39.86491	8.942258	116.912626
209	Blister	Non-affected	761.687775	39.915469	8.942659	102.265067
210	Blister	Non-affected	613.16636	39.906157	8.923874	91.254874
211	Blister	Non-affected	2427.992302	39.866172	8.940826	181.696212
212	Blister	Non-affected	1648.964202	39.866719	8.940444	153.926724
213	Blister	Non-affected	1169.250813	39.908185	8.920444	127.305341
214	Blister	Non-affected	324.177966	39.908723	8.917566	68.283297

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

215	Blister	Non-affected	3147.57582	39.849903	8.94371	203.963486
216	Blister	Non-affected	378.146666	39.909933	8.915706	71.275298
217	Blister	Non-affected	1005.639752	39.910226	8.919202	123.312917
218	Blister	Non-affected	474.64819	39.910734	8.918576	79.886795
219	Blister	Non-affected	536.654717	39.910546	8.918857	86.162738
220	Blister	Non-affected	1011.168219	39.915578	8.943146	116.664524
221	Blister	Non-affected	111.871207	39.903374	8.915519	39.300532
222	Blister	Non-affected	330.147569	39.910135	8.928848	67.360484
223	Blister	Non-affected	1693.361217	39.860815	8.931237	156.380163
224	Blister	Non-affected	3019.905717	39.863393	8.935531	203.263039
225	Blister	Non-affected	7592.991151	39.866057	8.931617	325.669361
226	Blister	Non-affected	376.327572	39.898862	8.926	72.359507
227	Blister	Non-affected	1934.633176	39.860337	8.942059	162.947001
228	Blister	Non-affected	571.527687	39.897977	8.92631	87.893959
229	Blister	Non-affected	1129.712542	39.858681	8.94113	122.739569

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

230	Blister	Non-affected	325.918605	39.858402	8.939627	71.284461
231	Blister	Non-affected	546.666261	39.860119	8.939858	88.412717
232	Blister	Non-affected	210.249948	39.897111	8.928245	52.730333
233	Blister	Non-affected	490.30724	39.85769	8.941038	82.262768
234	Blister	Non-affected	684.265366	39.923556	8.934489	96.948532
235	Blister	Non-affected	161.527679	39.858906	8.927264	46.586315
236	Blister	Non-affected	527.502801	39.898273	8.928435	83.786548
237	Blister	Non-affected	1838.281071	39.861271	8.943071	166.803886
238	Blister	Non-affected	89.538515	39.899317	8.936934	35.834474
239	Blister	Non-affected	247.147641	39.858145	8.943718	58.643274
240	Blister	Non-affected	490.564656	39.900699	8.936688	80.574666
241	Blister	Non-affected	682.277575	39.854311	8.940745	96.054514
242	Blister	Non-affected	960.936403	39.899811	8.93942	113.809816
243	Blister	Non-affected	3151.298522	39.854559	8.937768	202.783458
244	Blister	Non-affected	210.3994	39.857086	8.938242	53.822319

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

245	Blister	Non-affected	399.91167	39.902708	8.936037	74.181835
246	Blister	Non-affected	2364.839975	39.860579	8.935914	177.843618
247	Blister	Non-affected	591.802928	39.90228	8.937822	90.324614
248	Blister	Non-affected	12053.35776	39.867142	8.953958	421.701519
249	Blister	Non-affected	200.104908	39.899929	8.934652	52.728356
250	Blister	Non-affected	3552.809903	39.868043	8.937821	217.258361
251	Blister	Non-affected	1578.905368	39.869042	8.934692	146.17625
252	Blister	Non-affected	381.63807	39.924759	8.933725	71.4029
253	Blister	Non-affected	238.687054	39.905064	8.91828	56.277707
254	Blister	Non-affected	183.903151	39.857364	8.928931	51.206251
255	Blister	Non-affected	411.053163	39.899497	8.93418	74.471082
256	Blister	Non-affected	758.465921	39.868249	8.938642	100.335463
257	Blister	Non-affected	2651.460597	39.868175	8.936996	188.046476
258	Blister	Non-affected	70.974039	39.89913	8.93455	31.655921
259	Blister	Non-affected	677.237438	39.867899	8.941202	102.924252

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

260	Blister	Non-affected	28.112342	39.899188	8.934352	19.501899
261	Blister	Non-affected	1836.280931	39.867612	8.942892	158.102632
262	Blister	Non-affected	90.780654	39.899087	8.935584	35.330441
263	Blister	Non-affected	172.317518	39.865236	8.942948	49.104021
264	Blister	Non-affected	557.639016	39.863458	8.941156	85.798164
265	Blister	Non-affected	836.292764	39.900246	8.930101	107.561177
266	Blister	Non-affected	634.441226	39.868082	8.935666	92.531524
267	Blister	Non-affected	166.299156	39.900824	8.93738	48.288717
268	Blister	Non-affected	1512.019263	39.86721	8.935212	142.028403
269	Blister	Non-affected	809.844041	39.924832	8.932561	107.003599
270	Blister	Non-affected	264.203082	39.899407	8.932458	59.898689
271	Blister	Non-affected	317.764715	39.899389	8.936609	67.401347
272	Blister	Non-affected	450.133532	39.901668	8.93099	78.677082
273	Blister	Non-affected	213.454545	39.909257	8.925949	53.589663
274	Blister	Non-affected	839.292115	39.90722	8.924259	106.172317

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

275	Blister	Non-affected	657.941876	39.909696	8.923765	99.959841
276	Blister	Non-affected	203.847334	39.899111	8.926533	51.750903
277	Blister	Non-affected	458.769008	39.907988	8.92322	78.07442
278	Blister	Non-affected	261.792409	39.908357	8.925697	58.451199
279	Blister	Non-affected	688.095612	39.907895	8.924573	96.31495
280	Blister	Non-affected	293.61756	39.914047	8.91772	65.568861
281	Blister	Non-affected	266.697959	39.914233	8.91815	60.700071
282	Blister	Non-affected	305.161377	39.909436	8.918178	63.222778
283	Blister	Non-affected	103.182364	39.906698	8.919318	36.655574
284	Blister	Non-affected	109.45823	39.90465	8.918541	39.826724
285	Blister	Non-affected	25.87421	39.934126	8.908105	19.13617
286	Blister	Non-affected	396.429386	39.904366	8.919429	73.433138
287	Blister	Non-affected	729.656778	39.90429	8.918889	99.272784
288	Blister	Non-affected	261.078407	39.903452	8.919228	58.650312
289	Blister	Non-affected	845.841055	39.901587	8.922276	107.613928

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

290	Blister	Non-affected	1115.440289	39.904111	8.917824	122.017322
291	Blister	Non-affected	557.647597	39.903665	8.91831	89.328677
292	Blister	Non-affected	390.573768	39.903026	8.918411	72.225644
293	Blister	Non-affected	184.38674	39.902468	8.918176	53.164653
294	Blister	Non-affected	116.131174	39.90178	8.916719	39.236581
295	Blister	Non-affected	6.782661	39.929496	8.90672	9.810954
296	Blister	Non-affected	6.782661	39.929496	8.90672	9.810954
297	Blister	Non-affected	314.230043	39.907672	8.915145	66.73295
298	Blister	Non-affected	88.400679	39.904026	8.915867	34.307605
299	Blister	Non-affected	14.68667	39.929418	8.906848	15.110462
300	Blister	Non-affected	328.656292	39.904865	8.915881	66.889075
301	Blister	Non-affected	708.940329	39.869027	8.938904	98.253537
302	Blister	Non-affected	218.564173	39.905248	8.915579	56.723337
303	Blister	Non-affected	435.845172	39.866405	8.943138	76.529362
304	Blister	Non-affected	692.153499	39.904717	8.915562	95.215158

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

305	Blister	Non-affected	952.866061	39.865532	8.943196	111.940855
306	Blister	Non-affected	248.497589	39.902225	8.917067	57.527299
307	Blister	Non-affected	1389.438031	39.859319	8.945526	135.92103
308	Blister	Non-affected	248.28124	39.860546	8.944122	56.875123
309	Blister	Non-affected	362.833086	39.900775	8.916228	69.020772
310	Blister	Non-affected	514.192671	39.902723	8.915155	83.073742
311	Blister	Non-affected	304.441053	39.858148	8.944165	63.344941
312	Blister	Non-affected	560.009283	39.858803	8.943919	86.144877
313	Blister	Non-affected	947.798297	39.856217	8.939151	110.947083
314	Blister	Non-affected	1072.146321	39.90065	8.915212	118.084454
315	Blister	Non-affected	904.824288	39.865531	8.909352	111.542873
316	Blister	Non-affected	426.786128	39.859987	8.939222	75.325245
317	Blister	Non-affected	621.548481	39.901472	8.911083	91.92264
318	Blister	Non-affected	741.488336	39.859633	8.938458	99.185004
319	Blister	Non-affected	800.927217	39.858284	8.94053	102.877072

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

320	Blister	Non-affected	434.47008	39.857791	8.939867	76.015299
321	Blister	Non-affected	742.806862	39.90883	8.916126	99.897141
322	Blister	Non-affected	415.04058	39.857361	8.939476	73.874225
323	Blister	Non-affected	289.066856	39.848325	8.935709	61.16825
324	Blister	Non-affected	406.368526	39.921829	8.931193	81.775874
325	Blister	Non-affected	3497.631118	39.843776	8.951895	216.214286
326	Blister	Non-affected	611.887551	39.921204	8.931592	90.421035
327	Blister	Non-affected	320.161702	39.925387	8.925457	67.141021
328	Blister	Non-affected	3064.336964	39.83696	8.943879	204.335403
329	Blister	Non-affected	65.960361	39.929896	8.906561	31.528285
330	Blister	Non-affected	483.434834	39.841513	8.944848	79.227781
331	Blister	Non-affected	221.798669	39.925188	8.927931	54.513315
332	Blister	Non-affected	294.676723	39.925094	8.927644	63.082342
333	Blister	Non-affected	925.879044	39.923872	8.926072	112.333915
334	Blister	Non-affected	474.516742	39.854481	8.936983	79.505134

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

335	Blister	Non-affected	318.664681	39.926126	8.923178	67.166477
336	Blister	Non-affected	10.475366	39.924844	8.924252	12.623199
337	Blister	Non-affected	658.934456	39.854999	8.937391	93.020072
338	Blister	Non-affected	294.157486	39.924863	8.924878	62.568862
339	Blister	Non-affected	1217.859647	39.855768	8.932932	127.049172
340	Blister	Non-affected	234.520341	39.927789	8.921426	56.795966
341	Blister	Non-affected	1012.603677	39.929063	8.922585	114.868355
342	Blister	Non-affected	118.580337	39.878974	8.928829	39.339917
343	Blister	Non-affected	429.638568	39.927881	8.92335	77.246278
344	Blister	Non-affected	262.887757	39.879266	8.929131	59.314322
345	Blister	Non-affected	567.381794	39.927032	8.921955	91.307911
346	Blister	Non-affected	787.61826	39.928499	8.921673	102.352734
347	Blister	Non-affected	1330.67775	39.87809	8.928913	133.92013
348	Blister	Non-affected	141.857075	39.921698	8.921093	44.183327
349	Blister	Non-affected	458.659725	39.871389	8.934333	77.920675

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

350	Blister	Non-affected	4379.966506	39.933209	8.922762	242.229903
351	Blister	Non-affected	283.316558	39.921235	8.91051	63.329192
352	Blister	Non-affected	413.751053	39.873458	8.933952	73.301128
353	Blister	Non-affected	323.218434	39.931401	8.912254	66.660099
354	Blister	Non-affected	785.104633	39.873728	8.9326	102.191125
355	Blister	Non-affected	16.105866	39.932946	8.908653	15.447139
356	Blister	Non-affected	18.062024	39.933351	8.909071	17.78078
357	Blister	Non-affected	316.195801	39.873304	8.930726	65.108429
358	Blister	Non-affected	1306.877398	39.902738	8.930128	136.068098
359	Blister	Non-affected	904.824288	39.865531	8.909352	111.542873
360	Blister	Non-affected	49.221421	39.928845	8.906199	26.473808
361	Blister	Non-affected	571.46026	39.873228	8.930019	85.948925
362	Blister	Non-affected	323.218434	39.931401	8.912254	66.660099
363	Blister	Non-affected	413.751053	39.873458	8.933952	73.301128
364	Blister	Non-affected	141.857075	39.921698	8.921093	44.183327

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

365	Blister	Non-affected	190.907171	39.929247	8.921115	51.452238
366	Blister	Non-affected	823.471764	39.866602	8.908934	109.260126
367	Blister	Non-affected	60.260673	39.929131	8.906087	29.29788
368	Blister	Non-affected	1373.798698	39.846086	8.928545	136.731035
369	Blister	Non-affected	1224.303374	39.844144	8.942117	131.902629
370	Blister	Non-affected	808.502233	39.844382	8.941126	104.527915
371	Blister	Non-affected	1277.916828	39.9245	8.930618	136.658578
372	Blister	Non-affected	809.039551	39.842839	8.949254	104.923591
373	Blister	Non-affected	188.758952	39.907914	8.916599	52.772521
374	Blister	Non-affected	514.192671	39.902723	8.915155	83.073742
375	Blister	Non-affected	362.833086	39.900775	8.916228	69.020772
376	Blister	Non-affected	304.605152	39.901322	8.916542	64.778479
377	Blister	Non-affected	197.656893	39.900237	8.917499	58.817146
378	Blister	Non-affected	291.088889	39.90068	8.918676	61.73528
379	Blister	Non-affected	496.489837	39.899074	8.916169	81.03581

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

380	Blister	Non-affected	218.626101	39.898028	8.917606	54.450115
381	Blister	Non-affected	207.789684	39.899354	8.917155	52.953253
382	Blister	Non-affected	272.086273	39.899641	8.917204	61.466568
383	Blister	Non-affected	91.058316	39.900876	8.918055	35.646871
384	Blister	Non-affected	268.816297	39.90207	8.918245	59.931303
385	Blister	Non-affected	396.701459	39.901528	8.917591	72.473579
386	Blister	Non-affected	402.792359	39.902907	8.91969	72.965762
387	Blister	Non-affected	206.84028	39.867467	8.916941	54.017209
388	Blister	Non-affected	1090.589952	39.90787	8.922806	124.063869
389	Blister	Non-affected	650.921733	39.849952	8.922357	94.989139
390	Blister	Non-affected	286.474373	39.900764	8.924994	64.078782
391	Blister	Non-affected	514.023304	39.857866	8.914535	81.977682
392	Blister	Non-affected	577.104675	39.865392	8.923916	87.58094
393	Blister	Non-affected	160.446104	39.856565	8.930756	48.278485
394	Blister	Non-affected	364.055107	39.876799	8.928664	70.089678

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

395	Blister	Non-affected	196.154415	39.875649	8.928638	52.576366
396	Blister	Non-affected	517.485989	39.875919	8.928901	82.988611
397	Blister	Non-affected	159.245732	39.867719	8.91537	46.534767
398	Blister	Non-affected	209.108381	39.877323	8.935826	53.998862
399	Blister	Non-affected	6965.834045	39.863309	8.928066	323.015353
400	Blister	Non-affected	201.307728	39.871751	8.920289	51.419175
401	Blister	Non-affected	374.871611	39.867505	8.945798	73.205855
402	Blister	Non-affected	917.091971	39.838701	8.948015	109.734778
403	Blister	Non-affected	337.347819	39.862133	8.915058	68.320649
404	Blister	Non-affected	354.707521	39.856725	8.915753	72.224817
405	Blister	Non-affected	74.827609	39.85995	8.91315	32.2352
406	Blister	Non-affected	1121.902375	39.859731	8.937491	125.781756
407	Blister	Non-affected	476.735266	39.862377	8.908459	84.2538
408	Blister	Non-affected	6392.89693	39.866978	8.909827	291.065152
409	Blister	Non-affected	719.859424	39.859254	8.908238	106.496558

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

410	Blister	Non-affected	70.000541	39.860257	8.912934	30.796992
411	Blister	Non-affected	138.210671	39.865844	8.911758	43.240573
412	Blister	Non-affected	186.056101	39.913691	8.942198	50.221336
413	Blister	Non-affected	107.105688	39.870023	8.915757	38.371156
414	Blister	Non-affected	218.891558	39.873463	8.917244	56.278447
415	Blister	Non-affected	797.820015	39.858207	8.916333	104.440145
416	Blister	Non-affected	137.218406	39.922808	8.923435	42.485522
417	Blister	Non-affected	186.966029	39.922886	8.923555	50.415641
418	Blister	Non-affected	170.879295	39.918935	8.934837	48.210855
419	Blister	Non-affected	40.806629	39.870142	8.918467	23.389202
420	Blister	Non-affected	40.806629	39.870142	8.918467	23.389202
421	Blister	Non-affected	32.463051	39.91108	8.918439	21.195831
422	Blister	Non-affected	21.525483	39.869544	8.918567	17.283238
423	Blister	Non-affected	34.918918	39.86671	8.917681	21.909819
424	Blister	Non-affected	435.517539	39.913559	8.942618	75.64753

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

425	Blister	Non-affected	119.815798	39.867665	8.917269	41.26592
426	Blister	Non-affected	33.423082	39.867096	8.916902	21.46929
427	Blister	Non-affected	42.41786	39.866772	8.91736	23.82431
428	Blister	Non-affected	272.291742	39.867737	8.918905	61.02767
429	Blister	Non-affected	61.416715	39.872662	8.921795	28.885726
430	Blister	Non-affected	281.113833	39.86524	8.923348	61.472127
431	Blister	Non-affected	389.991307	39.903241	8.920695	72.486046
432	Blister	Non-affected	1800.22345	39.905125	8.923426	153.184739
433	Blister	Non-affected	668.82388	39.90142	8.915669	93.772743
434	Blister	Non-affected	1438.391934	39.850056	8.926933	141.634768
435	Blister	Non-affected	406.230736	39.907098	8.922846	75.022803
436	Blister	Non-affected	753.5686	39.862271	8.928136	107.085731
437	Blister	Non-affected	267.388034	39.910482	8.923143	60.685264
438	Blister	Non-affected	236.448867	39.908761	8.922963	56.961843
439	Blister	Non-affected	166.581606	39.869401	8.910055	46.911802

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

440	Blister	Non-affected	49.670951	39.8666	8.908424	26.948016
441	Blister	Non-affected	973.704184	39.905573	8.926167	117.013116
442	Blister	Non-affected	1611.82737	39.905152	8.925286	146.136932
443	Blister	Non-affected	3378.229732	39.849081	8.924667	214.768374
444	Blister	Non-affected	715.11329	39.902928	8.924633	97.042334
445	Blister	Non-affected	2530.535697	39.870601	8.94511	195.146893
446	Blister	Non-affected	7235.575595	39.871636	8.938907	322.652301
447	Blister	Non-affected	12627.50085	39.830867	8.967449	413.398011
448	Blister	Non-affected	1523.731226	39.90283	8.92094	142.701582
449	Blister	Non-affected	361.325251	39.896285	8.928558	70.154311
450	Blister	Non-affected	2643.46586	39.902336	8.930263	185.615892
451	Blister	Non-affected	284.466569	39.895284	8.939318	63.344721
452	Blister	Non-affected	367.674869	39.859615	8.937838	69.762551
453	Blister	Non-affected	121.961659	39.898027	8.934103	40.44092
454	Blister	Non-affected	825.056344	39.864604	8.911621	106.568667

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

455	Blister	Non-affected	422.416144	39.897731	8.93199	75.126493
456	Blister	Non-affected	741.322224	39.900478	8.916255	99.695091
457	Blister	Affected	31.790217	39.912799	8.900503	20.653538
458	Blister	Affected	30.891847	39.911477	8.902581	20.333709
459	Blister	Affected	76.760494	39.9126	8.898956	32.142268
460	Blister	Affected	103.534614	39.912752	8.899252	37.436261
461	Blister	Affected	34.841133	39.911583	8.902547	21.650909
462	Blister	Affected	30.795782	39.911439	8.902536	20.11004
463	Blister	Affected	20.897638	39.91139	8.902559	16.760685
464	Blister	Affected	57.282064	39.91318	8.90056	27.596666
465	Blister	Affected	34.326004	39.905145	8.907054	21.691552
466	Blister	Affected	26.271095	39.905828	8.904979	18.731461
467	Blister	Affected	9.720636	39.905984	8.904883	11.551557
468	Blister	Affected	8.634507	39.905614	8.904849	11.047028
469	Blister	Affected	192.227892	39.862436	8.905532	51.135103
470	Blister	Affected	23.890412	39.899535	8.908222	18.194189
471	Blister	Affected	733.110747	39.9034	8.910832	97.807203
472	Blister	Affected	117.978327	39.904389	8.912171	40.965064
473	Blister	Affected	136.833085	39.904476	8.912067	43.552668
474	Blister	Affected	75.298863	39.905851	8.904356	31.939034
475	Blister	Affected	24.743423	39.90486	8.906773	18.871967
476	Blister	Affected	167.962968	39.905179	8.906181	50.670164
477	Blister	Affected	118.09987	39.89635	8.906501	40.175941
478	Blister	Affected	193.564485	39.899805	8.908466	49.8259
479	Blister Cave	Affected	5010.443809	39.864629	8.929467	255.854318
480	Blister	Affected	23810.05574	39.843007	8.928473	553.832811

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave					
481	Blister Cave	Affected	7224.728884	39.857085	8.932053	314.095694
482	Blister Cave	Affected	5087.147458	39.857849	8.934984	258.765813
483	Blister Cave	Affected	129.301036	39.927067	8.919874	43.204525
484	Blister Cave	Affected	54.815223	39.922176	8.923683	27.294167
485	Blister Cave	Affected	6440.355603	39.871821	8.916765	293.108949
486	Blister Cave	Affected	1713.583089	39.873722	8.935071	150.11306
487	Blister Cave	Affected	8154.314799	39.92336	8.929421	347.028604
488	Blister Cave	Affected	4958.62105	39.918517	8.934068	261.123525
489	Blister Cave	Affected	2451.54106	39.873434	8.916264	180.402861
490	Blister Cave	Affected	1938.030687	39.908392	8.91454	165.40363
491	Blister Cave	Affected	2220.566942	39.901059	8.910794	170.83076
492	Blister Cave	Affected	3943.154228	39.898772	8.908749	228.284817
493	Blister Cave	Affected	1814.779264	39.899833	8.908974	157.528446
494	Blister Cave	Affected	914.156405	39.899153	8.909387	112.829948
495	Blister	Affected	3664.048722	39.870907	8.916729	234.145245

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave					
496	Blister Cave	Affected	886.986604	39.897746	8.908779	110.447256
497	Blister Cave	Affected	1430.508328	39.898845	8.917398	140.120365
498	Blister Cave	Affected	343.917822	39.898675	8.920376	66.726094
499	Blister Cave	Affected	6741.553545	39.872048	8.918475	299.379318
500	Blister Cave	Affected	1485.176442	39.900397	8.925331	139.993229
501	Blister Cave	Affected	10130.29551	39.911604	8.915221	361.77993
502	Blister Cave	Affected	20539.7538	39.921272	8.920277	520.224756
503	Blister Cave	Affected	1002.966678	39.871078	8.91635	116.636424
504	Blister Cave	Affected	6100.611503	39.855164	8.924889	290.2692
505	Blister Cave	Affected	422.967705	39.863129	8.91429	74.76275
506	Blister Cave	Affected	2747.724964	39.857453	8.920229	192.795717
507	Blister Cave	Affected	8375.173674	39.906626	8.927695	338.486735
508	Blister Cave	Affected	1524.787632	39.908966	8.929507	144.834983
509	Blister Cave	Affected	2012.219469	39.925399	8.922534	167.430275
510	Blister Cave	Affected	3707.431895	39.926603	8.920883	219.882654

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave					
511	Blister Cave	Affected	2056.005106	39.921942	8.926861	166.935445
512	Blister Cave	Non- affected	5451.538003	39.856772	8.942237	270.534319
513	Blister Cave	Non- affected	1701.596003	39.857763	8.941386	149.759299
514	Blister Cave	Non- affected	886.621851	39.858552	8.942142	108.903313
515	Blister Cave	Non- affected	8645.462873	39.837512	8.959557	347.389671
516	Blister Cave	Non- affected	7684.985014	39.837991	8.957328	317.17079
517	Blister Cave	Non- affected	2943.408244	39.837031	8.947889	195.978213
518	Blister Cave	Non- affected	14670.62037	39.834769	8.973512	441.520572
519	Blister Cave	Non- affected	149.318215	39.87957	8.933161	44.429197
520	Blister Cave	Non- affected	650.322773	39.860625	8.943293	95.508371
521	Blister Cave	Non- affected	4702.649059	39.859343	8.944846	254.98336
522	Blister Cave	Non- affected	2112.014882	39.859561	8.912523	168.569364
523	Blister Cave	Non- affected	2343.318249	39.849093	8.934641	174.811625
524	Blister Cave	Non- affected	3905.565043	39.845894	8.938797	226.430715
525	Blister	Non-	9925.852158	39.905758	8.920776	375.408269

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave	affected				
526	Blister Cave	Non- affected	2559.086044	39.926764	8.922612	185.585944
527	Blister Cave	Non- affected	7008.170128	39.865652	8.941854	303.14604
528	Blister Cave	Non- affected	1337.523641	39.927514	8.924337	133.851594
529	Blister Cave	Non- affected	187.419073	39.879808	8.933107	50.513598
530	Blister Cave	Non- affected	3555.43286	39.90664	8.923806	223.682878
531	Blister Cave	Non- affected	399.078333	39.878806	8.933548	72.661939
532	Blister Cave	Non- affected	3550.932176	39.922665	8.935062	217.019164
533	Blister Cave	Non- affected	382.415691	39.878595	8.934384	70.688459
534	Blister Cave	Non- affected	898.896173	39.920693	8.932768	109.458298
535	Blister Cave	Non- affected	1921.976079	39.875838	8.932333	160.171617
536	Blister Cave	Non- affected	1444.423819	39.858737	8.938497	140.799127
537	Blister Cave	Non- affected	10420.28574	39.843633	8.967834	377.667456
538	Blister Cave	Non- affected	427.311426	39.908047	8.926664	77.095604
539	Blister Cave	Non- affected	340.941166	39.914895	8.916378	66.947121
540	Blister	Non-	10130.29551	39.911604	8.915221	361.77993

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave	affected				
541	Blister Cave	Non- affected	2490.639474	39.86864	8.918557	184.528892
542	Blister Cave	Non- affected	2275.679569	39.910788	8.925067	174.740545
543	Blister Cave	Non- affected	3278.810981	39.910732	8.927268	211.079998
544	Blister Cave	Non- affected	1165.612497	39.908184	8.928024	127.224113
545	Blister Cave	Non- affected	1250.092839	39.907004	8.926573	129.265446
546	Blister Cave	Non- affected	2185.083717	39.907728	8.925595	171.988939
547	Blister Cave	Non- affected	1076.0052	39.901625	8.925185	118.370068
548	Blister Cave	Non- affected	1159.906146	39.898524	8.926537	124.929094
549	Blister Cave	Non- affected	234.261635	39.906372	8.918862	55.497468
550	Blister Cave	Non- affected	1037.406783	39.91016	8.920128	124.088813
551	Blister Cave	Non- affected	827.568001	39.90101	8.921847	104.693101
552	Blister Cave	Non- affected	141.641279	39.901359	8.920412	42.760461
553	Blister Cave	Non- affected	74.545782	39.900938	8.919729	32.688507
554	Blister Cave	Non- affected	87.807152	39.904231	8.91744	34.152747
555	Blister	Non-	94.198133	39.934575	8.908302	36.780569

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave	affected				
556	Blister Cave	Non- affected	727.703039	39.902775	8.917413	104.087856
557	Blister Cave	Non- affected	226.242815	39.900499	8.919245	54.154833
558	Blister Cave	Non- affected	332.963739	39.902932	8.91785	68.260277
559	Blister Cave	Non- affected	278.746177	39.903078	8.91585	61.064981
560	Blister Cave	Non- affected	452.447086	39.902817	8.915507	77.343663
561	Blister Cave	Non- affected	56.784992	39.934282	8.907687	29.51786
562	Blister Cave	Non- affected	405.977693	39.909162	8.91533	73.03554
563	Blister Cave	Non- affected	2617.662698	39.908255	8.915399	191.410371
564	Blister Cave	Non- affected	23.155055	39.929664	8.906374	18.282301
565	Blister Cave	Non- affected	3085.182328	39.927847	8.927466	222.005607
566	Blister Cave	Non- affected	224.273551	39.927329	8.926004	56.140023
567	Blister Cave	Non- affected	9021.998756	39.926962	8.927487	347.013855
568	Blister Cave	Non- affected	2041.601975	39.926579	8.924152	167.289568
569	Blister Cave	Non- affected	14.915852	39.929648	8.9069	15.543923
570	Blister	Non-	2873.726665	39.924556	8.9266	206.796819

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave	affected				
571	Blister Cave	Non- affected	377.032723	39.92435	8.923782	73.840524
572	Blister Cave	Non- affected	579.737199	39.925189	8.923912	88.815865
573	Blister Cave	Non- affected	580.942501	39.925197	8.923291	87.788073
574	Blister Cave	Non- affected	1594.769832	39.924084	8.925121	144.7729
575	Blister Cave	Non- affected	183.477152	39.927774	8.921238	50.018084
576	Blister Cave	Non- affected	142.94605	39.922936	8.919892	44.197991
577	Blister Cave	Non- affected	2877.346071	39.871809	8.915724	197.329138
578	Blister Cave	Non- affected	173.703125	39.923721	8.918669	48.940123
579	Blister Cave	Non- affected	4110.720458	39.838779	8.956389	232.889281
580	Blister Cave	Non- affected	1439.552177	39.846532	8.955033	138.296071
581	Blister Cave	Non- affected	2398.327182	39.921633	8.919096	177.458137
582	Blister Cave	Non- affected	2772.546447	39.844468	8.954578	192.845924
583	Blister Cave	Non- affected	654.712574	39.923318	8.919292	94.225606
584	Blister Cave	Non- affected	3438.363774	39.922534	8.918906	212.022054
585	Blister	Non-	2671.045503	39.921585	8.918158	188.682633

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave	affected				
586	Blister Cave	Non- affected	2641.548453	39.835827	8.948614	192.841786
587	Blister Cave	Non- affected	1486.485811	39.921608	8.917374	140.484333
588	Blister Cave	Non- affected	2302.621864	39.921218	8.916574	175.495985
589	Blister Cave	Non- affected	2953.436207	39.83918	8.945569	196.912913
590	Blister Cave	Non- affected	3106.864411	39.849893	8.933653	200.225818
591	Blister Cave	Non- affected	540.167785	39.928697	8.905795	83.848476
592	Blister Cave	Non- affected	2973.240041	39.83915	8.958743	198.593912
593	Blister Cave	Non- affected	6276.867803	39.866178	8.910701	289.926299
594	Blister Cave	Non- affected	4419.73968	39.848309	8.922226	240.120839
595	Blister Cave	Non- affected	2331.619425	39.928939	8.916928	178.849299
596	Blister Cave	Non- affected	12199.77362	39.855881	8.926037	397.721451
597	Blister Cave	Non- affected	10583.38441	39.845445	8.9339	371.285084
598	Blister Cave	Non- affected	1956.22284	39.849032	8.937167	160.892593
599	Blister Cave	Non- affected	706.629864	39.930018	8.918338	96.940209
600	Blister	Non-	676.503642	39.929086	8.905464	96.018731

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave	affected				
601	Blister Cave	Non- affected	540.167785	39.928697	8.905795	83.848476
602	Blister Cave	Non- affected	2650.923226	39.837289	8.950162	186.287609
603	Blister Cave	Non- affected	3869.351171	39.840949	8.951129	223.917765
604	Blister Cave	Non- affected	5596.484298	39.838758	8.951512	281.613121
605	Blister Cave	Non- affected	2466.969582	39.842568	8.95222	181.651007
606	Blister Cave	Non- affected	107.017486	39.924542	8.920396	39.212567
607	Blister Cave	Non- affected	441.08664	39.929734	8.905427	80.52425
608	Blister Cave	Non- affected	6913.480296	39.840244	8.955363	299.452353
609	Blister Cave	Non- affected	124.048943	39.927123	8.920657	41.404691
610	Blister Cave	Non- affected	6240.019317	39.836514	8.954655	289.838289
611	Blister Cave	Non- affected	2620.531819	39.839581	8.950167	189.990159
612	Blister Cave	Non- affected	3636.918881	39.834825	8.951675	223.367643
613	Blister Cave	Non- affected	3020.190748	39.832989	8.952935	203.23564
614	Blister Cave	Non- affected	1631.844341	39.919168	8.933528	152.593865
615	Blister	Non-	5277.799843	39.846872	8.922493	263.929755

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave	affected				
616	Blister Cave	Non- affected	2559.178965	39.909947	8.916317	186.300512
617	Blister Cave	Non- affected	1843.996246	39.897723	8.910629	159.713521
618	Blister Cave	Non- affected	345.402832	39.902077	8.913209	69.137245
619	Blister Cave	Non- affected	124.960614	39.906464	8.915149	42.904067
620	Blister Cave	Non- affected	242.175116	39.90565	8.9154	57.229519
621	Blister Cave	Non- affected	72.895485	39.905961	8.916493	31.819001
622	Blister Cave	Non- affected	941.114496	39.900257	8.920664	111.030632
623	Blister Cave	Non- affected	157.845545	39.901633	8.919823	46.509195
624	Blister Cave	Non- affected	129.90396	39.929324	8.909152	42.767484
625	Blister Cave	Non- affected	92.744411	39.932173	8.910148	36.019149
626	Blister Cave	Non- affected	1146.138186	39.906229	8.923042	125.069755
627	Blister Cave	Non- affected	1068.515257	39.923742	8.923931	119.12983
628	Blister Cave	Non- affected	1335.582069	39.859442	8.916986	137.653439
629	Blister Cave	Non- affected	1002.966678	39.871078	8.91635	116.636424
630	Blister	Non-	445.004935	39.908075	8.911258	76.839239

***Environmental Impact Analysis of Infrastructures Development and Lake Beseka Expansion
on the Integrity of the Fentale-Metehara Blister Caves, Main Ethiopian Rift***

	Cave	affected				
631	Blister Cave	Non- affected	4562.411626	39.90475	8.924701	250.08101
632	Blister Cave	Affected	6206.284167	39.900872	8.912804	285.625873
633	Blister Cave	Affected	811.065231	39.908185	8.905828	102.399055
634	Blister Cave	Affected	116.786972	39.911228	8.902775	39.054238
635	Blister Cave	Affected	436.211857	39.911801	8.901984	75.863689
636	Blister Cave	Affected	106.832969	39.909002	8.901604	37.837748
637	Blister Cave	Affected	131.921957	39.913103	8.90354	41.414537
638	Blister Cave	Affected	65.556327	39.913071	8.903667	29.796924
639	Blister Cave	Affected	166.108605	39.895937	8.906786	47.09068

