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VOLCANIC HAZARD AND RISK ASSESSMENT FROM FUTUREERUPTIONS OF FENTALE VOLCANO, NORTHERN MAIN ETHIOPIAN RIFT (NMER).

BY: **RAHEL AMENTIE**

ADVISOR: GEZAHEGNYIRGU (Prof.)

CO-ADVISOR: BINYAMTESFAW (Dr.)

A thesis submitted to: Addis Ababa University School of Graduate Studies in the partial fulfillment of Master of Science in Environmental Geology and Geo-hazard.

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Addis Ababa, Ethiopia.

Sep, 2021

Addis Ababa University School of Graduate program

This is to certify that thesis prepared by Rahel Amentie, entitled "***Volcanic hazard and risk assessment from future eruptions of Fentale volcano, Northern Main Ethiopian Rift (NMER)***." submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Geology and Geo-hazards obey the regulations of the university and meets the expected standards concerning the originality and quality. Approved by the thesis examining committee.

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DECLARATION

I hereby declare that the dissertation entitled "**Volcanic hazard and risk assessment from future eruptions of Fentale volcano, Northern Main Ethiopian Rift (NMER).**" has been carried out by me under the supervision of Prof. Gezahegn Yirgu and Dr Binyam Tesfaw, School of Earth Sciences, Addis Ababa University during the year 2019-2021 as a part of Master of Science program in Environmental geology and Geo-hazard. I further declare that this work has not been submitted to any other University or Institution for the award of any degree or diploma.

Addis Ababa, Ethiopia

Date: September 2021

Rahel Amentie

ABSTRACT

Fentale volcano is one of the Quaternary and most active volcanoes on the axial segment of Main Ethiopian Rift (MER) with long history of both effusive and explosive eruption styles. It is located adjacent to Awash national park, Lake Beseka, Metehara sugar plantation and factory where more than 50,000 people live. The most important and busiest highway and railway route of the country crosses the lower flanks of this volcano. However, this active volcano was not studied well in terms of its hazard, the vulnerability and risk of the area. Therefore, this research aims to evaluate the spatial extent of a possible future eruption of Fentale caldera using a GIS-based volcanic hazard tool to produce the hazard map, assess the vulnerabilities and risk of the area. First, the hazard of lava flow is assessed by analyzing various data such as distance from caldera, vent, fault, elevation and slope which were considered as factors and weighted based on their respective contributions to the hazard as a result the higher weight is given for both caldera and vent. Whereas satellite image (sentinel 2A) was used for pyroclastic eruption and ash fall hazard. Vulnerability is evaluated through a multi-criteria evaluation of population, infrastructure (road and rail), different facility and land use/land cover. To evaluate the overall risk, the hazard and vulnerability maps were aggregated through pairwise comparison matrices and creating risk maps. The greater risk will be expected from pyroclastic flow hazard and it is followed by ash fall hazard and lava flow hazard. The result risk maps show that Southern part of the Caldera is subjected for a very high risk including highly vulnerable cities, such as Metehara and Adis ketema (Haro Adi), and infrastructures like road, rail, and sugar plantation are also under high risk. The methodology presented in this work allows risk analysis posed by eruptions sourced from the Fentale caldera and is especially useful in focusing mitigation strategies to reduce the loss from such hazardous events.

Key words: Fentale volcano, Main Ethiopian Rift, Multi-criteria evaluation, volcanic hazard and risk, vulnerability

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ACRONYM

AHP	Analytical Hierarchy Process
ALOS PALSAR	Advanced land observation satellite Phased array L-band synthetic Aperture radar
ARC GIS	Aeronautical Reconnaissance Coverage Geographic Information System.
ASF	Alaska satellite facility
CSAE	Central statistical agency of Ethiopia
DEM	Digital Elevation Model
ERDAS	Earth Resource Development Assessment System
GII	Geospatial information institute
GIS	Geographic Information System
GSE	Geological Survey of Ethiopia
LU/LC	Land use/ land cover
MCE	Multi-criteria evaluation
MER	Main Ethiopian Rift
MSEP	Metehara sugar estate plantation
NNW	North North West
SSE	South South East

1. INTRODUCTION

1.1. General Background

1.1.1. Volcanic hazard and risk

A volcano is a vent in the earth's, by which hot earth materials such as molten rock, hot rock fragments, and hot gases are raised out. Large volumes of evolved, eruptible magma are held in intracrustal magma reservoirs. Large volumes of evolved, eruptible magma are a necessary requirement for activity bursts. It is commonly assumed such reservoirs can only form when the mantle-to-crust magma flux is much higher than the steady state (Burns et al., 2015). Through fissures in the earth's crust, molten magma containing dissolved gases rises beneath the surface. When lava (molten rock) is liquid, it might erupt as fire fountains or lava flows or as steep-sided domes (when it is viscous). Pyroclastic flow deposits are formed when hot avalanches of rock, ash, and gas slide down volcano slopes at a very high speed. When a volcano erupts, a dark ash column rises above it and is revealed as an ash fall deposit.

Based on the form of eruption, chemical composition, and gas concentration of the lava, volcanoes produce a variety hazard. A volcanic hazard is the likelihood of a volcanic eruption or related geophysical event occurring within a specified geographic location and time frame. Any potentially hazardous volcanic process that jeopardizes human lives, livelihoods, and/or infrastructure (Renschler, 2005, Toyos et al., 2007).Volcanic risk is defined as the expected amount of loss as well as the source of injury (from a variety of man-made activities) caused by the danger.

East African rift system is seismically and volcanically active region which is critical to investigate rifting and break-up because its sectors include basins in all stages of rift to passive margin development (Gezahegn Yirgu et.al. 2006). The Main Ethiopian Rift (MER) and the Afar Rift (Keranen and Klemperer, 2008) are two major active segments of the east African rift, and their volcanic activity is used to better understand the relationship between extensional tectonics, intra-continental rifting, and the formation of new oceanic basins (e.g., Ebinger et al., 2008).

The majority of volcanoes are mafic, with basaltic volcanic fields (cinder cones and fissures), shields, and monogenetic cones that erupt in an effusive manner (Bekele Abebe et al., 2007). However, felsic pyroclastic flow deposits have been found in seven Ethiopian volcanoes, including some large-volume ignimbrites (Brown et al., 2015).The most prevalent types of active volcanoes in Ethiopia are those with hot spring-dominated systems and those with fumarole-dominated systems (e.g., Aluto, Corbetti, and Fentale).The Fentale volcano is located in the rift valley's northernmost edge, where it broadens out into the Afar depression. Both inside the summit caldera and 15 kilometers to the north, there are numerous geothermal manifestations (Bekele Abebe et al., 2007). Many geothermal power stations are directly generated by volcanoes, and people living 5-10 kilometers away from active volcanoes take advantage of the resources generated by volcanic activity, such as soil fertility, physiography, and hot springs.

Those geothermal manifestations are a good sign of the presence of magma at depth, and thus the possibility of a future eruption, as well as the related volcanic hazard. An eruption will provide a hazard and risk, perhaps resulting in mortality and damage to nearby exposures such as towns, localities, and other economic operations. The Awash National Park, sugar plantations, sugar factories, and allied industries are all located on the outskirts of the area, which are vital to the country's development. Those elements will be made vulnerable to the hazard.

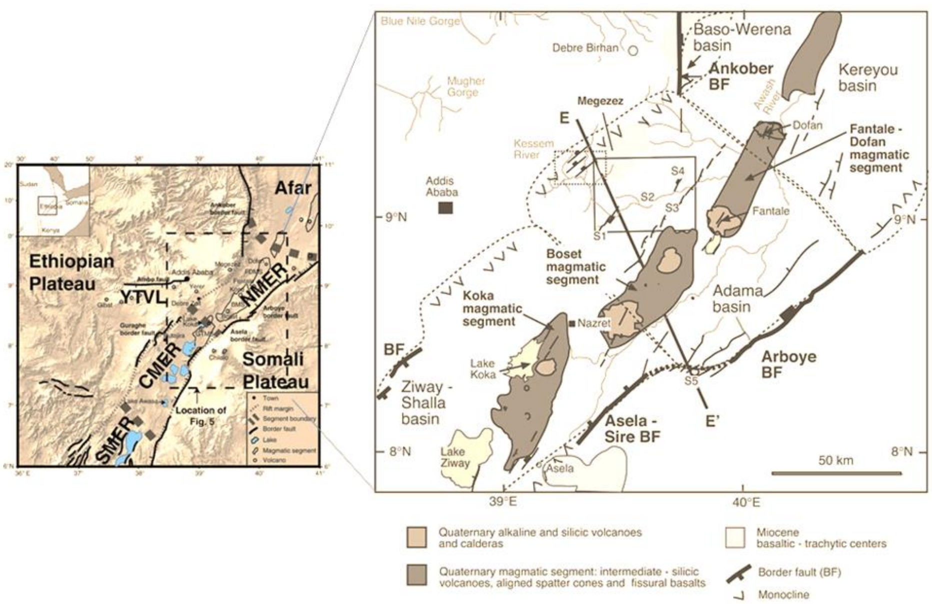


Figure 1.1 tectonic and volcanic map of the MER and Afar rift.(After Renschler et al. 2005 and Keranen and Klemperer, 2008).

1.2 Statement of the problem

Volcanic hazard constitute various problems in developing countries. It can immediately threaten big population centers and have an impact on a country's socioeconomic growth, as well as having serious environmental and economic consequences on a worldwide scale in the form of climate change (for example, Toba, Indonesia, around 75,000 years ago) (Oppenheimer, 2011).

Larger explosive eruptions can eject broad tephra deposits from silicic centers, which may have played a role in human population dispersal out of the Rift Valley (e.g., Basell, 2008). Approximately 500 million people live in the immediate vicinity of active volcanoes today (Auker et al., 2013).

Fentale is one of the most active silicic volcanoes on the northern MER's axial stretch. Exploratory and effusive eruption products are deposited with varying compositions, according on reconnaissance volcanological observations. On the volcano and its surrounds, there is a lot of fumarolic activity and significant geothermal activity. The volcano is characterized by seismic activity and is further pierced by youthful extensional faults and open cracks. Volcanological, geothermal, tectonic, and geophysical evidence all point to the possibility of a magma chamber beneath the volcano at a shallow depth. Like a result, Fentale is a little-known active volcano that, as it has in the past, could erupt effusively or explosively at any time.

As a result, future eruptions of Fentale are projected to pose a severe threat. As a result, such eruptions may cause human death and property damage. The settlements of Metehara and Addis Ketema, as well as Awash National Park and Lake Beseka, are all particularly vulnerable to a future eruption. In terms of infrastructural development (railroad, way network), urbanization, and large-scale irrigation, the Fentale-Metehara area is currently undergoing a rapid expansion. The study area's main irrigation lands are Metehara Sugar Estate Plantation (MSEP) and Awash Melka Farm (Dershaye Belay, 2017).Following Azais and Chambord (1931), who record a story by a priest describing the destruction of a church and hamlet near present-day Lake Metehara, Newhall and Dzurisin (1988) report a poorly documented “13th century” eruption in the southern part of the Fentale volcano (also known as lake Beseka,). As a result, it's clear that assessing and managing volcanic hazard and risk is a major scientific, economic, and political problem.

Volcanic hazards are evaluated through two approaches:

- ✓ Medium to long-term analysis – study of the volcano's eruptive history, volcanic hazard mapping (for each category of volcanic hazard), and modeling, mapping volcanic deposits and assessing explosivity (VEI), intensity, magnitude, and length of previous volcanic eruptions. This is used to describe a volcano's overall activity as well as its potential threat.
- ✓ Short term analysis: The volcano is being monitored both by humans and by instruments (precursory phenomena)

In this study the hazard assessment will be done based on medium to long-term analysis. Assessment of volcanic hazard is done by using geologic (stratigraphic), petrologic information, distribution and volume of the eruptive products. Understanding the eruptive style, eruptive products and observed features i.e., different geothermal feature is important to assess volcanic hazard and risk of an area (Clarke, Benjamin Andrew 2020).The eruption history of volcano can be reconstructed based on the idea past is the key for the future (Tilling et.al, 1989).

Volcanic hazard studies employing remote sensing and geographic information system(GIS) to model and map the spatial extent of different volcanic hazards (e.g., Felpeto et al., 2001) and to assess the vulnerability of various elements at risk (e.g., Aceves et al., 2007). The main purpose of this study is reconstructing the past eruption history of Fentale volcano and assessing exposure to volcanic hazard and risk.

1.3 Research question

As Fentale is little studied and poorly understood, there are a number of open questions about its eruptive behavior in the past and its current status. The following are some of the research questions that need to be investigated in order to have a better understanding of the volcano.

- ✓ What are the styles and magnitudes of eruptions and products recorded at Fentale?
- ✓ What compositional variations exist among the eruptive products?
- ✓ Does a magma chamber exist at some depth beneath the caldera volcano?
- ✓ Which part of the area (where human settlements and different economic activities occur) is more exposed for volcanic hazard from future eruptions?

- ✓ What are the expected impacts (level of risk) of volcanic hazard for different exposures?

1.4. Objectives of the research

1.4.1. General objective

The main objective of the study is assessing and mapping the volcanic hazard and risk from future eruptions of Fentale volcano.

1.4.2. Specific objective

- Reconstruct the eruptive history of the volcano (geology, stratigraphy)
- Produce a preliminary geological volcano-tectonic map of the volcanic complex area using available results and interpreting satellite imagery (sentinel 2A).
- Assess the vulnerability and exposures (population, infrastructures, Landuse/Landcover) of the area at risk.
- Produce probabilistic volcanic hazard and risk maps.

2. MATERIAL AND METHODS

2.1. The study area

2.1.1. Location and accessibility

The study area is located between East Shoa Zone of Oromia Regional State, North Showa Zone of Amhara and South Afar region in Ethiopia. Its geographical extent ranges from 970000m North to 1012000m North, and 580000m East to 630000m East. It has a total area of1690 km^2.There are around six weredas in the study area;Minjar Shenkora, Berehet , Anchar ,Fentale ,Awash Fentale and Amibara wereda. There are three towns at the south and north ends of the Fentale caldera. The main town is Metehara which is founded at a distance of 96 and 200kms from Adama and Addis Ababa respectively. It is found on the railway from Addis Ababa to Djibouti. The second town is Haro Adi (Adis Ketema) within Fentale woreda amd located a short distance on the sub-road taking from the main town, Metehara, towards Metehara Sugar Factory. The study area also lies at Awash National Park that covers 850 square killometer area where many different wildlifes, (Fauna and Biomes) that are a key for economic development to be found.Sabure is found at northern part.

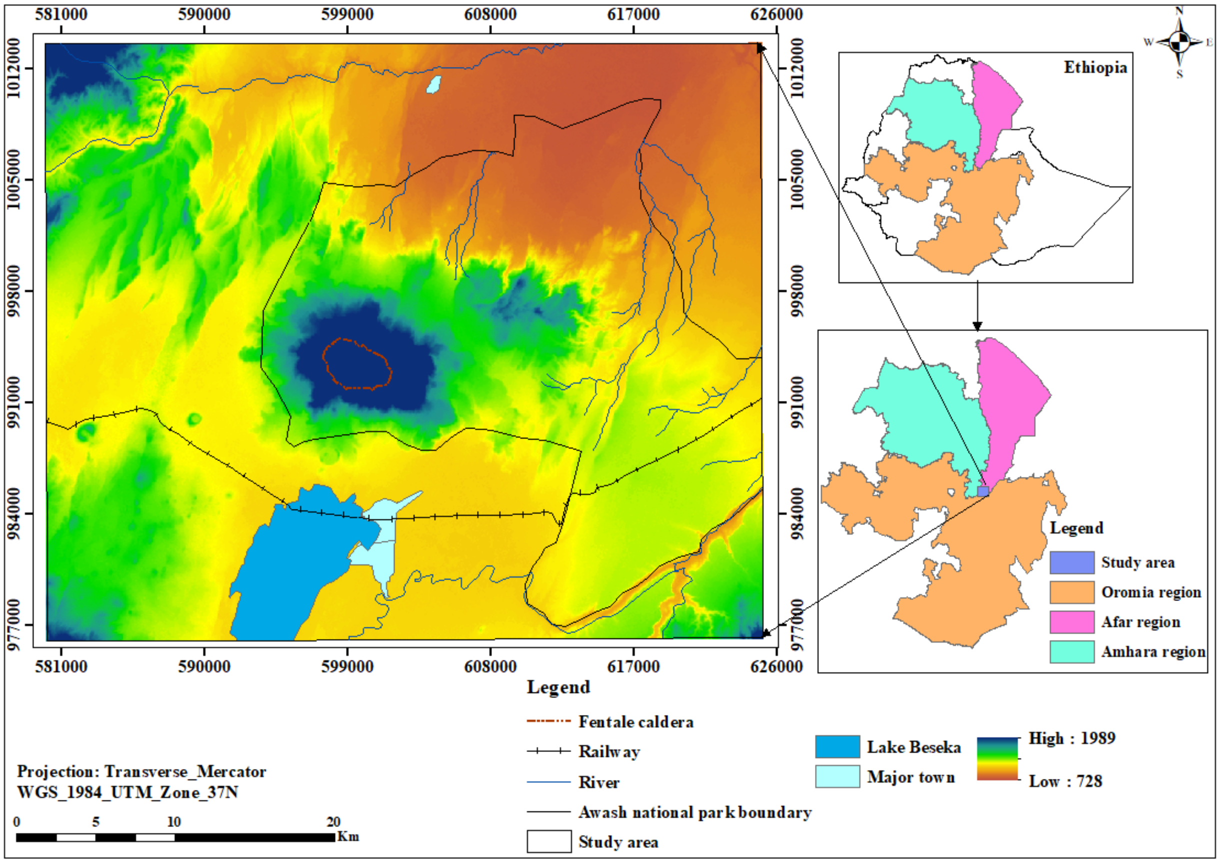


Figure 2.1 location map of the study area.

2.1.2. Topography

The topography of the study area varies from 750 meters above sea level (flat plains) to 1988 meters above sea level (parts of Fentale Mount), although it reaches 2007 meters at the volcano's heart. The highest peak is Mount Fentale (2400 meters). At an elevation of 957 meters, Metehara and Haro Adi may be located. Awash National Park is around 1019 meters above sea level.

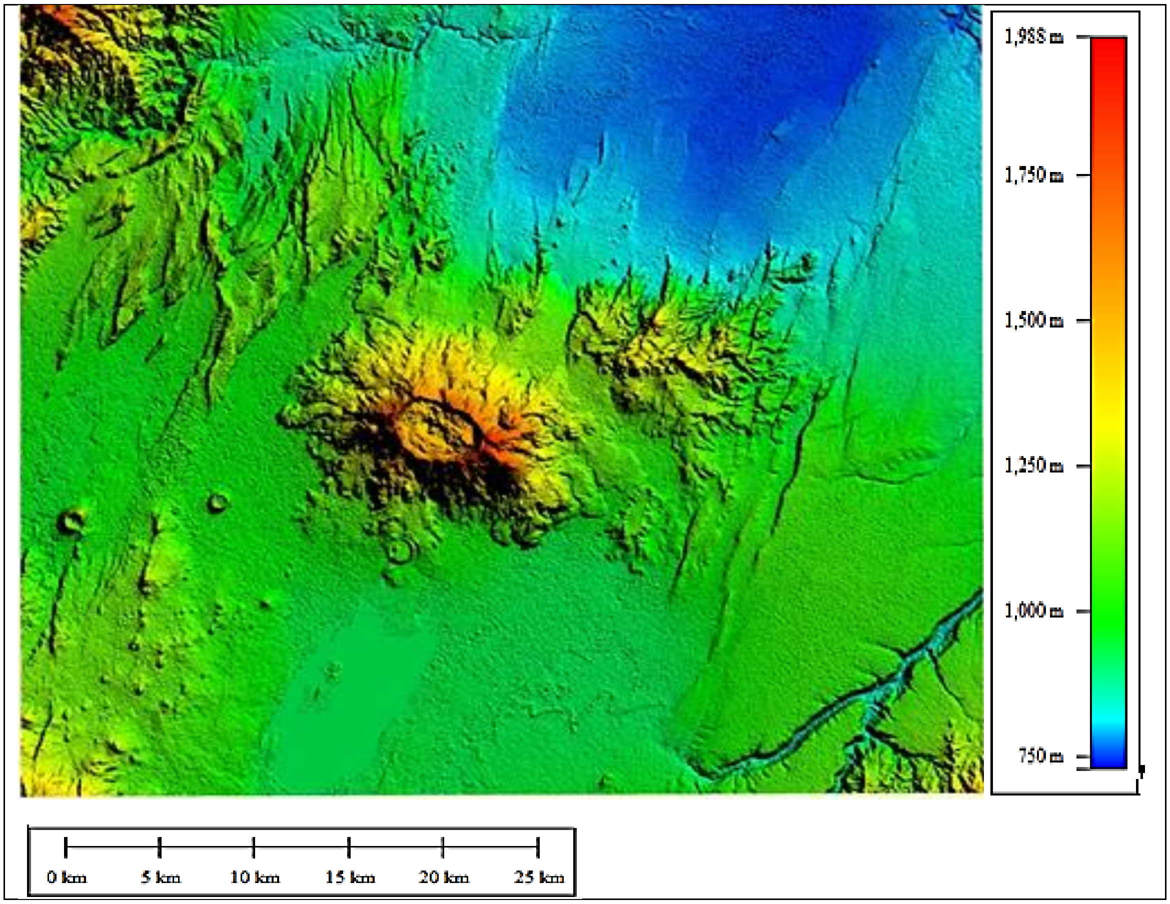


Figure 2.2 Physiography map of Fentale and surrounding area.

2.1.3 Climate

The climate in the study area is characterized by arid and semi-arid environments. Its mean minimum and mean maximum monthly temperature ranges between 12.8^{0}C-20.9^{0}C and 31.0^{0}C-36.7^{0}C respectively. Its mean monthly temperature within a year ranges between 21.9^{0}C to 29.2^{0}C in the months of December and June. The yearly maximum temperature ranges from 32.7 to 34.8^{0}C while the minimum temperature ranges from 16.5 to 18.8^{0}C.

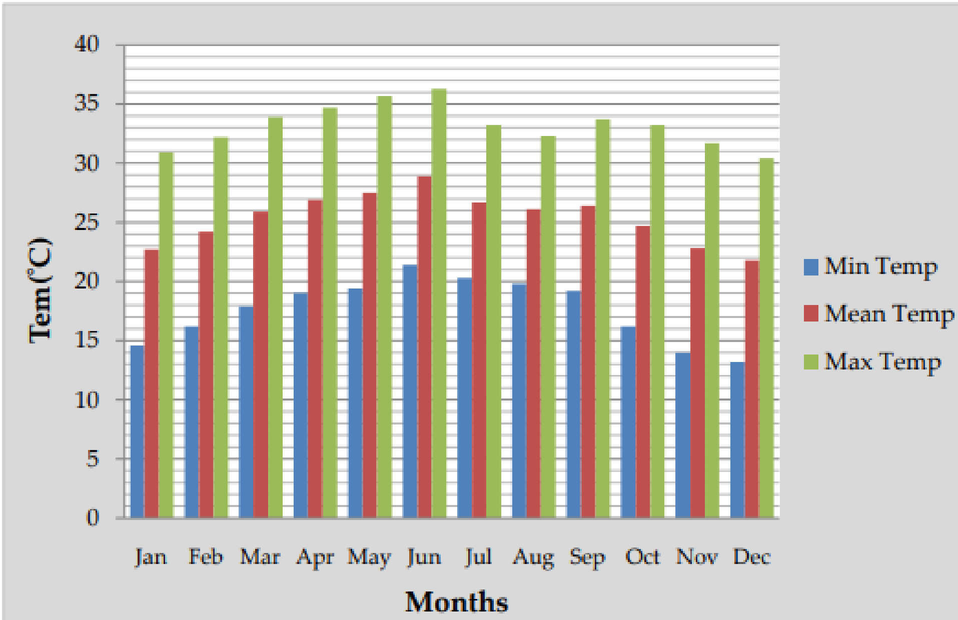


Figure 2.3.Mean monthly temperature from 1970-2015 (source: Tewabe Melkamu, 2019).

2.1.4 Population projection

There are six Wereda in the study area such as Amibara, Awash Fentale, Fentale, Minjar Shenkora, Berehet and Anchar Wereda. Demographic data was obtained from the Ethiopian Central Statistical Agency (CSAE) for each Wereda. The population prediction shows a progressive increase based on the collected data. Anchar Wereda has the highest population estimate among the seven Wereda, followed by Minjar Shenkora.

Table.2.1. Population projection values of the study area in 2020(CSAE)

Region, Zone and wereda	**Population**			**Area in square kilometer**
	Male	**Female**	**Total**	
Afar region, Zone 3, Amibara Wereda	59,022	47,338	106,360	2007.05
Afar region, Zone 3, Awash Fentale Wereda	27,648	25,751	53,399	1046.41
Amhara region, North Showa Zone, Minjar Shenkora wereda	84,308	78,671	162,979	1509.93
Oromia region, East Showa Zone, Fentale Wereda	63,534	56,078	119,612	1521.78
Amhara region, North Showa Zone, Berehet Wereda	22,581	22,018	44,599	791.44
Oromia region, West Harerge Zone, Anchar Wereda	58,220	53,377	111,597	827.08

2.2 Data and Software

2.2.1. Data

Field observation were conducted to identify and define volcanic products, investigate some geological characteristics and geothermal manifestations, estimate the risk area, and confirm land use land cover, and lithology categorization. The lithological and compositional characteristics of the volcanic products are used to determine whether the eruption style is effusive or explosive as well as hazard types (lava flow, PDC, ash fall, etc.…). The thicknesses and surface coverage of the eruptive products are used to infer the eruption magnitudes and degree of explosivity. These parameters are in turn utilized to determine the volcanic hazard types (lava flow, PDC, ash fall, etc.…). Secondary data, such as geological maps, topographic maps, and various statistical data, can be gathered from a variety of sources for different purpose.

The advancements in remote sensing technology to acquire the geological aspect of the earth's surface have been of great benefit to geologists who study geological structures, lithology discrimination, geo-hazard identification and mitigation, geomorphology, geothermal features and landform processes, etc. (Ali, et al., 2012). Satellite images can be used in a variety of geological fields, including volcanology research. They're utilized to extract crater, caldera, cone, fault, vent, hot spring, and fumaroles, among other geological features and structures.

Satellite images (Sentinel-2A and ALOS PALSAR) are downloaded from Copernicus open access hub and Alaska satellite facility (ASF) respectively. Sentinel-2A/MSI is a thermal anomaly detector for lava flows, domes, lakes, and open-vent activity. As a result, they can be used to identify ground deformation as well as monitor recent and ongoing volcanic activity (Francesco et al., 2020). Sentinel-2A provides important measurements for volcano thermal monitoring. Specifically, analysis of thermal and morphometric features of heat sources facilitates tracking of a series of volcanic processes, including lava flow advancements, lava lake pulses, extrusion phases of lava domes, fumarolic activity, thermal activity at multiple active craters, and rise of magma column in open-vent volcanic systems. They are more preferable imagery for identification of different lithology due to their high spectral and spatial resolution (Atillah et al, 2019).

Many volcanologists use remote sensing tool in order to derive digital elevation models (DEMs), monitor volcano deformation, document thermal emission changes, track eruptions and emissions using ground-based instruments, as well as sensors onboard airborne and space borne platforms. Hutchinson etal. (2015) used Lidar hill shade DEM to extract various features of Aluto volcano such as CO_2 degassing observations and structural interpretations to study fumaroles, vents and surface alteration mapping. Satellite for advanced land monitoring. The Advanced land observation satellite Phased array L-band synthetic aperture radar (ALOS PALSAR) is-band synthetic aperture radar that has a resolution of 12.5 meters and a sweep width of 70 kilometers and has been operational since 2006. It's used for things like ground deformation, surface roughness mapping, and elevation and slope extraction, among other things. ALOSPALSAR DEM was employed to create slope, topography, extract fault, and other features, whereas sentinel 2A was used to produce both lithology and LU/LC classification for the study purpose.

Table 2.2. Data and source

Data type	Data	Resolution	Source
Satellite image	Sentinel 2A	10m	Copernicus open access hub
DEM	ALOS PALSAR	12.5m	ASF
Population	Population density		CSAE
Geological map	Geological map	1:250,000	GSE
Topographic map	Topographic map	1:50,000	GII
Spatial population data	Population density		DIVA GIS
Statistical data(vector)	Population, locality, infrastructures, and different facilities		CSAE

2.2.2. Software

Table 2.3. GIS and remote Sensing software with their application

No	Software	Version	Application
1	ArcGIS	10.6	Data analysis Map preparation Fault, vent, cone extraction
2	ERDAS IMAGINE	2014	Image processing

2.3 Methods

To accomplish the research's goal, several methods were chosen and implemented. The study mainly employed satellite image interpretation (image processing and band ratio), supervised maximum likelihood classification, and multi-criteria evaluation (MCE).

A. Image processing

Once the satellite images are downloaded from their source then the next step will be image preprocessing. Mosaicking, Subseting, radiometric, atmospheric, and geometric correction, and spatial augmentation are the several stages of image processing. Four Sentinel 2A images from 2020 were downloaded from the Copernicus open access hub, while ALOS PALSAR was downloaded from ASF for the analysis. After correcting those images as described above, they were mosaicked and masked out by area of interest (AOI).

Table 2.4 Sentinel-2A bands selected and stacked to map both land use/land cover (LU/LC) and lithology (Atillah et al., 2019).

Sentinel-2 band	**Central wavelength(μm)**	**Resolution**
Band 2-Blue	0.490	10
Band 3-Green	0.560	10
Band 4- Red	0.665	10
Band 5- Vegetation red edge	0.705	20
Band 6- Vegetation red edge	0.740	20
Band 7- Vegetation red edge	0.783	20
Band 8- NIR	0.842	10
Band 8A- Narrow NIR	0.865	20
Band 11- SWIR	1.610	20
Band 12- SWIR	2.190	20

The land use/land cover map was created by using image processing techniques such as layer stacking and neighborhood resampling in a 10 m pixel resolution. The categorization is done using a maximum likelihood classifier and supervised classification.

For the study area, six land-cover/land-use classifications were intended to be mapped. Farm land, bare land, built-up area, forest, shrub, and water body are among these kinds.

Table 2.5. Land use/ land cover class description (Tewabe Melkamu, 2019)

Land use land cover class	Description
Bare land	Including bare exposed rocks and bare soil
Built up	Mixed urban and rural settlements
Farm land	Economic vegetation such as Metehara sugar Plantation, Awash-Melka farm
Forest	Natural forests
Shrub	Scattered trees and bush land,
Water body	Lakes, artificial dams and river

B. Band ratio

The fundamental geological element of satellite image processing is improvement and expansion of the visibility of lithological units. Principal component analysis, color composites, band ratios, and other approaches may be necessary for this purpose. These techniques are used to distinguish the various lithologies and to draw attention to the lithological boundary (Bentahar and Raji 2021). Band ratio combination has been proven to be one of the most useful image processing methods for lithological discrimination (Simon et al., 2016).Three band ratio combinations were produced in this study to demonstrate a better discrimination of different rock types. Various bands of 10 and 20 megapixel photos were used and layered using the nearest neighbor resampling approach (Richards, 1999). The band ratio technique was used to distinguish between different lithologies as well as to assess both pyroclastic flow and ash fall hazard .

Table.2.6. Band ratio applied to classify different lithologies(Atillah et al., 2019).

Band ratio	Lithologic unit
8/11,12/2	Welded tuff
12/3	Alluvium, Fine sandstone, Basalts
12/11	Rhyolite,Trachyte lavas

C. Classification

The supervised maximum likelihood classification technique was used to identify and characterize lithologies and land use/land cover.

The data layers are classified by the aid of expert-based manual classification and natural breaks. Natural breaks classes are based on natural groupings inherent in the data. Class breaks are identified that best group similar values and that maximize the differences between classes. Five numbers of classes are chosen to take consideration of the logical analytical hierarchy process (AHP) classes (i.e., very low, low, medium, high and very high). The class also assigned a value based on their contribution to generate volcanic hazard map of the proposed lava flow as well as the risk map. The features are divided into classes whose boundaries are set where there are relatively big differences in the data values (https://learn.arcgis.com/).

D. Multicriteria-evaluation (MCE) technique

Multi-criteria evaluations (MCE) or multi-criteria decision analysis (MCDA) is the collective name for formal methodologies that help decision making by explicitly and transparently considering many criteria. It is done by assigning a relative weight (assigning a value) based on how important that criterion is to a certain situation. It is a semi-qualitative process of pair wise comparisons of controlling factors help to assign weight values to them varying from 1 to 9 (Satty, 2008).

A pairwise comparison matrix is a component of many standard decision-making systems that is used to determine the relative importance of criteria or alternatives. The Analytic Hierarchy Process (AHP) is a pairwise comparison approach developed by Thomas Saaty in 1980 for use on criteria related to the goal. These pairwise comparisons are carried out for all relevant components inside an analysis.

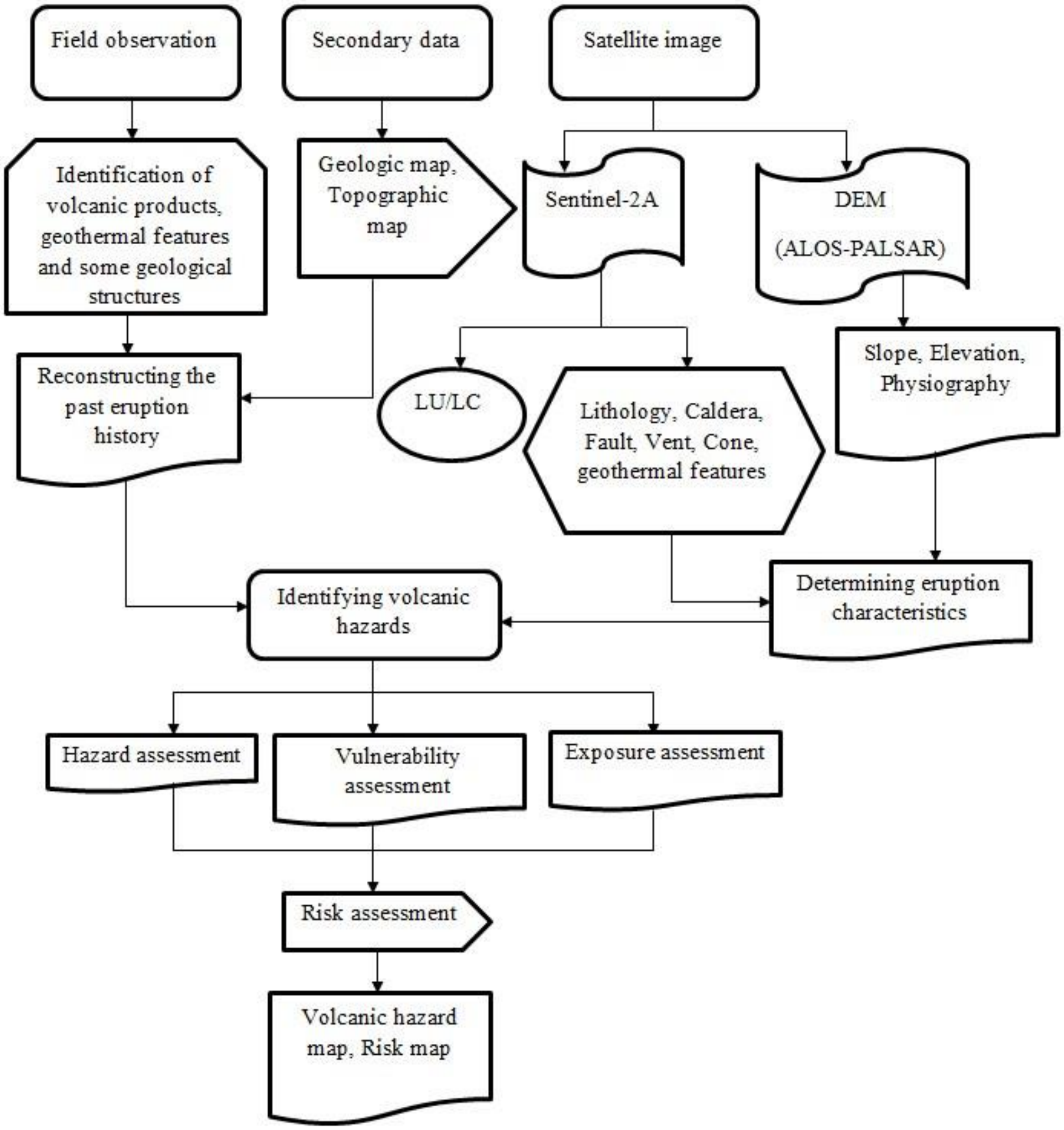


Figure 2.4. General workflow of the study

3. REGIONAL GEOLOGICAL AND TECTONIC SETTING

3.1. Volcanoes of MER

Surface magmatism in the MER takes two distinct forms: large silicic volcanoes and dispersed mafic cones (Bekele Abebe et al., 2007). The primary MER eruption centers from north to south are Fentale, Kone, Boset-Bericha, Gedemsa, Bora-Baricha, Aluto, Shala and Corbetti. The Kone volcanic complex (KVC) is part of a tectono-magmatic segment that has influenced the evolution of the MER's northern region (Kurz et al., 2007). The recent eruption has been taking place at Tullu Moje (syn. Bora) in 1900, at Kone (syn. Gariboldi) in ∼1820, and in ∼1810 at Fentale (Wadge et al., 2016) (Figure 2.1). Several centers, such as the elliptical calderas Kone, Gedemsa, and Fentale, however, are located along pre-rift faults (Acocella et al., 2002).

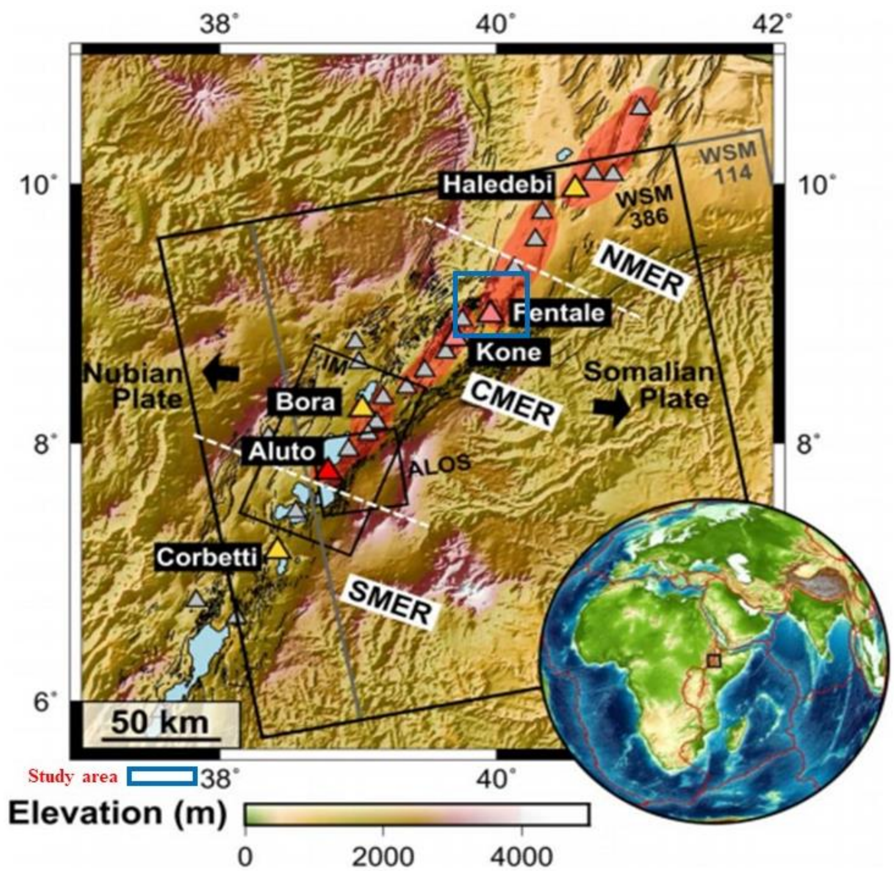


Figure 3.1 Shaded relief map of the Main Ethiopian Rift (MER) with Holocene volcanic centers that are shown as triangles. (Siebert and Simkin, 2002).

3.2. Geologic Setting and Structures

Fentale is one of the most active volcanoes in northern MER, with a variety of explosive and effusive eruption products. Its magmatic history has been dominated by intermediate and silicic volcanic eruptions, which have produced a substantial amount of ignimbrites and ash falls in the early stages and lava flows (obsidian and rhyolites) in the latter stages (Gibson, 1967)

The major volcanic edifice stands 600 meters above the Rift Valley level, and its lavas, excluding welded tuff, encompass a 100-square-kilometer. The volcano's upper half has an elliptical caldera with a diameter of around 3.5 kilometers and a depth of 300 meters. The major lavas appeared to have erupted from the volcano's core or near the pre-collapse zone (before the formation of the caldera). The lower slopes of the volcano were carved by a fault that is linked to the caldera's regional stress pattern and structure (Gibson, 1967). Trachytes and pantelleritic rhyolites are the most common types of rhyolites. K/Ar dating of trachytic lava flows about 3 km north of the caldera yielded a 1.86 0.1 Ma age (William et. et al., 2004).

The spatial distribution of the basaltic eruptive center is controlled by the intra-rift normal fault, while the silicic center is generated by the reactivation of transtensional faults, which create zones of limited extension, concentrating rising magma, and promoting magma reservoir formation (Abebe et al., 2007, Acocella et al., 2002).

Since 1.8 Ma, magmatism and faulting have concentrated into isolated, en echelon Boseti and Dofan-Fentale magmatic segments that cross-cut the Adama and Kereyu basin boundaries. These patterns show a shortening of the zone of active extension, magmatism, and subsidence with time, as well as shifting plate kinematics (Boccaletti, et al., 1999). Normal faults, fissures, joints, fractures, and other rift extensions can be seen. Along the rift axis, fissures are connected to normal faults (Acocella, et al. 2003). The continental rheologies as well as the local volcanic and seismic hazards are determined by the spatial and temporal variations in strain partitioning between faulting and magmatism during progressive extension.

3.3. Magma characteristics at Fentale volcanics

At Fentale (and elsewhere in the rift), there are experimental studies on the rheology of peralkaline rhyolites in progress (Giordano et al., 2014).

Viscosities of lava during the emplacement period are higher due to lower temperatures, as well as crystal and bubble content, but high water content (found at Fentale; Webster et al., 1993) reduces viscosity, particularly for peralkaline melts.

The viscosity of per-alkaline rhyolitic magma is lower than that of calc-alkaline rhyolitic magma (Giordano et al., 2008; Genova et al., 2013; Hughes et al., 2017).Lava flow morphology determines the system's eruptive behavior. Fentale has erupted in a number of small-volume eruptions (less than 0.1 km^3). At Fentale, several vents with a separation of 200–2,000 m erupt to form small-volume coulees.

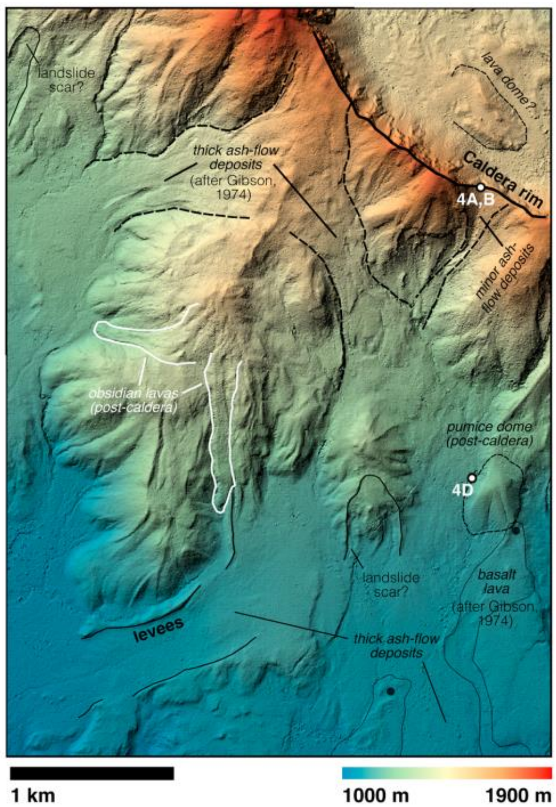


Figure 3.2. Combined hill shade and elevation map of the south-west ridge of Fentale (Gibson, 1974),

The post caldera features of Fentale volcano are lava coulee coulees (S, NE, Central, and W part), Dome (W), pumice cone, and tuff ring (tinsh sababor). Those post-caldera coulees commonly cease before reaching the flat plain surrounding Fentale's edifice. The total volume of this post caldera is <1km^3.

Table.3.1 Post caldera features of Fentale studied by Hutchinson et al, 2019

	Post caldera features							
	Dome	Lava coulee					Pumice cone	Tuff ring
		S	NE	C	W1	W2		
Volume (km^3)	0.061	0.015	0.091	0.034	0.0038	0.0029	0.0036	0.0054
Area(km^2)	6.08	3.84	9.72	12.0	1.84	1.31	1.33	2.88
Vol/Area(km)	10	3.8	9.4	2.8	2.1	2.2	2.7	1.9

3.4. Geothermal manifestations of volcano

Fluid injection from depth into an inflating source region causes active calderas to be raised (Parks et al., 2012, 2015). These tremors are linked to hot fluid pulses entering the geothermal system, and two physical mechanisms (clay swelling and thermoelastic expansion) could be to blame. Uplift, fluid ejection and degassing are caused by hot magma fluids entering a 5km reservoir (Samrock et al., 2015)

Many geothermal regions are located more than 10 kilometers from the nearest volcanic core, implying that regional volcanism poses persistent risks. Seismic and volcanic dangers are possible in the region. The discharge of a single hot mantle plume beneath southwestern Ethiopia 45 Ma caused widespread volcanism across East Africa (Ebinger and Sleep 1998).Volcanoes in the MER are demonstrating deformation which is linked to geothermal activity (Biggs et al. 2011).Volcanic hot spring-dominated systems (Filoa, Hippo Pool, Sodere, and others) and fumarole-dominated systems (Filoa, Hippo Pool, Sodere, and others) are found on several active volcanoes in Ethiopia (e.g., Aluto, Corbetti, and Fentale).

Fentale volcano is one of the most seismically active areas in the MER (Keir et al., 2006), with various hydrothermal manifestations both on and off the edifice. In the area surrounding the Fentale volcanoes, MER, Tesfaye Kidane et al. (2013) conducted paleomagnetic research.

Around the two Fentale (Tinishu and Tilik) volcanic centers, about 28 paleomagnetic sites were sampled. This research took samples of lava and pyroclastic flows. The end result indicated the Fentale magmatic segment's transtensional deformations. Assessing hazards and associated volcanic threats requires knowledge of the subsurface volcanic processes that create unrest at these calderas.

3.5. Volcanic hazard and risk around MER

The wide range of eruptive styles and rates at similar volcanoes along the MER requires a regional assessment of volcanic hazard and risk. Reconnaissance investigations are used to guide hazard and risk mitigation approaches in the East African Rift System. (Online https: //doi. org/10.1016/j.jvolgeores.2018.02.001). The study on the styles of post caldera volcanism and the consequences of volcanic hazards in MER was undertaken by Fontijn et al., (2018). On tephra deposits, new and previously published field observations and geochemical data were combined. The volcanic dangers from the central MER's primary late quaternary volcanic centers are analyzed at the conclusion of the study.

The Bishoftu volcanic field, Corbetti Caldera Sodore, Butajira Silti Field, Bilate River Field, and Hobicha Caldera all have greater population exposure indexes than the rest of Ethiopia. Other volcanoes, such as Aluto, Fentale, Kone, and Tulu Moje, that have been active since 1900 and have a smaller population exposure, may pose larger dangers as a result of a higher hazard ranking. The population statistics for GAR15 came from the Land Scan 2011 dataset at Oak Ridge National Laboratory (Bright et al., 2012).

Hutchinson et al., 2016 studied the causes of silicic caldera instability at Aluto volcano. To assess the causes of ground deformation, the researchers integrated field and remote sensing studies. Interferometric synthetic aperture radar (InSAR) data was used to examine the spatial and temporal aspects of surface uplift. Geodetic data of ground displacement combined with geochemical constraints from degassing are used to assess the magmatic-hydrothermal interactions at Aluto volcano. Lava flows, being buried by layers of ash, or being hit by hot incandescent avalanche clouds, among other things, poses a threat (Kusky 2008).

Tewabe Melkamu (2019) investigated the vulnerability of existing infrastructures in the Middle Awash Basin (MER).The study used remote sensing and GIS technology to map geo-hazard vulnerability. He used the analytical hierarchy approach to create maps for three geo-risks: landslide, seismic, and volcanic hazards at the end of the study. Fekadu Adugna (2013) explored merging field observation, previous work, GIS, and remote sensing together to determine the volcanic hazard assessment of Chabbi volcano from potential eruption. Finally, he created a hazard map as well as an interpretation of the area's volcanic evolution and current activity. Yonas Teshome (2015) studied the possible volcanic dangers posed by the Holocene Gebalaytu and Kurub volcanoes in the central Afar depression. The assessment is made based on the volcano's previous eruptive activity. Finally, from the discovered vents, preliminary volcanic hazard maps and zones for the research region have been created.

Active faults of the Wonji Fault Belt cross-cutting Fentale, Kone, and Gedemsa, according to Giordano et al., (2014), allow basaltic magma eruptions, resulting in scoria cones and lava flows. Seismic and volcanic hazards are possible in the region. Fresh basaltic lava flows, comparable to those found at the Kone caldera complex, have been discovered in Fentale, implying that previous eruptions had occurred. The eruptions of Fentale volcano, which occurred during the 13th century, were reported by Newhall and Dzurisin (1988). A church and a village near today's Lake Metehara, also known as Lake Beseka, were destroyed by the eruption in 1820. (Azais and Chambord, 1931).

4. GEOLOGY OF FENTALE VOLCANO AND SURROUNDING REGION

4.1. Lithologic unit

The Geological map is done by combining both Nazreth Sheet (EIGS, 1978) and Debre Berhan sheet. The units are overlapped from (EIGS, 1978) and identified as basalt, rhyolite, trachyte and obsidian flow of the two groups: Nazreth Group (oldest) and Wonji Group (youngest) of the Fentale and post-Fentale volcanics. According to the map, the oldest and youngest rock units in this study area are Bofa Basalts and Recent pantellerites and comenditic obsidian flows and domes, respectively. There are sixteen mappable lithological units in the study area. However, the most prevalent unit in the study area is young ignimbrites of Fentale.

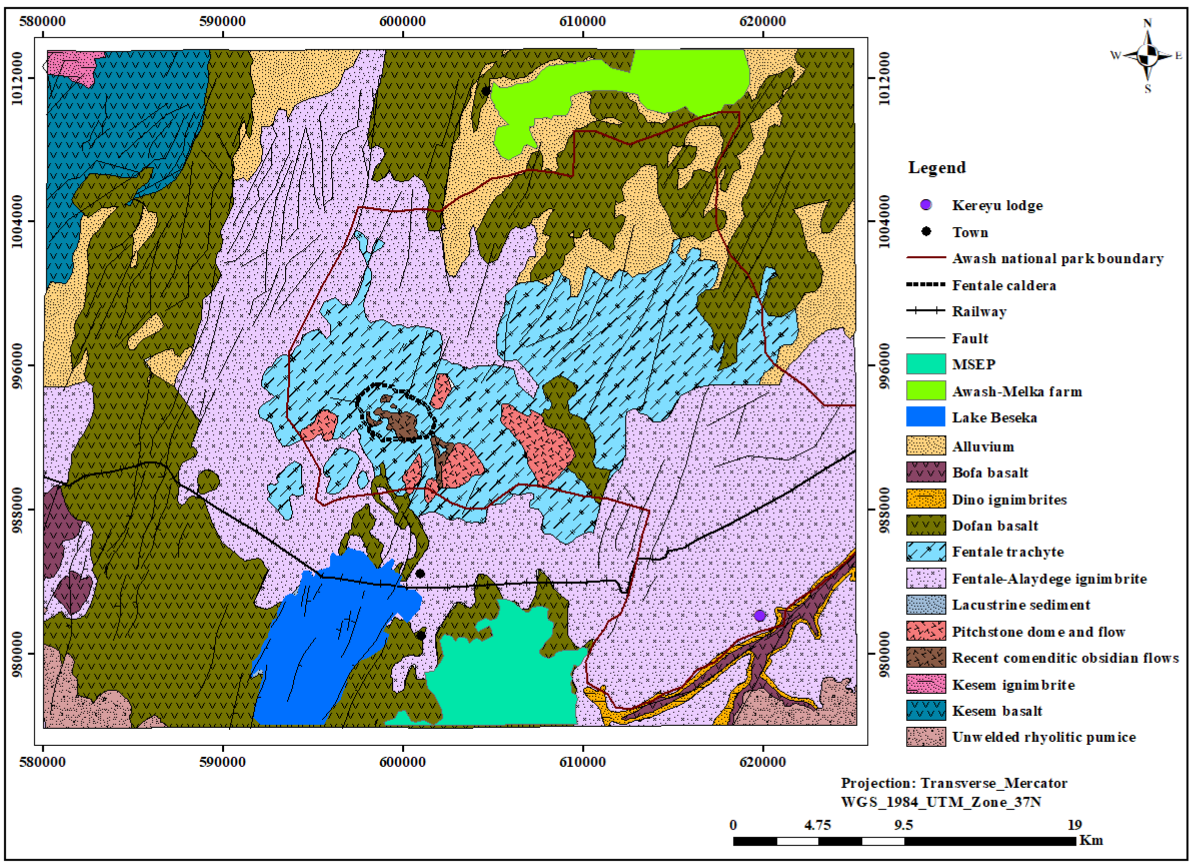
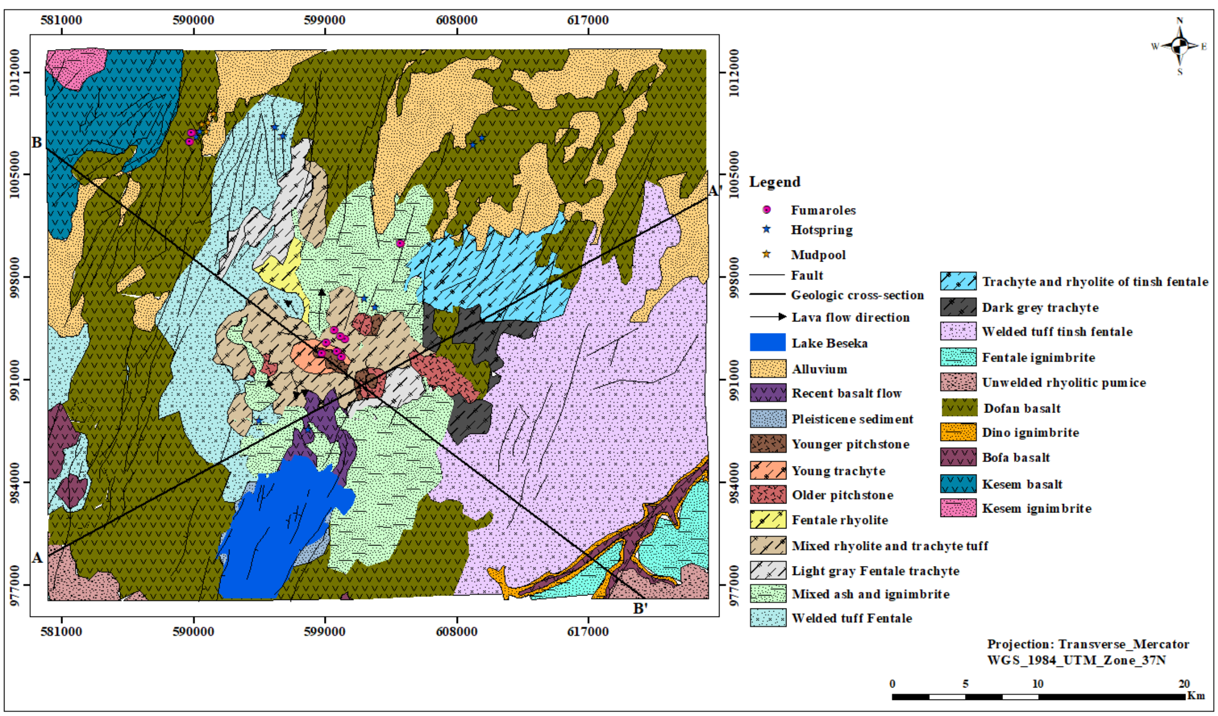


Figure 4.1 Geological map of Fentale volcanic center (modified from GSE, 1978).

4.2. The Fentale volcanic sequence

Volcanic rocks of silicic and mafic affinity formed from lava or pyroclastic material were identified during field investigation. In comparison to the other unit, welded tuff is exposed to be voluminous. From older to younger, the following lihologic units make up the volcanic strata of Fentale volcano examined during fieldwork.

- Pre-Fantale units
  - Dofan basalt
- Main cone
  - Mixed rhyolite and trachyte lavas and pyroclastic deposits
- Fentale welded tuff/ignimbrite
- Post caldera flow and fall deposits
  - Pumice fall
  - AA basalt lava



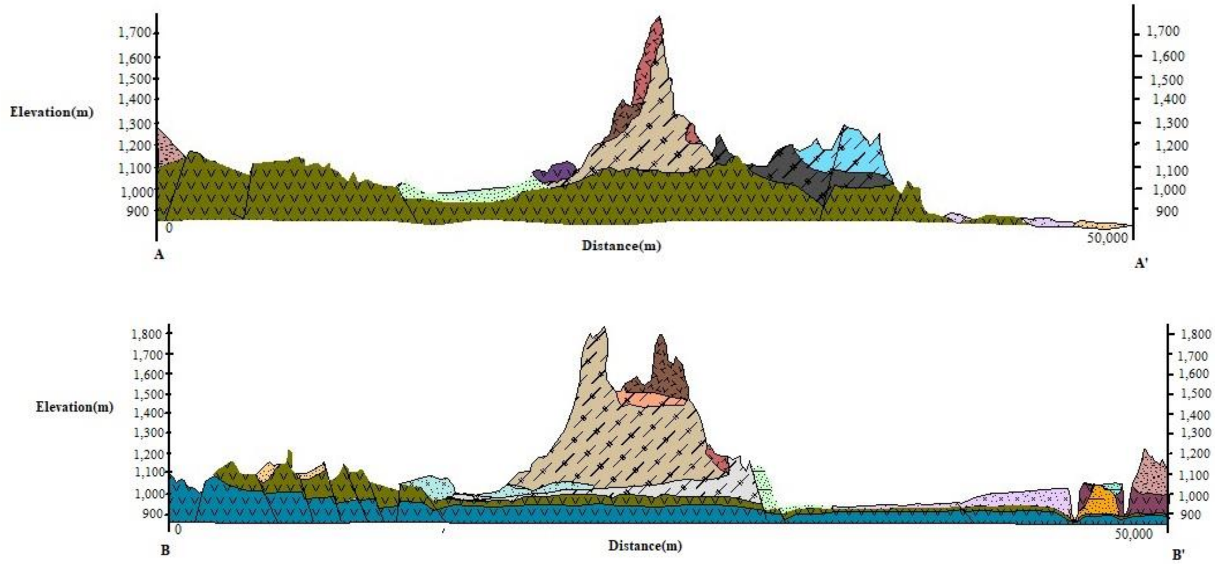


Figure.4.2 Geologic map and geologic cross-section

4.2.1. Dofan basalt

The Dofan basalt is abundantly exposed in and around Tikur Beret, Dofan, Sabure, Awash Arba, Arba Bordede and Da-Itele localities. Its vertical thickness ranges from tens of meters in flat places to hundreds of meters in the Arba Bordede area. It is quaternary in age affected by step faults in Sabure, Awash Arba and Arba Bordede localities. The one depicted in the diagram is found on the volcano's northwestern flank (E-0590711, and N-1006692). It can be located in the eastern portion of Kesem Dam, where there are some fumarolic activities.

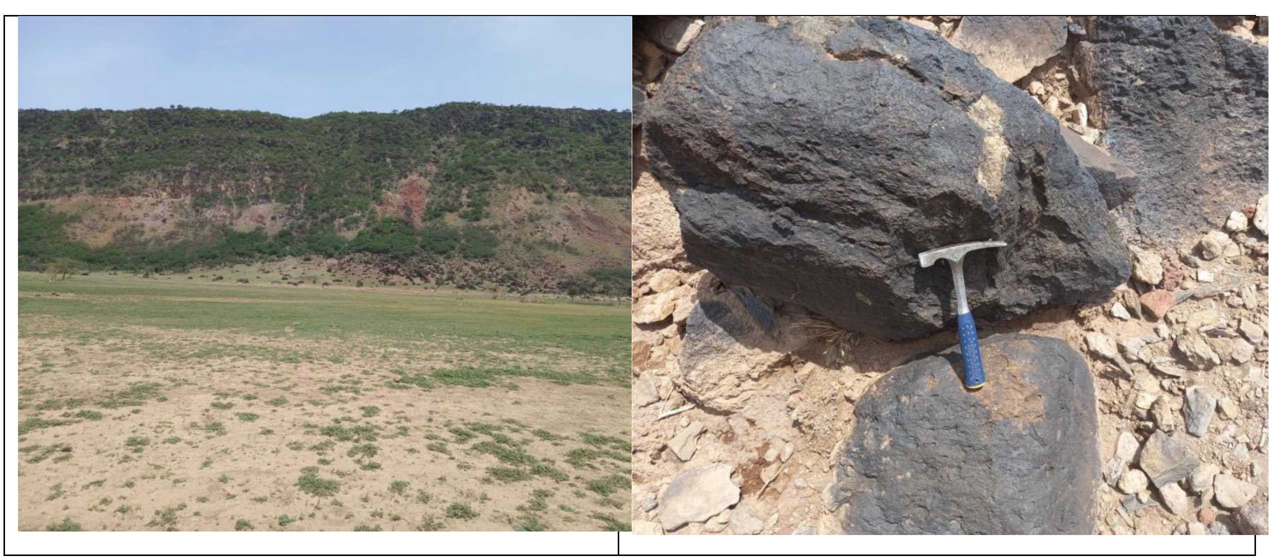


Figure 4.3. Dofan basalt found at NW (GPS location)

The unit can also be found in the Fentale caldera's western and eastern parts, as well as the Metehara Sugar Estate Plantation's eastern part (MSEP). Quarry site exposure located at E-0592483, and N-0981524 in the southeast of Lake Beseka has vertical and horizontal joint, as well as NNE-SSW trending normal faults. The total thickness of the segment is 3.5 meters. Four basaltic lava flow levels have been detected within the aggregate quarry. From bottom to top, these are phaneritic (plagioclase) basalt, porphyritic phaneritic basalt, huge aphanitic basalt, and porphyritic aphanitic basalt. One lava layer conforms to the shape of the other. They did, however, have distinguishing characteristics, such as rock texture.

a) b)

Figure 4.4 Basaltic unit; a) Massive basalt outcrop, b) Basalt unit showing porphyritic texture

4.2.3. Main cone

The Main Cone of the volcano consists ofsome undifferentiated components of rhyolitic and trachytic lavas and obsidian flows intercalated with fallout pyroclastic deposits. All of these rocks were erupted from vents located in the caldera's current region.Some of these vents created pumice cones, which were sometimes fused, and extruded glassy flows in the later stages of their activity. Three lateral vents were characterized by a similar eruption dynamic that evolved from explosive to effusive over time throughout the cone's final stages of expansion.

i. **Trachyte and rhyolite of tinsh Fentale**

An older, eroded caldera (Tinish Fentale) about 8 km northeast of the main Fentale caldera appears to have had a similar but earlier geological history to that of Fentale. Trachytes and pantelleritic rhyolites make up the majority of the rocks. It's a road cut exposure with coordinates E-0612898, N-0997500. The outcrop is roughly 8 meters thick, with a huge rhyolite unit in the middle that is sparsely stratified and extensively broken.

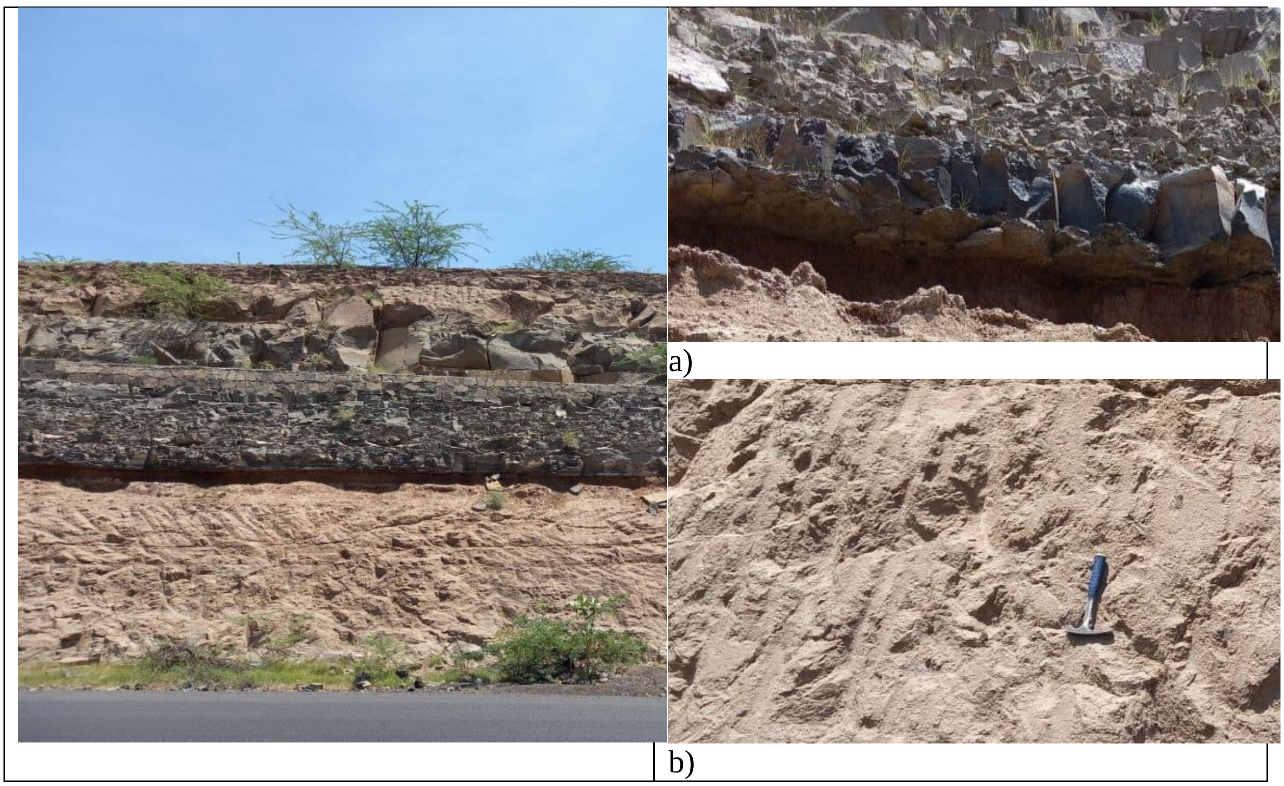


Figure.4.5 Trachyte and rhyolite flow a) layered rhyolite with fractures b) massive trachyte unit

ii. Intercalated rhyolite and trachyte of Fentale

Peralkaline rhyolites and trachytes, along with pumice, pitchstone, and obsidian, are a primary product of Fentale's pantelleritic volcanic eruptions, which are exposed in the caldera's east and south ends, as well as the northwestern slopes of Mount Fentale (E-0602535, and N-0987806). A few thin welded tuffs have been discovered with numerous series of silicic lavas and intercalated tuff succession. These mixed rocks cover the trachyte flows associated with the Fentale volcano. They have the same chemical composition as Tinsh Fentale trachyte and rhyolite. In terms of age, they are different. According to Williams et al., this unit is a younger group of trachytes and rhyolites that erupted about 3.5 km from the main caldera's center via a satellite vent (2004). Flow banding can be seen in the silicic flows, which are grayish in color.

Figure 4.6.Main cone unit; mixed rhyolte and trachyte deposit in NE of the caldera. The rhyolite shows flow banding.

4.2.4. Welded tuff (Fentale ignimbrite)

After the growth of main cone, the quiescence period was followed and it was accompanied by the collapse of the summit caldera culminated in the eruption of the voluminous Fentale Welded

Tuff. With the use of the fission tracks method, this big event was recently dated at 168, 00038 years (Williams et al., 2004).Tuff is channelled through troughs on the volcanic edifice's slopes, eventually covering the entire lower slopes and plain surrounding the volcano. It is the dominating exposed unit in the study area, covering the plains to the south and west of Fentale as well as part of the mountain's lower slopes, before thinning out and becoming confined to valley fills on the upper slopes. The ignimbrite unit shows variegated color as well as the size of fiamme at NE of the caldera (E-0595716, and N-0984546). Grey ignimbrite is visible at the top, while green ignimbrite is exposed at the bottom. Both deposits have fiamme and flow horizontally at the surface. Fiamme come in a variety of sizes, from enormous to small. Grey ignimbrite has big fiamme with pumice fragments. In comparison to green ignimbrite, fiamme has smaller sizes and is more tightly welded. The grey ignimbrite, on the other hand, has subrounded big fiamme.

a) b) c)

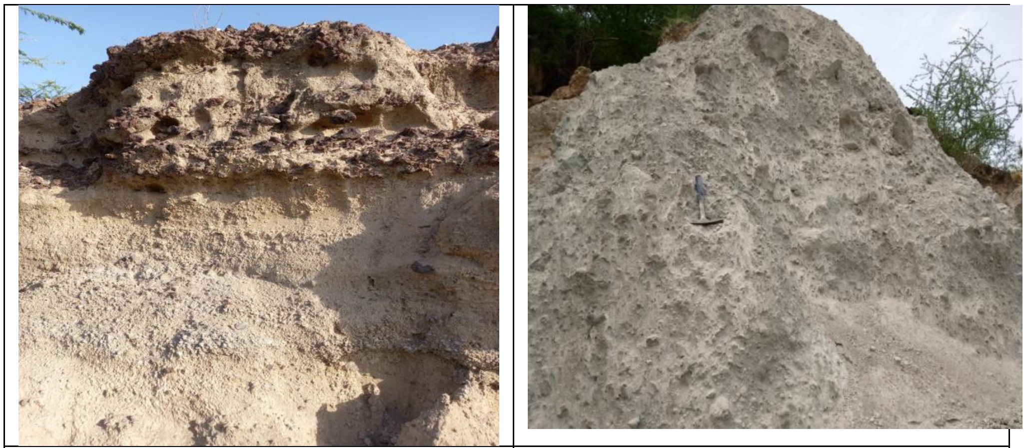
Figure 4.7. Fentale Welded tuff; a) massive ignimbrite unit b) the ignimbrite unit is variegated in color (green and grey), c) grey ignimbrite

4.2.5. Post caldera products

The Products of the Post-caldera activity have been erupted from vents located both inside and outside the caldera. The caldera's youngest trachyte is limited to the caldera floor, intersected and tilted by 120-150E trending faults that run parallel to the caldera extension and orthogonal to the Wonji Fault Belt. This activity was followed by the eruption of pantelleritic pumice cones and lava domes, both inside the caldera and along the slopes of the edifice, aligned along NNE and WNW directions (GSE 1978).

i. Ash fall deposit

Unwelded ash fall deposit mainly covers north and southern part of the Fentale caldera. Some of the pyroclastic units in the research area are unwelded, with thin pumice beds interspersed between the lavas (Gibson, 1967). Intercalated units of unwelded ash and pumice deposits are located north of Lake Beseka and south of the caldera (E-0592468, and N-0986139; E-0592395, and N-0986206). The ash deposit is unwelded (highly fragmented) which interlayered with thin scoria at the top and pumice deposit at the middle. The top layer is dominated by sparsely bedded scoria, the intermediate layer is dominated by pumice, and the bottom layer is dominated by ash. The pumice cone deposit, which is light pink and white in color, may be found in the north eastern part of Lake Beseka and the south eastern half of the caldera (E-0600472, and N-0988761).



a) b)

Figure 4.8. Ash fall deposit; a) layering of scoria (top) and pumice (bottom) dominated deposits, b) pumice cone deposit

ii. Historic basalt flow (Aa basalt)

The recent and the last activity were occurred in 1828 and generated basaltic lava flows and scoria cones, between the volcanic edifice and the Metehara town. It is Holocene basaltic lava which covers an area is found between northern shore of lake Beseka and the Fentale caldera (E-0598098, and N-0984989).The unit is fresh basalt outcrop with vesicular texture having a jacked surface with a black color. The most recent flow, according to several historical reports and local oral tradition, occurred around 1810 AD (Buxton, 1949; Williams et al., 2004). The plagioclase phenocrysts are placed in a fine-grained groundmass formed of pyroxene and plagioclase lathes in these porphyritic basalts (MOWIE/OWWDSE, 2014).

Figure 4.9. AA basalt located at south of Fentale caldera

4.3. Geologic structures

In rift habitats like EARS, geologic features (brittle structures) are more common. Craters, calderas, volcanic vents, geysers, and hot springs are all common features linked with volcanoes or volcanic environments. Fentale has a large number of vents and craters in comparison to its post-caldera erupted volume, indicating frequent but small-scale eruptions. There are also two cinder and scoria cones on the island and five cinder and scoria cones northwest of Lake Beseka. Craters are depressions seen at the summits of volcanoes. A youthful intra-caldera crater that is elongated in the same direction as the main caldera can also be found. Resurgent domes and intra-caldera craters are examples of this.

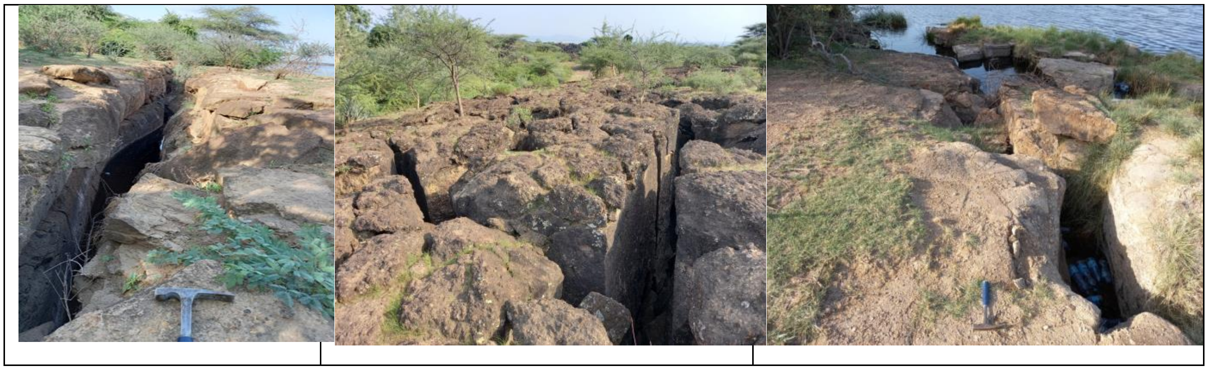
4.3.1. Normal faults

There are many normal faults with general trend of NE/SW that were identified and measured during field study. Different fault escarpments are observed towards the center of Fentale caldera. The orientation of the fault is N30°E, and 80^0SW, N40°E, and 80^0SW.

Figure 4.10. Normal fault near Kesem Dam

4.3.2. Fissures and surface cracks

Fissure is an elongate fracture or crack at the surface from which lava erupts. There are various fissures and fractures in the study area consisting different orientation. The fissures are propagated and form many joint sets with different orientation. Fissures are associated with normal faults in the rift axis (Acocella, et al. 2003). Rift-related faults/fissures are also strongly associated with vents (Williams *et al.*, 2004). They are located at E-0595705, and N-0984674;E-



0595811, and N-0984651; E-0595825, and N-0984678.

Figure 4.11. Surface cracks or joint and joint sets

Table 4.1. Orientation of the joint set

Joint set												
Joint set 1						Joint set 2						
Strike	032	055	015	042	030	297	335	325	310	335	347	327
Dip	90^0					90^0						

4.4. Volcanic stratigraphy of Fentale

The volcanic history indicates that Fentale caldera have bimodal style of eruption i.e., having both effusive and explosive eruption. There are different local geologic units that are deposited at different stages of caldera (pre-caldera, during caldera formation or caldera collapse, and post c aldera).The stratigraphy indicates the age difference between distinct units from Plateau to post-caldera activity. Pre-caldera units are welded tuff (2) of tinsh Fentale, trachyte and rhyolite of tinsh Fentale, dark grey trachyte, welded tuff (1) of tinsh Fentale, Dofan basalt, Dino ignimbrite, and Bofa basalts. Young pitchstone, young trachyte, ancient pitchstone, Fentale welded tuff, Fentale rhyolite, mixed rhyolite and trachyte, and light grey trachyte are some of the units deposited during the development of the Fentale caldera. Post-caldera deposit includes alluvium, Pleistocene to sub recent basalt, and Pleistocene sediment. The plateau is connected with the rest of the Kesem basalt and Kesem ignimbrite.

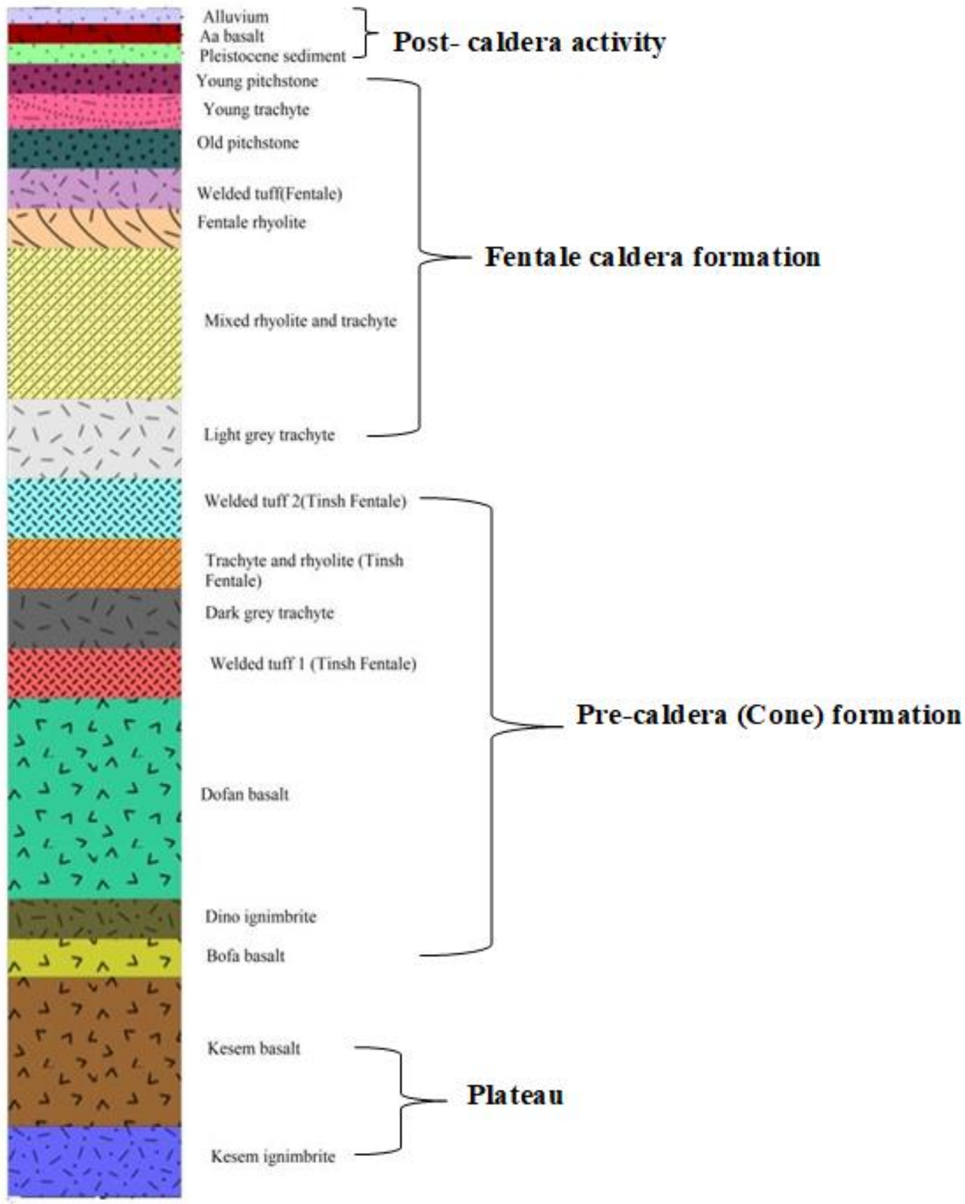


Figure 4.12.Volcanic Stratigraphy of Fentale from younger (top) to older (bottom)

4.5. Geothermal manifestations

Many geothermal regions are found more than 10 kilometers from the nearest volcanic core, implying that regional volcanism poses persistent dangers. Fentale volcano which sits at NMER hosts several manifestations of hydrothermal activity both on-edifice and off-edifice. It is one of the most seismically active regions in the rift (Keir et al., 2006), warning of the potential for seismic and volcanic hazards including numerous geothermal manifestations both inside the summit caldera and 15 km to the north (Bekele Abebe et al., 2007). Similarly, there are abundant hot springs around the O'a caldera coupled with seismic activity and the unknown present state of volcanic unrest underlying volcanic complex (Mohr et al., 1980).A steep gorge down the caldera rim on eastern side with a column of steam rising from the base suggests the presence of a hot spring or fumarole. There are various geothermal features in NW part of the caldera around Kesem locality such as fumarole, hot spring, and mud pool.

4.5.1. Fumaroles

Fentale is categorized under fumarole dominated volcano on which most fumarolic activity are taking place at its volcanic center (Hunt et al., 2017). Fumaroles are holes in the earth's surface that release steam and volcanic gases like sulfur dioxide and carbon dioxide. Near active volcanoes or in locations where lava has risen into the earth's crust without exploding, they can appear as holes, cracks, or fissures. During field studies in the NW section at ancient basalt, some fumarolic activity was discovered (E-0590507, and N-1006884; E-0590512, and N-1006900).

Figure 4.13.Fumarolic activity around Kesem area NW part of the caldera.

4.5.2. Hot springs

It's a thermal spring with water that's warmer than 98°F (37°C): the water is usually heated by evaporation from or passage near hot or molten rock. Groundwater is heated by subsurface magma, which produces steam and hot water. The heated, less dense water rises through the ground's fractures and crevices. Geysers, fumaroles, hot springs, and mud pits are formed when the water reaches the surface. Hot springs can be located at an alluvium deposit in the northwestern half of the Fentale volcano. They're also found in the vicinity of alluvium deposits where fumarole is abundant.(E-0590631, and N-1007378; E-0590624, and N-1007427; E-0590713, and N-1007790).

Figure 4.14. Hot spring

4.5.3. Mud pool

Mud pools are hot springs or fumaroles with little water but a lot of clay from the surrounding rock and soil, resulting in boiling slurry. They are found at an alluvium deposit in the Artu locality in the NNW part of the Fentale caldera. (E-0590605, and N-1007558; E-0590700, and N-1007766;E-0590614, and N-1007436).

Figure 4.15. Mud pool

5. VOLCANIC HAZARD AND RISK

5.1. Definition of volcanic hazard, risk, vulnerability, and exposure

- A **volcanic hazard** refers to any potentially dangerous volcanic process that puts human lives, livelihoods or infrastructure at risk of harm.
- **Exposure** refers to the location, characteristics, and value of assets such as people, building, infrastrucres (road, rail, and transport networks), health facilities, etc. located in the area that are subjected to volcanic hazard.
- **Vulnerability** is defined as the proportion of the lives, property or productive capacity threatened likely to be in a volcanic hazardous event (degree of damage resulting from the volcanic hazard). In general, vulnerability means the potential to be harmed. Vulnerability to volcanic hazards is thus the potential to be harmed by volcanic hazards.
- **Volcanic risk** is defined as the expected amount of loss, cause of damage (for various man-made activities) caused by volcanic hazard. It is the combination of both the hazard and vulnerability of an area.
- **Risk** = Hazard x Exposure x (Vulenerability – Resilience)
- **Hazard/Risk Index** = (recurrence + magnitude)/ (style + population exposure)

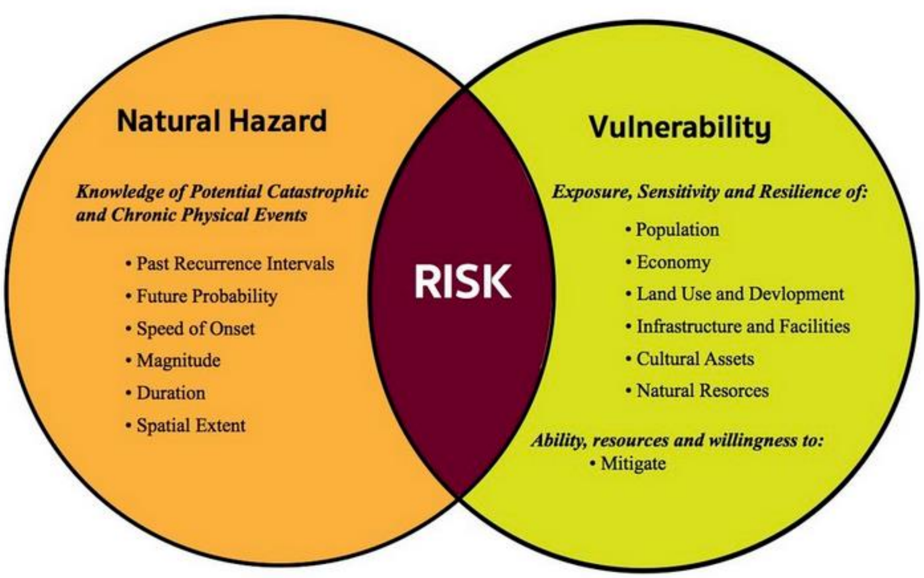


Figure 5.1.Risk of Disaster Diagram (Source: Rainer and Wood (2011))

Volcanoes eject highly flammable gases, ash, lava, and rock, all of which are highly destructive. People have died from volcanic blasts. Volcanic eruptions can result in additional threats to health, such as floods, mudslides, power outages, drinking water contamination, and wildfires. Different types of volcanic hazards such as;

- Tephra/Ash.
- Lava Flows.
- Lahars.
- Volcanic Gas.
- Climate Change.
- Pyroclastic Density Currents.
- Volcanic Landslides.

The three primary hazards including pyroclastic flow, ash fall and lava flow hazards are discussed for the purpose of this study.

5.1.1. Pyroclastic flow hazard

A pyroclastic flow is a chaotic mixture of rock fragments, gas, and ash that moves quickly (tens of meters per second) away from a volcanic vent or collapsing flow front. They are formed by the explosive eruption of molten or solid rock pieces, as well as the non-explosive eruption of lava when dome portions or a thick lava flow collide down a steep slope. Pyroclastic flows can be extremely destructive and deadly because of their high temperature and mobility. They are so fast and so hot that they can;

- Knock down, shatter, bury, or burn anything in their path.
- Small flows can destroy buildings, flatten forests, and scorch farmland
- Kill animals and people.

Figure 5.2. Pyroclastic flow

5.1.2. Ash fall hazard

When magma or vent material explodes, it produces volcanic ash, which is made up of rock and glass pieces. All explosive volcanic eruptions produce ash, which is the most common and widely distributed volcanic danger. Volcanic activity produces hazards that can affect areas far from the volcano, such as tephra or ash falls, releases of gas. Volcanic ash is then carried downwind by the eruption column, dropping out of suspension and potentially harming populations over hundreds, if not thousands, of square kilometers. Even at thicknesses of barely a few millimeters, ash falls infrequently. They are hard, abrasive, moderately corrosive, and non-water soluble. Threats to public health from volcanic ash, as well as disruptions to vital infrastructure services, aviation, and primary production, can have significant societal consequences and costs, including:

- Endanger human life directly (irritant to eyes, nose and lungs as well as breathing problems).
- Cause problems for jet engines (forcing airlines to cancel flights through the affected area)
- Cause minor to major damage to vehicles and buildings,
- Contaminate water supplies,
- Lead to temporary socio-economic disruption (e.g., evacuation, school and business closures, cancellations).

- Disrupt sewage and electrical systems (conducts electricity when wet) and damage or kill vegetation.
- The most dangerous features of volcanic ash are swift, ground-hugging avalanches of searing hot gas, ash and rock.

Communities exposed to any magnitude of ash fall commonly report anxiety about the health impacts of inhaling or ingesting ash (as well as impacts to animals and property damage). The impacts of any ash fall can therefore be experienced across large areas and can also be long-lived, both because eruptions can last weeks, months or even years and because ash may be remobilized and re-deposited by wind, traffic or human activities.


Mount Veniaminof on the Alaska Peninsula erupts on August 18, 2013. Image courtesy of AVO/USGS. Photo by Game McGimsey.

Figure 5.3.Volcanic ash and ash fall (source; AVO/USGS)

5.1.3. Lava flow hazard

When magma erupts from a volcano, lava forms. As pressure is released, gases dissolved in the magma bubble to the surface, changing the composition of the lava. The majority of lava flows are created by the eruption of heated basalt magma (about 1200ºC). It is so heated deep within the Earth that some rocks slowly melt and create lava, a viscous, flowing material. Since it is lighter than the solid rock around it, magma rises and collects in magma chambers. Eventually, some of the magma pushes through vents and fissures to the Earth's surface.

Magma that has erupted is called lava. Because lava flows create enormous amounts of pressure, and are extremely hot between 1,000-2,000°C (1,800 - 3,600° F) bury, crush, cover, and burn everything in their path. They can cause;

- Severe burns and often burn down vegetation and structures.
- Crush or bury whatever survives being burned.
- If it enters a body of water or water enters a lava tube, the water may boil violently and cause an explosive shower of molten spatter over a wide area.
- Sometimes lava melts ice and snow to cause floods and lahars.
- Lava flows can dam rivers to form lakes that might overflow and break their dams causing floods

Figure 5.4. Lava flow

6. RESULTS AND DISCUSSION

6.1. Result and interpretation

6.1.1. Hazard assessment

In the investigation of the probabilistic volcanic hazard of Fentale volcano, the following key questions need to be addressed.

- What is the distribution in time of Fentale past eruptions?
- What is the likelihood and size of future eruptions affecting the surrounding towns and infrastructure?
- What are the likely styles and hazards of future eruptions?
- Where are we in the lifespan of the Fentale volcanic system?
- How do we calculate probabilistic volcanic hazard for the surrounding towns and infrastructure?
- What is the probabilistic volcanic hazard?
- How intensive should the monitoring be to provide adequate warning of Fentale volcanic eruption?
- Who and what are exposed to volcanic hazards around Fentale area?
- How will each hazard affect people and infrastructure?

Volcanic hazard and risk assessment of Fentale volcanic field is done based on the theory of uniformitarianism (the past is the key for the future). Volcanic activities will most likely be broadly similar to what has happened in the past. Hazard and risk assessment can therefore be attempted by considering the recent eruption history and by identifying the youngest volcanic products of the volcanic center or field. There are previous investigations that have been undertaken to understand the past eruption history about Fentale volcano. Previous investigators studied and mapped the volcanic units and also made some dating of the volcanic products. The available information from previous and present studies have provided pertinent knowledge about the types, magnitudes and area coverage of past eruptive events and by inference, to identify areas that could be similarly affected by future events.

Furthermore, the active state of Fentale volcano is evidenced by the presence of geothermal manifestations including hot springs mud pools and fumaroles within the caldera as well as northwest of the volcano (around Kesem dam), which were observed during field work. Fumaroles, hot-springs and mud pools are aligned along normal NNE-trending faults which indicate that the Fentale volcano and its surroundings are tectonically active. Vents are closer to each other and most are located near the caldera rim.

The volcanic history of Fentale indicates that it has experienced post-caldera eruptions. The presence of small craters, pumice cones and domes, together with observations of thin pumice deposits, suggest multiple intra-caldera explosive and effusive eruptions (Hunt et al., 2019). The general eruptive sequence of the volcano, from base upward, includes: old lavas (trachytic lava flows), main cone (intercalation of rhyolitic lava and obsidian flow with pyroclastic deposits), the Fentale welded tuff (ignimbrite), and products of the post-caldera activity (pumice cone, lava dome). Unlike short lava flows, pyroclastic falls and flows cover a larger region. At craters, there is a younger obsidian coulee. Volcanic products such welded tuff (ignimbrite), lava flows (Aa basalt, rhyolitic flow), and pyroclastic fall-out deposit (pumice and ash fall) were discovered during the field study.

The Fentale welded ignimbrite unit covers the majority of the region. The Metehara basaltic lava flows and scoria cones, located between the Fentale volcanic edifice and Metehara town, were generated during the last eruptive activity in the area in 1828. The emergence of NNE-trending fissures most likely preceded and accompanied this historic eruption. In most regions of the volcanic area, pyroclastic flow and fall deposits can be found. The presence of felsic lava domes inside and outside the Fentale caldera complex shows that Fentale volcano's previous eruption mode was mostly explosive.

The past eruptive products together with the present thermal manifestations on and around Fentale volcano (numerous fumaroles, hot springs, mud pools, hot grounds and the probable presence of magma at shallow depths, presence of young and active faults and ground fissures) imply that future eruptions of Fentale volcano will possibly include lava flows and explosive eruption types.

Some insight into the future eruption of Fentale may be obtained by considering the 2011 eruption of Nabro volcano (Afar depression, Eritrea) which has a close similarity and eruptive history to that of Fentale. From geological and geomorphological perspectives, Nabro is notable for its approximately 7-km-wide summit caldera, which opens towards the southwest, and for the wide apron of silicic ignimbrites that surrounds it. Nabro erupted for the first time in recorded history in 2011 (Goitom et al., 2015). The eruption started with the effusion of lava from a fissure within the summit caldera and followed shortly by a significant explosion. A 17.5 km long lava flow, up to 1 km wide in places, was emplaced to the northwest of the caldera, close to the Eritrean-Ethiopian border. Explosions generated ash plumes that reached heights of 15 km and generated deposits on the ground that covered an area of 700 km^2 over the first 6 days of the eruption. Sulphur dioxide gas emitted by the eruption produced a plume that reached up to 18 km high (stratospheric) and was the largest emission (4.5 million metric tons) since the eruption of Pinatubo volcano in the Philippines in 1991.

The possible explosive eruption types and associated hazards from Fentale may include any one of the following:

- Pyroclastic flow and fall deposits accompanying dome collapse.
- Vulcanian and Pelean types of eruptions containing pyroclastic flows and pyroclastic falls.
- Phreato-magmatic eruptions: will possibly occur from vents lying on faults connected to the ground water or lakes i.e.: lake Beseka. Magmatic vents located on fumaroles and hot springs will also result in Phreato-magmatic eruptions. The phreatomagmatic eruptions that will likely occur here can be caused by basaltic magmas interacting with water and producing pyroclastic flows and falls and maar type eruptions.
- Partially explosive Strombolian eruptions containing the formation of scoria/cinder cones and basaltic eruption.

Based on the variety of past eruptive products described in earlier sections as well as future expected eruption types the potential hazards are inferred to be:

- ❖ Lava flow hazards (both high viscosity silicic and low-viscosity basaltic lavas)
- ❖ Pyroclastic flow (Pyroclastic Density Currents) hazards

- ❖ Pyroclastic fall hazards (tephra fall), and
- ❖ Emission of volcanic gases.

According to Loughlin et al (2015), Fentale ignimbrite erupted explosively some 8,000 years subsequently forming the prominent caldera. This is considered to be the largest recorded Holocene eruption in Ethiopia. The most recent eruption, (Metehara basalt flow) occurred only ~200 years ago. The volcanic complex is likely to erupt again. Most Fentale vents are located within the caldera. This means that it is very likely that the next eruption will be in any one of the vent locations within the caldera.

With very limited scientific investigations, no spatial (where) or temporal (when) patterns of eruption have been identified. As such, the volcano is wholly unknown where or when the next eruption will be. Further, the size of the next eruption is difficult to address, as the last series of eruptions account for very small parts of the erupted volume of the volcanic complex, and it is unclear whether these eruptions are anomalies or signal changes in the eruptive behaviour of the volcano. These difficulties of assessing location, time and size of next eruption pose a considerable problem for addressing hazard, risk and emergency management.

In assessing the volcanic hazard at Fentale volcano, it is assumed that the volcano will continue to have similar eruptive behaviour in the future. Consequently, the inferred styles and characteristics of the past eruptions could be considered as indicators of the future eruptions. The expected and probable eruptions will, therefore, include the following types:

a. Effusive eruptions producing lava flows of basaltic, trachytic and rhyolitic compositions
b. Explosive eruptions producing ash falls
c. Explosive eruptions forming pyroclastic flows (PDC)

In the following sections, volcanic hazards from future three eruptions styles at Fentale are assessed.

A. Lava flow hazard from future eruptions of Fentale volcano

i. Geologic features and structures from satellite imagery

Satellite imaging is used to extract factors that facilitate lava flow hazard, such as elevation (topography), slope, vent location, and so on. Aside from geological and lithological distinctions, structural delineations are carried out to better understand structural elements that contribute directly or indirectly to volcanic hazard and risk. Based on a prior study, certain structural features (fault, caldera, cone, vent, etc.) and the direction of lava flows are also retrieved from satellite imagery (William et al, 2014).

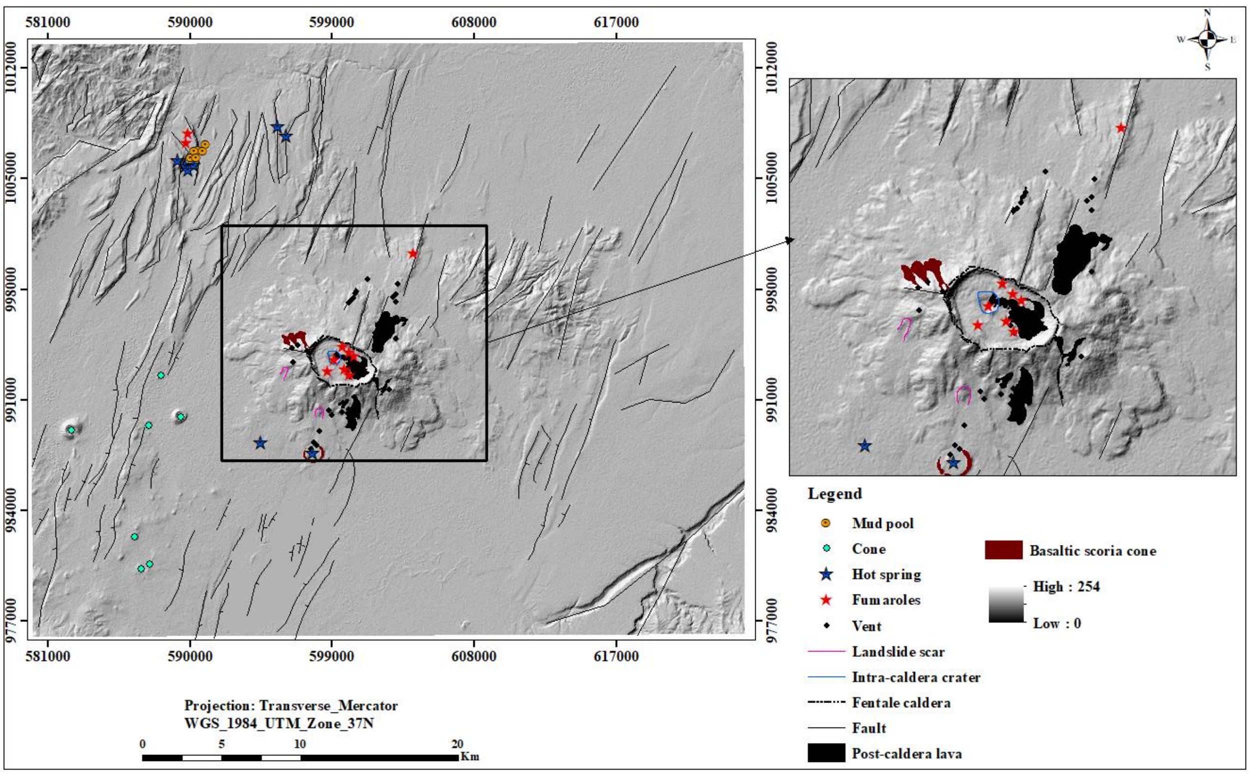


Figure 6.1. Surface features and geological structures at Fentale

i. Classification

A total of five classes are chosen and evaluated using a logical Analytical hierarchy process (AHP). There are five levels of important consideration: very low, low, medium, high, and very high. Caldera distance, fault, vent, slope, and elevation are the input data utilized to create the danger map. Those classes were given a monetary value based on their contribution to facilitate lava flow hazard.

Table 6.1. Factor evaluation table

Factor	Class interval	Value	Class importance
Slope	0 -5º	1	Very low
	5 - 12º	2	Low
	12 - 30º	3	Moderate
	30 - 45º	4	High
	>46	5	Very high
Elevation	728 – 883	1	Very low
	883 - 1,018	2	Low
	1,018 - 1,161	3	Moderate
	1,161- 1,413	4	High
	1,413 - 1,989	5	Very high
Fault	0 - 0.20866	1	Very low
	0.20866- 0.5738	2	Low
	0.57382 - 0.9129	3	Moderate
	0.9129 - 1.3476	4	High
	1.3476 - 2.217	5	Very high
Vent	0 - 5,141.14	5	Very high
	5,141.14 - 9,960.95	4	High
	9,960.95 - 14,352.34	3	Moderate
	14,352.34 - 18,957.94	2	Low
	18,957.94 - 27,312.29	1	Very low
Distance from caldera	0 - 6,670.82	5	Very high
	6,670.82- 11,886.19	4	High
	11,886.19 - 16,495.12	3	Moderate
	16,495.12 - 21,225.34	2	Low
	21,225.34 - 30,928.35	1	Very low

1. Slope

The difference between the elevations of two places multiplied by the distance between them is the slope. The slope of the study area varies from gentle to quite steep. Metehara and Addis Ketema, as well as Lake Beseka, are all located on flat plains at low heights. The Metehara Sugar Factory and irrigations (Abadir Farm and Metehara Sugar Estate) are characterized by flat to rough plains in comparison to Lake Beseka. Tinishu Sababor and the southern portion of the Metehara sugar plantation are situated in a rough, slightly sloping plain north of the infrastructural lines. The slope of Mount Fentale is extremely steep. The MSEP, as well as the northwest and southeast of Lake Beseka, have some volcanic cones.

It is one of the most important topographic elements that increase the likelihood of volcanic eruptions. A steep slope allows lava to flow quicker than a gradual slope. The slope is generated using a DEM.

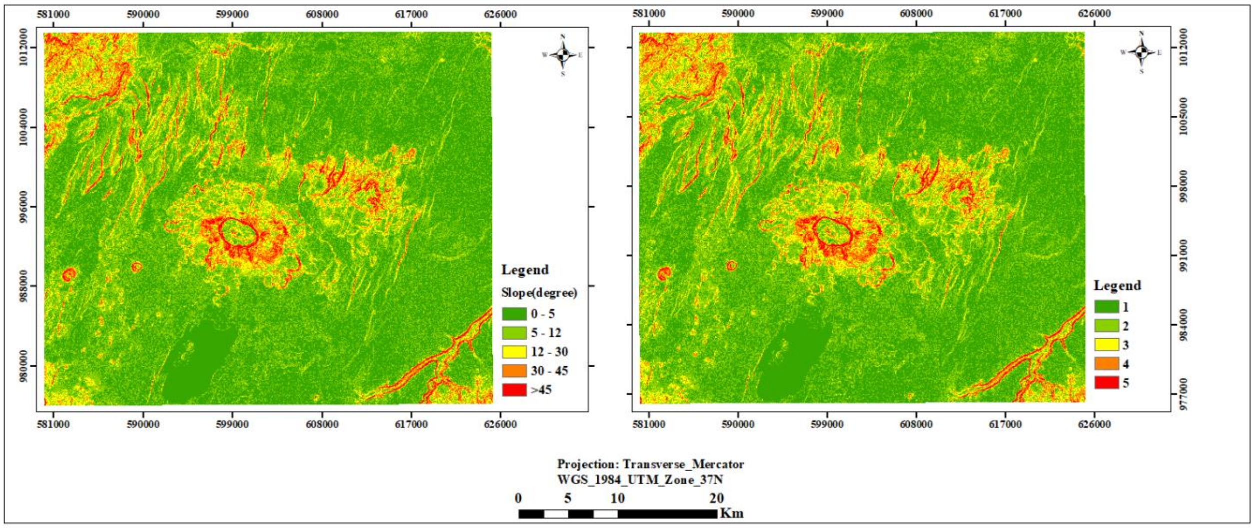


Figure 6.2.Classified and reclassified slope map of the study area (Filagot Mengistu et al, 2019)

2. Elevation

A geographic location's elevation is its height above or below the datum (mean sea level). An area's elevation also determines the surface shapes and features associated with it. The caldera rim and the mountain have higher elevations. The lava will flow from high to low elevations. The flow of this volcanic material (lava) over the land surface with different elevation is important to assess volcanic hazards. Scott et al., 2001 stated that, the proximal volcanic hazard zone is defined as those areas which are subjected to rapidly moving, devastating pyroclastic flows, debris avalanches, and lahars. Elevation of the study area is generated from ALOSPALSAR and classified using ArcGIS.

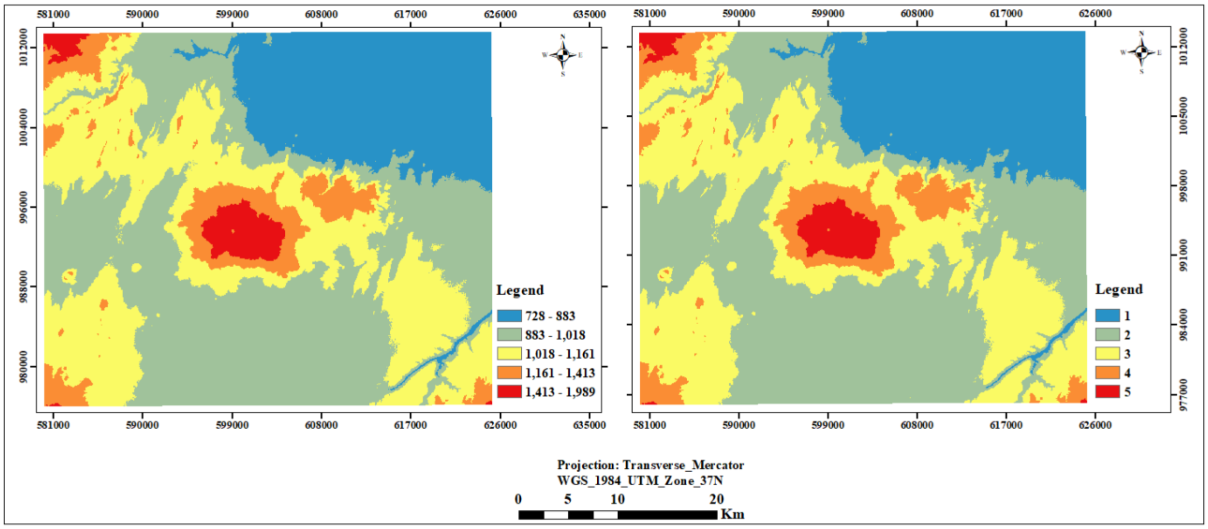


Figure 6.3.Classified and reclassified elevation map

3. Fault

One of the geological structures that can be utilized to predict future surface ruptures is the fault. Through the rupture surface, volcanoes will erupt. As a result, surface rupture traces from the past have been employed to assess and map volcanic hazard (Mark et al., 2004). Many normal faults run NNE to SSW through the study area, especially in the northwest. A fault striking is suggested by the alignment of vents, a geothermal manifestation, and a steep gorge. ~ESE. As a result Rift extension can be detected by normal faults (Acocella, et al. 2003). The continental rheology as well as local volcanic danger is determined by the spatial and temporal variations in strain partitioning between faulting and magmatism during the rift's ongoing extension.

A proximity analysis by density tool could be used to determine the effect of the fault on the volcanic hazard. The reverse effect of fault line density was ranked by reclassifying the density raster into five classifications using Arc GIS' natural break categorization.

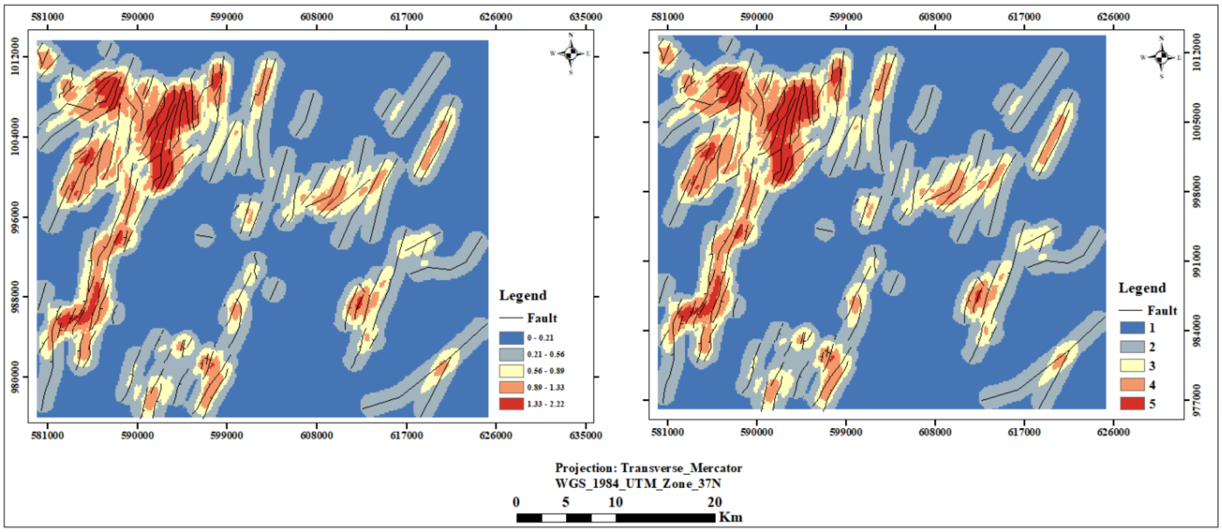


Figure 6.4.Classified and reclassified fault density map

4. Vents

Volcanic vents are openings in the earth's crust where lava and pyroclastic flows are ejected. The shape of vents, which determines the kind of eruption, can also be used to determine the type of eruption. The magma chamber, which is an underground pool of molten rock (magma) beneath the Earth's surface (https://owlcation.com/stem/Types-of-Volcanic-Vents), is where volcanic vents emerge. Vent location can be determined based on the knowledge of past eruption history and their spatial interrelations will give insights for establishing the probability of vent opening (i.e., volcanic susceptibility). In comparison to the volume of post-caldera eruption, there are multiple vents and craters, indicating high-frequency, low-volume eruptions. Vents are elevated points in the coulee where a single flow is fed by a number of vents. The vents which feed central and southeastern flank of the caldera are aligned in WNW-ESE direction. Pre-caldera flows are fed by sharing vents aligned along the western ridge. The lava coulee on the southern flank is fed by vents oriented NNE-SSW, a trend seen in surrounding faults and fissures. The northward extension of this trend on the northeastern flank could connect the coulee vent (Hunt. et al., 2017). Vents are retrieved using a combination of sentinel 2A and DEM data, and distance tools such as Euclidean distance and natural break are used to assess them.

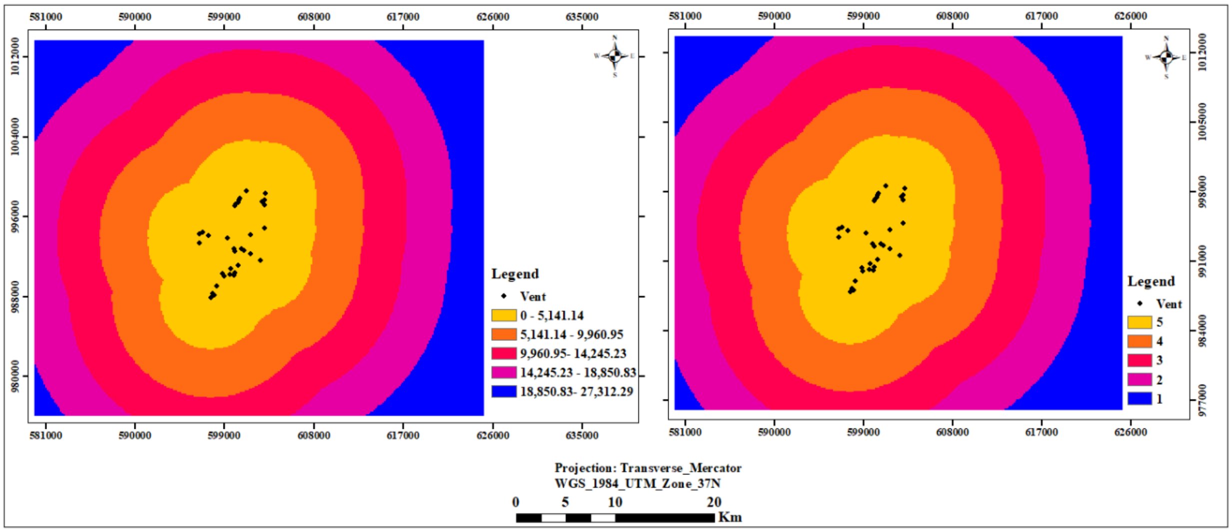


Figure 6.5.Classified and reclassified vent distance map

5. Distance from caldera

Inside the caldera, there are geothermal features like as fumaroles and hot springs. These actions show signs of volcanic activity. The majority of vents in Fentale caldera are close by. The caldera contains silicic deposits (rhyolite and trachyte), as well as immediately erupted pitchstones. The closer the distance the higher the hazard. The analysis is done by distance tool Euclidean distance and natural break.

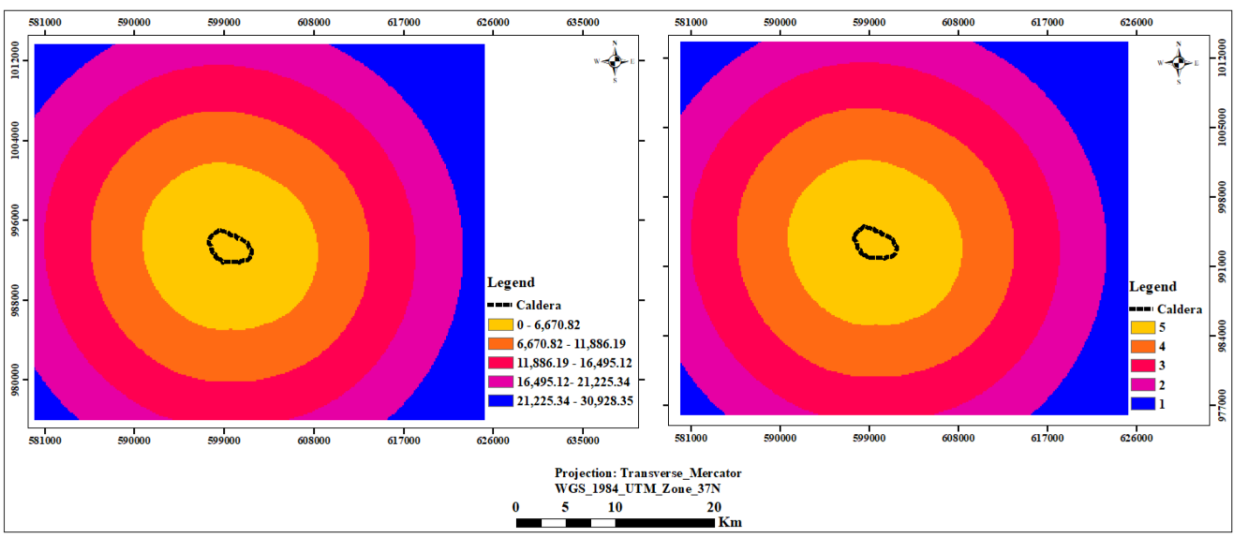


Figure 6.6.Classified and reclassified caldera distance

ii. GIS based Multicriteria evaluation

The conventional scale for making pair-wise comparisons, according to Satty (2008), is based on their contribution or relevance. Five different input data were chosen as criterion depending on their level of volcanic danger factor. An analytical hierarchy technique was used to rank each of the criteria in relation to one another (AHP). The importance of the criterion in each row is compared to the importance of the criterion of the column. The criterion may be considered extremely less important (1/9), very strongly less important (1/7), strongly less important (1/5), moderately less important (1/3), equally important (1), moderately more important (3), strongly more important (5), very strongly more important (7), or extremely more important (9) than the criterion indicated by the column. For example, because fault is deemed significantly less relevant than vent, it is given a value of 1/3.

Table 6.2. The level importance of for the criterion

Numerical values	Verbal term	Explanation
1	Equally important	Two elements have equal importance
3	Moderately more important	Judgement slightly favors one element
5	Strongly more important	Judgement strongly favors one element
7	Very strongly more important	Dominance of one element proved in practice
9	Extremely more important	The highest order dominance of one element over another
2,4,6,8	Important intermediate values	Compromise is needed

Table 6.3. Pairwise comparison matrix

Criterion	Vent locations	Caldera distance	Fault	Elevation	Slope
Vent location	1	1	3	5	7
Caldera distance	1	1	3	5	7
Fault	1/3	1/3	1	3	5
Elevation	1/5	1/5	1/3	1	3
Slope	1/7	1/7	1/5	1/3	1
∑ **Column**	2.676	2.676	7.533	14.33	23

The next step will be normalization and weight determination;

- ❖ The priority vector is referred to as normalized.
- ❖ To normalize the values, multiply the cell value by the sum of the column.
- ❖ The mean values of the rows can be computed using a priority vector or weight.

Table 6.4. Normalization and weight determination

Criterion	**Vent**	**Caldera distance**	**Fault**	**Elevation**	**Slope**	**Row total**	**Average weight (Row tot /n)**
Vent	0.37	0.37	0.398	0.3489	0.304	1.7909	0.35818
Caldera distance	0.37	0.37	0.398	0.3489	0.304	1.7909	0.35818
Fault	0.12	0.12	0.132	0.2	0.217	0.789	0.1578
Elevation	0.074	0.074	0.044	0.069	0.1304	0.3914	0.07828
Slope	0.053	0.053	0.0265	0.02326	0.04347	0.19923	0.039846

- ✓ Priority vector is also called normalized principal Eigen vector.
- ✓ Determine the mean value of the rows to get the priority vector or weight..
- ✓ Calculating the consistency ratio;

CR = Consistency index (CI)/Random Consistency Index (RI)

CI = (λmax – n)/n – 1

λmax is the Principal Eigen Value; n is the number of factors

λmax = Σ of the products between each element of the priority vector and column totals

• λmax = (2.676×0.35818) + (2.676×0.35818) + (7.533×0.1578) + (14.33×0.07828) + (23×0.039846)

λmax = 5.143897

- ➢ CI = (λmax – n)/n – 1, where n = 6
- ➢ CI = 5.143897– 5/5 – 1 = 0.036
- ➢ CR = CI/RI

Table 6.5 Random Consistency Index (RI) (Saaty, 1980).

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

- ➢ CR = 0.036/1.12
- ➢ **CR = 0.032< 0.1**, it is acceptable.

Weighted overlay analysis in Arc GIS was used to map the volcanic hazard-prone area for lava flow. Based on the class of weighted overlay analysis generated from the computation, the derived values were also classified into four classes. As a result, there are four hazard classes: low, moderate, high, and very high.

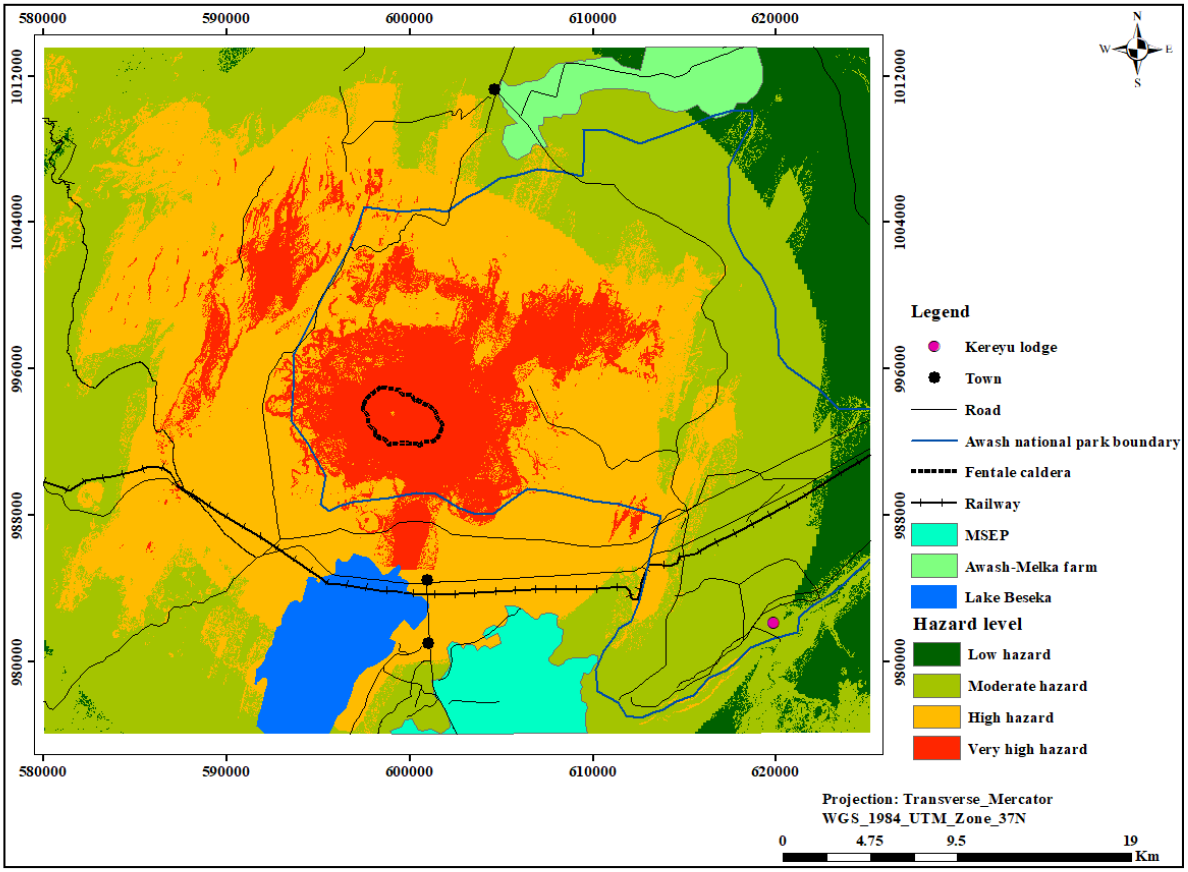


Figure 6.7.Lava flow hazard map

Table 6.6 Area estimates for lava flow hazard

Value	**Lava flow hazard level**	**Area (km^2)**	**Percentage**
1	Low hazard	161.8525	9.60
2	Moderate hazard	705.833281	41.87
3	High hazard	634.3142	37.63
4	Very high hazard	183.427	10.88

B. Pyroclastic flow and Ash fall hazards from future eruption of Fentale volcanics

i. Classification of lithology from satellite iagery

The units with the same composition but different ages are combined into one. i.e.

- Fentale's welded tuff and Tinsh Fentale's welded tuff were combined and renamed Welded tuff.
- Fentale and Tinsh Fentale's mixed rhyolite and trachyte lava have been combined to become Mixed ryolite and trachyte lava.
- Old basalt combines Dofan, Bofa, and Kesem basalts.
- Old pitchstone and young pitchstone are merged as pitchstone, etc.

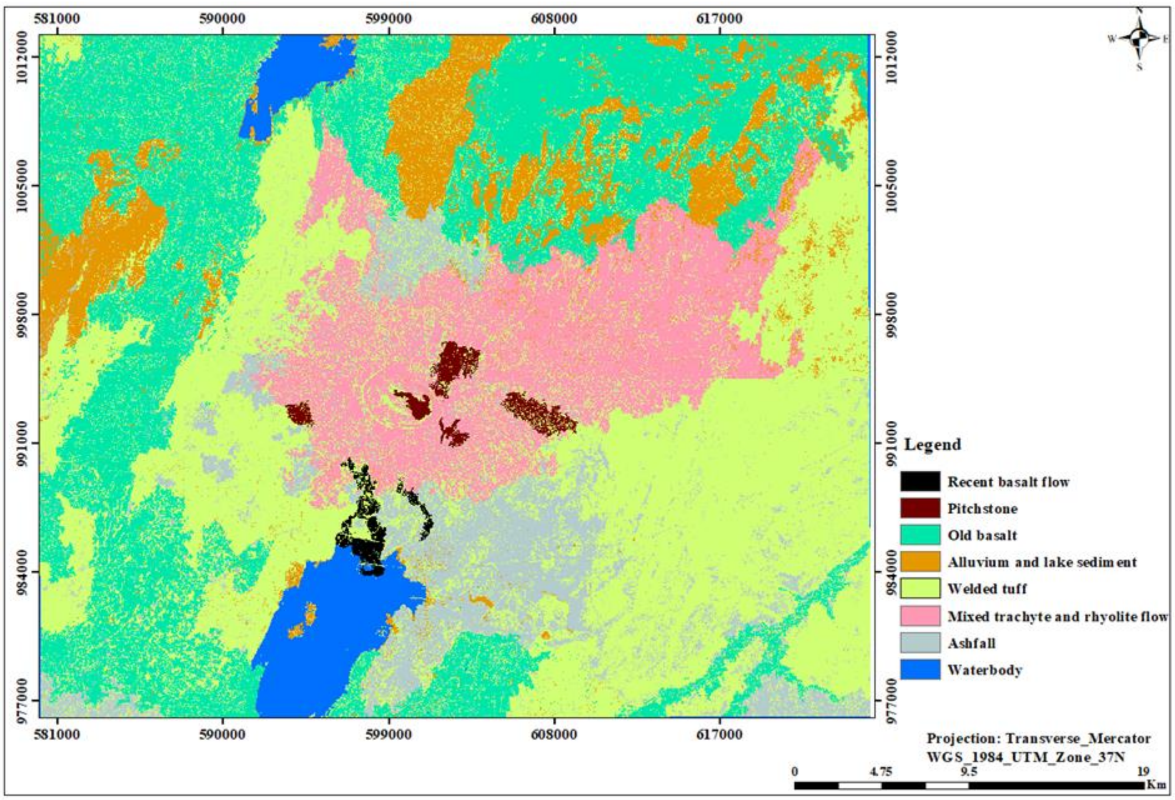


Figure 6.8. Lithology map using Sentinel 2A images of 2020.

A combination of regional geologic map, field observations, and hand specimen(rock samples) were applied for validating the output results.

1. Pyroclastic flow hazard

Pyroclastic flow is the voluminous deposit in the study area which is erupted from the center of Fentale caldera as well as from Tinish Fentale. The unit includes welded tuff of Tinsh Fentale and the welded tuff of Fentale. The hazard map shows36% of the area is classified as very high hazard.

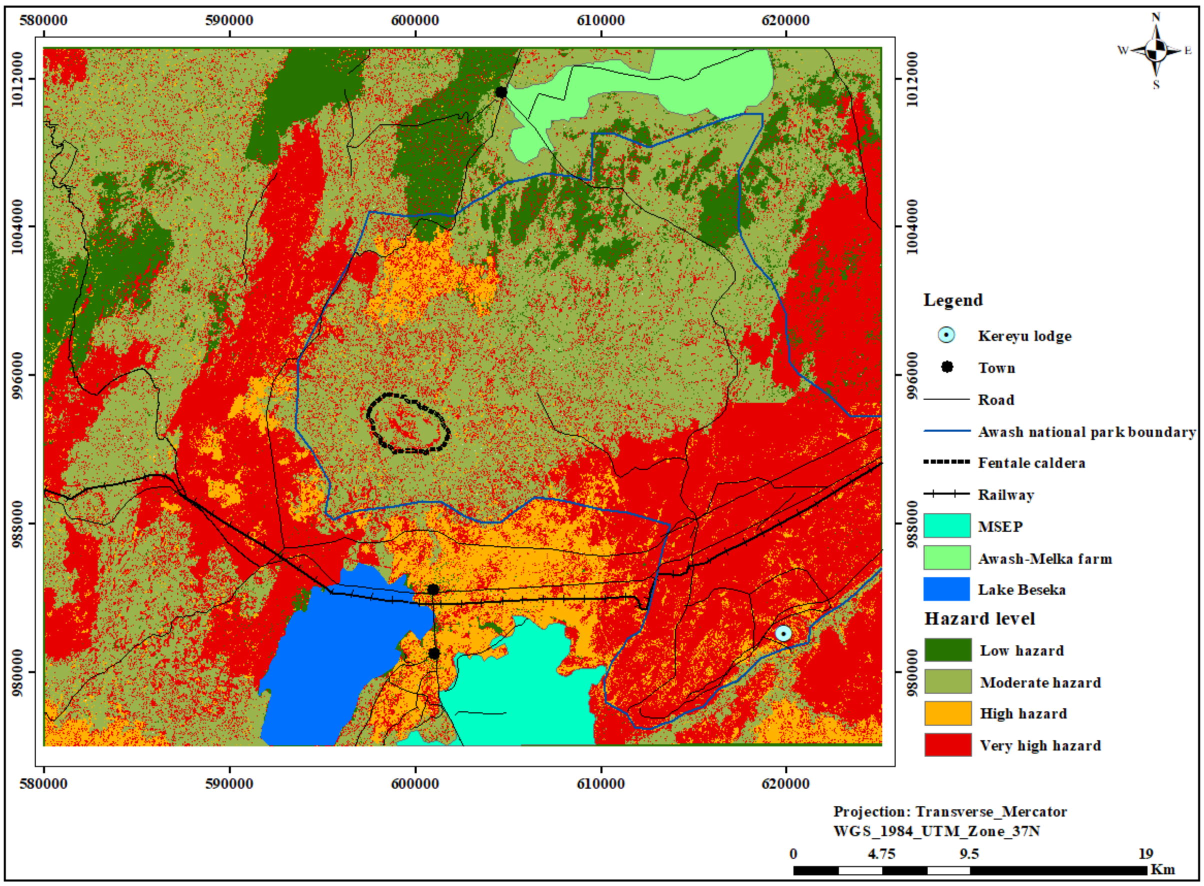


Figure 6.9. Pyroclastic flow hazard map

Table 6.7.Area estimates for pyroclastic flow hazard

Value	Pyroclastic flow hazard	Area	Percentage
1	Low hazard	221.41	13.00
2	Moderate hazard	692.65	40.68

3	High hazard	164.78	9.67
4	Very high hazard	623.77	36.63

2. Ash fall hazard

Volcanic ashes are deposited mainly in the northern and southern and partly distributed in both south-eastern and south-western portions of the Fentale volcano.The southern ash falls (pumice cone deposit) are intercalated with mixed trachyte and rhyolite flow. Unwelded rhyolitic pumice is found in the south-eastern and south-western portions. The very high hazard spans 9.7 % of the region.

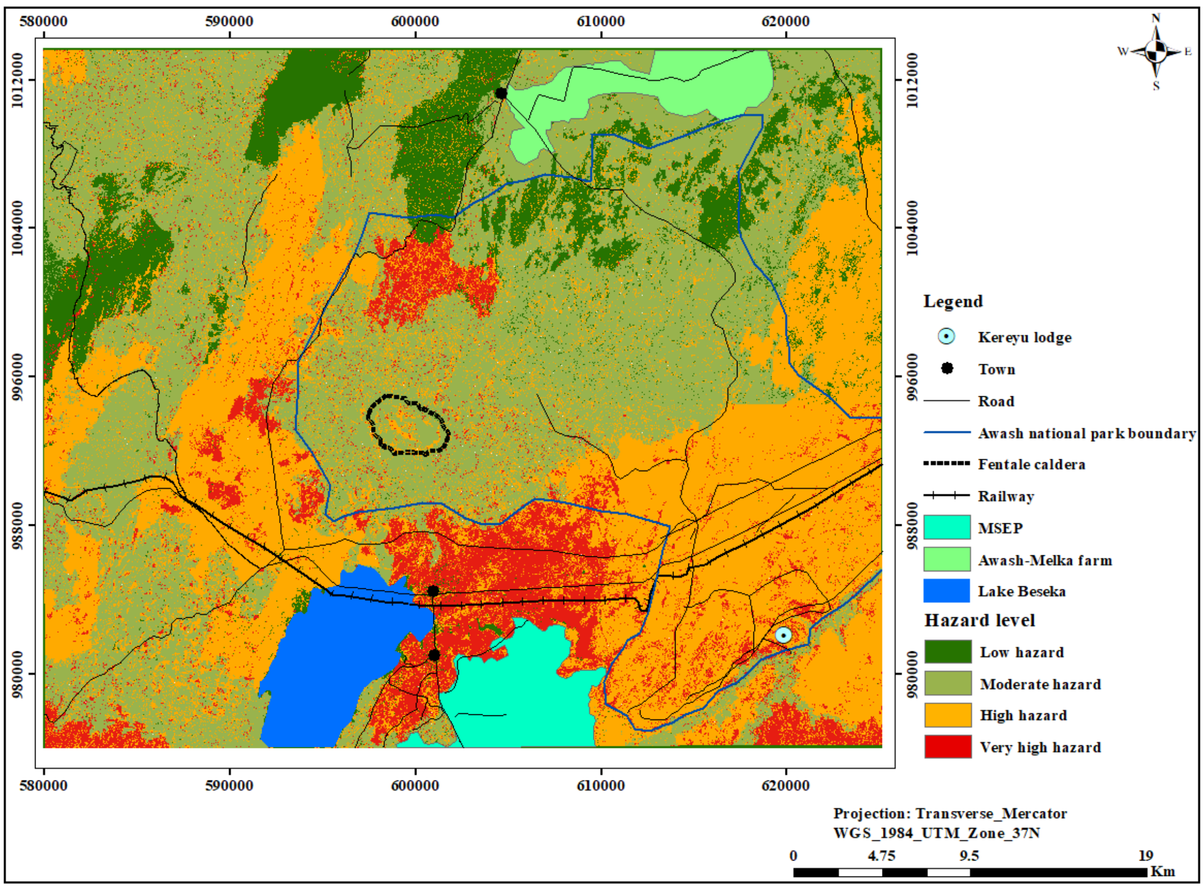


Figure 6.10. Ash fall hazard map

Table 6.8. Area estimates for ash fall hazard

Value	Ash fall hazard	Area(km^2)	Percentage
1	Low hazard	221.41	13.00
2	Moderate hazard	692.65	40.68
3	High hazard	623.77	36.63
4	Very high hazard	164.78	9.6783

6.1.2. Exposure assessment

Exposure is defined as the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected. There are various elements that are exposed to Fentale caldera such as roads, railway, towns, Metehara sugar factory, irrigated farmland, Awash national Park, lake Beseka, different facilities, etc. They are primary source of economic development of the country. The closest exposure units for Fentale caldera are the main highways from Addis to Djibouti and the Addis Ababa to Djibouti railway, asphalt roads, towns (Metehara and Adis ketema), and Awash National Park. The caldera is around 4-5 kilometers away from Metehara town, several highways and trains, and Lake Beseka.

Table 6.9. Population exposure for Fentale volcano (Azais and Chambord, 1931)

Distance from the caldera	Populations
Within 5 km	1,919
Within 10 km	14,201
Within 30 km	169,357
Within 100 km	3,482,286

Table 6.10.Exposures availability near Fentale volcano(Ethiopia disaster risk profile,2019)

Exposures	**Volcanic hazard types**	
	Ash fall hazard	Lava flow hazard
Population(total)	190,000	
Buildings	$86 million	$2 million
Health facilities	$65 million	$20 million
Education facilities	$90 million	$50 million

6.1.3. Vulnerability assessment

Vulnerability is the likelihood that exposures will be damaged/destroyed/affected when exposed to a hazard. Various exposures exist in the area, including people, LU/LC, settlements/localities, infrastructure (road and railway), and different facilities (water, education, religious, health and etc. facility).

I. Classification

Different data from CSAE were obtained, and the categorization was done in Arc GIS software using expert-based manual classification (Euclidean distance) and natural breaks.

Table 6.11.Factor evaluation table for vulnerability assessment

Factor	**Class interval**	**Value**	**Class importance**
	0 – 26	1	Very low
Population	26 – 112	2	Low
	112 – 639	3	Moderate
	639 - 2,112	4	High
	2,112 - 4,591	5	Very high
	0 - 3,940.69	5	Very high
Locality	3,940.69 - 8,460.89	4	High
	8,460.89 - 13,792.42	3	Moderate
	13,792.42 - 19,935.26	2	Low
	19,935.26 - 29,555.18	1	Very low
	Built up	4	Very high
Landuse/landcover	Water body/Crop land	3	High
	Forest/ Shrub	2	Moderate
	Bare land	1	Low
	0 - 24.70835248	1	Very low
Infrastructures	24.71 - 77.21	2	Low

	77.21 - 140.53	3	Moderate
	140.53 - 220.83	4	High
	220.83 - 393.78	5	Very High
	0 - 5,515.98	5	Very high
Water facility	5,515.98 - 10,405.14	4	High
	10,405.14 - 15,795.76	3	Moderate
	15,795.76 - 22,189.28	2	Low
	22,189.28 - 31,967.61	1	Very low
	0 - 4,209.75	5	Very high
Education facility	4,209.75 - 7,255.11	4	High
	7,255.11 - 10,479.60	3	Moderate
	10,479.60 - 14,868.49	2	Low
	14,868.49 - 22,840.15	1	Very low
	0 - 5,809.02	5	Very high
Health facility	5,809.02 - 10,607.77	4	High
	10,607.77 - 16,164.22	3	Moderate
	16,164.22 - 22,604.65	2	Low
	22,604.65 - 32,202.16	1	Very low
	0 - 4,836.26	5	Very high
Economic activity	4,836.26 - 8,967.23	4	High
	8,967.23 - 13,400.47	3	Moderate
	13,400.47- 18,135.97	2	Low
	18,135.97 - 25,692.62	1	Very low
	0 - 4,059.59	5	Very high
Religious facility	4,059.59 - 7,367.42	4	High
	7,367.42 - 10,600.06	3	Moderate
	10,600.06 - 14,058.24	2	Low
	14,058.24 - 19,170.32	1	Very low

a. Population density

The population density has been increasing from time to time. Because there have been many economic activities in the study area. Fentale Wereda has a larger population density than the neighboring Wereda. Metehara and Haro Adi, two towns in this Wereda, have populations of 17,756 and 20,837 people, respectively, for a total population of 38,593.

Table 6.12. Population projection values of the study area in 2020(CSAE)

Wereda	**Town**	**Population**		
		Male	**Female**	**Total**
Fentale	Metehara	9,155	8,601	17,756
	Haro Adi	10,295	10,542	20,7837
Berehet	Metehibla	4,077	4,037	8,114

Minjar Shenkora	Arerti	10,578	10,264	20,842
	Balchi	2,114	2,016	4,130
Amibara	Melka Werer	9,224	8,036	17,260
	Melka Sedi	6,725	5,413	12,138
	Andido	658	549	1,207
Awash Fentale	Sabure	2,323	2,025	4,348
	Awash 7 kilo	16,778	16,040	32,818
Anchar	Bedayu	2,123	2,057	4,180
	Cheleleka	2,756	2,456	5,212
	Deay	1,460	1,351	2,811

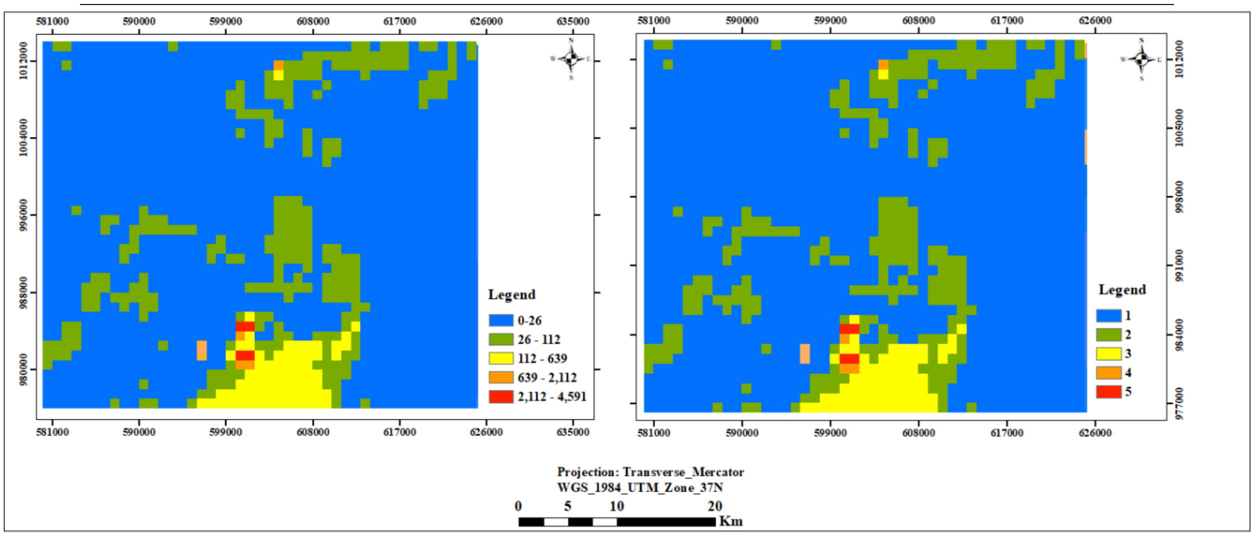


Figure 6.11. Population map of the study area

b. Landuse/Land over

The six LULC classes were divided into four groups for risk assessment purposes based on their relative relevance. Built up (very high), farm land and water body (high), forest (moderate), shrub and bare land (low).

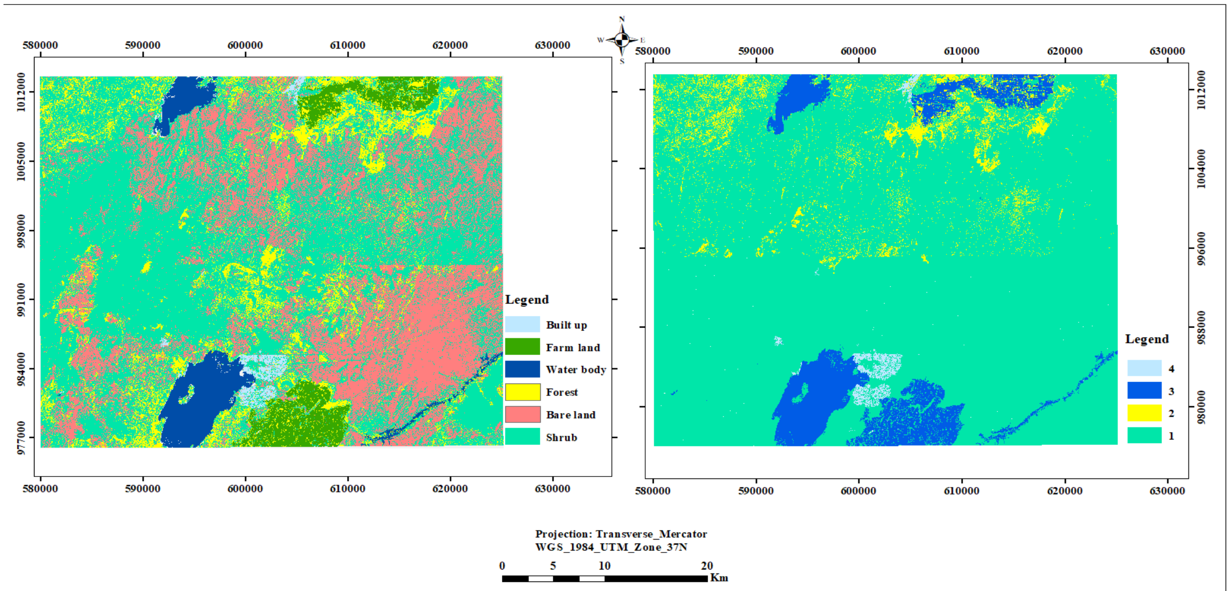


Figure 6.12 Map showing; Classified and reclassified LU/LC

c. Locality/settlement

In the research area, there are 45 localities/settlements, with the majority of them located in the south, east, and south-east of Fentale volcano. Haro Adi, Birtukan, Golecha, Balchi, Tututi, Gola, Kechcechelo, Norz, Meldiba, Mogasa, Dega Edu, Dinbaba, Jilo, Kobo, Kalowa, Ajo, Ajo Tere, Kubi, Kara Ferda, Leba, Barak, Pimiru, Kereri, Edo Luko, , Werefa, Benti, Sogido, ,Ledi, Bulo, Sumale, Meldiba, Biyoseg, Arboye, Mesgid, Geda, Muda, Ajo Salu, Funyan, Dinbaba, Horkoncha, Awre, Mariga, Mehammed Jilo,and Muke Bedena.

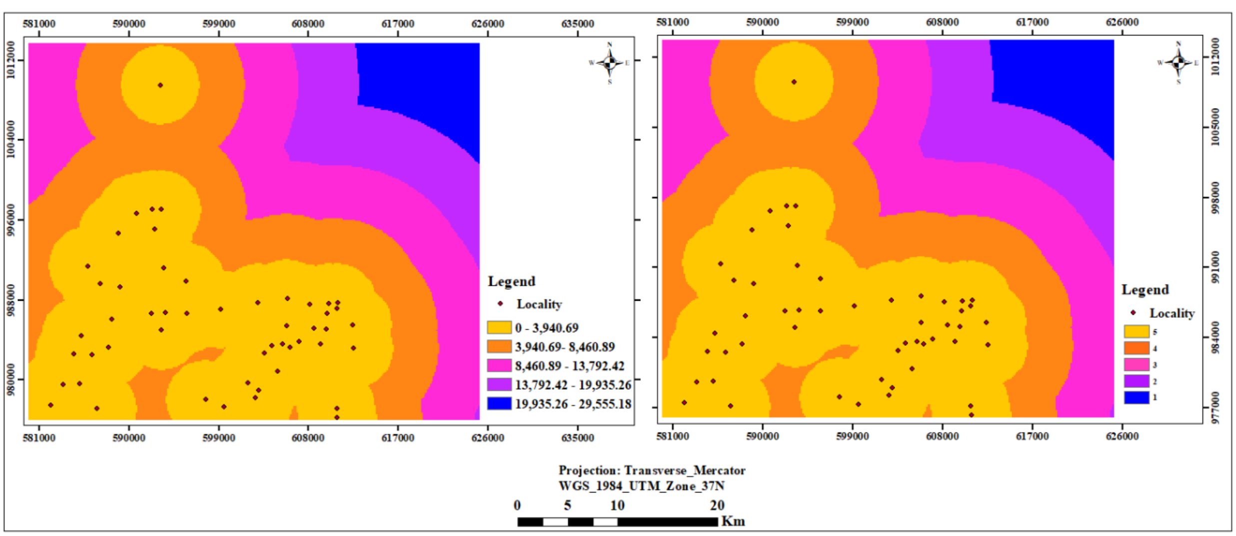


Figure 6.13 Reclassified locality

d. Economic activity

Many diverse economic activities have been taking place around Fentale volcano, such as Metehara sugar plantation, Awash Melka farm, Awash national park, Metehara sugar factory, Kereyu resort, commerce, and so forth. Almost all are located in the study area's south and south-eastern regions.

- ✓ **Awash National Park** is one of the national parks in Ethiopia where diverse range of plains wildlife and offers tremendous bird watching opportunities, with over 400 species are lived. It is known for the natural hot springs. In establishing this park, as well as the Metehara sugar plantation to the south, the livelihoods of the indigenous Karayu Oromo people have been endangered an effect that is contrary to the Ethiopian government's original intention of these establishments serving to benefit the local population.
- ✓ The **Metehara sugar factory** is one of the main large-scale sugar establishments operating within Ethiopia. It is a company that produces sugar which is located 200 kilometers from Addis Ababa in the Oromia Regional State. It was built by the H.V.A. Company of the Netherlands, just like the Wonji/Shoa Sugar Factory. The factory started sugar production in 1970.It was Ethiopia's third sugar mill, built as a joint venture between the Ethiopian government and a construction company. It has a sugarcane plantation with a total area of 10,235 hectares. Sugarcane is being grown on 10,100 hectares of land. It was the best until recently in terms of production capacity, which is 136,692 tons of sugar per year (Ethiopian Sugar Industry Profile, 2015 https://www.slideshare.net/meresaf/en-43942877).

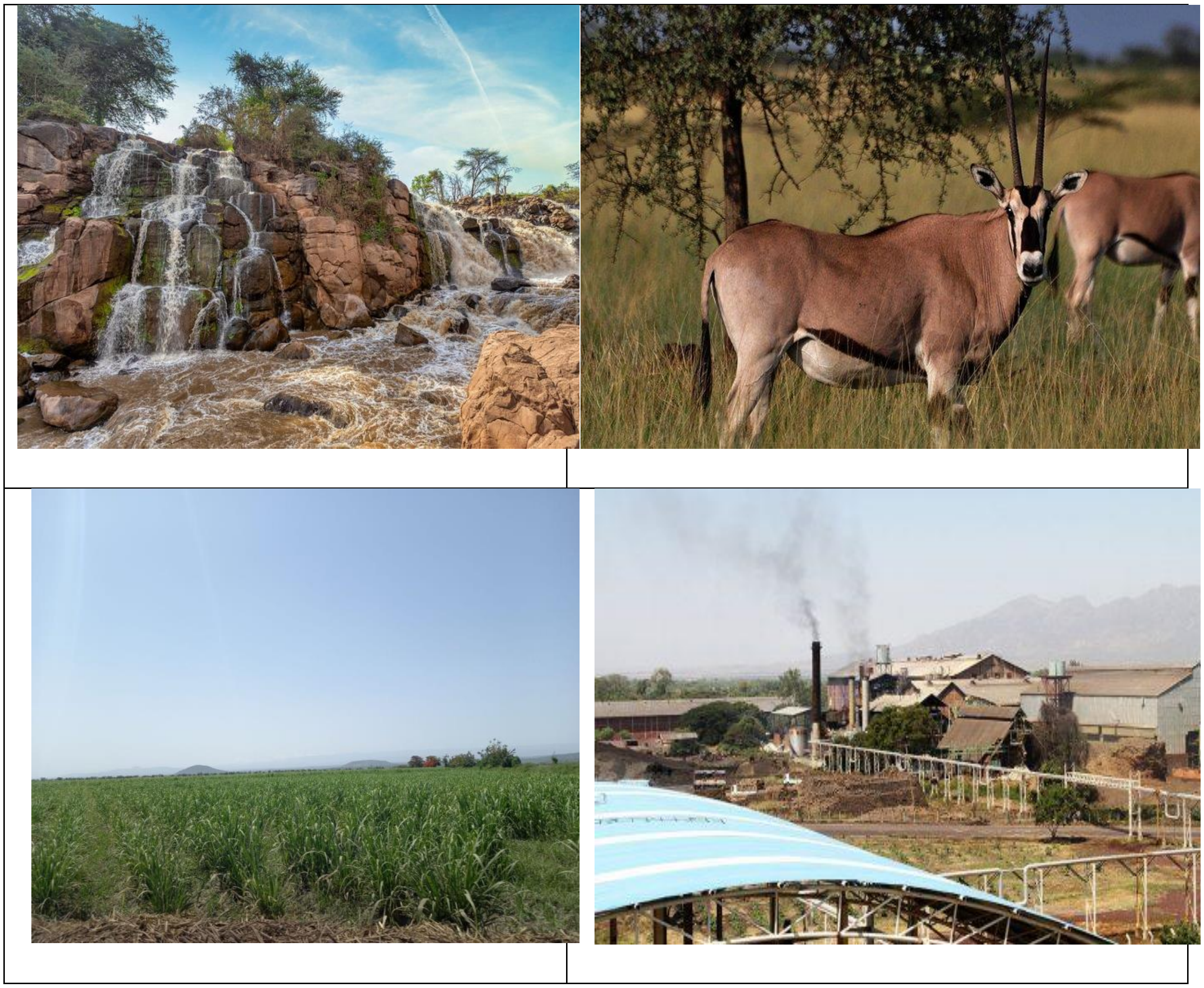


Figure 6.14.The major economic activities; the top two images are Awash National Park while the bottom are sugar plantation and factory.

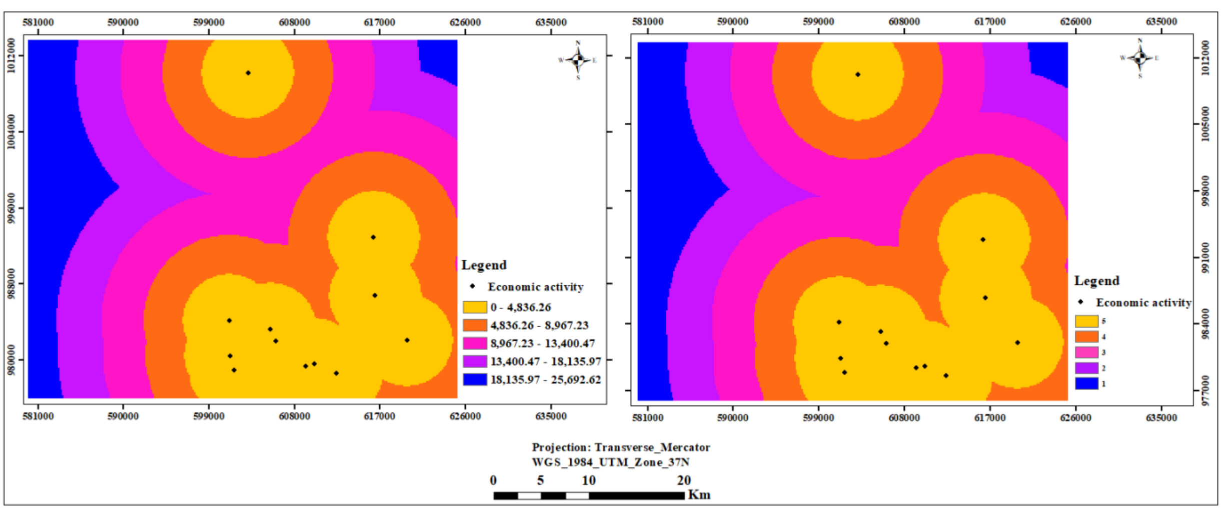


Figure 6.15Classified and reclassified economic activity

e. Health facility

Six health facilities are available, five of which are clinics and one of which is a health center (Tena tabiya). They're largely in the study area's southern and southwest corners, while the health center is in the Far East. The clinics are named for the towns in which they are located, such as Lege-Benti and Tututi.

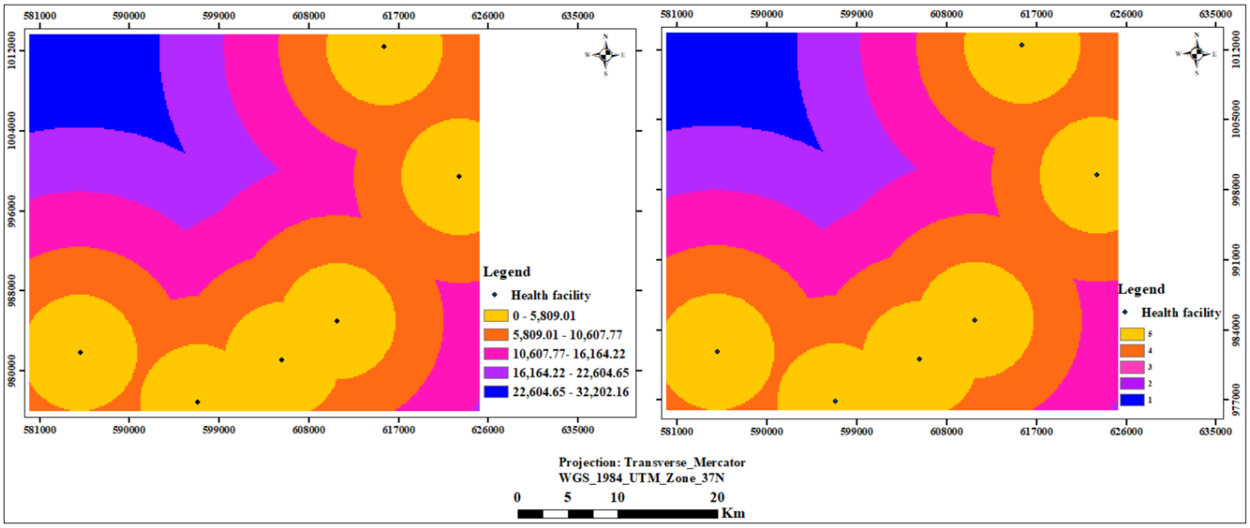


Figure 6.16 Reclassified health facilities

f. Religious facility

The eleven religious facilities in the study region include four mosques, two churches, one Christian cemetery, and three Muslim cemeteries. The majority of them may be located in the two towns (Metehara and Adis Ketema) in the southernmost section of the study area

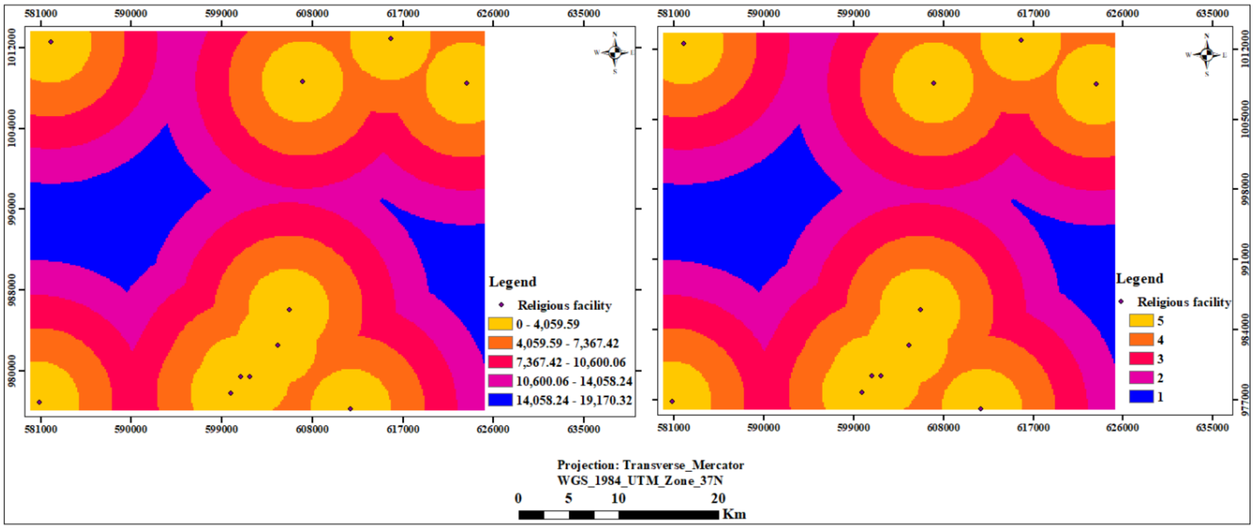


Figure 6.17Classified and reclassified religious facilities

g. Infrastructures (Road and railway)

There are many asphalt and weather roads in the study area, as well as a railway connection between Addis Ababa and Djibouti. Metehara and Nazreth, as well as Metehara and Awash and Metehara and Chole, all meet here. Elala Awara-Melka, Meleka Werer to Awash and Metehibla are all severely vulnerable. The majority of the roads, including Metehbela, Meleka Wererto Awash, Awash to Debreselam, Meleka Werer to Awash, and others, are asphalted, however Metehara to Chole and Elala to Meleka Werer have gravel surfaces.

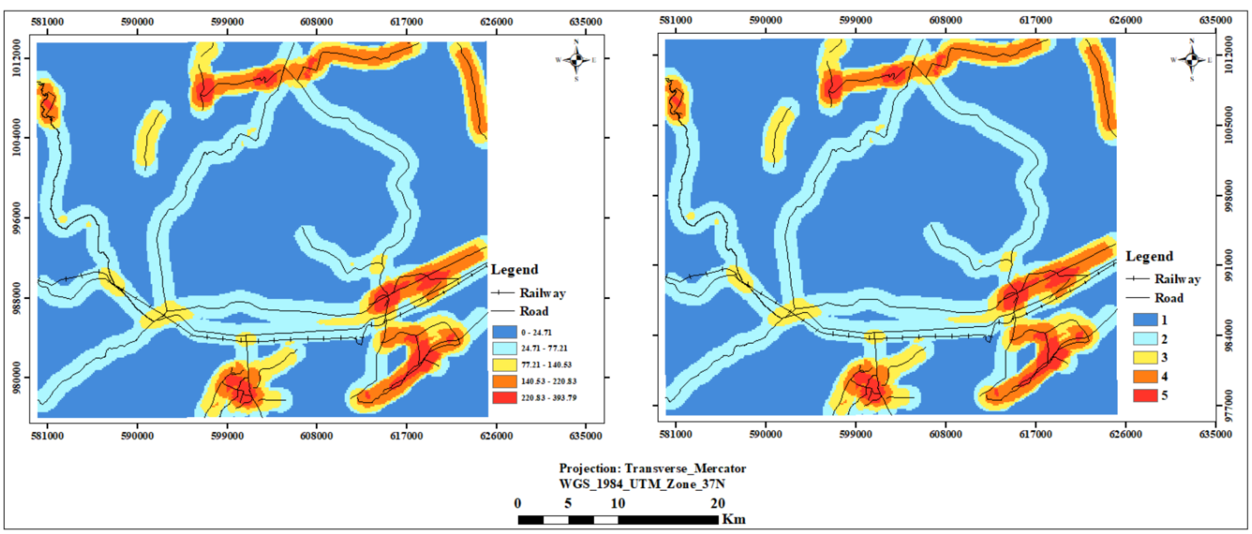


Figure 6.18Classified and reclassified infrastructures

h. Education facility

In different parts of the study region, there are nine educational establishments. They're all elementary (primary) school. The name of any school is determined by its location. Dandi Gudina, Kobo, Lege Benti, Tututi, Gola primary school, and others are only a few of them.

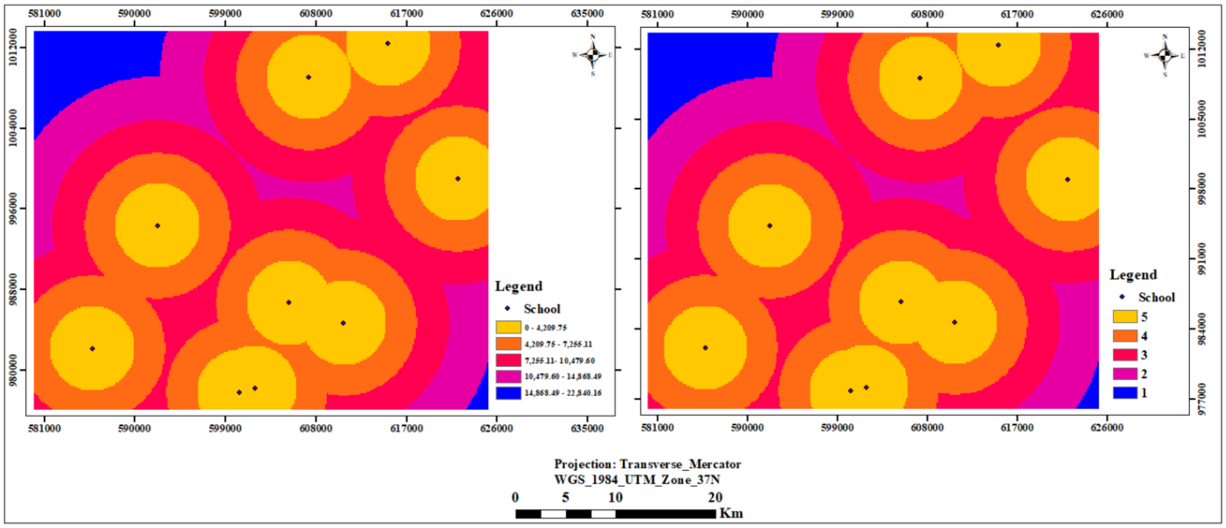


Figure 6.19Classified and reclassified education facilities

i. Water facility

In the research region, there are ten water facilities: one tanker, five bono water, two ponds, and two spring waters. The spring water is found in the NNW section of the study area and is used by Kesem and adjacent communities, whereas the Tanker is found in the SW region.

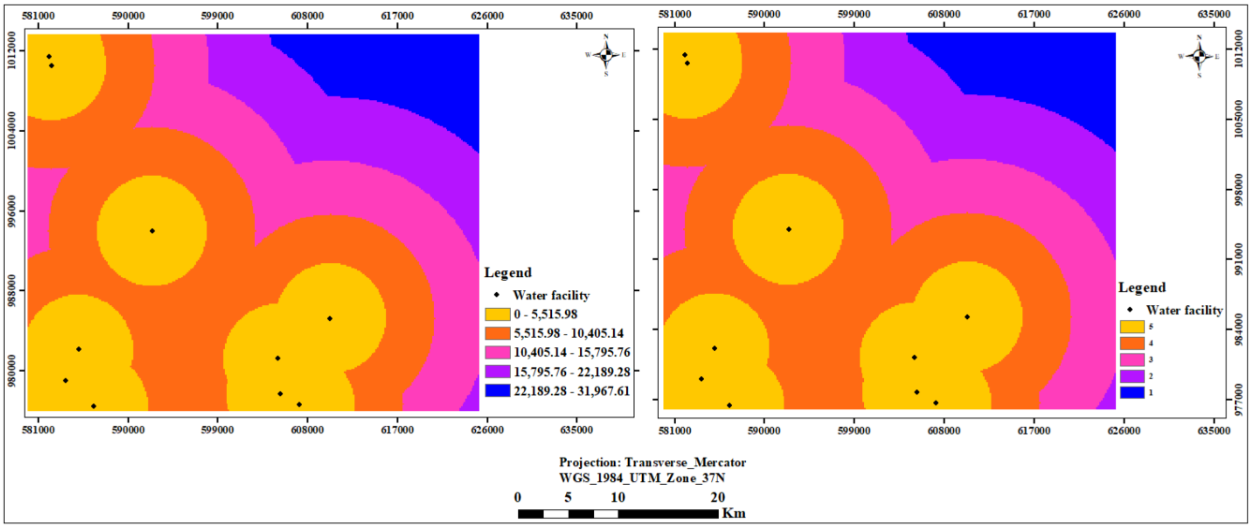


Figure 6.20 Classified and reclassified water facilities

6.1.4. Risk assessment

6.1.4.1. Multicriteria evaluation technique for risk assessment

Different exposures (population, land use/land cover, and infrastructure) are classified and a vulnerability map is provided and they were assigned weights relative to their importance through a pairwise comparison and summed together in order to create the final risk maps, which are then combined with the hazard map using a weighted overlay technique. The weights allocated to each map were established through a pairwise comparison of ten parameters, with dangers receiving the most weight, followed by population, land use, land cover, localities, and infrastructure (road and railway) and other facilities receiving the same weight. The pairwise comparison matrix is used to create the risk map for the three-hazard type, as illustrated below.

I. Complete the matrix

Table 6.13. Pairwise comparison matrix for the three-risk map

Criterion	Hazard	Population	LU/LC	Locality	Economic activity	Education facility	Health facility	Water facility	Infrastructures	Religious facility
Hazard	1	3	5	7	7	7	7	7	7	7
Population	1/3	1	3	5	7	7	7	7	7	7
LU/LC	1/5	1/3	1	3	7	7	7	7	7	7
Locality	1/7	1/5	1/3	1	1	1	1	1	1	1
Economic activity	1/7	1/7	1/7	1	1	1	1	1	1	1
Education facility	1/7	1/7	1/7	1	1	1	1	1	1	1
Health facility	1/7	1/7	1/7	1	1	1	1	1	1	1
Water facility	1/7	1/7	1/7	1	1	1	1	1	1	1
Infrastructures	1/7	1/7	1/7	1	1	1	1	1	1	1
Religious facility	1/7	1/7	1/7	1	1	1	1	1	1	1
∑Column	2.53	5.39	10.19	22	28	28	28	28	28	28

II. Normalization & weight determination

Table 6.14. Normalization and weight determination

Criterion	Hazard	Population	LU/LC	Locality	Economic activity	Education facility	Health facility	Water facility	Infrastructures	Religious facility	**Weight (mean of row)**
Hazard	0.395	0.556	0.49	0.318	0.25	0.25	0.25	0.25	0.25	0.25	0.32
Population	0.13	0.185	0.29	0.227	0.25	0.25	0.25	0.25	0.25	0.25	0.23
LU/LC	0.079	0.06	0.098	0.136	0.25	0.25	0.25	0.25	0.25	0.25	0.18
Locality	0.056	0.037	0.032	0.045	0.035	0.035	0.035	0.035	0.035	0.035	0.038
Economic activity	0.056	0.026	0.014	0.045	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Education facility	0.056	0.026	0.014	0.045	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Health facility	0.056	0.026	0.014	0.045	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Water facility	0.056	0.026	0.014	0.045	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Infrastructures	0.056	0.026	0.014	0.045	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Religious facility	0.056	0.026	0.014	0.045	0.035	0.035	0.035	0.035	0.035	0.035	0.035

III.Calculate the Consistency Ratio (CR)

CR = Consistency index (CI)/Random Consistency Index (RI)

- CI = (λmax – n)/n – 1
- λmax = Σ of the products between each element of the priority vector and column totals.
- λmax = (2.53×0.32) +(5.39×0.23) +(10.19×0.18) +(22×0.038) +((28×0.035) ×6)
- λmax = 10.59
- CI = (λmax – n)/n – 1
- CI = (10.59–10)/10–1
- CI = 0.065
- CR = CI/RI
- RI = 1.49 when n = 10,
- CR = 0.065/1.49
- **CR = 0.0436**< 0.10 **(Acceptable).**

A. Risk for Pyroclastic flow hazard

Pyroclastic flows can be exceedingly destructive and lethal because of their tremendous temperature and movement. They travel quickly and obliterate anything in their way. Almost all exposures, including the towns of Metehara, Adis Ketema, and Sabure, MSEP, communities, and various facilities, are classified as extremely high to high risk. It will demolish buildings in cities and villages, scorch sugar plantations (Awash Melka farm and MSEP), kill animals (biome and wildlife present in Awash national park), and trigger mudslides or lahars when it mixes with flowing water (Awash River).

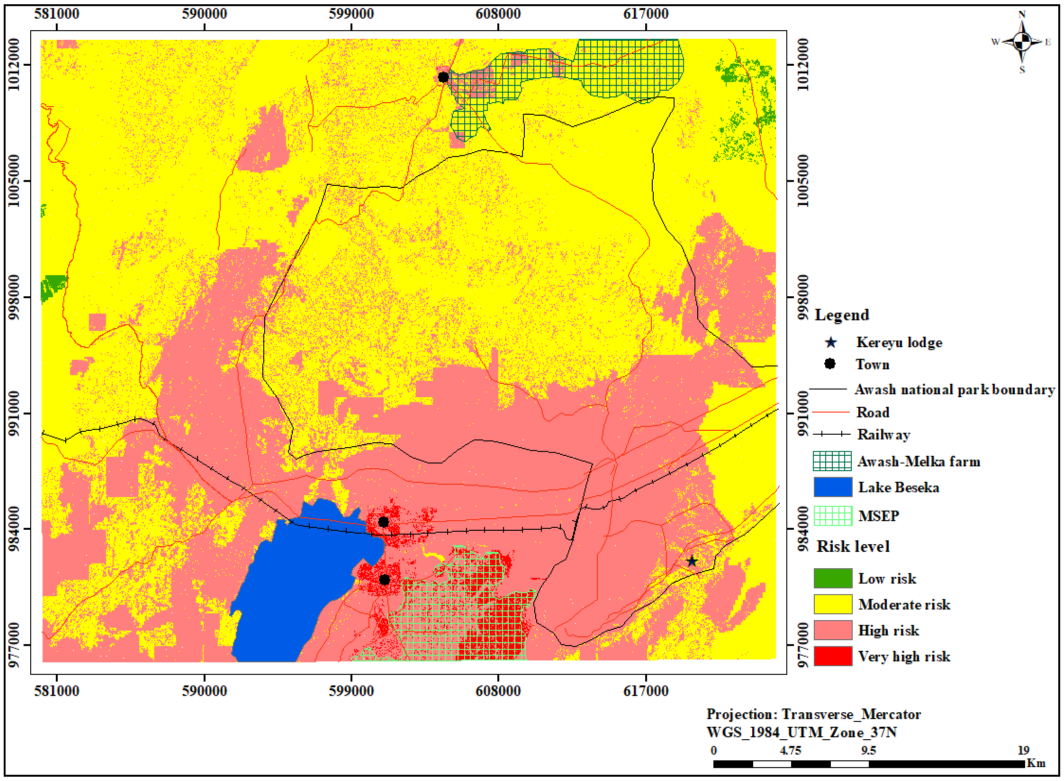


Figure 6.21. Risk map for pyroclastic flow hazard

Table 6.15. Area estimates for the risk map of pyroclastic flow hazard

Value	Risk from pyroclastic flow hazard	Area	Percentage
1	Low risk	6.59080	0.391920
2	Moderate risk	956.31360	56.866920
3	High risk	690.8690	41.082331
4	Very high risk	27.8960	1.6588278

B. Risk for ash fall hazard

When compared to pyroclastic flow, ash fall poses a moderate to high risk. The risk is larger in the southern portion of Fentale volcano. It will cause health issues (irritants to the eyes and lungs for residents of Metehara, Adis Ketema, Sabure town, and other areas), infrastructure disruption (Adis to Djibouti rail line, roads), socioeconomic disruption (cancellation of various facilities (water, religious, educational, and health facilities, among others), and the burying of many buildings in the three towns.

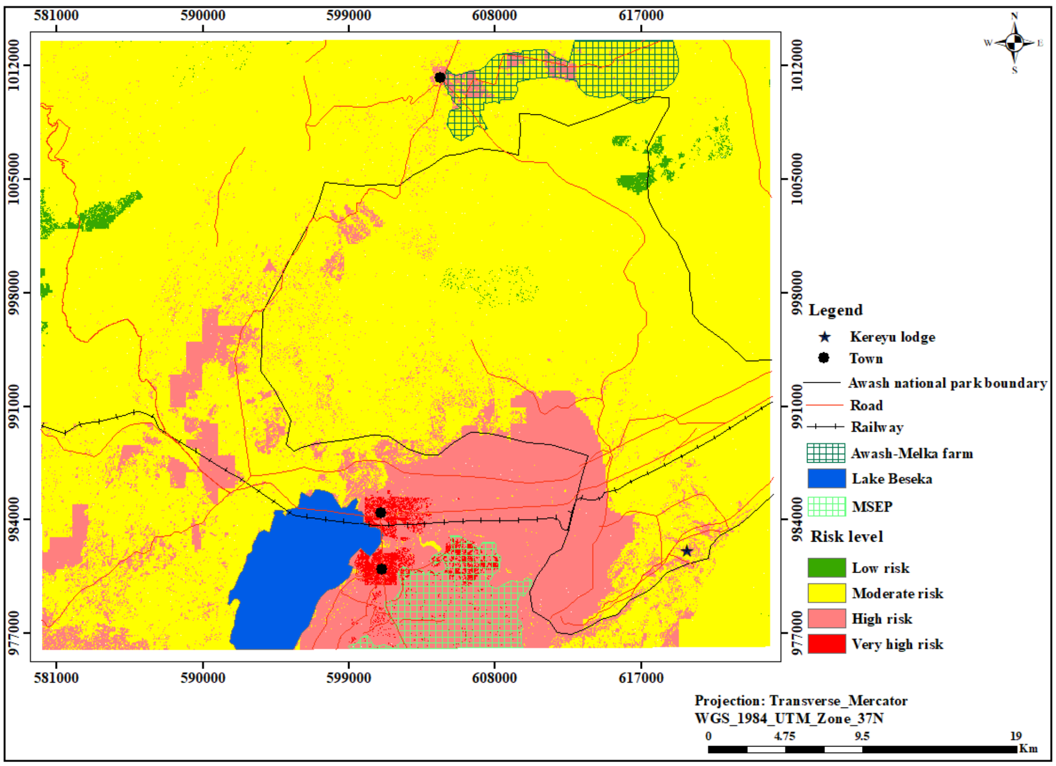


Figure 6.22. Risk map for ash fall hazard

Table 6.16. Area estimates for the risk map of ash fall hazard

Value	Risk from ash fall hazard	Area	Percentage
1	Low risk	11.8350	0.70376496
2	Moderate risk	1349.48930	80.2470033
3	High risk	305.23810	18.1508981
4	Very high risk	15.1070	0.8983335

C. Risk for lava flow hazard

The risk of lava flow is smaller than the risk of pyroclastic flow and fallout. According to history, the recent Sababor eruption produced basaltic lava that flowed south, destroying the town and cathedral. Lake Beseka, Metehara town, Awash national park, and a few places in the caldera's south are extremely vulnerable. Because the caldera is surrounded by Awash National Park, some of its areas will be harmed. If it enters Lake Beseka, it could boil violently, resulting in an explosive shower of molten spatter across a large area. It also caused minor damage in Metehara and other places. If the lava is silicic or viscous, it will flow slowly and people will be able to get out quickly.

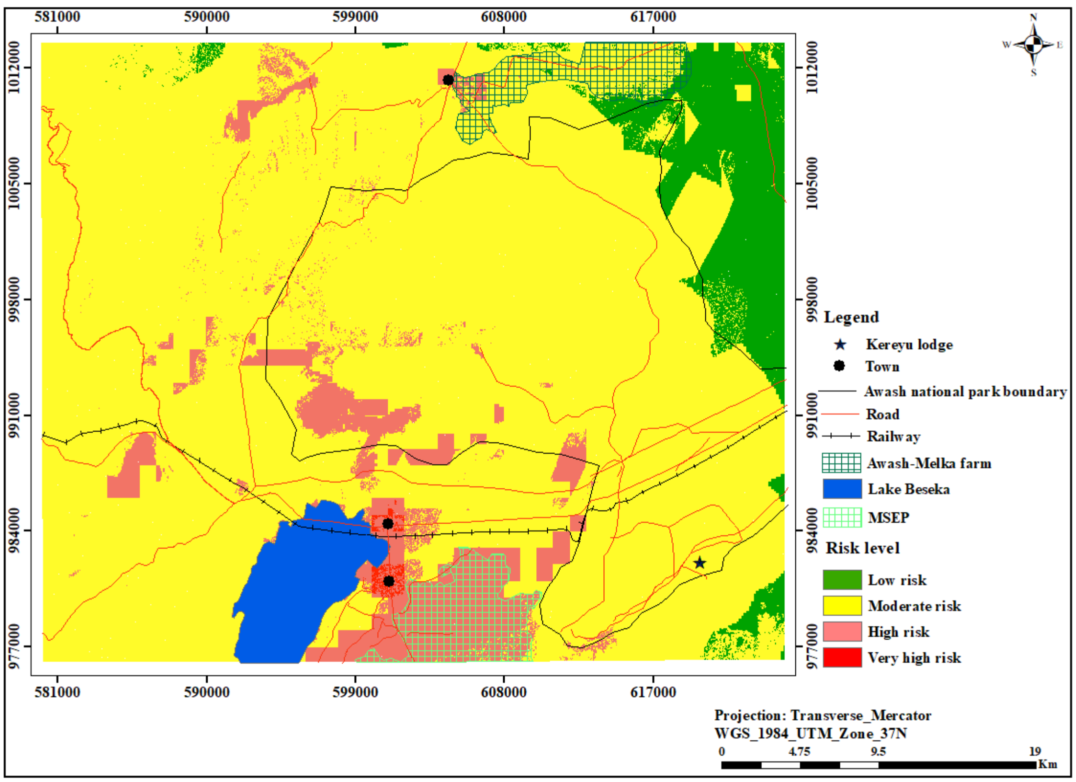


Figure 6.23. Risk map for lava flow hazard

Table 6.17. Area estimates for the risk map of lava flow hazard

Value	Risk of lava flow hazard	Area	Percentage
1	Low risk	122.32710000000	7.29469998531
2	Moderate risk	1381.81980000000	82.40169900830
3	High risk	169.75480000000	10.12294362460
4	Very high risk	3.02950000000	0.18065738177

6.2. Discussion

Because of limitations in volcanological data, quantitative assessments of volcanic hazards and risk are still only available in a few localities worldwide. Hazard mapping is one method of assessing and communicating hazards around individual volcanoes. There are many different forms of volcanic hazard maps and the most commonly used geology-based hazard maps are based on knowledge of previous eruptions and their distributed products (Calder et al. 2015). However, this does not represent the range of possible future eruption scenarios. To tackle this limitation and fill the gaps in knowledge, probabilistic computational modeling is required.

A preliminary assessment based on indices of hazard and population exposure for Ethiopia was attempted but became problematic as a result of insufficient data for many of the known volcanic systems (Brown et al. 2015c). The data to inform this assessment were generally poor and consequently there were large uncertainties about the scale and likely impact of past and future volcanism. Although none of the 59 active volcanoes in Ethiopia were classified at the highest hazard level, large uncertainties in the data reflect poor baseline geological and historic knowledge.

There have been numerous volcanic hazard studies employing geographic information system(GIS) to model and map the spatial extent of different volcanic hazards (e.g., Felpeto et al., 2001) and to assess the vulnerability of various elements at risk (e.g., Aceves et al., 2007). Based on the rate of population development and expansion of infrastructure, economic activity and different facilities, one can guess how much the hazard will be severe. GIs-based Multicriteria evaluation methodologies were used by Alcorn et al., (2013) to analyze the volcanic hazard and risk of the Valles caldera in Mexico City (MCE).

A two-hazard map was created (pyroclastic density current and lava flow). Then combine the hazard map with vulnerability (social and economic vulnerability) map and produced the total risk map of the area. Mesfin Mengistu (2018) used GIS to conduct a study on volcanic hazard zonation in Aluto. The study's major goal was to forecast future volcanic hazards and create a prospective volcanic hazard zonation map for the Aluto volcano. He studied many aspects such as height, slope angle, drainage networks, and distance from the caldera using MCE and (GIS).

The following possible hazards are extrapolated from the range of past eruptive products detailed in previous sections, as well as prospective eruption type;

- Pyroclastic flow hazard
- Pyroclastic fall hazards (tephra/ash fall hazard)
- Lava flow hazards, and

The volcanic hazard map of lava flow was created using the AHP approach. Vent and caldera were assigned equal weight with higher value and followed by fault. The sentinel-2A image was used to create a hazard map for both pyroclastic flow and ash fall hazards using a band ratio and supervised classification technique.

When compared to ash fall and lava flow, the risk of pyroclastic flow is projected to be higher. They are swift, have the ability to traverse large distances, and destroy anything in their way. As a result, the majority of exposures are classified as very high to high risk.

Table 6.18. The level of risk for pyroclastic flow hazard on exposures

No	Element at risk group	Risk level			
		Very high to high	**High**	**Moderate to high**	**Moderate**
1	Locality	Haro Adi,Norz,Gola, Barak, Birtukan, Mesgid	Kereri, Sobeber, Leba, Kubi, Jilo, Muda, Ajotele, Dinbaba, Boru, Balchi, Kechechelo, Sogido, Jaranuna, Werefa, Ledi, Kubi	Ajosalu,Mariga, Pimiru, Edoluko, Melka	
2	Economic activity	Sugar plantation, Wereda capital town	Park headquarter, DA office, Kereyu lodge, Awash national park	Awash - Melka farm	
3	Health facility	One clinic	Tututi clinic, Lege-Benti clinic, Health center, and another two clinics		
4	Religious facility	Hawariyat church,Chrstian cemetery, One mosque, Muslim cemetery	One mosque	Church and other Muslim cemetery	Mosque
5	Education facility	Gola and primary school	Lege Benti,Kobo, Dandi Gudina primary schools	One primary school	Two primary school
6	Water facility	Two pond, one Bono water	Three Bono, one Tanker, and one spring water		One spring water
7	Infrastructures (road and railway)	Metehara-Chole,Metehara-Awash,Chelekeleka-Ancha, Railway	Elala-Metehara, Elala-Awara Melka, Metehbela-Metehara, Awash-Debreselam, and other weather road	Melka werer-Awash, other weather roads	

8	Landuse/Landcover	Built up, Water body(lake Beseka), Crop land(sugar plantation)	Some part of shrub

Exposures will be moderately affected by the ash fall. It has the potential to inflict small to substantial harm to adjacent locality vehicles (railways and roads), taint water supplies, disrupt electrical systems (various power lines), and damage or kill plants.

Table 6.19. The level of risk for ash fall hazard on exposures

No	**Element at risk group**	**Risk level**			
		Very high to high	**High**	**Moderate to high**	**Moderate**
1	Locality	Haro Adi, Norz, Birtukan, Gola	Kobo, Leba, Sobeber, Awre, Ahmed Jilo, Golecha, Kubi, Ledi, Barak, Gola, Arboye, Boru ,Mogasa,Berti, Muke Bedera, Kalowa,Sumale	Edoluko, Kereri, Ahmed jilo, Kechechelo, Dinbaba, Mariga, Balchi,Kereri, Tututi,	Melka, Meldiba
2	Economic activity	Sugar cane plantation, MSEP,	Sugar factory, DA office, Mertiskuar,	Kereyu lodge, Awash national park, Park head quarter,	Park main entrance,Awash -Melka farm
3	Health facility	One clinic	Lege Benti clinic, other one clinic	Three clinic	Three clinic
4	Religious facility	Hawariyat church,	Hawariyat church, two mosque,Chrstian cemetery, and Muslim cemetery		Two muslim cemetery, one mosque
5	Education facility	Gola primary school	Kobo primary school, Lege-Benti primary school,	Dandi Gudina primary school, Tututi, and another one primary school	Two primary schools
6	Water facility	One Bono water	One Bono and two pond water,	One Tanker, one Bono water	Two spring and two bono water

7	Infrastructures(road and railway)	Metehara-Chole, Cheleleka-Ancha, Metehara-Awash, Nazreth-Metehara, Railway	Metehara-Metehbela, Elala -Metehara-Awash, Awash-Debreselam, Melka Werer-Debreselam, other weather road(earth surface)	Some roads of earth surface	
8	Landuse/landcover	Built up	Water body and crop land	Forest	

In comparison to ash fall and pyroclastic flow, the lava flow hazard will provide a modest risk. The very high classes are located around the volcanic center and near recent active volcanic vents (caldera). Main towns such as Metehara, Adis ketema, Lake Beseka, Awash national park, other neighboring localities, health facilities, water facilities, religious facilities, education facilities, and infrastructures will all be affected by the potential volcanic threat (road and railway).

Table 6.20. The level ofrisk forlava flow hazard on exposures

No	**Element at risk group**	**Risk level**			
		Very high to high	**High**	**Moderate to high**	**Moderate**
1	Locality		Boru, Mehamed jilo, Jilo, Golecha, Kechechelo, Balchi, DegaEdu, Sogido,Kobo, Norz, Sobeber	Birtukan, Gola, Kalowa, Mogasa, Horkoncha, KaraFerda, EdoLuko	Werefa, Ledi, Muda, Berti, Kubi, Mariga, Meldiba
2	Economic activity			Sugar plantation, Factory, DA office	
3	Health facility		Two clinic,	Lege Benti clinic	Tututi clinic
4	Religious facility		Hawariyat church, Muslim cemetery, Christian cemetery	One Mosque	Church and two Mosque
5	Education facility		Gola primary school, Dandi Gudina primary school, Kobo primary		Lege Benti, Tututi and one

			school	primary school
6	Water facility		Two bono and two pond water	Three bono, one tanker and one spring water
7	Infrastructures(road and railway)	Railway, Metehara – Chole, Metehara-Awash	Nazreth-Metehara, Chelekeleka-Ancha, Elala-Awara Melka, Elala Metehara-Awash	Meleka werer-Berehet, Metehara-Metehbela
8	Landuse/landcover	Built-up(Metehara town)	Water body(Lake Beseka), sugar plantation	

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

There are various geo-hazards such as landslide, seismicity, and volcanism causing risk and environmental problems in Ethiopia, particularly in the Rift region (Bekele Abebe et al., 2010). Fentale is a stratovolcano in which the magma storage is probably developed to shallow depth. It is active volcanic center consists various surface manifestations such as hot spring, mud pool, faults, carter, cones, etc. indicates the presence of eruption in the future. Both explosive and effusive eruption products are exposed with various compositions. Remote sensing and Geographic Information Systems (GIS) are used as a good scientific tool in assessing volcano hazard and risk. Different surface features of volcanoes such as cones, vents, faults and caldera were extracted from DEM (ALOS PALSAR) and sentinel 2A images and mapped by ArcGIS. The analysis is done by ranking those geological features based on their role on facilitating the hazard. The preparation of hazard map is done by AHP technique weighted overlay analysis.

The voluminous exposed unit in the study area is pyroclastic flow deposit so called welded tuff (ignimbrite).Pyroclastic flow hazard causes a great loss of lives, damage, and destruction of everything (population, infrastructures, land use/land cover, localities and different facilities) in its path due to its high speed. There are also basaltic flow and ash flow deposit at southern part of the calderas. In addition to such health complications, fallout deposits as little as 3 mm have been shown to cause serious damage to different vulnerable elements in the area including buildings, machinery, lifelines, and agriculture. For example, tephra deposits just millimeters thick can cause significant harm to water quality, increasing the turbidity, lowering the pH, and adding harmful chemical substances to water sources (Wilson et al., 2012). Lake Beseka will be vulnerable for ash fall hazards. Small amounts of ash sized material may also infiltrate wastewater management systems clogging the equipment, causing failure and shutdown, and possible flooding (Wilson et al., 2012). Similarly, as little as 1–3 cm of tephra may also significantly disrupt ground transportation networks. Ash may impair drivers' visibility, because roads to become slippery, cover road markings, and abrade vehicle engines. Different road types and railway (Addis Ababa to Djibouti) are more vulnerable for ash fall hazard. Additionally, depending on the building structure and ash load, fallout deposits may cause roof collapse, especially if wet. Lava flow will cause less damage than pyroclastic and ash fall. It will burn everything and will also cause explosion when it interacts water bodies.

Metehara and Adis Ketema are more vulnerable towns where high numbers of populations are lived. Metehara is found 7.7 km away from the caldera. Addis Ketema town is located at south end of Metehara town where the sugar plantation and factory are located. Metehara sugar factory is one of the main large-scale sugar establishments operating within Ethiopia. There are different facilities that are available in different localities such as water facility, education facility, religious facility, health facility, and economic activities. Awash National Park is highly vulnerable to the three hazards. A variety of wildlife and high number of vegetation are found within the park that acts as tourist attractions as well as economic development of the country.

The following results and conclusions have been reached from the hazard and risk assessment from future eruptions of Fentale volcano:

The hazard level is classified into four classes for the three hazard types.

- For pyroclastic flow hazard, the area is rated as low hazard with 13%, Moderate hazard 40.68%, high hazard 9.68%, and very high hazard 36.63%. The risk level is classified in to four classes. Low risk encompasses0.39%, moderate risk area covers 56.87%, high risk area covers 41.1%, and very high risk covers 1.66% of the study area.
- For ash fall hazard, the area is classified as low hazard with 13%, moderate hazard 40%, high hazard 36.63%, and very high hazard 9.68%. The risk level is divided into four categories. Low risk overs0.7%, moderate risk area covers 80.25%, high risk area covers 18.15%, and very high risk covers 0.9% of the study area.
- For lava flow hazard, the area is classified as low hazard with 9.6%, Moderate hazard 41.88%, high hazard 37.63%, and very high hazard 10.88%. The risk level is categorized in to four classes. Low risk spans7.3%, moderate risk area covers 82.25%, high risk area covers 10.12%, and very high risk covers 0.18% of the study area.

Because the majority of exposures are placed south of Fentale caldera, the risk map indicates that the level of risk is higher there.

Pyroclastic flow danger has a greater risk level, and it mostly affects areas with a high population density, economic activity (such as sugar plantations and factories), and a variety of facilities. The volcanic record for Fentale is poor and its key eruptive stages not well-known. Our knowledge of Fentale's stratigraphy can only capture parts of the eruptive history of the volcano. As such, under-reporting may underestimate the hazard and attendant risks posed both in the past and at present.

7.2. Limitation of the study

- Because the area is not well studied, the magnitude of the future eruption product is not estimated.
- Remote sensing technique requires small scale data interpretation and provides information about features that are too small for detection by satellite imagery.
- MCE have a potential weakness of higher subjectivity, difficult to give consistent scores, high qualitative uncertainty analysis, etc.

7.3. Recommendation

There are different economic activities around Fentale caldera that are a key factor for economic development of the country. The most significant elements exposed to the volcanic hazards in case of renewal of volcanism are: a large population, partly concentrated in the city of Metehara and partly distributed over a large area around the volcano, the main road and the only railway which connect Ethiopia to the sea, at Djibouti, sugarcane and banana plantations north and south of the volcano, along the Awash river, which is a mean of subsistence for local population and for the entire country, the Awash National Park, etc.

There is the probability for re-eruption of Fentale volcano. Because the area is geologically active where there is continuous tectonic activity showing volcanic unrest. Volcanic eruption is followed by hazards and it will pose risk. It is must to give proper attention to save human life and economic loose from future eruption. There must be a detail hazard assessment (such as energy cone modeling and other techniques) to study the magnitude of future eruption.

In developing countries like Ethiopia where there is scarcity of volcanic hazard and risk awareness, the government should use society awareness creation about volcano. In such case people may know and get ready if they will be some geologic changes happened over active areas. Early warning systems and continuous volcano monitoring are the two most important elements for reducing the risk of volcanic hazard.

The federal and regional governments should collaborate on this strategy of early warning and catastrophe management. Thus, Fentale caldera is surrounded by increasing number of population and various economic activities there should be volcano monitoring. Scientists and researchers should conduct a thorough examination utilizing both geological and geophysical approaches in order to arrive at a plausible conclusion that will aid the environment in reducing the risk from future Fentale eruptions.

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Appendix I. Accuracy assessments of lithology classification

Row- ID	Recent basalt	Pitchstone	Old basal	Alluvium & lake sedim	Welded tuff	Trachyte & Rhyoli	Ash fall	Water body	Total	Commissior	User accuracy
Recent basalt	9	0	0	0	0	0	0	0	9	0	100
Pitchstone	0	11	0	0	0	0	0	0	11	0	100
Old basalt	0	0	8	1	1	0	1	0	11	0.2727273	72.73
Alluvium & lake sediment	0	0	0	7	0	0	1	0	8	0.125	87.5
Welded tuff	1	1	1	1	10	1	0	0	15	0.3333333	66.67
Trachyte & Rhyolite	0	0	0	0	0	8	0	0	8	0	100
Ash fall	0	0	1	0	0	1	9	0	11	0.1818182	81.82
Water body	0	0	0	1	0	0	0	10	11	0.0909091	90.91
Total	10	12	10	10	11	10	11	10	84		
Ommision	0.1	0.0833333	0.2	0.3	0.09090909	0.2	0.18182	0			
Producer accuracy	90	91.67	80	70	90.91	80	81.82	100			
Over all accuracy	85.71										
p(t)	0.10										
Kappa	0.95										

Appendix II. Accuracy assessments of LU/LC classification

LU/LC	Farm land	Bare land	Shrub	Grass land	Built up	Water body	Total	Commission	User's accuracy
Farm land	27	0	0	0	1	0	28	0.04	96.43
Bare land	0	25	1	1	0	1	28	0.11	89.29
Shrub	0	0	44	1	1	0	46	0.04	95.65
Grass land	0	0	1	40	0	0	41	0.02	97.56
Built up	0	0	1	0	15	0	16	0.06	93.75
Water body	0	0	1	0	0	30	31	0.03	96.77
Total	27	25	48	42	17	31	190		
Omission	0	0	0.08	0.05	0.12	0.03			
Producer's accuracy	100	100	91.67	95.24	88.24	96.77			
Overall accuracy						0.95			
Kappa						0.94			
P®						0.18			