University of Nairobi

Faculty of Engineering

FOREST FIRE VULNERABILITY ASSESSMENT IN THE ABERDARE FOREST RESERVE

BY

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A Project submitted in partial fulfillment for the Degree of Master of Science in Geographic Information Systems, in the Department of Geospatial and Space Technology of the University of Nairobi

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Declaration

I, NDEGWA JANE MUKAMI, hereby declare that this project is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any other Institution of Higher Learning.

NDEGWA JANE MUKAMI 21st July 2022

Name of student Signature Date

This project has been submitted for examination with our approval as university supervisor(s).

Prof. Dr.- Ing John Bosco Kyalo Kiema 21st July 2022

Name of supervisor Signature Date

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Dedication

I dedicate this work to my family.

Acknowledgement

I acknowledge the help of my supervisor, Prof. Dr.-Ing John Bosco Kyalo Kiema for his continued guidance, correction and direction throughout the research project. I thank Mr Richard Mwangi from the Fire Department of Kenya Forest Service Nairobi, for his valuable expert opinion in this project. I am also grateful to my colleagues and the staff from the Department of Geospatial and Space technology for their support and assistance any time I needed it. Above all, I am grateful to God for good health during my years of study.

Abstract

Forests, being an important resource in our environment, require intentional conservation. There is an increasing need to protect forests even as the battle for climate change continues. Threats to the existence of these forests should be addressed so as to maintain and increase forest cover globally. Despite the importance of fires in balancing the ecosystem, uncontrolled occurrences lead to devastating losses. Forest fires occur as a result of either natural or human activity.

In the recent past, forest fires have caused a menace to the ecosystem by disrupting the very nature of their existence. They have led to the loss of forest cover and biodiversity upset in the Aberdare region, the recent fire outbreak being at the Eburu region on 5th February 2022. This came a few days after the Kenya Meteorological Department issued a warning on the possibility of forest fire outbreaks.

This research project will address a challenge in the mitigation phase of forests' disaster management. Various fire models were analyzed and one was created as a best fit to Kenyan forests. The model was created in a GIS environment to identify, classify and map fire risk regions. Inputs for this model was based on three main criteria; climatic, topographic and anthropogenic factors. A fire risk assessment was done on the Aberdare Forest Reserve using GIS based Analytical Hierarchical Process (AHP) and Multi Criteria Decision Making Analysis (MCDA) to come up with a Forest Fire Risk Map. MODIS data obtained aboard Terra and Aqua satellites was used as a measure of evaluation of the fire risk model covering the Aberdare Forest reserve.

A fire risk map was produced, depicting severity zones of the areas that are prone to fire, ranging from very low to very high. 65.14 % of the area in the Aberdare Forest Reserve was found out to lie in the high-risk region, 33.21 % in the moderate risk region while 1.95 % was in the low-risk region. The deliverables of this research project are important in forming a basis for the development of forest fire management plans specific to the Aberdare region and as an important input to efforts channeled in monitoring these areas by the Kenya Wildlife Service (KWS) and Kenya Forest Service (KFS).

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List of Acronyms/Abbreviations

GIS – Geographic Information Systems

KMD – Kenya Meteorology Department

FIRMS – Fire Information for Resource Management System

KFS – Kenya Forest Service

KWS - Kenya Wildlife Service

IEBC – Independent Electoral Boundaries Commission

FAO – Food and Agricultural Organization

AHP – Analytical Hierarchy Process

MCDA – Multi-Criteria Decision Analysis

DEM – Digital Elevation Model

UNEP – United Nations Environmental Program

RCMRD – Regional Center for Mapping and Resource Development

WRI - World Resource Institute

MODIS – Moderate Resolution Imaging Spectroradiometer

CHAPTER 1: INTRODUCTION

1.1 Background

Approximately 2 billion people around the world depend on forests directly or indirectly (FAO 2006). Services derived from forests contribute greatly to the economic value of a country. Despite the value of forests, they continue to face threats arising from either natural occurrences or human-induced disturbances (Koziowski, 2002).

Forest fire can be defined as the unwanted free nature of fire occurring in regions with forest vegetation, caused by either humans or due to natural causes (Chuvieco, 2009). The main reason why fire hazards are often difficult to contain is because of the uncontrolled course they take after starting. However, predicting their occurrence is a safer way to manage this phenomenon as it minimizes chances of even starting.

The forest cover in the country is 7%, which is below the global minimum of 10% (Forest Policy, 2014). Article 69 (1) (b) of the Kenyan constitution emphasizes the need to "work to achieve and maintain a tree cover of at least 10 per cent of the land area of Kenya". In the last 20 years, various forests fires have occurred, some of which have taken up to a week to contain. The total area under forest cover has reduced from 39,267 square kilometers in 2001 to 36,111 square kilometers in 2020.

For a country that plans to achieve 10% cover by the end of the year 2022, forest fires are not only an undesirable phenomenon, but also not a welcome occurrence. Among the phases of disaster management, mitigation and preparedness are often overlooked when trying to avert forest fires while response and recovery are focused on. Vulnerability assessment falls under the mitigation phase of disaster management. The goal is to reduce vulnerability to the negative impacts of fire hazards. Most fires are caused by various human activities, yet it may not be possible to accurately model human behavior.

Various approaches have been developed showing relationships between number of fire incidences and proximity to roads and settlements. It is more likely that a fire will start in a region that has close proximity to settlements, roads or motorable tracks and camping sites. The model to be adopted in this project will take into consideration the effect of this anthropogenic factors on forest fire hazards, thus the choice to include anthropogenic criteria. Most fires occur from January to

March and August to September because of the high temperatures and low humidity. The rainy season is from April to May and October to November. This informs the choice to include climatic factors.

1.2 Problem Statement

The origin of a forest fire is often difficult to determine due to the absence of material evidence resulting to the percentage of undetermined causes being very high. Previous studies have focused on the recovery and response phases of disaster management while few focus on preparation and mitigation.

Previous studies focus on the burnt area analyses after a fire has occurred using space-based technologies. Despite this also being an important aspect of the recovery phase of disaster management, mitigation takes precedence to avoid the fires in the first place.

There are many models used to assess fire risk but none of them has been applied to a Kenyan forest. Previous models have been customized for forests in the Mediterranean region such as the one used in M. S. Guettouche et al 2011 and thus cannot be used as a best fit for Kenyan forests since it is a tropical country. Kenya lacks a current comprehensive fire management plan for the Aberdare region and a vulnerability map would be an important addition towards this cause by the relevant stakeholders.

1.3 Objectives

1.3.1 Overall Objective

The main objective is to assess the vulnerability of the Aberdare Forest Reserve to fires using GIS.

1.3.2 Specific objectives

To evaluate existing forest fire models that can be adopted to Kenyan Forests

To create and validate a model to identify and classify fire risk areas

To create a fire risk map of the Aberdare Forest Reserve

1.4 Justification for the Study

Kenya experiences an average of 78 fires annually (World Bank, 1999). The Kenya Wildlife Service (KWS) and Kenya Forest Service (KFS) together with the local community have always channeled efforts in containing forest fires. However, sometimes they are overwhelmed and the forest fires spreads for days. To avoid this, continuous monitoring of risky regions will lead to early detection and containment of fires.

Human activity being the main cause for forest fires in the Aberdare region, a vulnerability assessment will be a useful addition to minimize frequency of fire occurrences and averting damage. The model can be used as an input into an early warning system and an emergency management system.

Prevention, preparedness and monitoring of forest regions prone to fire can be carried out effectively by prioritizing high risk areas. An integrated fire management approach and a national forest fire policy may include this proposed model in their development.

1.5 Scope of work

This study covers the Aberdare Forest Reserve Region and does not include any forested areas outside this zone. The factors that were considered included climatic, anthropogenic and topographical factors. Decision variables such as species composition and stand crown closure were not included in the model. Only hazard analysis and vulnerability analysis were assessed in this study. Evacuation and response mechanisms in cases of fire were not considered.

1.6 Report Organization

The report is organized into five chapters. Chapter one tackles introduction and it comprises of the background to the study, the project’s objectives, scope and limitations and justification of the study. Chapter two is the literature review regarding the study area, existing fire risk models and use of GIS for fire modelling. Chapter three discusses the methodology applied in the project. Chapter four gives the results and analysis. The final chapter contains the conclusions and the recommendations as determined from the results analysis.

CHAPTER 2: LITERATURE REVIEW

2.1 Forest Fires

According to Act for Libraries organization, Forest Fires can be divided into three;

a) Ground Fires

   Ground fires are dangerous since they are hard to detect and difficult to control. They may also rekindle, adding to the challenge of stopping the fire.

b) Surface Fires

   Surface fires spread easily but do not cause significant damage to trees unless it grows very large.

c) Crown Fires

   They spread very quickly through the forest and are very hard to control because of their heat and intensity.

2.1.1 Forest Fires in the Aberdares

In 2017, more than 17,000 acres of the Aberdare Forest were destroyed by fire and 700 hectares more in 2019. According to the Aberdare Forest Reserve Management Plan 2010- 2019, fire incidences spanning 5 years from 2005 to 2009, resulted in burnt area of 4449.2 hectares. It also indicates that forest fire incidents in the reserve have been consistently occurring since 1912.

Figure 2.1 A burning section of the Aberdare - The Star,7th February 2022

Figure 2.2 Volunteers putting out a fire at the Aberdare, The Standard 14th January 2016

2.1.2 Statistics

Table 2.1: Forest Fire Incidences in the Aberdare Forest Reserve (Aberdare Management Plan 2010-2019)

Zone	Station	Total Area Burnt (ha)				
		2005	2006	2007	2008	2009
Thika	Kimakia	0	0	0	0	0
	Kieni	0	4	0	0	0
Nyeri	Muringato	40	0	0	0.05	0
Nyandarua	S. Kinagop	0	0	0	0	14.75
	Ol Borosat	0	0	0	0	3.5
	Geta	1631	1200	0	69	888.1
	Ndaragwa	0	0	0	0	63.8
	N. Kinagop	0	136	0	0	2
Kiambu	Uplands	33	0	58	0	15
	Kinale	223	0	9	0	59
TOTAL		**1927**	**1340**	**67**	**69.05**	**1046.15**

2.2 Causes of Forest Fires

2.2.1 Global Outlook

Forest fires occur either naturally or through human activity. Natural fires are caused by lightning or spontaneous combustion. Despite the lack of actual evidence that lightning causes these fires, it is assumed as the cause since the regions in which these fires occur are remote with no sign of human interference. Regions that have had such incidents are Canada and Russia.

Fires can be caused intentionally as a way of balancing the forests' ecology and vegetation species. In such instances, the fires are supposed to be monitored but can spiral out of control causing wildfire and vegetation loss.

Human activities attributed to forest fires include illegal logging, hunting, arson, cigarette smoking, camp fires and burning weeds for farm preparation.

2.2.2 In Kenya

All fires in Kenya are started by people (World bank, 1999). Of the fires caused by human activity in Kenya, 40% are classified as arson, 20% are caused by negligence and carelessness and 40% are due to unknown causes. Kevin W. Nyongesa and Harald Vacik (2005) highlighted the main human activities that had led to forest fires occurring in Mt Kenya in a study of Gathiuru Forest Station on Fire Management in Mount Kenya. They include charcoal burning, hunting, honey harvesting, land preparation, timber harvesting, herbal medicine collection, camping activities, collecting wild fruits and performing cultural rituals.

2.2.3 In the Aberdare Forest Reserve

According to results obtained from an aerial survey of the destruction of the Aberdare Range forests by UNEP, KWS and Rhino Ark, the human causes of fires occurring in the reserve included illegal logging, illegal farming of Marijuana, charcoal production, shamba system practices, settled encroachments, land preparation and pest control.

In March 7th 2022, wildfires were reported in the moorlands of Northern Aberdares. There has been concerted efforts by RhinoArk's Aberdare Joint Surveillance Unit to contain the fires that were caused by marijuana farmers. An operation then followed in which marijuana was uprooted to discourage the practice. In early February, cannabis farmers caused bushfires destroying over 700 hectares of moorlands vegetation, within the Aberdare National Park and adjacent Forest Reserve.

2.3 Parameters in Forest fires

Despite fires occurring in most forests in the world, most of the factors affecting fire vulnerability are common. They can be categorized into the following factors;

2.3.1 Topographic

i. Elevation

Areas of low elevation are more susceptible to fires than areas lying in higher elevations. This is attributed to suitability of settlements in low elevation areas.

ii. Slope

Slope, being the rate of change of elevation, affects the amount of fuel available and the rate of fire spread. The steeper the slope, the greater the preheating of fuels that can occur, and the faster the fire will spread. Fire spreads best uphill thus those that start at the base of a slope become the largest fires.

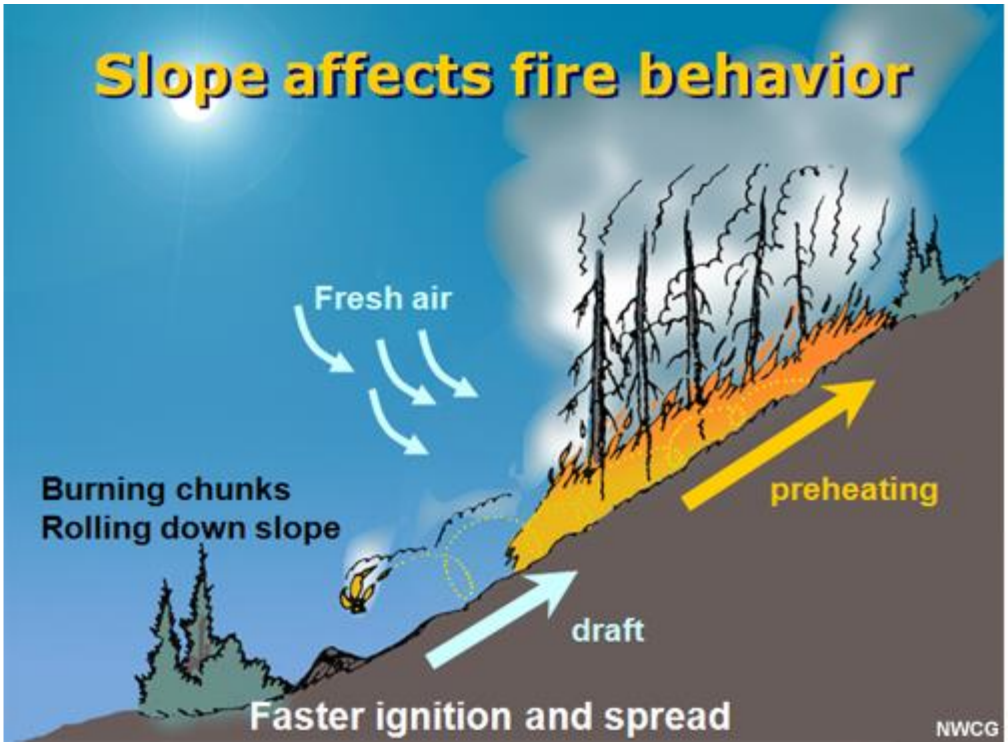


Figure 2.3 Influence of Slope on forest fires

iii. Land Use/Land Cover

This factor has the highest influence on the ability of a fire to start. Water and aquatic vegetation will have the least influence while grasslands and shrubs have the highest influence. A fire is more likely to start in areas covered by croplands due to the practice of land preparation for cultivation than in areas that are bare. Trees have a high rating although different tree species have different fuel types and each of them has a different affinity to fire.

iv. Aspect

Aspect refers to the direction the slope faces. Aspect is expressed as one of the eight cardinal directions: North, South, East, West, Northeast, Northwest, Southeast, or Southwest. The aspect determines the amounts of sunshine, precipitation, and wind a slope receives, directly affecting fuel conditions.

South and southwest aspects receive the most direct sunshine, leading to higher fuel temperatures, drier conditions, and earlier snowmelt dates. These aspects tend to be most favorable for fire spread. South and South West facing regions receive the most direct sunshine hence high fuel temperatures, drier conditions hence most favorable for fire spread.

North-facing aspects have more shade, resulting in lower temperatures, higher humidity, and heavier fuels with higher fuel moistures. When burning conditions are favorable, the heavier fuel loads can lead to increased fire behavior.

East-facing aspects will experience heating in the early part of the day and cooling in the afternoon and evening. West-facing aspects do not begin to heat until later in the day. Fire spread on these aspects can depend to some degree on the time of day as well as on other local factors.

2.3.2 Anthropogenic

i. Distance to roads

Due to many fires being caused by human activity, forest regions close to roads are highly susceptible than those far from any road network. In the forests, there exists motorable tracks and paths that are used by various people for different purposes in accessing the forests.

ii. Distance to settlements

The closer human settlement is to forests the higher the probability that forest fires will occur.

iii. Population Density

Highly populated areas near forest regions pose a high threat to possibility of forest fires occurring.

2.3.3 Climatic

i. Rainfall

Areas experiencing less amount of rainfall are highly susceptible to forest fires since the land is drier, providing a conducive environment for a fire to quickly ignite and spread.

ii. Temperature

Drier areas are highly vulnerable to fires starting, explaining why most of the fires in the Aberdare region occur in the months between January and March.

2.4 GIS in Forest Fires

2.4.1 Forest Fire Mapping

A geographic information system (GIS) is a system that involves collecting, organizing, storing, analyzing and presentation of geographical data. It consists of components such as hardware, software, data, people and procedures. The primary goal in using GIS is to improve the ability to make decisions. Forest Fire mapping is done to visualize areas affected by fire. In Kenya, various studies have been done for purposes of burnt area analysis and normalized burn ratio. This is important as it aids in the recovery phase of the fire disasters. In a study by D. Ongeria and B. K. Kenduiywo (2020), GIS was used to produce a burnt area severity map after hotspot confirmation and validation by reference data.

2.4.2 Forest Fire Modelling

Previous studies have suggested the integration of various fire causative variables into one fire model (Chuvieco and Congalton, 1989; Hernandez et al. and 2006; Carrão et al., 2003). The variables have been different for different models applied in different areas of study. In a model suggested by Lafraguetta 2013, constraints such as waterbodies and settlements were not used as factors in the model. While it is acceptable that proximity to water bodies may not have a direct correlation of forest fire occurrences, settlements should be considered. The weakness of this model is the lack of inclusion of settlements as an input in a model which have an overall effect to fire occurrences.

2.4.3 Model Analysis

2.4.3.1 Fire Risk Model for Gallipoli Peninsula

This model suggested by Esra Ertena, Vedat Kurgunb and Nebiye Musaoluc in 2002, is suitable for Mediterranean forests. It includes vegetation, slope, aspect, distance to roads and distance to settlements as parameters into the model. It also includes an aspect of Remote sensing in line with the objectives of that research undertaken which was to assess the effect of fire on a certain day, so images were obtained before and after the fire and thus analysis done. Additional factors that I found to be equally important in this study were the forest fire towers, fire stations, intervention places and the characteristics of the staff that will intervene in cases of fire.

For a Kenyan forest however, this model cannot be effectively used as it is since there are no fire towers within the forests. However, slope, distance from roads and settlement parameters can be adopted. No climatic factors were considered in this model.

This model also focused on burnt area analysis using LANDSAT imagery, which introduces an aspect of post analysis of fire occurrence in the recovery phase of disaster. Despite this being an important part of the research, this research focuses on mitigation which concerns everything before a fire occurs.

2.4.3.2 Fire Risk Model for Southeastern Honduras

This model focused on Hotspots Analysis and Forest Fire Risk Zones Mapping in the Yeguare Region. It was suggested by Claudia F. Cáceres (2011) and can only be applied to Mesoamerican countries. It incorporates 6 parameters: slope, vegetation, aspect, distance from roads, distance to settlements, and elevation. The weakness of this model in its application to tropical forests is that no climatic factors were considered. The Chuvieco and Congalton 1989 fire rating scheme was used to come up with the final fire rating classes.

2.4.3.3 Fire Risk Model for Nepal Landscapes

Independent variables used in this model include Aspect, slope, elevation, vegetation, temperature, road, settlement. It was suggested by A. Parajuli et all 2020. The differentiating factor from the above two models is the inclusion of land surface temperature. This is an important element that has a direct relationship with the relative humidity of the atmosphere. High humidity levels mean high temperatures and the vice versa is true. This model comes close to being a good fit for Kenyan forests. Its weakness however is failure to incorporate rainfall as well as part of a climatic factor. The Chuvieco and Congalton 1989 fire rating scheme was also used to come up with the final fire rating classes.

2.4.3.4 Fire Risk Modelling for Forest of Bouzareah Clump, Algiers (Algeria)

This model also focuses on Mediterranean forests. In addition to independent parameters used in previous models, Climatic station data (temperature, rainfall, relative humidity and wind), were used to calculate the drought index and the wind. Population was not considered in the model. Suggested by Mohamed Said Guettouche et al 2011, additional indices were considered including combustibility and urbanization indices as depicted in Figure 2.4.

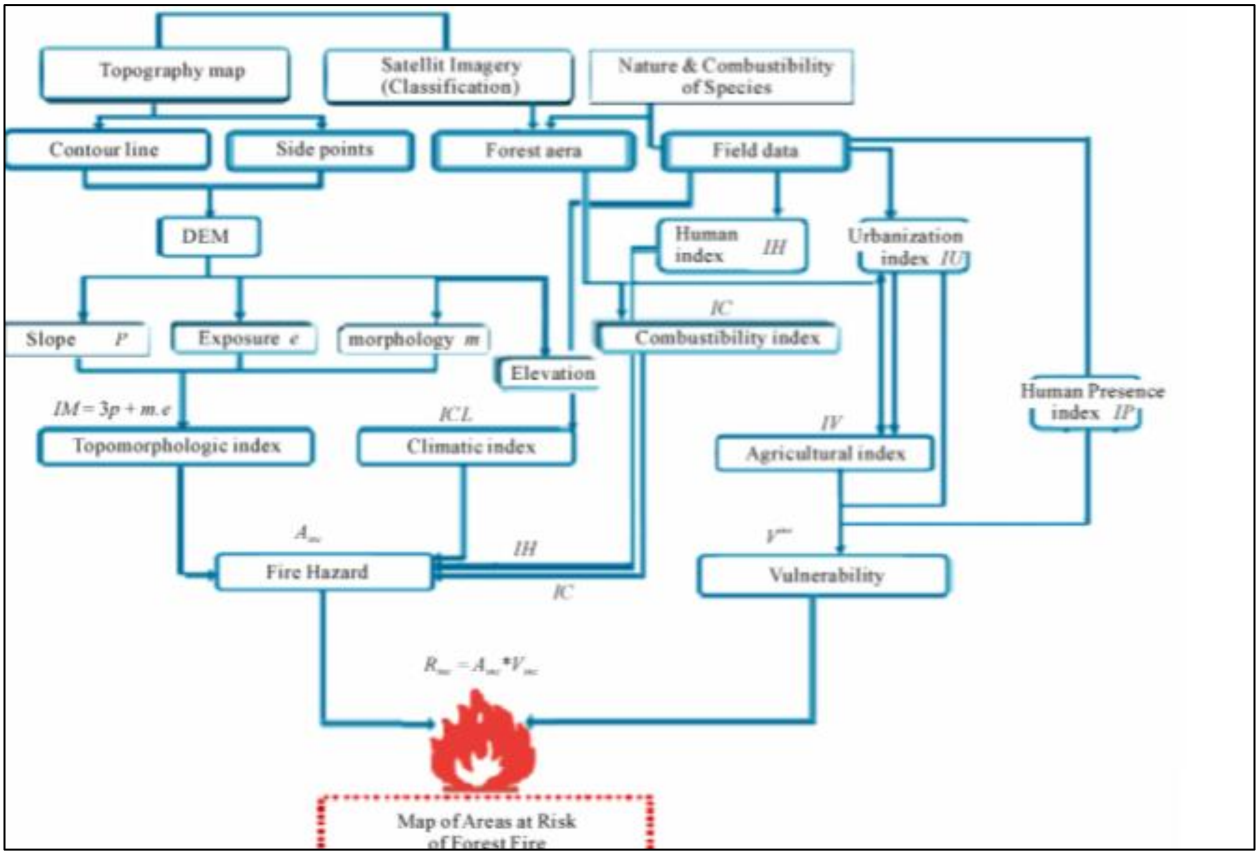


Figure 2.4 GIS Graph Process (M. S. Guettouche et al. 2011)

2.5 Analytical Hierarchy Process (AHP)

Different cases have made use of the AHP technique and has been proven to be efficient in weight estimation. (Saaty LT 1980). In this project, I purpose to engage with experts from KFS in using this structured technique and applying it on the fire causative factors. AHP guides the decision makers in finding a best suited solution regardless of the complexity of their problem. It allows the active participation of decision makers in exploring all possible options in order to fully understand the underlying problems before reaching an agreement or arriving at a decision (Estoque, 2012). Therefore, the purpose of AHP is to judge the given alternatives for a particular goal by developing priorities for these alternatives and for the selected criteria. AHP is thus based on three principles: decomposition, comparative judgment, and synthesis of priorities (Saaty LT 1980).

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter highlights the various research methodologies in conducting the study and the techniques used in obtaining research data and how data was processed to obtain the subsequent results. The aspects to be covered in this chapter include the description of the study area, data sources and tools, data collection, processing and analysis.

3.2 Study Area

The Aberdare Forest Reserve is one of the five main water towers in the country alongside Mt Elgon, Cherangani Hills, Mau Complex and Mt Kenya. It has 19 forest stations. It covers Nyandarua, Nyeri, Muranga and Kiambu counties and has an acreage of 103,024.930 hectares. It is gazetted under Legal notice 48/1943 (KFS 2018). It comprises of various vegetation types such as Natural forests, plantation, bamboo, bush, teazones and moorland. It has 5 forest blocks, South Laikipia, Kipipiri, Nyeri, Kikuyu Escarpment, Aberdare Forest and Aberdare National Park.

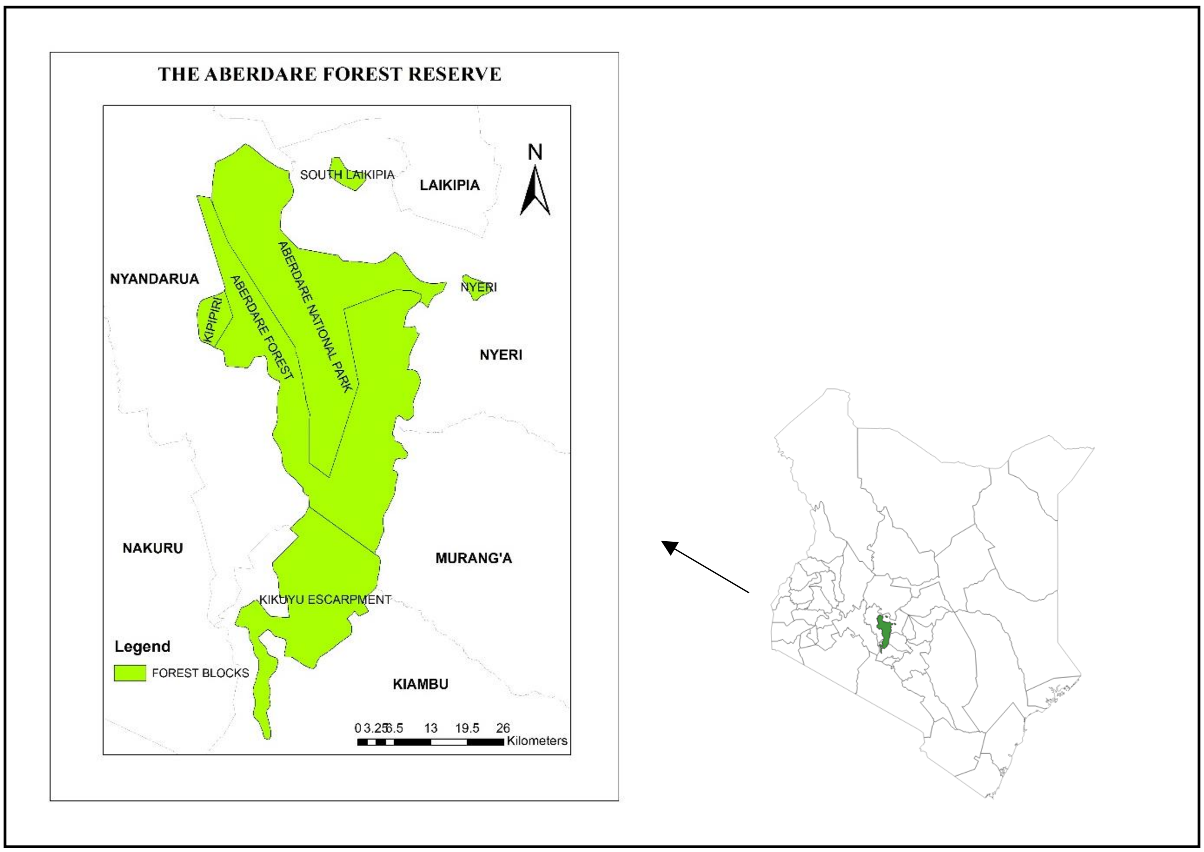


Figure 3.1 Area of study

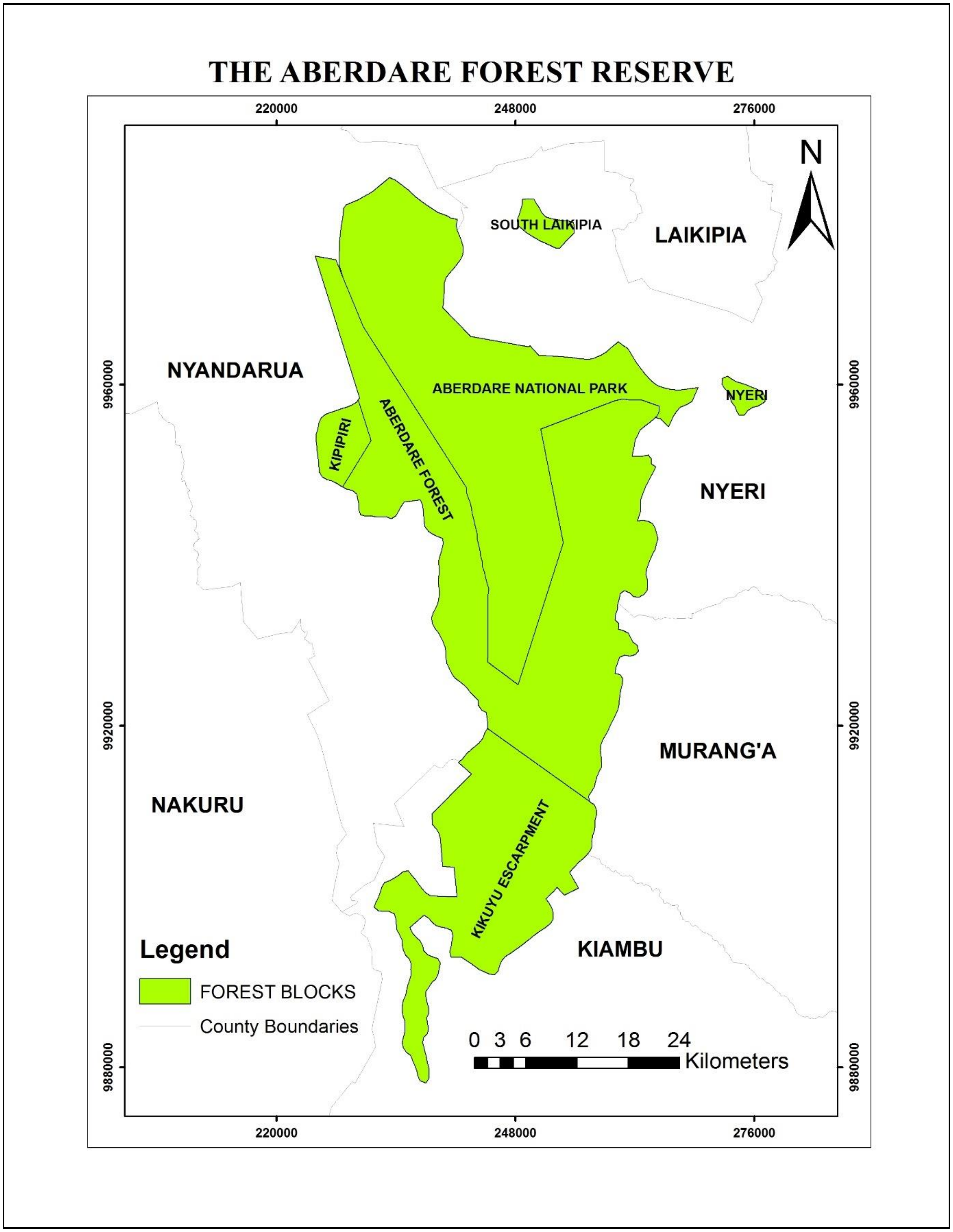


Figure 3.1.1 Aberdare Forest Blocks

3.3 Methodology

The methodology approach is illustrated in the following schematic;

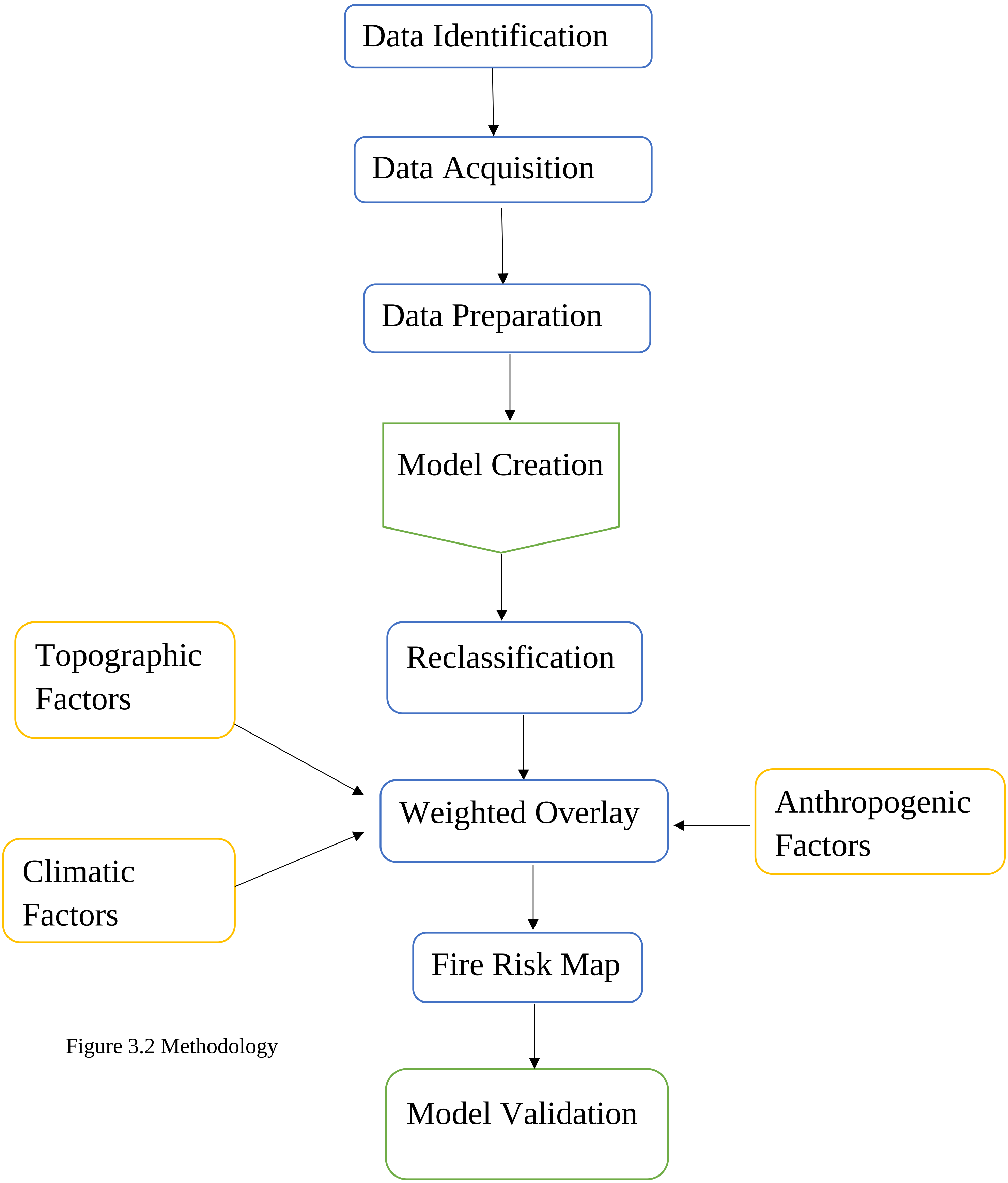


Figure 3.2 Methodology

3.3.1 Data Identification

According to the objectives of this research project, the data was identified as follows;

a) Temperature
b) Rainfall
c) Digital Elevation Model
d) Roads
e) Administrative Boundaries
f) Archived Fire Data
g) Settlements
h) Kenya Forests
i) Land Use

3.3.2 Data Acquisition

The data required was collected from the following sources

Table 3.1: Data Sources

DATA	SOURCES	FORMAT
Temperature	KMD	TIFF
Rainfall	KMD	Shapefile
DEM	RCMRD	TIFF
Administrative boundaries	IEBC	Shapefile
Road Network	OSM	Shapefile
Settlements	Humdata	Shapefile
Population	Kenya High Resolution Settlement Layer	TIFF
Forests	WRI	Shapefile

Land Use	RCMRD	TIFF
Archived Fire Data	FIRMS	CSV

3.3.3 Data preparation

This process involves loading each of the datasets separately in a GIS environment and confirming completeness, coverage in the area of interest, existing relevant attributes, coordinate systems and formats.

3.3.4 Tools

Table 3.2: Tools

Description	Type of Usage
Hardware	
HP Elitebook Laptop, corei7,4GB RAM,500GB	Report compilation, data entry and internet access
HP DeskJet Printer	Print project report
Software	
ArcGIS Desktop 10.6	Model creation, mapping and data analysis
QGIS	Data Preparation
Microsoft office 2016	Report writing and compilation
Google Drive	Cloud Storage for the project reports

3.4 Data Processing and Analysis

3.4.1 Factor Maps

Factor maps were produced for each of the variables used as inputs to the model.

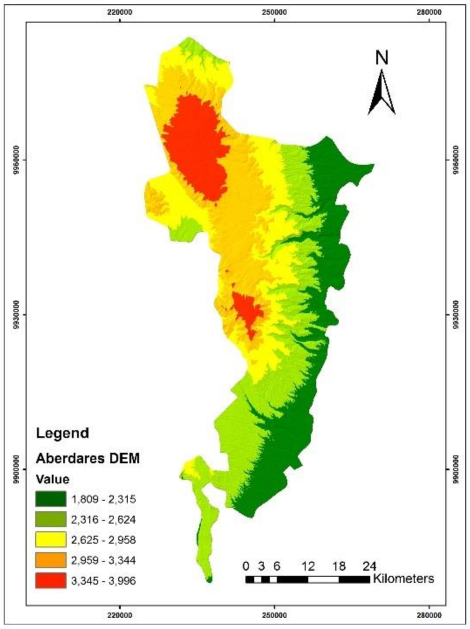


Figure 3.3 Elevation

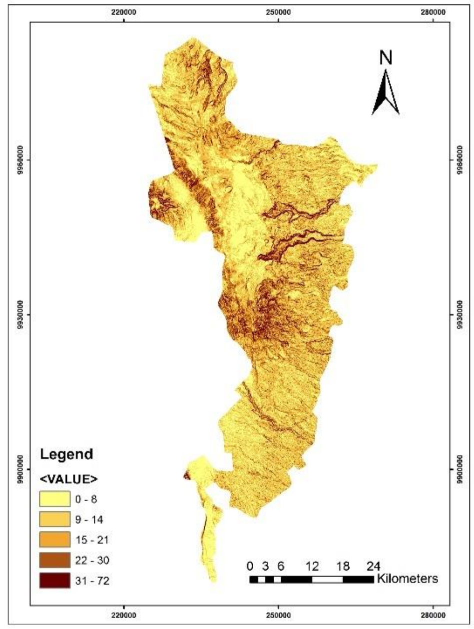


Figure 3.4 Slope

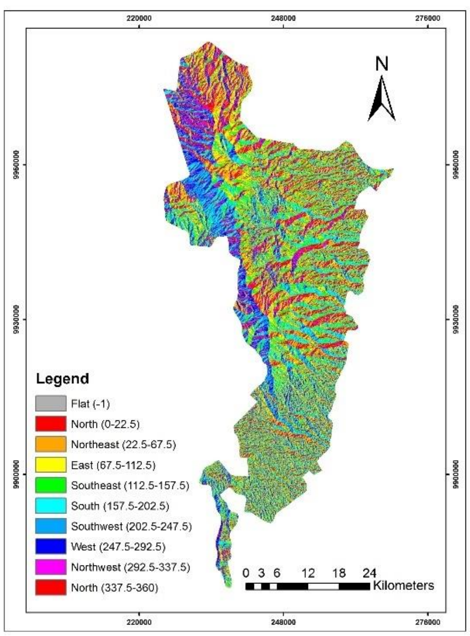


Figure 3.5 Aspect

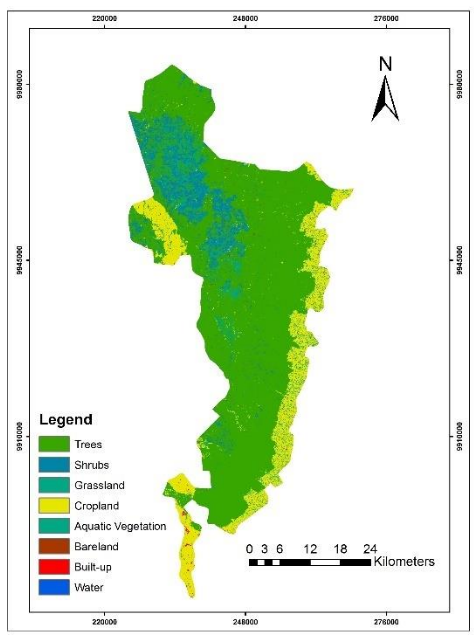


Figure 3.6 Land Use

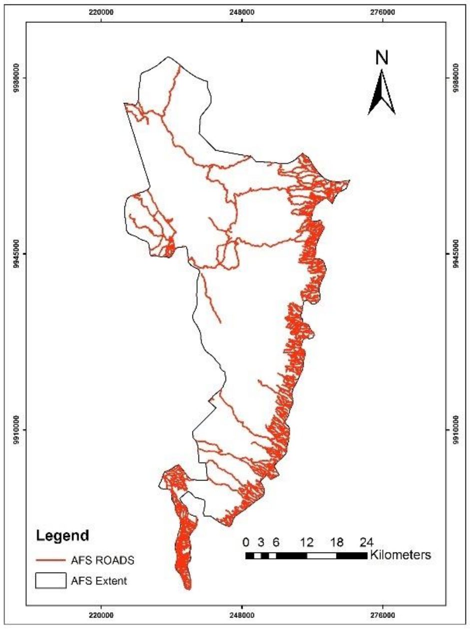


Figure 3.7 Roads

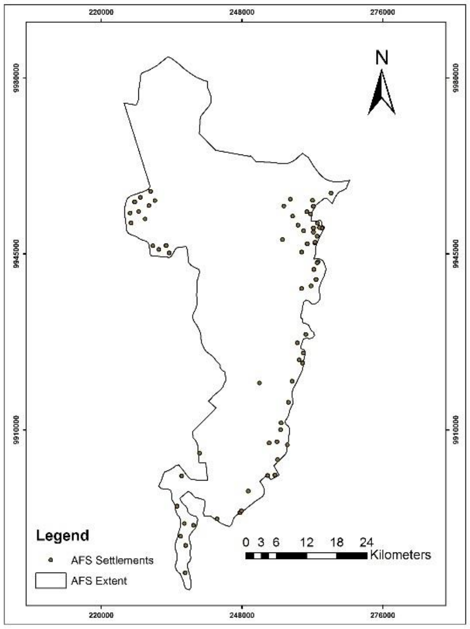


Figure 1.8 Settlements

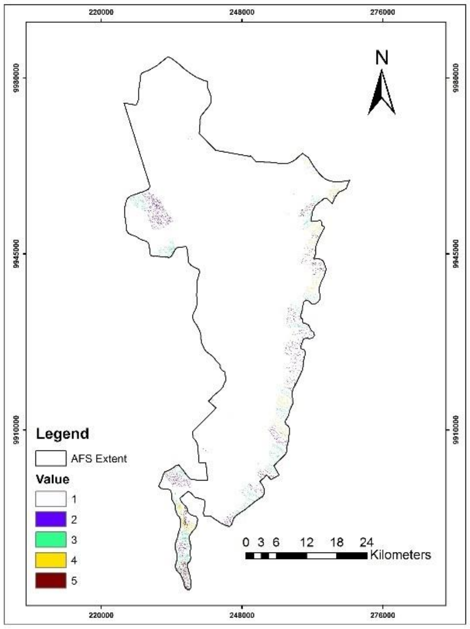


Figure 3.9 Population

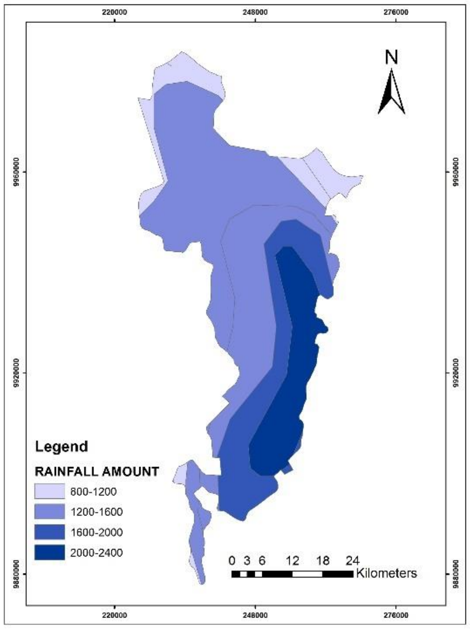


Figure 3.10 Rainfall

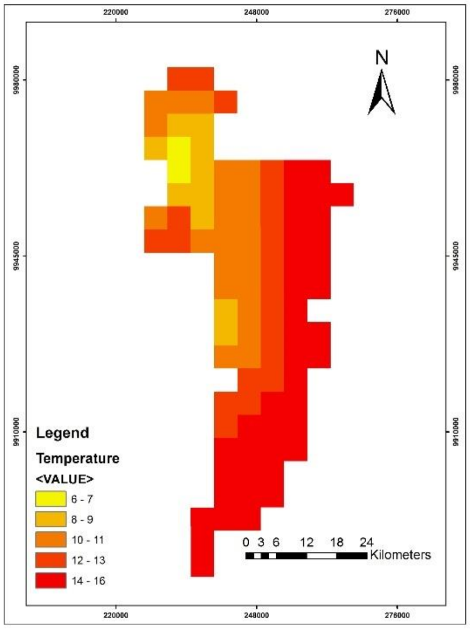


Figure 3.11 Temperature

3.4.2 AHP Concept

AHP and MCDA was used to generate a fire weighting scheme. Each factor within the three sub criteria was prepared through conversion to a uniform format. Each of the factors was weighed separately before being used as inputs to the weighing model. The weighing model used was the Weighted Overlay Combination. The scale vulnerability for the different factors was determined and presented in a tabular format. The decision on what weights to assign to various factors was informed by GIS staff at the Fire Department of KFS.

The conceptual procedure used is shown below, where SC represents sub criteria.

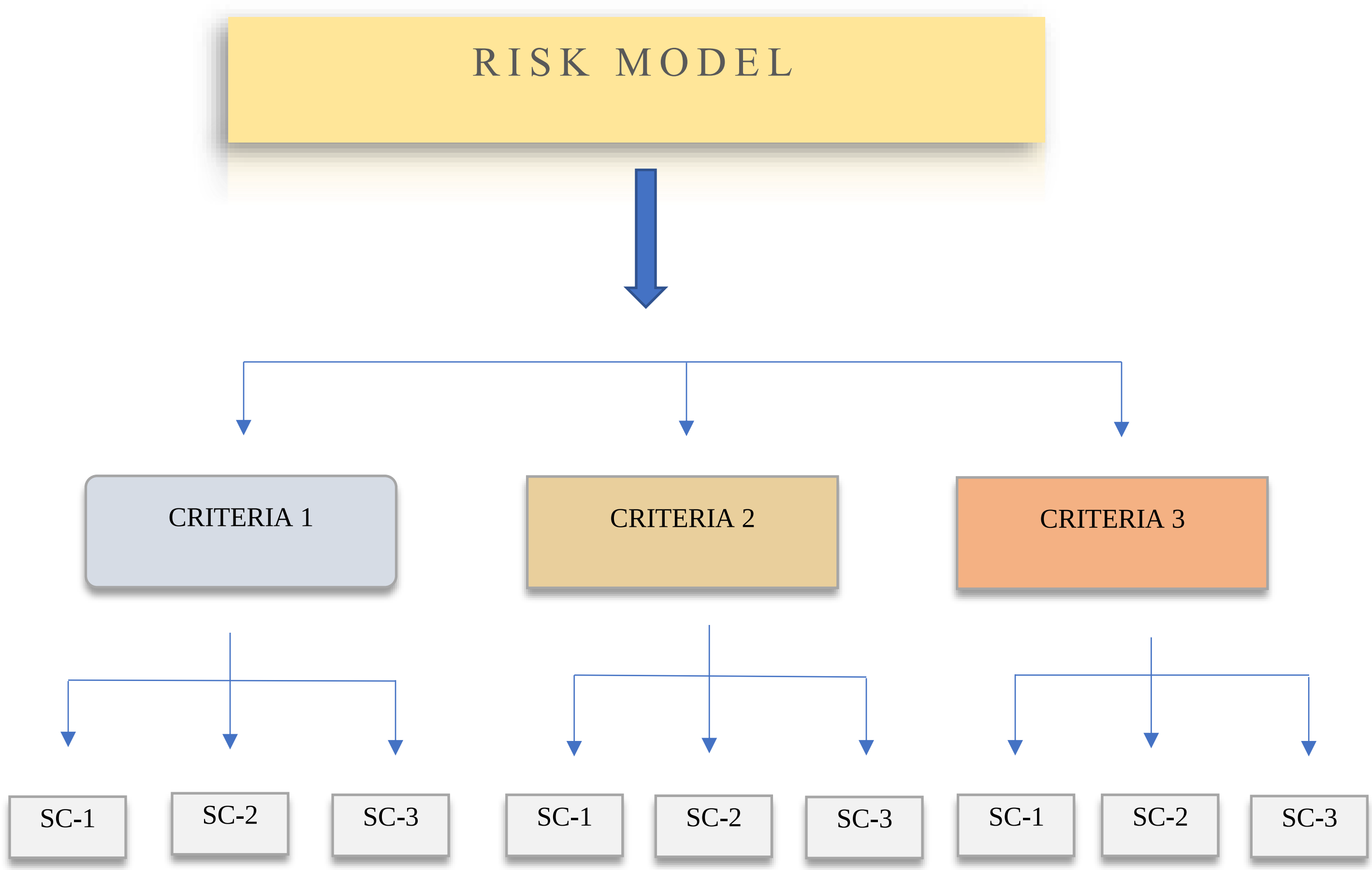


Figure 3.12 Conceptual Procedure

3.4.2 Fire Causative Factors

Table 3.3: Factors and Fire Rating Classes

Factor	**Fire Rating Class**
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

Table 3.4: Generalized Classes

Factor	**Fire Rating Class**
1	Low
2	Moderate
3	High

Topographical factor tables are as shown from Table 3.5 to Table 3.8

Table 3.5: Elevation

Elevation (m)	**Interpretation**	**Fire Rating Class**	**Factor**
1809-2315	Very Low	Very High	5
2316-2624	Low	High	4
2625-2958	Moderate	Moderate	3

2959-3344	High	Low	2
3345-3996	Very High	Very Low	1

Table 3.6: Slope

Slope	**Interpretation**	**Fire Rating Class**	**Factor**
0-8	Very Low	Very Low	1
9-14	Low	Low	2
15-21	Moderate	Moderate	3
22-30	High	High	4
31-72	Very High	Very High	5

Table 3.7: Aspect

Aspect	**Fire Rating Class**	**Factor**
Flat (-1)	Moderate	3
North (0-22.5)	Very Low	1
North East (22.5-67.5)	Low	2
East (67.5-112.5)	Moderate	3
South East (112.5-157.5)	Moderate	3
South (157.5-202.5)	Very High	5
South West (202.5-247.5)	High	4

West (247.5-292.5)	Moderate	3
North West (292.5-337.5)	Low	2
North (337.5-360)	Very Low	1

Table 3.8: Land Use

Land Use	**Fire Rating Class**	**Factor**
Trees	High	4
Shrubs	Very High	5
Grasslands	Very High	5
Croplands	Moderate	3
Aquatic vegetation	Very Low	1
Bare land	Low	2
Built-up	Moderate	3
Water	Very Low	1

Anthropogenic factor tables are as shown from Table 3.9 to Table 3.11

Table 3.9: Distance to Settlements (m)

Distance to Settlements (m)	**Interpretation**	**Fire Rating Class**	**Factor**
0-1000	Very Low	Very High	5
1000-2000	Low	High	4

2000-3000	Moderate	Moderate	3
3000-4000	High	Low	2
4000-5000	Very High	Very Low	1

Table 3.10: Population (Household Size)

Population (Household Size)	**Interpretation**	**Fire Rating Class**	**Factor**
0-2	Very Low	Very Low	1
3-5	Low	Low	2
6-8	Moderate	Moderate	3
8-10	High	High	4
10-15	Very High	Very High	5

Table 3.11: Distance to Roads (m)

Distance to Roads (m)	**Interpretation**	**Fire Rating Class**	**Factor**
100	Very Low	Very High	5
200	Low	High	4
300	Moderate	Moderate	3
400	High	Low	2
500	Very High	Very Low	1

Climatic factor tables are as shown in Table 3.12 and Table 3.13

Table 3.12: Temperature (Degrees Celsius)

Temperature (Degrees Celsius)	**Interpretation**	**Fire Rating Class**	**Factor**
6-7	Very Low	Very Low	1
8-9	Low	Low	2
10-11	Moderate	Moderate	3
12-13	High	High	4
14-16	Very High	Very High	5

Table 3.13: Rainfall (mm)

Rainfall (mm)	**Interpretation**	**Fire Rating Class**	**Factor**
800-1200	Very Low	Very High	5
1200-1600	Low	High	4
1600-2000	High	Low	2
2000-2400	Very High	Very Low	1

3.5 Model Creation

The Aberdare model was developed using ArcMap's Model Builder in Arc Toolbox. A new toolbox was created, labelled as 'Aberdare' then the new model developed under it. Input datasets were added and the relevant processes such as necessary format conversion, buffering, clipping introduced. The final tool was the Weighted Overlay that finalized the processes of the model. The calculated weights were added into the tool for each respective factor. The model was then run successfully. The resultant deliverable was the Fire Risk Map.

3.5.1 Reclassification

The reclassification in the model was done in order to base each of the factor maps on a scale of 1 to 5 for fire vulnerability. The factors used in Tables 3.5 to 3.13 were used in reclassification in the model. An illustration of slope and aspect reclassification is shown in the figures below.

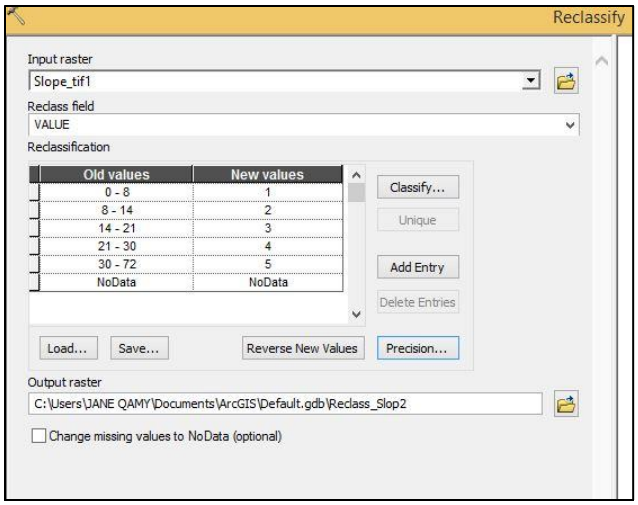


Figure 3.13 Slope Reclassification

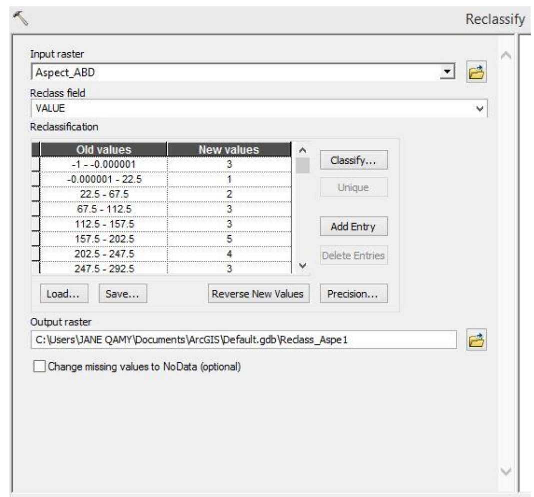


Figure 3.14 Aspect Reclassification

3.5.2 Weighted Overlay

Table 3.14: Weighted Percentage Influence

Factor	**Abbreviation**	**Percentage**
Land Use	LU	40
Temperature	T	10
Rainfall	R	10
Slope	S	10
Distance to Roads	Dr	10

Distance to Settlements	Ds	5
Population Size	Ps	5
Aspect	A	5
Elevation	E	5
Total Influence		**100**

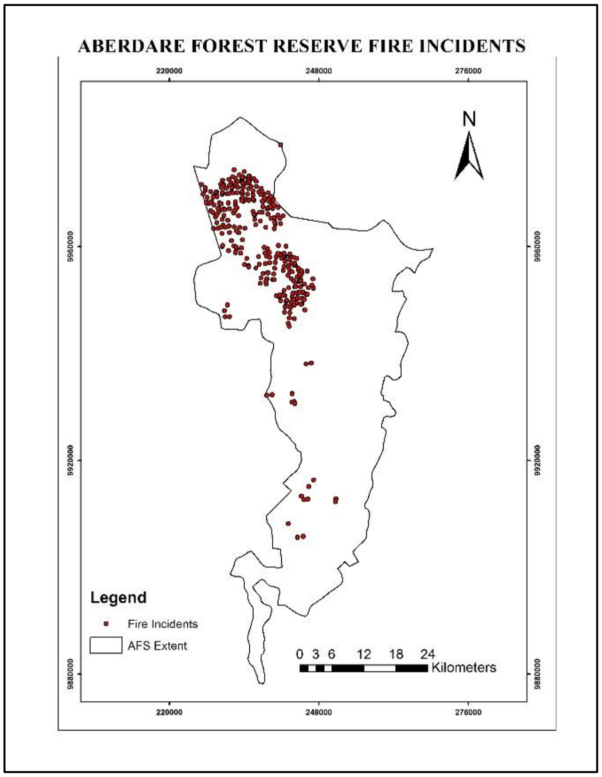
The Fire Rating Index (FRI) is the numerical index of the forest fire rating classes and is summarized as in Equation 1.

FRI =40LU+5(A+S+E) +10Dr+10Ds+5Ps+10T+10R……………………………. **Equation (1)**

Topographic factors accounted for the highest weights, followed by anthropogenic and climatic factors respectively.

3.5.3 Model Validation

FIRMS fire event data was loaded on ArcGIS then clipped by the year of interest which was 2017, owing to it having the highest number of fire incidents in the years between 2012-2020. The data was then clipped using the AFR extent to create the map shown below.



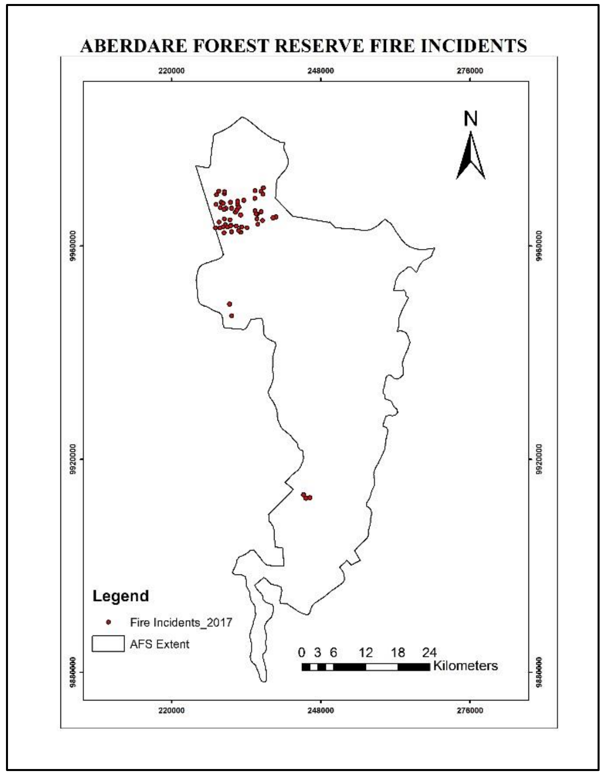


Figure 3.15 Fire Incidents 2012-2020

Figure 3.16 Fire Incidents 2017

CHAPTER 4: RESULTS AND DISCUSSION

This chapter displays the results of this research project and discussion arising therein.

4.1 RESULTS

4.1.1 Fire Vulnerability Model

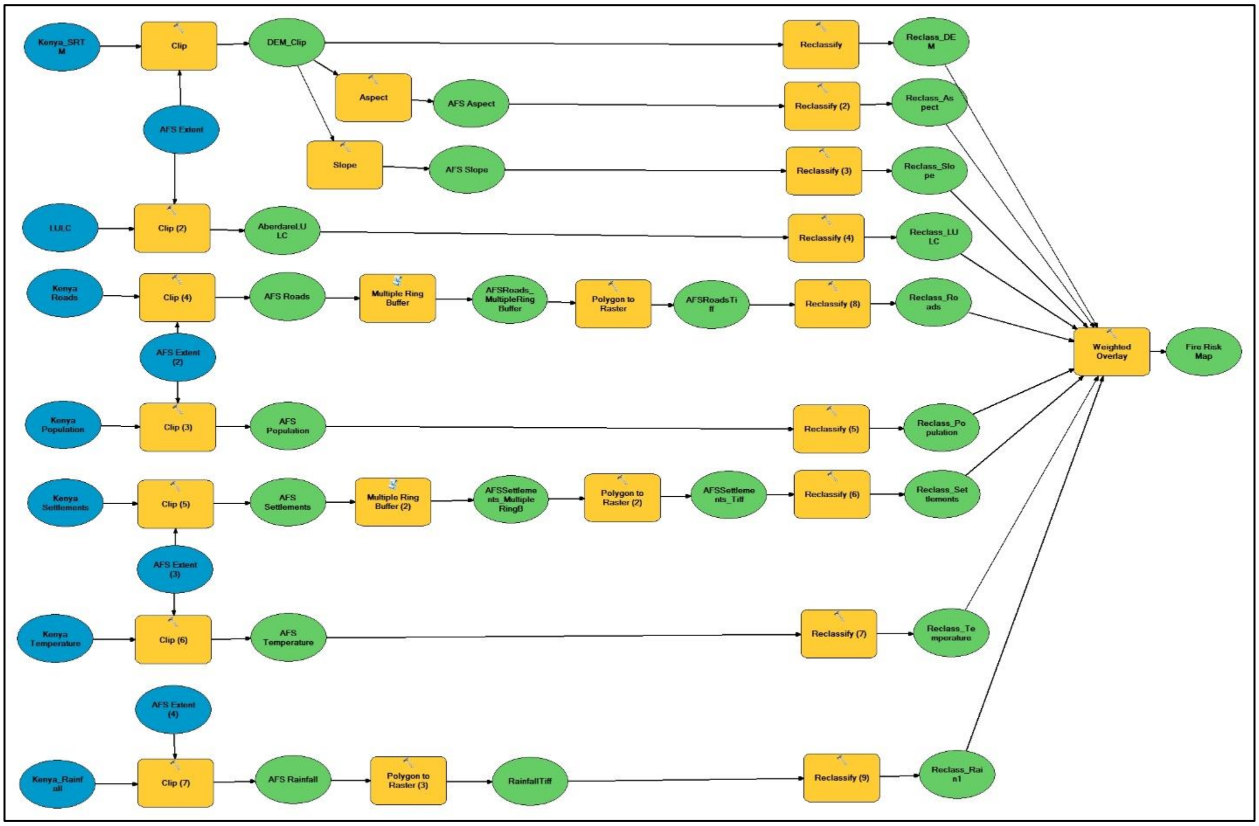


Figure 4.1 The Aberdare Model

4.1.2. Fire risk map of the Aberdare Forest Reserve

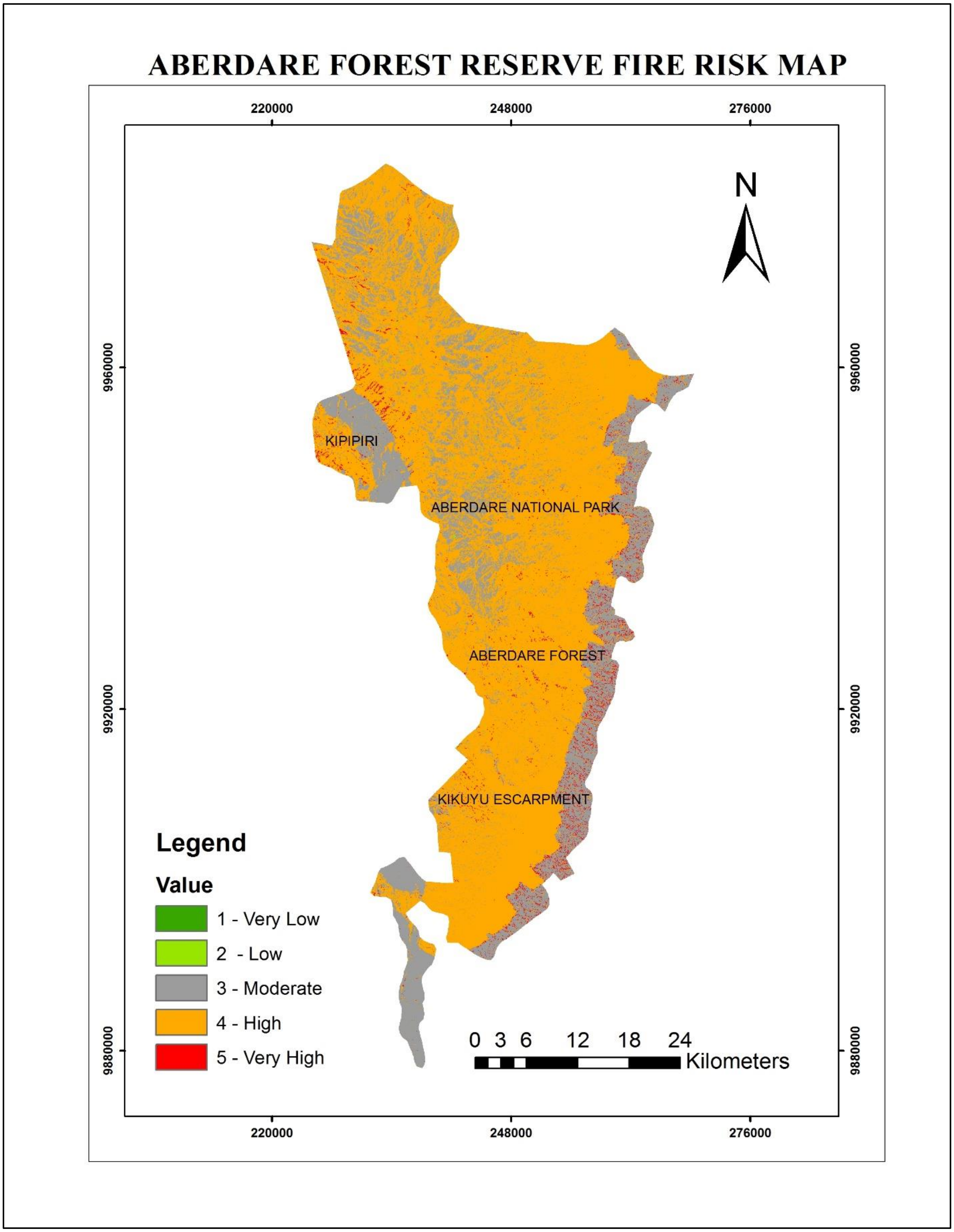


Figure 4.2 Fire Risk Map

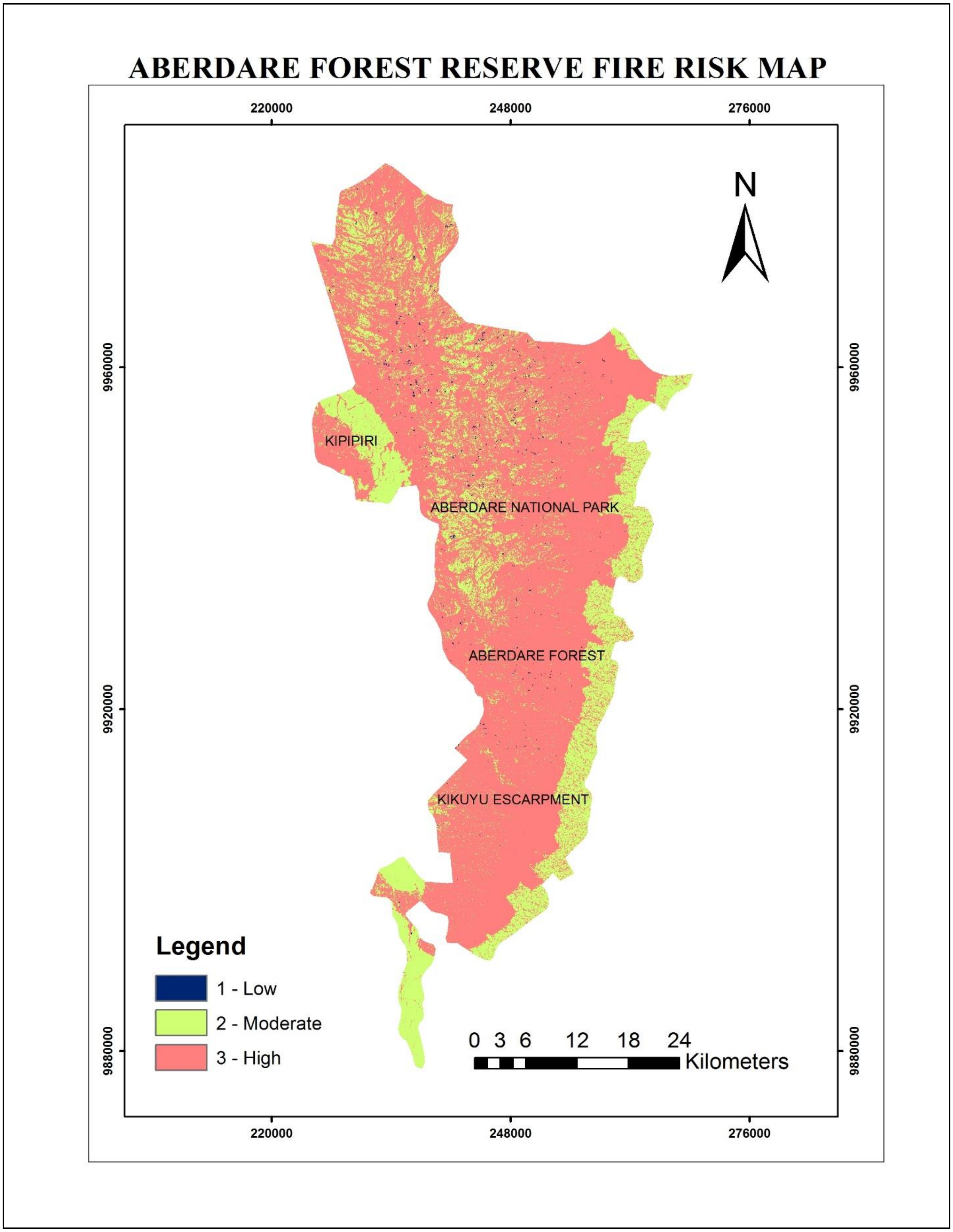


Figure 4.3 Generalized Fire Risk Map

4.1.3 Vulnerability Area Analysis

Table 4.1: Risk Regions Areas

Scale Value	Fire Risk	Area (Square Kilometers)	Percentage (%)
1	Very Low	12.74	0.65
2	Low	25.59	1.30
3	Moderate	652.02	33.21
4	High	1124.35	57.27
5	Very High	154.62	7.88
	Total	**1963.32**	**100**

Table 4.2: Risk Regions Areas (Generalized)

Scale Value	Fire Risk	Area (Square Kilometers)	Percentage (%)
1	Low	38.33	1.95
2	Moderate	652.02	33.21
3	High	1278.97	65.14
	Total	**1963.32**	**100**

4.1.4 Model Validation

MODIS data obtained aboard Terra and Aqua satellites was used as a measure of evaluation of the fire risk map obtained from the model covering the Aberdare Forest reserve. Figure 4.4 depicts all fire incidences that occurred within the reserve from 2012-2020 while Figure 4.5 shows the fire incidents that occurred in 2017. Figure 4.6 shows an overlay of the 2017 fire incidents on the generalized fire risk map.

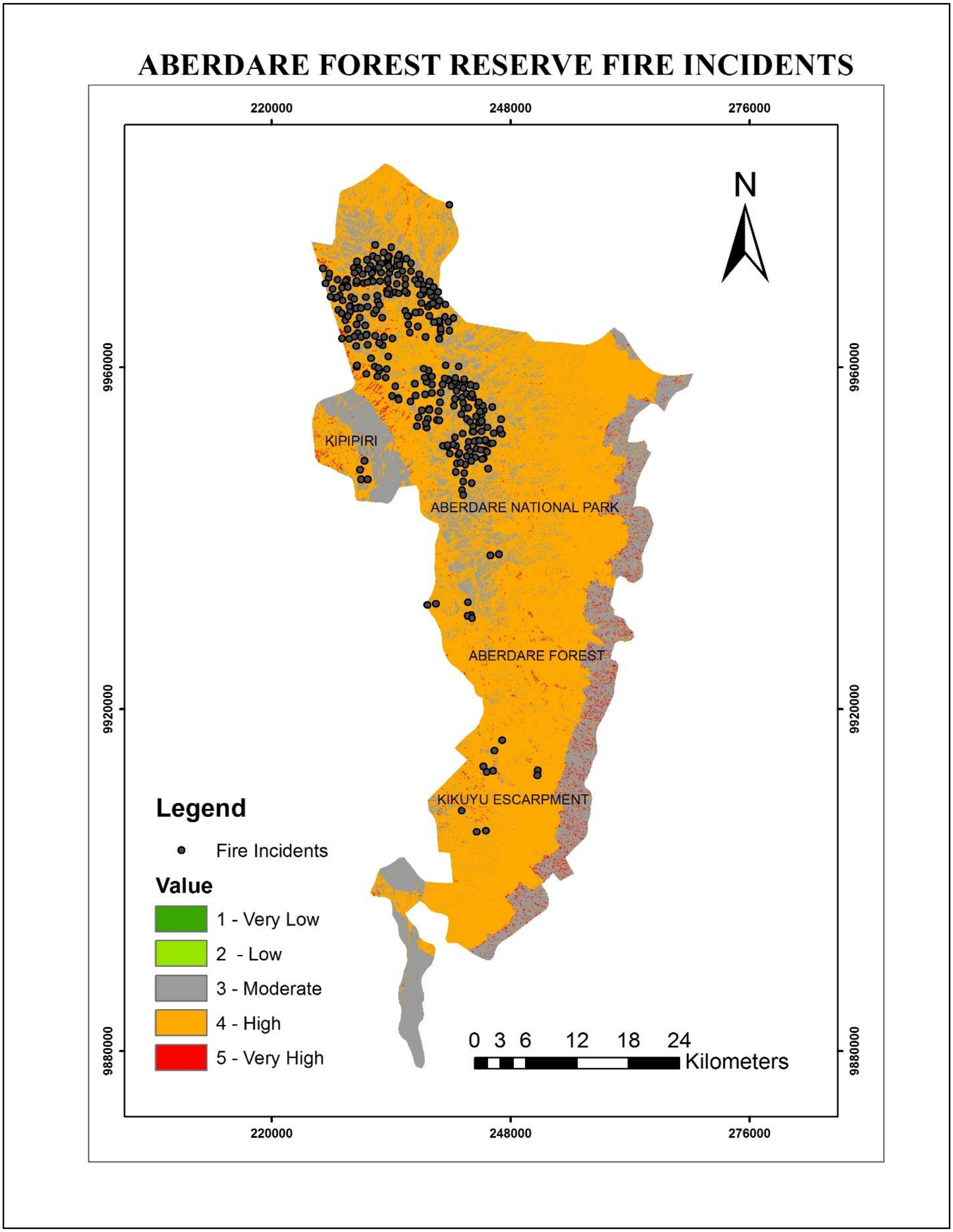


Figure 4.4 Forest Fire Incidents 2012-2020

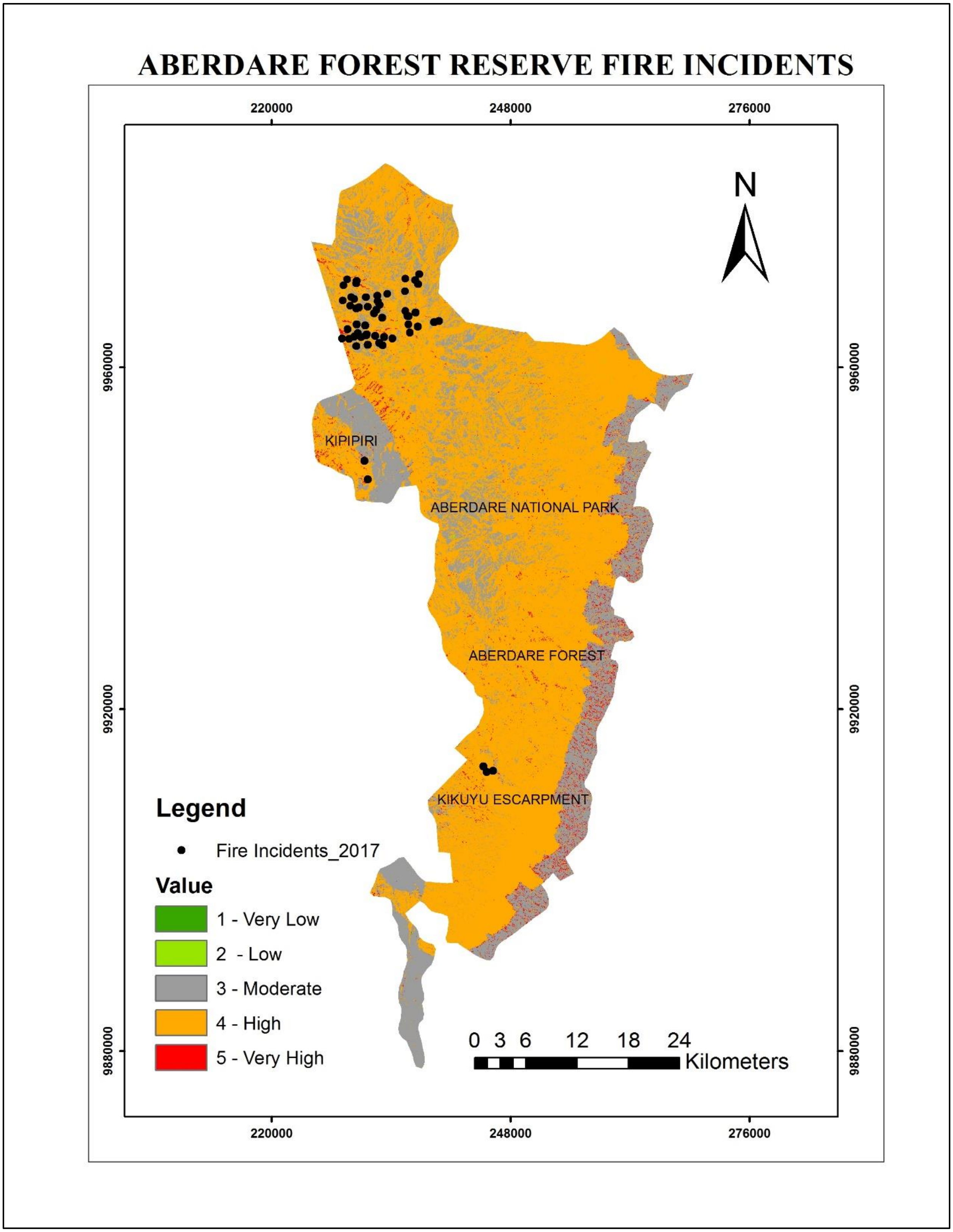


Figure 4.5 Fire Incidents, 2017

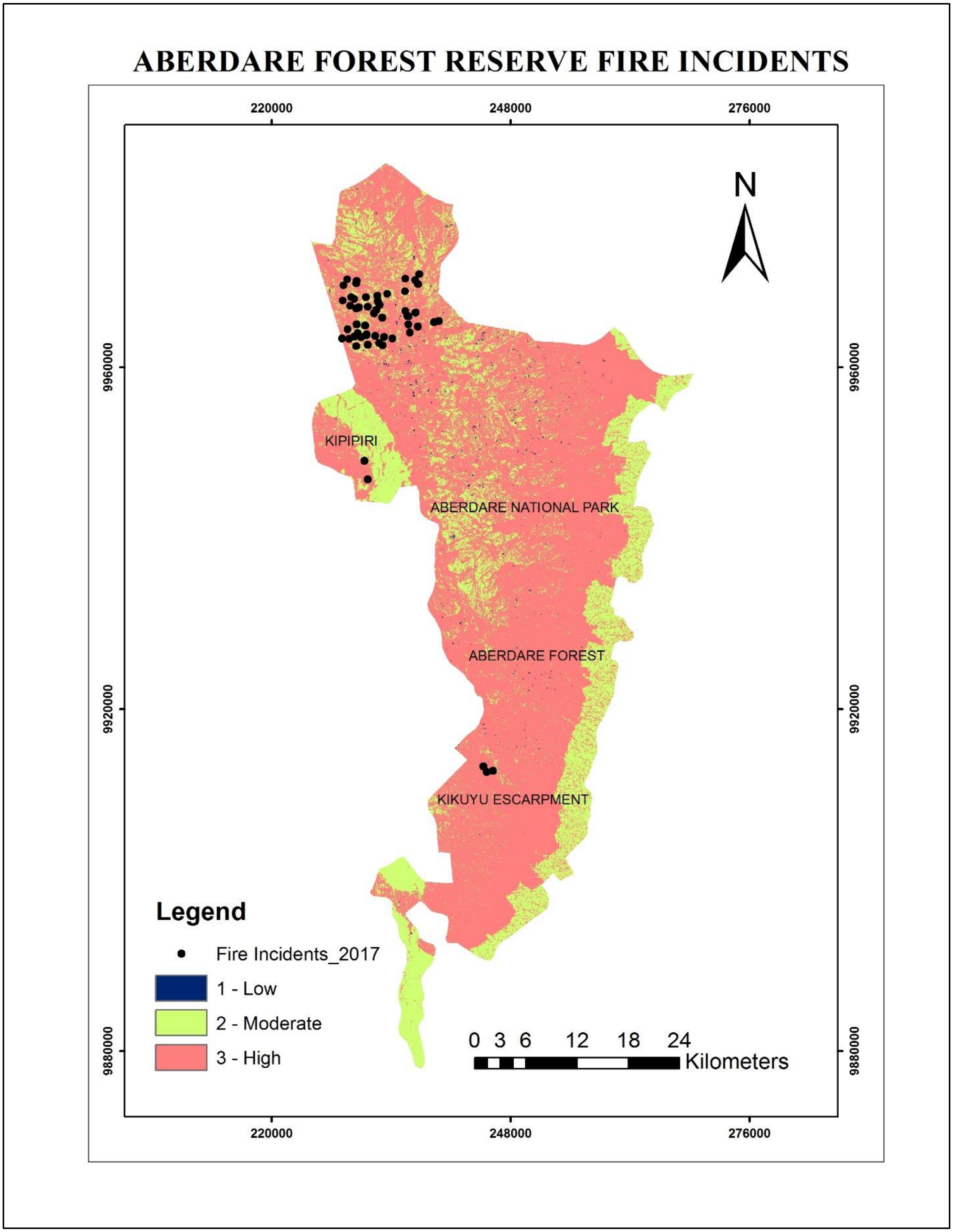


Figure 4.6 Fire Incidents, 2017 (Generalized)

Table 4.3: Fire Incident Counts in Risk Regions

Scale Value	**Fire Risk**	**Fire Incident Count**	**Percentage (%)**
1	Very Low	0	0
2	Low	0	0
3	Moderate	19	34.55
4	High	32	58.18
5	Very High	4	7.27
		Total 55	**100**

Table 4.4: Fire Incidents in Risk Regions (Generalized)

Scale Value	**Fire Risk**	**Fire Incident Count**	**Percentage (%)**
1	Low	0	0
2	Moderate	19	34.55
3	High	36	65.45
		Total 55	**100**

4.2 DISCUSSION

4.2.1 The Model

Based on a review of literature, the created model was found to be best suited for tropical forests considering the independent variables chosen. The models analyzed from other regions could only be modified to suit a tropical forest as none can be used as is. Using a combination of factors used in those models and an addition of the population factor, the resultant Aberdare model yielded results that were positively validated. As such, this model can be applied to other tropical forests in the country and result in useful deliverables too.

4.2.2 The Fire Risk Map

The Aberdare Forest Reserve is highly vulnerable to forest fires as the largest acreage falls in the high severity level. Consequently, a large part of the Aberdare National Park also lies in the highly vulnerable region. Moderate regions lie at the edges of the reserve where there exists a lot of settlement. Considering the weighed overlay table, the weights assigned to settlements and population were less than land use thus the results were consistent. Low and very low risk regions had the least area and is visualized as small patches existing in the mid to lower area of the reserve.

4.2.3 Model Validation

The overlay of the fire incidents on the final risk map allows the map to be incorporated into a more comprehensive risk assessment process. High risk areas were found to have a high number of fire occurrence events overlayed on them as compared to low-risk areas. This positively validates the model as one that can be used by KFS, KWS and other supporting agencies.

From the FIRMS data obtained, a total of 309 fire incidences occurred within the reserve from 2012-2020, with 55 of them occurring in 2017.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The main objective of the study was to demonstrate use of Geographic Information Systems (GIS) to assess the vulnerability of the Aberdare Forest Reserve to fires using GIS. This objective was met using the various tools combined with expert advice from the Fire Department at KFS.

The model created is specifically suited for tropical forests and therefore it can be used for other forests in Kenya susceptible to fires like Mt Kenya and the Tsavo. The use of GIS as a tool in this research project has demonstrated that the Aberdare Forest reserve is highly vulnerable to forest fires and intensified efforts should be upscaled to conserve the forest.
It can therefore be concluded that this research project met its stipulated objectives.

5.2 RECOMMENDATIONS

The following recommendations could be adopted by the relevant institutions and stakeholders in the forestry sector to improve decision making and enhance conservation.

5.2.1 Recommendations on policy

a) Forest fire management policies -National Policy on Disaster Management generalises on all fires and doesn't have a mention on specific issues related to forest fires. The forest Policy 2014 does not also include forest fires as a key threat. Fire risk maps would be a valuable inclusion into these policies.
b) Incorporation of fire risk maps in strategized monitoring efforts.

5.2.2 Recommendations on Further work

a) Improvement on the model can be done by incorporating additional parameters such as;

i. The value of forest resources to the community living near forested areas
ii. Climatic factors such as relative humidity and windspeed
iii. Emergency response factors in terms of location of forest stations, fire response units, water source proximity
iv. Fuel type factors e.g Ban Oak Forest, Blue-pine Forest, Chir-pine Forest, Dry Mixed Deciduous Forest, Juniper Forest, Moderate Mixed Coniferous Forest, Moist Deodar Forest

b) Service analysis of areas served by forest stations in the risk regions

c) Suitability analysis of construction of fire towers in the reserve using the fire vulnerability map as an input/resource to the study.

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