SPATIAL AND TEMPORAL ANALYSIS OF EARTHQUAKES TO IDENTIFY EXISTING SEISMIC ZONES IN THE UNITED REPUBLIC OF TANZANIA

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A Dissertation Submitted to the Department of Geospatial Sciences and Technology in Partially Fulfilment of the Requirements for the Award of a Bachelor of Science in Geoinformatics (BSc. GI) of Ardhi University

CERTIFICATION

The undersigned certify that, she read and hereby recommend for acceptance by Ardhi University a dissertation titled, "**SPATIAL AND TEMPORAL ANALYSIS OF EARTHQUAKES TO IDENTIFY EXISTING SEISMIC ZONES IN THE UNITED REPUBLIC OF TANZANIA**" in partial fulfilment of the requirements for the Degree of Bachelor of Science in Geoinformatics of Ardhi University.

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Date: ………………………..	Date: ………………………..

DECLARATION AND COPYRIGHT

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Jones G. Kamwenda

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Lastly special thanks to my family and friends for their companionship and support throughout this journey, truly a great blessing to be within their community.

DEDICATION

I dedicate this dissertation to my beloved family; my parents Mr Gerald Kamwenda and Mrs Jemima Kamwenda. Also, to the victims of previous earthquake events in Tanzania, for those lost may their souls rest in peace and may this work pave the way to a safer future.

Abstract

Earthquakes are seismic events that result in abrupt ground shaking due to the sudden release of energy as seismic waves traverse Earth's rocks. In recent years, the impact of earthquakes on Tanzania has been profound, causing loss of life and significant property damage. Compounded with the increase in settlements (due to population growth) that often transpire without adequate consideration for seismic resilience and awareness of existing seismic zones.

To address these challenges, the identification of seismic activity hotspots is important, as it facilitates mitigation strategies, preparedness, and effective response. Through a comprehensive analysis of the spatial and temporal characteristics of earthquake events, the study aims to identify high-risk seismic zones and uncover potential trends and patterns. This study’s results will also support earthquake forecasting by identifying windows of heightened seismic activity, enabling targeted research efforts, eliminating the need to encompass Tanzania as a whole in future forecasting studies.

The study draws upon earthquake event data and administrative shapefiles of Tanzania's international boundary. Data visualization and cleansing were executed to prepare for a two-phase analysis encompassing both temporal and spatial aspects. Additionally, demographic data was incorporated to visualize population distribution within the identified seismic zones. The spatial analysis initially tested the hypothesis of clustering seismic events within zones, confirmed by a K-function plot. Then visualization of these seismic zones was accomplished through kernel density estimation, yielding density values classified using the Jenks natural breaks algorithm. This algorithm optimally groups similar values, effectively delineating zones of high to low seismic activity frequency. Since seismic activity varies across regions, this approach is chosen due to the absence of a consistent classification basis. Temporal analysis entailed visualizing earthquake magnitudes, depths, and frequency against time.

In summary, the study successfully identified three prominent zones of heightened seismic activity which were Arusha's central region, Dodoma's northern area, and Kigoma's coastal region all coinciding with the Great Eastern Africa Rift Valley system. This alignment underscores the correlation between seismic activity and faulted regions, where landmasses' movements along faults trigger tremors. The temporal analysis reveals an ongoing cyclic pattern in earthquake frequency every 8 to 12 years, with an overall impending rise in activity. Most historical earthquakes are characterized by magnitudes of 4 to 4.9 and shallow depths (about 10km), further emphasizing the need for focused seismic preparedness measures

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ACRONYMS AND ABBREVIATIONS

CSR	Complete Spatial Randomness
GST	The Geological Survey of Tanzania
NBS	National Bureau of Statistics
USGS	United States Geological Survey

CHAPTER ONE

INTRODUCTION

1.1 Background

Earthquakes are seismic events resulting from the sudden release of energy stored in the Earth's crust, inducing ground shaking due to seismic waves passing through rocks. These events often stem from fractures causing the slip of rock masses, leading to catastrophic outcomes like deaths, destruction, tsunamis, and landslides (Britannica, 2023). Tanzania has experienced notable earthquakes in the past decade, garnering attention due to their impact on casualties and infrastructure damage (The Citizen, 2023). As Tanzania's development progresses, concerns arise about the susceptibility of critical infrastructures like underground pipelines and buildings to seismic events, raising alarms about structural instability and potential hazards (Channel 24, 2023).

Seismology, emerging in the early 20th century, has unravelled the enigma of earthquakes, illuminating their causes and mechanisms. While offering valuable insights, accurate earthquake forecasting remains a multifaceted challenge demanding understanding of seismology, geophysics, statistical modelling, and data analysis. Challenges and uncertainties persist, yet investigating seismic activities remains justified, as saving even one human life justifies such research.

The exploration of seismic activities can be advanced through point pattern analysis, a discipline visualizing, characterizing, and modelling event patterns tied to geographical positions. Addressing nature and distribution questions over space, point pattern analysis comprehends generating processes in observed data (Gao, 2022).

As earthquakes can be recorded by magnitude, occurrence time, and geographical position, combining spatial and temporal analysis creates informative point patterns. Analysing seismic activity through point pattern analysis offers insights that enhance earthquake prediction in Tanzania. Understanding earthquake characteristics and spatial distribution contributes to refined forecasting models, guiding resilient infrastructure development. Coupled with robust building codes, engineering standards, and public awareness, these endeavours collectively mitigate earthquake risks, ensuring Tanzania's stability and safety in ongoing development.

1.2 Statement of the problem

Tanzania's ongoing development brings the promise of increased sensitive infrastructures and a growing population, both of which expose more lives to zones prone to seismic activities. Given the absence of documented high seismic activity zones, a critical assessment of seismic events and an exploration of potential temporal trends become imperative. Such insights are essential for informed decision-making, enabling the implementation of protective measures against these natural forces.

In the context of Tanzania as a developing nation with an estimated population of about 62 million, existing infrastructure's limited capacity to withstand earthquakes and associated hazards presents a concerning backdrop. The combination of a rapid increasing population and infrastructure vulnerabilities underscores the challenges of mounting an effective emergency response in the event of these destructive natural occurrences.

Uncovering historical seismic event patterns holds the potential to improve future earthquake forecasting efforts. By anchoring forecasts in the temporal windows associated with identified seismic zones, this study aims to establish a foundation for reliable earthquake predictions. Recognizing that earthquake occurrences are unevenly distributed across Tanzania, the identification of these significant processing windows (the identified seismic zones) is important.

1.3 Objectives

1.3.1 Main objectives

To identify regions with significant seismic activity and to analyse the temporal and spatial characteristics of seismic events. By achieving these objectives, we aim to uncover potential trends and patterns exhibited by these events in both spatial and temporal dimensions.

1.3.2 Specific objectives

From the main objective, the specific objectives to be achieved are as follows:

- Evaluate Affected Areas: Examine regions predominantly affected by earthquakes during the period from 1973 to 2022.
- Analyse Temporal Trends: Investigate the temporal aspects of seismic activities within this timeframe (1973 to 2022) to discern potential trends and patterns.
- Study Spatial Distribution: Explore the spatial distribution of seismic events to elucidate existing spatial patterns.

1.4 Research questions

The study aims at answering the following question:

1. What areas in Tanzania are most affected by the seismic events?
2. When do most of these seismic events occur?
3. What are the magnitudes of these seismic events?

1.5 Significance of the study

The study holds significant value for both informed infrastructure development and risk mitigation for sensitive construction projects. By analysing potential seismic zones and the characteristics of seismic events, decision-makers can make informed choices regarding infrastructure development. This includes implementing appropriate engineering practices and construction techniques to enhance infrastructure resilience, ensuring that future projects, such as buildings, bridges, pipelines, and critical facilities, can withstand earthquake impacts. Moreover, the study aids in identifying areas with a high risk of seismic activity, enabling decision-makers to assess the feasibility of sensitive construction projects, like oil and gas pipelines. With this knowledge, they can establish suitable mitigation measures to minimize potential impacts and strike a balance between project benefits and associated risks, ultimately safeguarding the environment and human lives.

Also, understanding the seismic activity and potential seismic zones enables effective emergency response and planning. By identifying areas prone to earthquakes, authorities can develop and implement emergency response strategies tailored to those specific regions. This includes establishing early warning systems, evacuation plans, and training programs to enhance the preparedness of communities residing in high-risk areas. The study's findings can also provide crucial insights into the characteristics of seismic events, facilitating more accurate forecasting and timely emergency response efforts.

Public safety and awareness: The study's outcomes can contribute to raising public awareness about earthquake risks in Tanzania. By disseminating information on potential seismic zones, the study can educate individuals, communities, and stakeholders about the risks associated with seismic events. This increased awareness can empower people to take necessary precautions, make informed decisions regarding their safety, and actively participate in building resilient communities.

1.6 Beneficiaries

From the significance of the study the following groups would be the potential beneficiaries from the results of the study:

- Urban planning development; Urban zones that are prone to earthquake could be more considerate in locations of public open spaces that could offer safety during earthquake events and response (Alawi et al., 2023).
- Emergency response organizations; The emergency response could be more focused on zones prone to these seismic activities and the intensity of damages to be expected based on the earth magnitudes expected.

1.7 Scope and limitations of the research study

The study is based on the earthquake dataset provided by the U.S Geological Survey within the past 50 years (1973 up to 2022) while not taking into consideration the different magnitude scale measurements methods of the earthquakes in the dataset, as the scale measurement could influence how severe the earthquake magnitude was at the time of recording. Some scales account for the distance between the earthquake and the recording seismometer (device for measuring seismic wave properties) such that the calculated magnitude is the same no matter where it is measured. Another scale is based on the physical size of the earthquake fault and the amount of slip that occurred (which is highly dependent on the geological properties of the area where the earthquake occurred). Then there are also measures of earthquake shaking intensity which varies from place to place.

1.8 Description of the study area

The United Republic of Tanzania is a country in East Africa, bordering Uganda to the north, Kenya to the northeast, the Indian Ocean to the east, Malawi and Mozambique to the south, Zambia to the southwest and Rwanda, Burundi, and the Democratic Republic of Congo to the west. With a population of nearly 62million encompassing the 947,303 square kilometres of the country making it the most populous country located entirely south of the equator, located between the longitudes 28° to 41°East and the latitude 0° and 12°South. The justification for choosing this study area would be on the rapid development and increase in population in Tanzania thus, the potential impacts of earthquakes on lives and assets becomes increasingly significant.

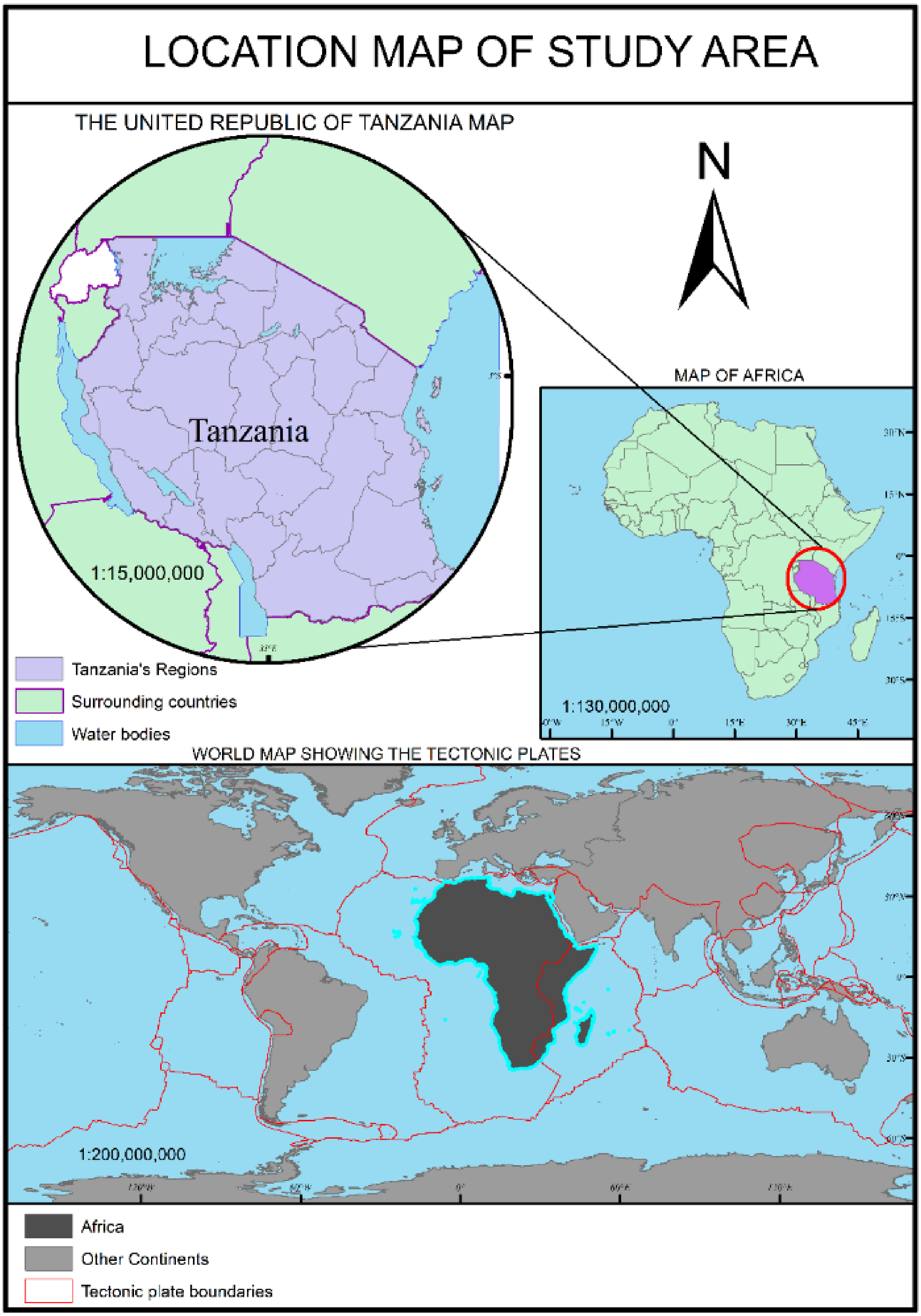

Figure 1-1: Location map depicting tectonic positioning of the study area

As of recent in 2016, a magnitude 5.7 earthquake struck North western regions of Tanzania with its epicentre being in the Kagera Region killing 16 people and leaving 253 injured. The impacts were also felt in Rwanda, Burundi, Kenya, the Democratic Republic of Congo and Uganda. Though minor infrastructural damages were observed, many houses were demolished, roofs blown away as shown in figure 1-2 and figure 1-3 leaving people homeless (according to the Tanzania Red Cross at least 270 houses were demolished in the Bukoba District and electricity cut off). The report states that Earthquake are common in recent years in the Great Lakes region but usually of relatively low magnitude. (Africanews, 2016).

Figure 1-2: Tanzania Emergency response at the site of the Earthquake wreckage

Figure 1-3: Earthquake devastation on non-urban settlements.

CHAPTER TWO

LITERATURE REVIEW

2.1 An overview of Earthquakes in Tanzania

Earthquakes are relatively rare in Tanzania, but they can be strong and cause damage. The most active seismic region in Tanzania is the Western Branch of the East African Rift System, which runs through the western part of the country. Some of the notable earthquakes that have occurred in Tanzania are as follows (World data info, 2023):

- 1910 Lake Tanganyika earthquake; This earthquake had a magnitude of 7.4 and was the strongest earthquake ever recorded in Tanzania. It caused widespread damage in the western part of the country, including the collapse of buildings and infrastructure
- 1964 Mbulu/Babati earthquake; This earthquake had a magnitude of 6.4 and caused significant damage in the Mbulu and Babati districts of Tanzania. There were at least 10 fatalities.
- 2000 Lake Tanganyika earthquake; This earthquake had a magnitude of 6.6 and caused damage in the western part of Tanzania, including the collapse of several buildings. There were no reports of fatalities.
- 2005 Lake Tanganyika earthquake; This earthquake had a magnitude of 6.8 and caused damage in the western part of Tanzania, including the collapse of several buildings. There were at least a dozen fatalities.
- 2016 Kagera earthquake; This earthquake had a magnitude of 5.9 and caused damage in the Kagera region of Tanzania, including the collapse of several buildings. There were 19 fatalities and 253 injuries.

The Geological Survey of Tanzania (GST) monitors seismic activity in the country and provides information on earthquake preparedness and mitigation. The GST also conducts research on earthquakes and their effects.

2.1.1 Introduction on Earthquakes

Earthquakes are one of the most destructive of natural hazards. Earthquakes occur due to sudden transient motion of the ground as a result of release of elastic energy in a matter of few seconds. The impact of the event is most traumatic because it affects large area, occurs all on a sudden and unpredictable. They can cause large scale loss of life and property and disrupts essential services such as water supply, sewerage systems, communication and power, transport.

2.1.2 Interior Structure of the Earth

Through analysis of seismograms from various earthquakes three main levels of within the earth were deduced, namely the crust, the mantle and the core as shown in figure 2-1

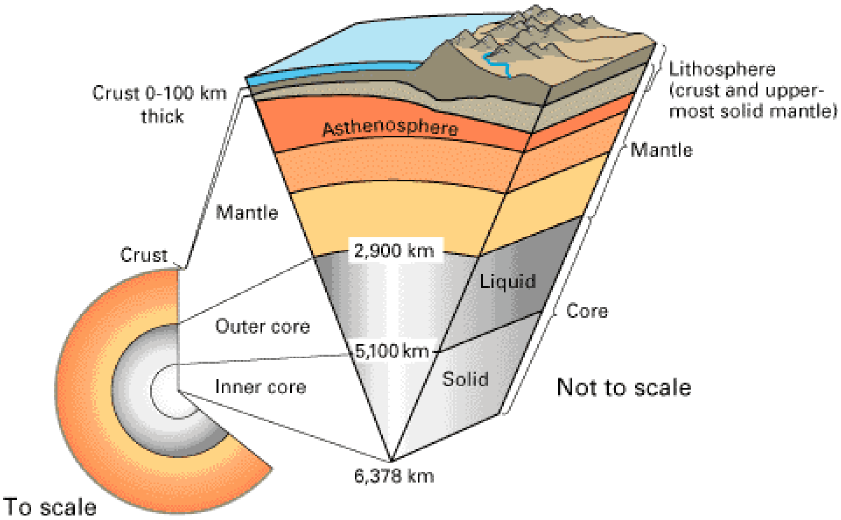

Figure 2-1: Interior structure of the Earth (Earle, 2015)

The Crust; The Earth's outermost surface that is relatively light and brittle where most of the earthquakes occur (Scientists believe that below the lithosphere is a relatively narrow, mobile zone in the mantle called the asthenosphere.)

The Mantle; The dense and hot layer of semi solid rock approximately 2,900km thick region just below the crust and extending all the way down to the Earth's core. The part of the mantle near the crust about 50 to 100km down is especially soft and plastic, and is called the asthenosphere. The rigid lithosphere is thought to "float" or move about on the slowly flowing asthenosphere as illustrated in figure 2-2.

The Core; The region below the Earth's mantle with a fluid outer core and a solid inner core. Convection currents develop in the viscous Mantle, because of prevailing high temperature and pressure gradients between the Crust and the Core as shown in Figure 2-2. The energy for the above circulations is derived from the heat produced from the incessant decay of radioactive elements in the rocks throughout the Earth's interior. These convection currents result in a circulation of the earth's mass; hot molten lava comes out and the cold rock mass goes into the Earth. The mass absorbed eventually melts under high temperature and pressure and becomes a part of the Mantle, only to come out again from another location, someday. Many such local circulations are taking place at different regions underneath the Earth's surface, leading to different portions of the Earth undergoing different directions of movements along the surface.

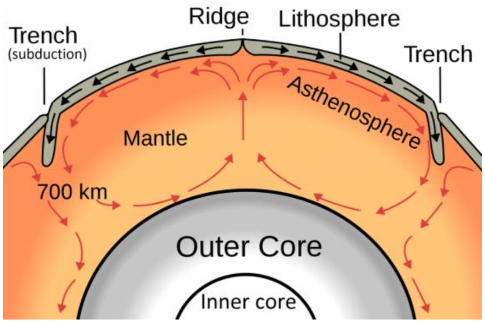

Figure 2-2: Local convention currents in the mantle (Earle, 2015)

The convective flows of Mantle material cause the Crust and some portion of the Mantle, to slide on the hot molten outer core. This sliding of Earth's mass takes place in pieces called Tectonic Plates. The surface of the Earth consists of seven major tectonic plates (North American Plate, South America Plate, Antarctic Plate, African Plate, Australian Plate, Eurasian Plate and Pacific Plate) and many smaller ones as shown in Figure 2-3.

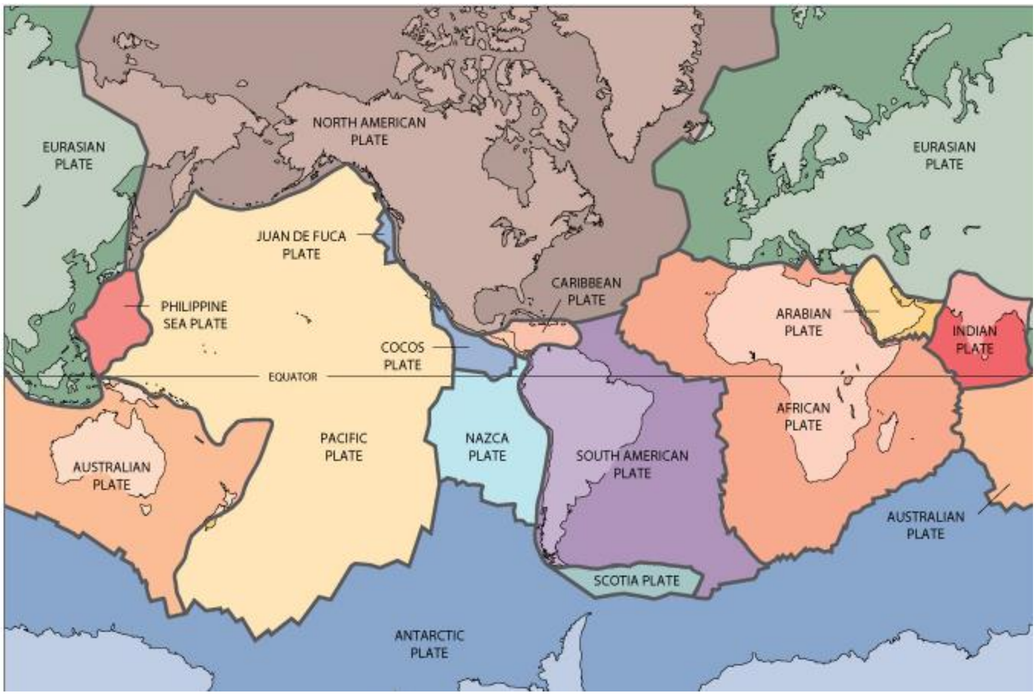

Figure 2-3: Major tectonic plates on the Earth's Surface (USGS, 2011)

These plates move in different directions and at different speeds from those of the neighbouring ones. Sometimes, the plate in the front is slower; then, the plate behind it comes and collides (and mountains are formed). On the other hand, sometimes two plates move away from one another (and rifts are created). In another case, two plates move side-by-side, along the same direction or in opposite directions. These three types of inter-plate interactions are the convergent, divergent and transform boundaries respectively (as shown in figure 2-4).

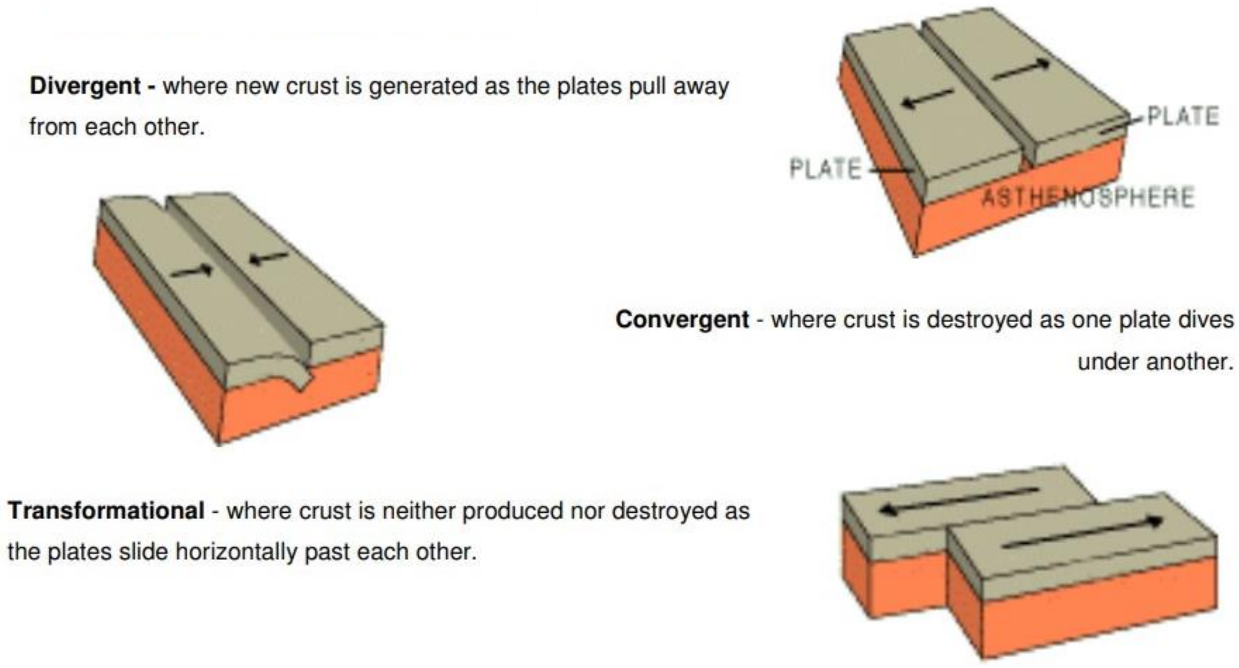

Figure 2-4: Types of Inter-plate boundaries (USGS, 2011)

2.1.3 Elastic rebound theory

The sudden slip at the fault causes the earthquake. Thus, a violent shaking of the Earth when large elastic strain energy released spreads out through seismic waves that travel through the body and along the surface of the Earth. And, after the earthquake is over, the process of strain build-up at this modified interface between the rocks starts all over again Earth scientists know this as the Elastic Rebound Theory as shown in figure 2-5.

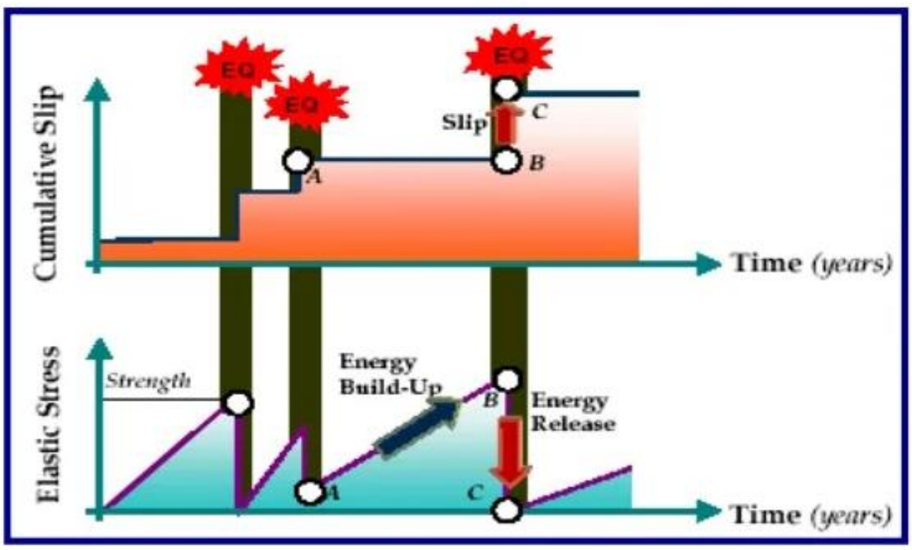

Figure 2-5: Illustrating the elastic rebound theory (Shakeel, 2014)

2.1.4 Depth of Earthquakes

Earthquake focus depth is an important factor in shaping the characteristics of the waves and the damage they inflict. The focal depth can be namely; Deep (from 300 to 700 km), rarely destructive because the wave amplitude is greatly attenuated by the time it reaches the surface, Intermediate (60 to 300 km) and Shallow (less than 60 km) are more common and are extremely damaging because of their close proximity to the surface.

2.1.5 Earthquake measurement scales

Earthquakes can be described by use of two distinctly different scales of measurement demonstrating magnitude and intensity. Earthquake magnitude or amount of energy released is determined by use of a seismograph, and instrument that continuously records ground vibrations.

A scale developed by a seismologist named Charles Richter mathematically adjusts the readings for the distance of the instrument from the epicentre. The Richter scale is logarithmic. An increase of one magnitude signifies a 10-fold increase in ground motion or roughly an increase of 30 times the energy.

Thus, an earthquake with a magnitude of 7.5 releases 30 times more energy than one with a 6.5 magnitude, and approximately 900 times that of a 5.5 magnitude earthquake. A quake of magnitude 3 is the smallest normally felt by humans. The largest earthquakes that have been recorded under this system are 9.25 (Alaska in 1969) and 9.5 (Chile in 1960).

A second type of scale, the earthquake intensity scale, measures the effects of an earthquake where it occurs, which is usually influenced by how close the earthquake is to the surface as well as the nature of the surrounding geology and the infrastructure present in the area (proximity to urban area).

2.2 Spatial Analysis

2.2.1 Introduction

Spatial analysis is defined as multiple techniques for describing, analysing, simulating and predicting the spatial patterns, where the spatial data can be geo-referenced points to identify their pattern and associations and to predict the unknown values of the concerned attribute in relation to its affecting variables (Gao, 2022).

2.2.2 Spatial statistics

According to the Esri's GIS Dictionary it is defined as the statistical methods that use space and spatial properties such as volume, length, height, distance, area, and other similar properties directly in their mathematical computations (Gao, 2022). Thus, spatial statistics can be used to analyse spatial distributions, patterns, processes and relationships.

It differs from spatial analysis in such that it focuses more on statistical properties of the attributes of the geographic phenomenon in contrast to the much broader connotations of spatial analysis. These analyses in spatial statistics may be descriptive, inferential, exploratory and possibly even geostatistical.

2.2.3 Spatial pattern

Spatial patterns can be defined as spatial arrangement or distribution of a group of spatial entities of either identical or different identities. A pattern implies some kind of unique and regular repetition or occurrences of the same entities, such that a spatial pattern can be analysed for point, linear or areal features and the pattern can be described as clustered (spatial grouping of these entities), dispersed (spatial repulsion of these entities) or random (where there is no definitive clustering nor dispersion of the entities).

Spatial patterns aren't so easy to analyse quantitatively as all patterns involve some kinds of geometric properties that are not easily quantifiable. In contrast, it is relatively easy to compare an observed pattern with some standard patterns to assess its nature (clustered or dispersed). It is also possible to test whether the observed pattern conforms to a standard one statistically. (Gao, 2022)

2.2.4 Dispersion and Clustering

Dispersion refers to the wide scattering of observations over the area of study. A dispersed distribution is characterised by a lack of compactness for a group of observations of the same attribute. The observations spread out so widely that they occupy the entire area without obvious gaps. Clustering, in contrast, refers to the spatial grouping of certain observations that are much closer to each other than to the members of another group. Dispersion and clustering are analogous to the two sides of the same coin, in that the lack of clustering is manifested as dispersion, and vice versa. Dispersed observations have low density, while clustered distributions tend to result in higher density locally. (Gao, 2022).

2.2.5 Kernel density analysis

When points (events) are heavily overlapped with one another (too close to one another) it is impossible to appreciate their spatial density (first order analysis of point patterns) clearly, but using kernel density the intensity of clustering can be shed light on. Kernel density is analysed by counting the number of events per unit area within a moving window, such that the events within the window are weighted in terms of their distance from the point in question. Thus, it is able to yield smooth estimates of univariate probability densities from points f(x,y); (Gao, 2022) calculated as shown in the equations (i) and (ii).

$$\hat{f}(x,y) = \frac{1}{nh_x h_y}\sum_{i}^{n} k\left[\frac{x-x_i}{h_x}, \frac{y-y_i}{h_y}\right] \quad \text{.... (i)}$$

where $k\left[\frac{x-x_i}{h_x}, \frac{y-y_i}{h_y}\right]$ represents the kernel weighting function, in which

$$h_x = \sigma_x \left(\frac{2}{3n}\right)^{\frac{1}{6}} \quad \text{... (ii)}$$

From the equation (i) and (ii), n stands for the number of points enclosed in bands h_x and h_y, while σ_x denotes the standard deviation of all the enclosed observations within the bandwidth in the x (h_x) and y (h_y) directions of the kernel. Thus, it is effective at showing the degree of spatial clustering when numerous points overlap each other thus showing the level of clustering quantitatively and the spatial pattern clearly. (Gao, 2022). Kernel density is different from ordinary point density, in that the calculated kernel density around each observation is based on a quadratic formula with the maximum value at the centre (where the point observation is located), and it tapers to 0 at close to the search radius, whereas in ordinary density the same value applies to the entire search neighbourhood and the density is spatially homogeneous.

2.2.6 Ripley's k-function

Ripley's K-function is one of the most commonly used second order analysis of point patterns methods of calculating ranged based point density. It requires the calculation of point density at multiple ranges or distances, within which the number of observations is compared with the expected pattern under the CSR (Complete Spatial Randomness) distribution. It can detect departure from CSR over different ranges (r). Similar to the Moran's I function, it is able to yield information on the observed point distribution at the user-specified scale, and the distribution of a collection of point data.

Since the K-function is virtually a multi-distance spatial clustering analysis, the user can determine whether the distribution is dispersed, clustered, or random at different ranges of analysis. (Gao, 2022).

$$\hat{K}(r) = \frac{1}{\hat{\lambda}} \sum_{i=1}^{N} \sum_{j=1(i \neq j)}^{N} \frac{w(S_i, S_j)^{-1} \, i\left(\left\| S_i - S_j \right\| \leq r\right)}{N, t > 0} \qquad \text{… (iii)}$$

From the equation (iii); r represents the step size, N denotes the number of points enclosed in the area formed by r, w (S_i, S_j) refers to the portion of the circumference of `a circle centred at S_i passing through S_j, within the study area A and $\hat{\lambda}$ stands for the estimated point density calculated as (= N/A). (Gao, 2022).

Using the R-library the K-function results to a plot with curves of different estimates of the K-function using different `edge correction' techniques. Also, one of the curves is the theoretical value of the K function indicated by the theoretical Poisson (Kpois) curve, K(r) = πr^2, corresponding to a completely random pattern. The other curves are border-corrected estimate of K(r) (Kbord), translation-corrected estimate of K(r) (Ktrans) and Ripley isotropic correction estimate of K(r) (Kiso).

The estimates of K(r) by different techniques should be roughly equal. If the curves for `iso', `trans' and `border' are wildly different, this suggests that estimation of K is difficult for these data (e.g. because there are too few data points, or the window is too irregular).

The standard interpretation of the plots of the K function is that, if the estimated K function curve lies above the theoretical curve, then the pattern is clustered, while if the estimated K lies below the theoretical curve, then the pattern is regular. (Spatstat, 2022).

CHAPTER THREE

METHODOLOGY

3.1 Overview

This chapter entails all the description, sequence of the various procedures and methods used to conduct this study. The sequence of the research study is illustrated as shown in figure 3-1 in which it can be branched into five major steps; Data collection, Data processing, Spatial analysis, Temporal analysis and finally output product preparation, where the proceeding sections will further explain the steps and procedures illustrated in figure 3-1.

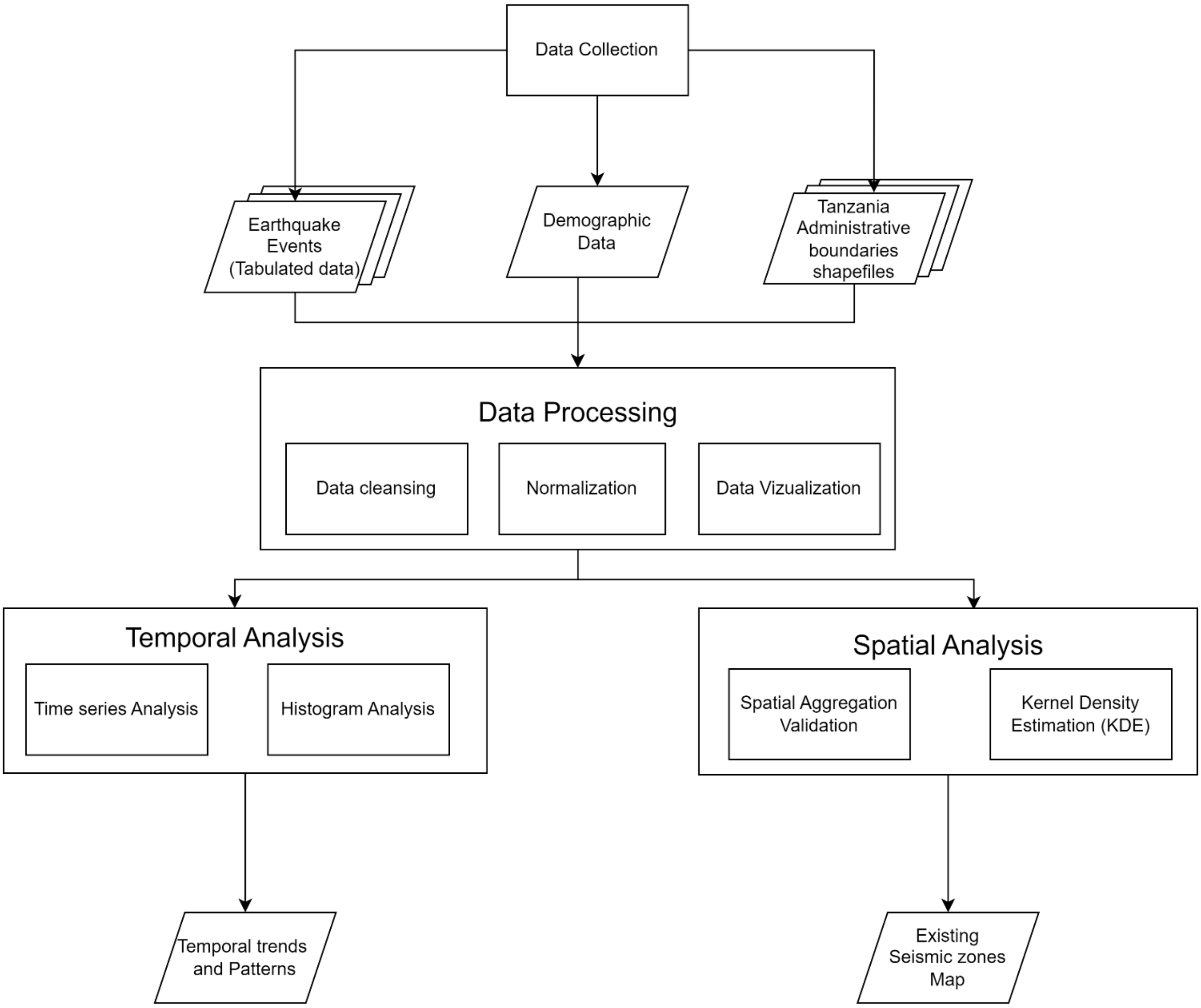

Figure 3-1: The Methodological Framework

3.2 Software used

The study was achieved using the following software for processing purposes described throughout the following section of the methodology. The software are listed in the Table 3-1.

Table 3-1 Showing list of software used in the study

S/N	Name	Uses	Version
1.	Microsoft's Excel	Data normalization, Temporal analysis (Earthquake frequency against time)	2019
2.	R studio	Spatial analysis (K-function plot), Temporal analysis (Earthquake magnitudes over time, Earthquake depths overtime)	RStudio 2023.03.1+446 "Cherry Blossom"
3.	Esri's ArcMap	Data visualization, data cleansing(masking), spatial analysis (Kernel Density estimation), Histogram analysis (magnitude against frequency)	10.8.0.12790

3.3 Data collection

In data collection there were three groups of data that were used in the study, namely the earthquake events of the past five decades (50 years), comprising a total of 820 events being from 1973 up to 2022 located between the longitudes 28° to 41°East and the latitude 0° and 12°South provided by the USGS earthquake catalog (U.S.G.S, 2023) in form of text file (with the extension .csv meaning comma separated values) as shown in the figure 3-2.

1	time	latitude	longitude	depth	mag	magType
2	2005-12-05T12:19:56.620Z	-6.224	29.83	22	6.8	mwc
3	2000-10-02T02:25:31.310Z	-7.977	30.709	34	6.5	mwb
4	2002-10-24T06:08:37.980Z	-1.884	29.004	11	6.2	mwc
5	2009-12-19T23:19:15.550Z	-10.108	33.818	6	6	mwc
6	2020-08-12T17:13:16.180Z	-7.3327	39.8126	17.55	6	mww
7	2009-12-08T03:08:57.240Z	-9.948	33.878	8	5.9	mwc
8	2017-02-24T00:32:17.800Z	-8.4404	30.0305	30	5.9	mww
9	1994-08-18T00:45:47.200Z	-7.433	31.751	25.2	5.9	mwb
10	1997-09-21T18:13:22.780Z	-7.36	30.37	10	5.9	mwc
11	2007-07-17T14:10:42.460Z	-2.734	36.362	8	5.9	mwb
12	2008-02-03T07:34:12.180Z	-2.296	28.9	10	5.9	mwb
13	2016-09-10T12:27:33.410Z	-1.0355	31.6181	40	5.9	mww
14	2009-12-06T17:36:36.010Z	-10.126	33.87	9	5.8	mwb
15	2007-03-28T21:17:10.650Z	-6.268	29.673	8	5.8	mwc
16	1986-06-29T21:47:59.670Z	-5.336	29.539	20.2	5.8	mw
17	2015-08-07T01:25:02.540Z	-2.1412	28.8973	11	5.8	mww
18	1976-09-19T14:59:43.700Z	-11.056	32.857	27	5.7	ms
19	1985-02-23T14:45:35.940Z	-6.966	30.928	10	5.7	mb
20	2007-12-08T19:55:19.370Z	-7.558	37.646	6	5.6	mwc
21	1999-05-07T14:07:28.740Z	-7.491	31.683	10	5.6	mb
22	1977-12-15T23:20:53.600Z	-4.761	34.913	33	5.6	ms
23	2009-12-12T02:27:03.780Z	-9.942	33.911	10	5.5	mwc
24	2019-03-21T09:15:40.309Z	-7.9143	32.1088	22	5.5	mww
25	1975-09-21T09:22:04.000Z	-7.907	31.611	33	5.5	mb
26	2002-02-20T19:07:17.100Z	-7.679	31.895	38.5	5.5	mwc
27	2005-12-09T23:30:23.930Z	-6.176	29.709	10	5.5	mwc

Figure 3-2: A screenshot of some of the Earthquake data acquired in a tabular form

The other data was Demographic data from the 2022 census acquired from NBS (National Bureau of Statistics of Tanzania) (NBS 2023) which was used to visualize a hazard assessment by assessing the population of each region and respective districts that were in the risk zone due to these seismic events. The data is as shown in the figure 3-3.

1	Region	Population Size
2	Arusha	2356255
3	Dar-es-salaam	5383728
4	Dodoma	3085625
5	Geita	2977608
6	Iringa	1192728
7	Kagera	2989299
8	Kaskazini Pemba	272091
9	Kaskazini Unguja	257290
10	Katavi	1152958
11	Kigoma	2470967
12	Kilimanjaro	1861934
13	Kusini Pemba	271350
14	Kusini Unguja	195873
15	Lindi	1194028
16	Manyara	1892502
17	Mara	2372015
18	Mbeya	2343754
19	Mjini Magharibi	893169
20	Morogoro	3197104
21	Mtwara	1634947
22	Mwanza	3699872
23	Njombe	889946
24	Pwani	2024947
25	Rukwa	1540519
26	Ruvuma	1848794
27	Shinyanga	2241299
28	Simiyu	2140497
29	Singida	2008058
30	Songwe	1344687
31	Tabora	3391679
32	Tanga	2615597

Figure 3-3: A screenshot of the demographic data of Tanzania in regional level as of 2022 census.

Lastly, the Tanzania's Administrative boundaries in form of shapefiles as of 2019 acquired from the NBS in three levels, level one being Tanzania as a whole, level 2 showing the regional administration and level 3 showing the respective district administration of the regions, which all three levels set the windows of processing and visualization of the data collected.

The table 3-2 shows all the groups of data collected in a summarized form, stating their respective sources, time periods and respective uses in the research study;

Table 3-2: A summary of the data collected.

Data	**Time period**	**Format**	**Source**	**Purpose**
Earthquake events	1973 to 2022	CSV (Comma Separated Values)	USGS Earthquake catalog	The main data for spatial analysis processing that was used throughout the study.
Demographic data (in both regional and district levels)	As of 2022	CSV	NBS	To assess the amount of people likely to be affected by the seismic activities.
Tanzania Administrative boundaries (international, regional and district boundaries)	As of 2019	(Shp) Shapefile	NBS	Set windows for processing and visualizing the two data above.

3.4 Data pre-processing

The data was processed in order to be usable for further analysis and discussions, the processes were branched into three, namely outlier detection and removal, Normalization and Data visualization. These processes are described in the following sub sections as follows;

3.4.1 Normalization of the Earthquake data timestamp

Among the headers in the data there was a time post that indicates the time at which each of the earthquake events occurred. The format as it was could not be used in further processes as observed in figure 3-2. Thus, using the SUBSTITUTION function and the DATEVALUE function provided in the Microsoft excel processing software to transform the time post into number of days from a certain point in time (In this case the beginning of the data). This would later be useful in the Temporal analysis section of the methodology as illustrated in figure 3-1.

3.4.2 Data cleansing by masking Area of interest(study)

In this process, exclusion of some of the earthquake events data, since the earthquake events data query method from the USGS earthquake catalog involves using a bounded box and considering that our area of study was Tanzania, whose boundary is an irregular polygon unlike the rectangular bounded box for the data query. Thus, some of the events queried were situated in areas that aren't within the area of study as shown in the figure 3-4.

Hence, visualization of the data and masking out the events that aren't within the study area was performed with the aid of the ArcMap software, where the text file was imported and visualized since among the headers, the longitude and latitude were provided of each event. And after that a masking process was performed to exclude those events that are not situated within our study area. Thus, the resulting earthquake events within the study area summed up to a total of 366 events (Note: events that were situated within water bodies were boundaries aren't clear such as lakes were included as within the study area.)

3.4.3 Data visualization

As stated in section 3.3, the data collected were mainly in a text file format (Demographic and Earthquake events) thus, conversion of these data into a form that can be visualized and integrated with other data was implemented.

Both the demographic and earthquake events data were integrated with the Tanzania shapefiles in both regional and district levels. Which allowed a clearer pre-understanding of the distribution of the data in the study area. Using various functions and methods such as spatial joins, table joins and relate functions as well as various symbolization, various visualization of the data was achieved.

The visualizations were population distribution map of Tanzania in both regional and district levels, Population density maps in both regional and district levels and finally Earthquake distribution maps in regional levels in Tanzania.

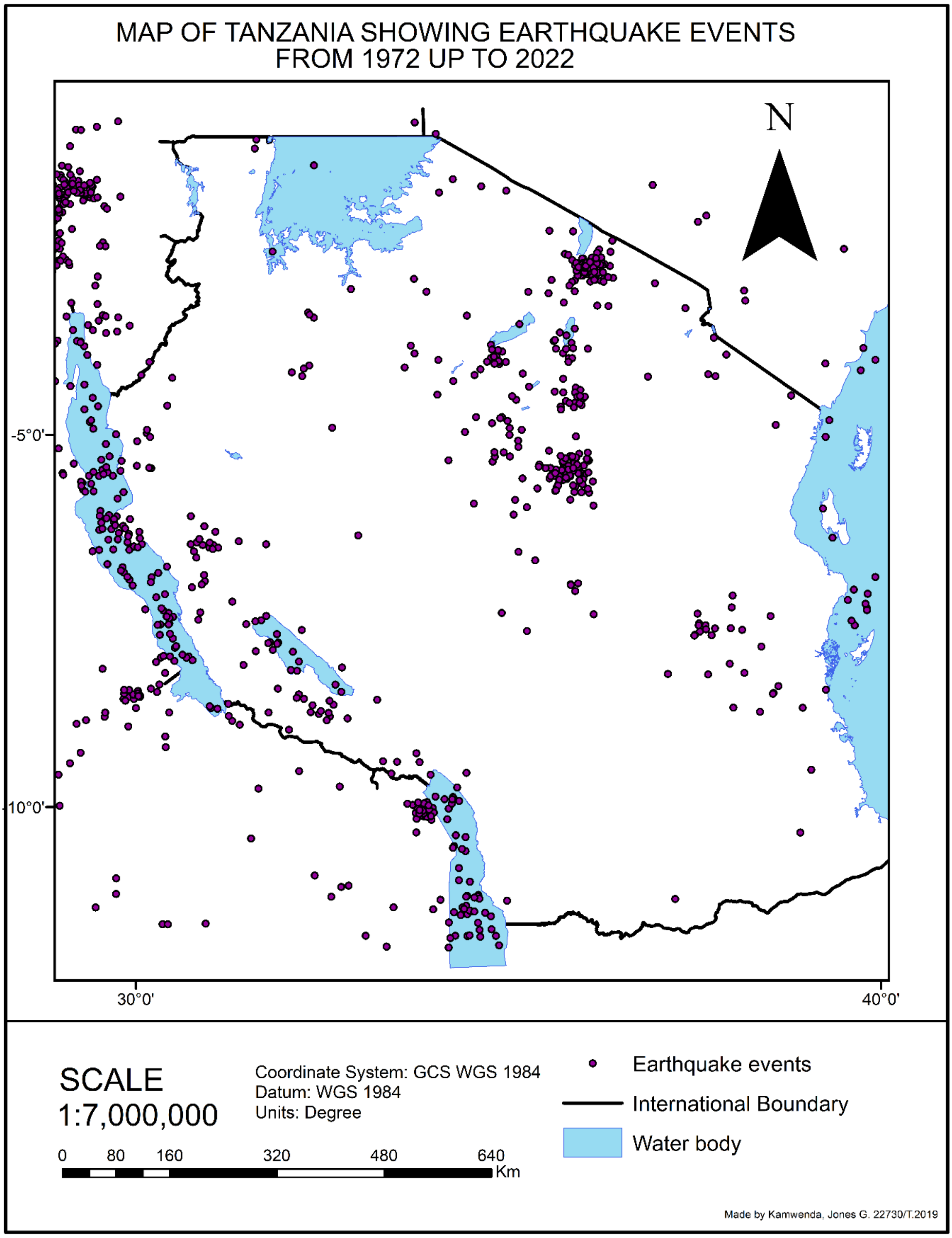

Figure 3-4: Map showing the Earthquake events queried before data cleansing

3.5 Analysing the spatial distribution of the Earthquake events

This section involved the analysis of the point positions to determine potential seismic zones but this was stating that the point data exhibited a spatial clustering characteristic. As the saying goes In God we trust but all others must provide data, stating clustering exists must be proven and was done through the K-function method using R-library "**spatstat**", and the resultant plot confirmed the hypothesis. This allowed further analysis to be done by observing the intensities of different magnitude occurrences to determine areas where the points tend to cluster together thus, determining zones where these seismic activities highly occur, marking these areas as existing seismic hazards and assessing what portion of the population is likely to be affected by falling into these zones of seismic activities.

Using Kernel density estimation functions in ArcMap, intensity maps were created from the Earthquake data basing on their location of occurrence. Since the kernel density results only to a raster with ranges of values an interpretation of these ranges of values was required. As to the time of this study there were no consistent basis for classifying the density values. Thus, a natural break (Jenks) classification algorithm was used since it best groups similar values together and maximizes the differences between the classes (in this case seismic zones that have higher frequency of seismic activity than other areas). Thus, zones of seismic activities in Tanzania were defined from the classification of the density estimates from five classes labelled as Safe (0-3), Relatively safe (above 3 to 9), Low Threat (above 9 to 20), Moderate Threat (above 20 to 35) and High threat (above 35 to 55) zones, where designation of relatively high density values (above 9 according to the Jenks classification) as likely existing seismic zones.

3.6 Analysing the temporal patterns and trends of the Earthquake events

This section entails analysis of the temporal aspect of the seismic activities as the earthquake occurrence attributes (magnitude, depth and frequency) were visualized in various time perspective to attain a better understanding on whether there is a trend or pattern in the occurrences of these seismic activities using various histograms and line plots to perform a time series analysis of the dataset.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Overview of Results

This section entails the results of the whole research study and is branched into two sections; The spatial analysis where the potential seismic zones would be entailed and the Time series where the temporal trend and pattern of the earthquake occurrences would be entailed in summary as follows;

4.1.1 Identified Existing Seismic zones

The results obtained after performing Kernel density estimation was a map that shows areas (central arear of Arusha region, northern area of Dodoma region and coastal region of Kigoma) that are of high prevalence to occurrence of earthquakes as shown in figure 4-14. The Earthquake events density were made basing firstly on overall data, then basing on magnitudes to identify areas that are mostly affected by certain ranges of earthquake event of certain magnitudes.

These ranges of event magnitude were, magnitude of 3 to 3.9 (shown in figure 4-10), then magnitude of 4 to 4.9 (shown in figure 4-11) and finally those with magnitudes from 5 and above (shown in figure 4-12), resulting to the designation of areas of high density as being mostly affected by earthquake events thus, identified as the existing seismic zones. Then maps of these zones on a larger scale to assess the regions and their respective districts that fall within these zones.

4.1.2 Temporal Trends and Patterns

The resultant graphs and charts attained were used to analyse the potential trends and patterns viewing various aspects such as magnitudes, frequency and depths over time (against time) and describing the prevalence characteristics of earthquake events that occur in Tanzania though observation of those characteristics (magnitude, frequency and depth) through the research study time scope.

4.2 Discussion and presentation of Results

4.2.1 Spatial distribution of Earthquake events

As observed in figure 4-1 after visualization and masking out of the earthquakes outside of the study area, visually the earthquakes seem to exhibit a cluster like pattern observed in the north eastern region of Tanzania.

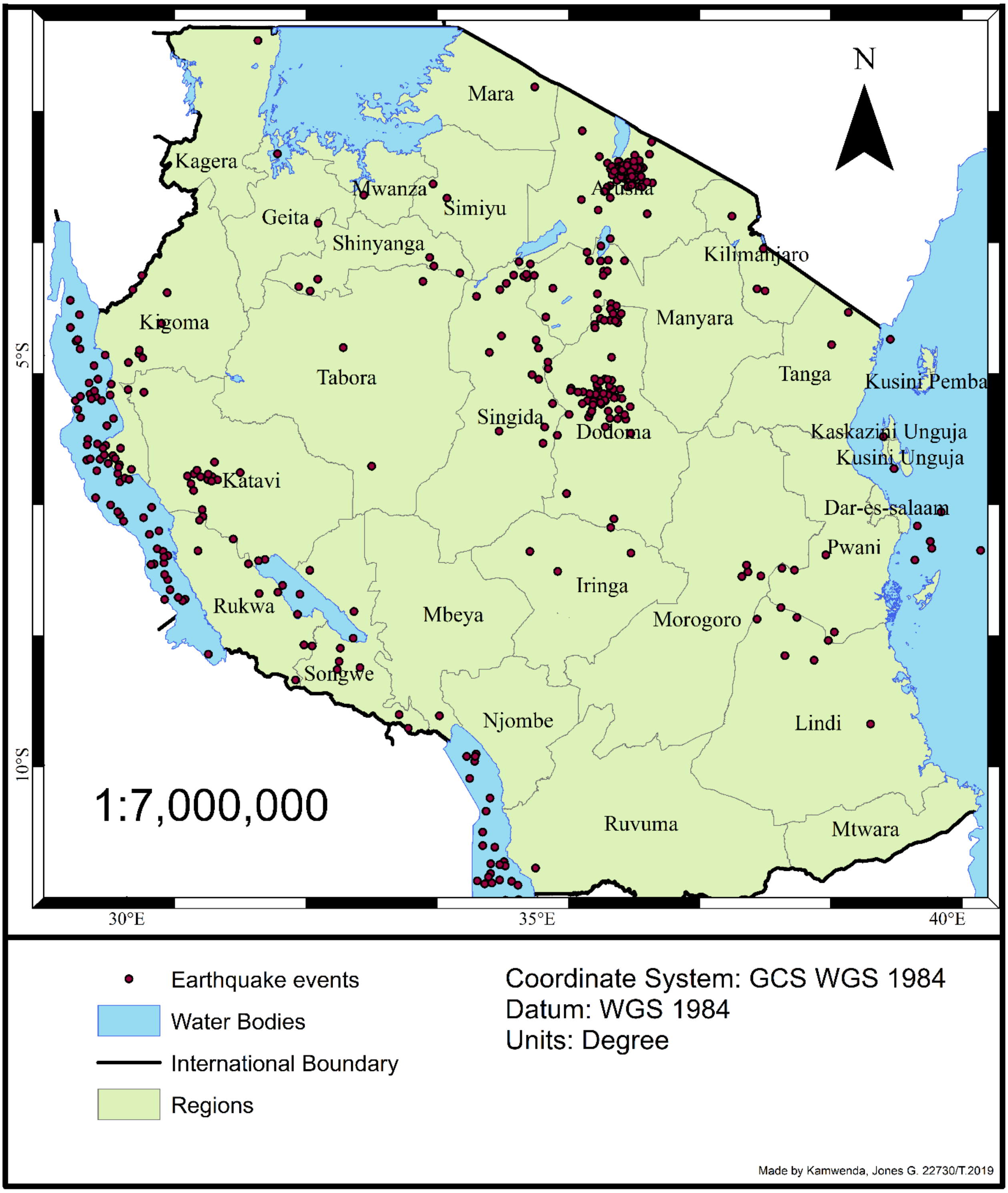

Figure 4-1: Earthquake distribution (1972 to 2022) in Tanzania regions.

Also, as shown in the histogram in figure 4-2, most of the magnitudes lie in the range values of magnitude 4s (4.0 to 4.9) followed by those lying in the range of magnitude 5, then those in the magnitude range of 3 and the rest being in magnitude 6 and above with a max of 6.8 magnitude.

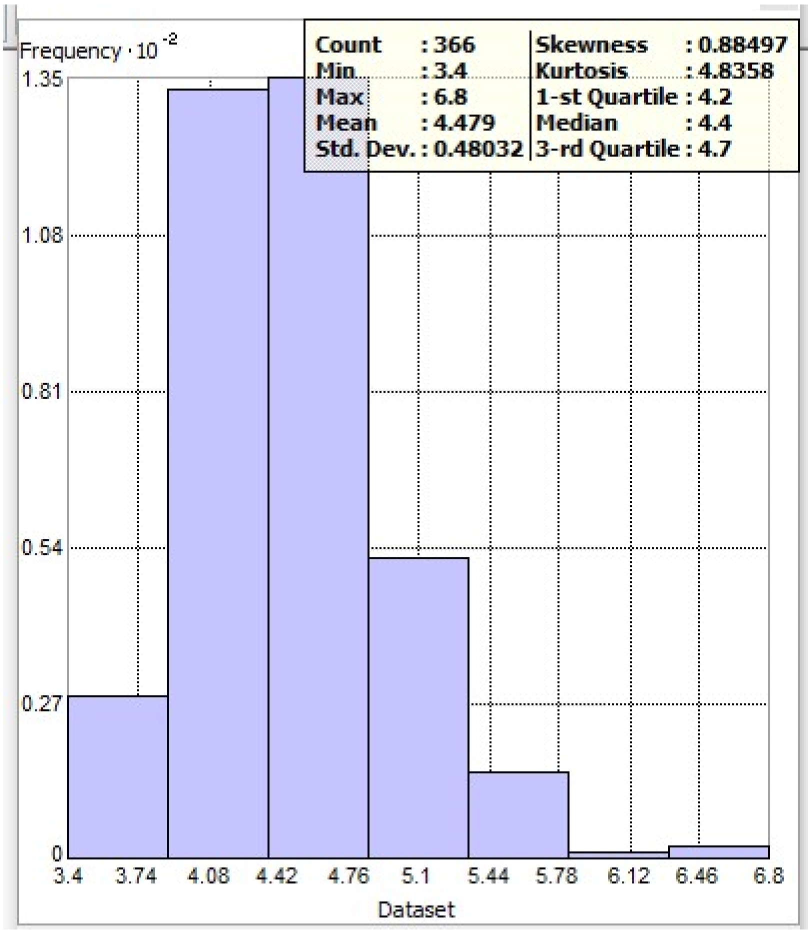

Figure 4-2: Histogram of Earthquake events (x-axis=magnitude and y-axis=frequency x 10^{-2})

An earthquake occurrence count in each region as shown in figure 4-3 indicates that regions Njombe, Geita, Kusini Pemba, Kaskazini Pemba, Mjini Magharibi and Kusini Unguja have no earthquake occurrences from the data of the last 50 years. While Arusha and Dodoma regions visibly having the highest counts of earthquake occurrences in Tanzania. (Note: These counts associated only those earthquake events situated within the region's administrative boundary and not within water bodies).

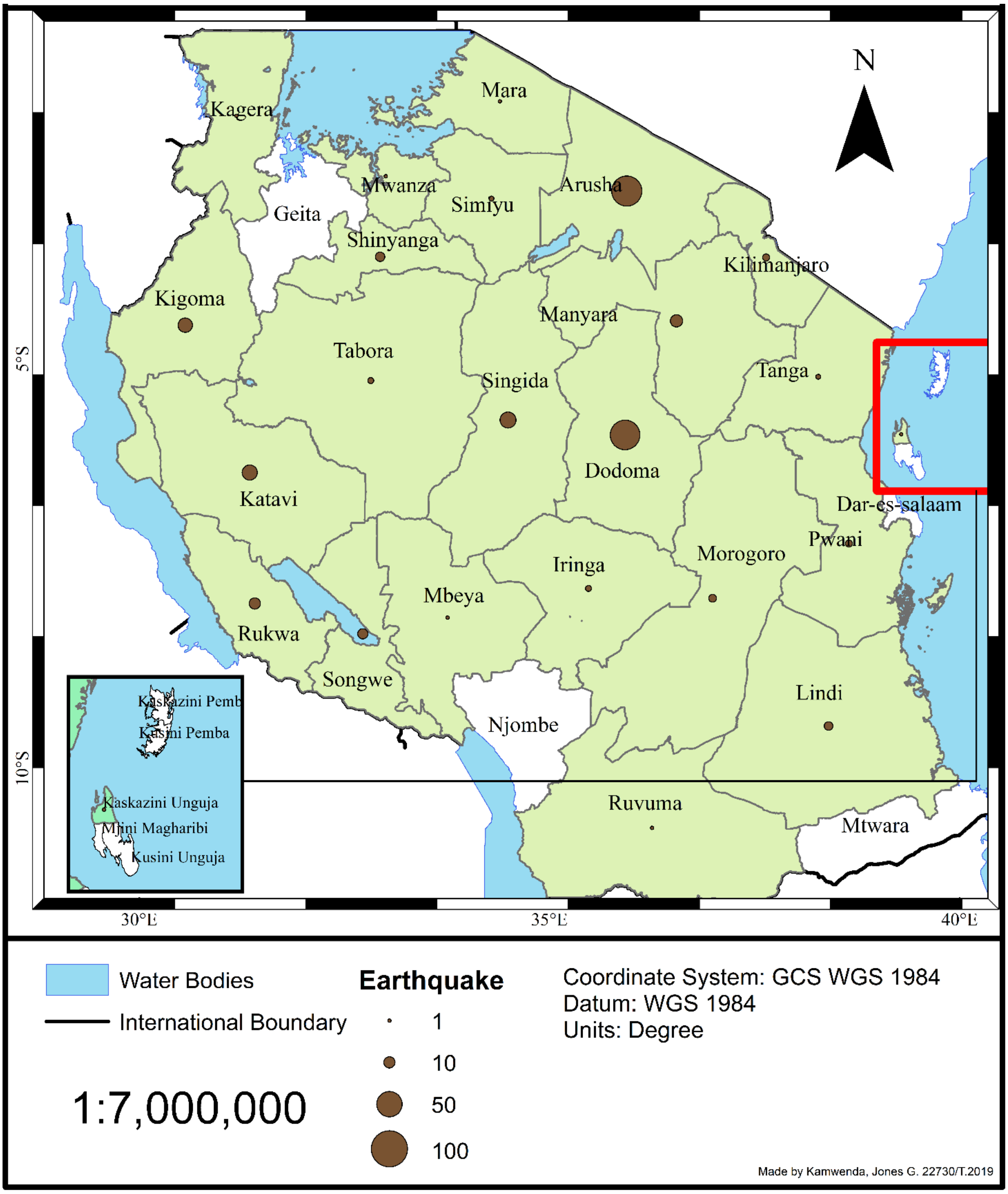

Figure 4-3: Earthquake counts (1973 to 2022) in Tanzania regions depicting regions without any earthquake occurrences (Indicated as white).

4.2.2 Population Distribution in Tanzania

Through the visualization of the demographic data of Tanzania, a depiction that the regions Dodoma, Morogoro, Tabora, Dar es Salaam and Mwanza having a population of over three million, while the region of Njombe having relatively the lowest population of all the regions of less than a million people with the rest ranging from one million to three million people as indicated in the figure 4-4 and their respective population density in figure 4-5.

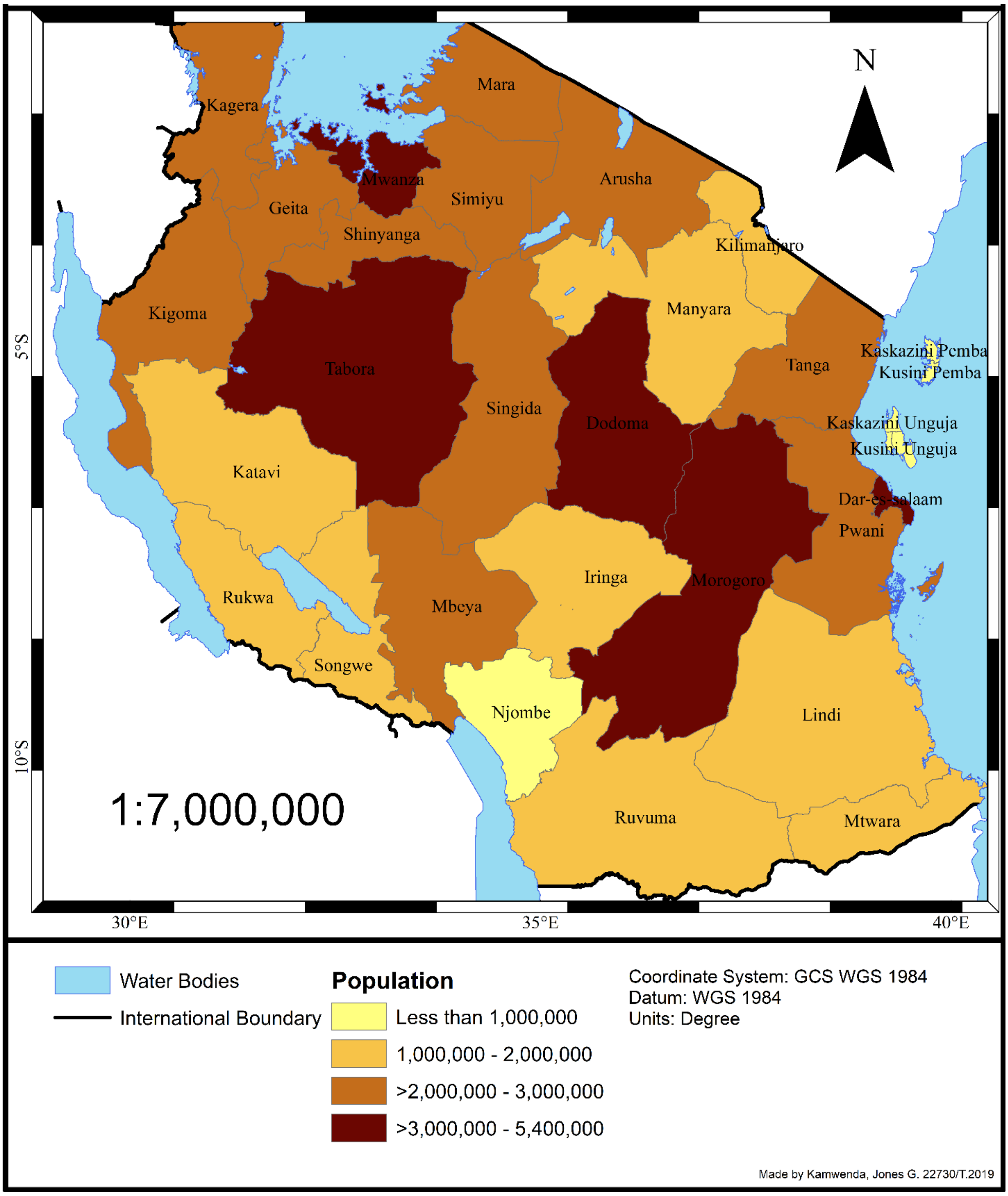

Figure 4-4: Population distribution of Tanzania regions as of the 2022 census.

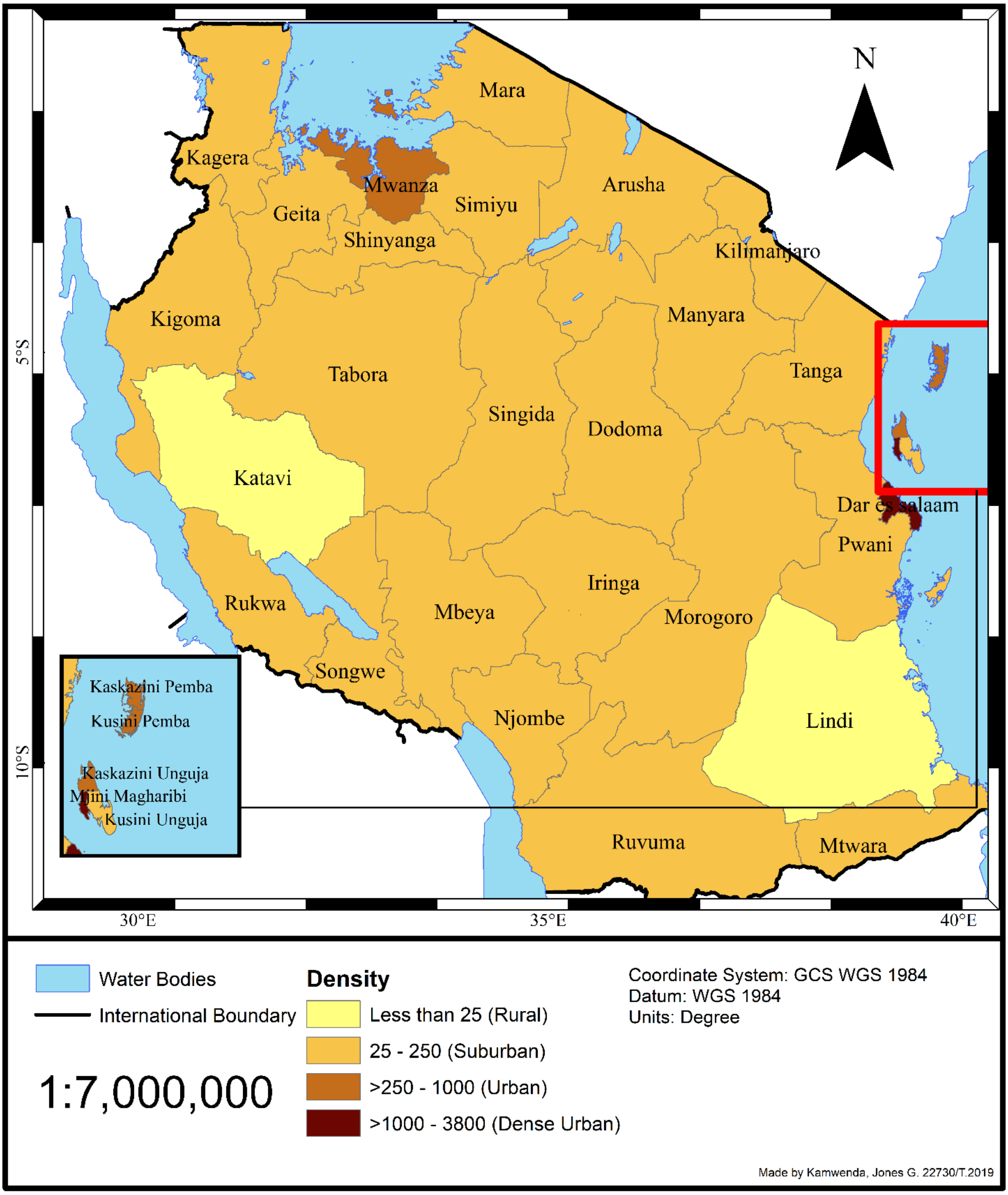

Figure 4-5: Population density of Tanzania regions as of 2022 census.

While in the figure 4-6 and 4-7 indicating the population and population density in district level respectively, indicating that most of the districts having a population of 200,000 to 500,000 people. Also, with most districts having a sub-urban population density of greater than 25 to 250 people per square kilometre.

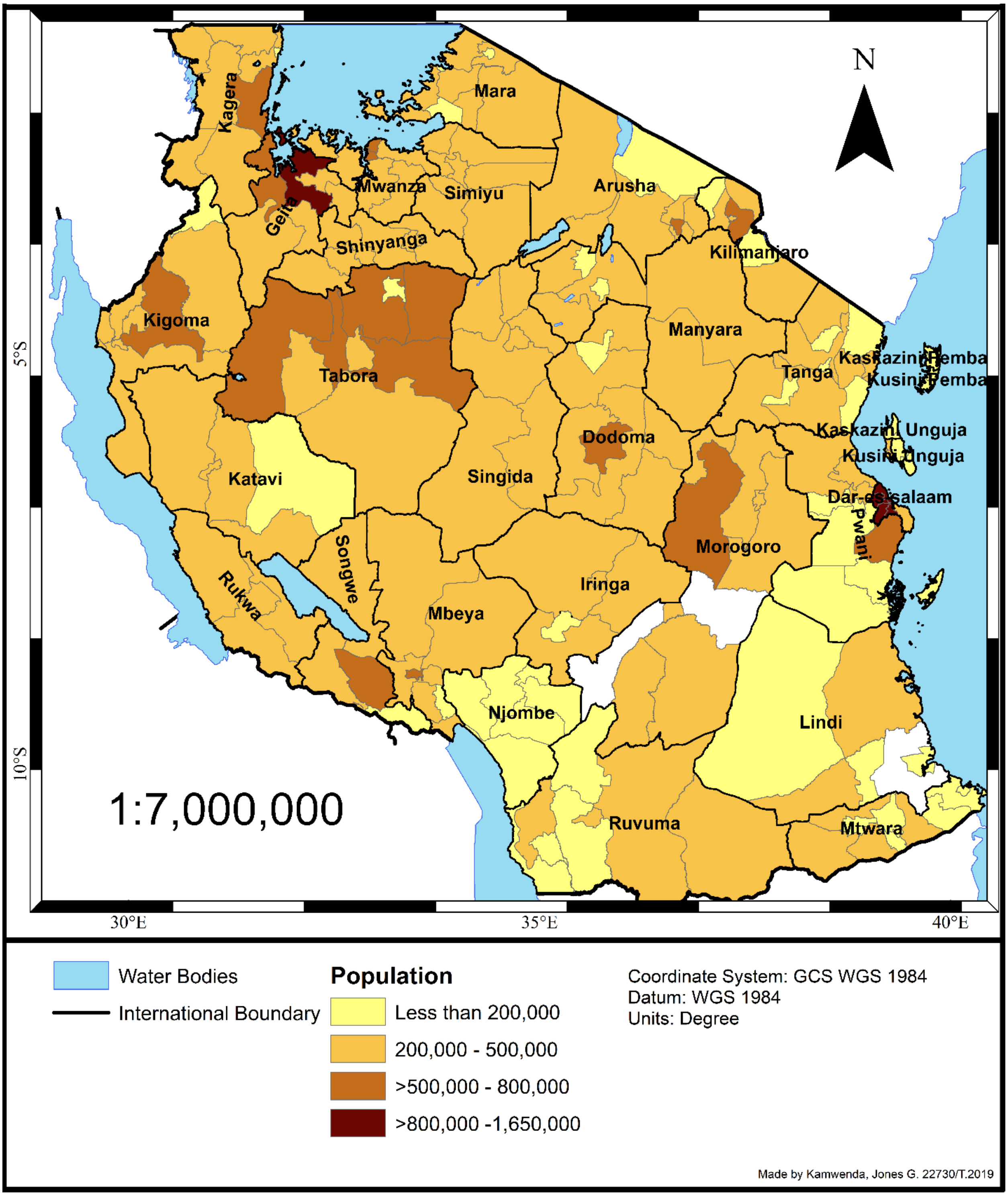

Figure 4-6: Population distributions in in Tanzania districts as of 2022 census.

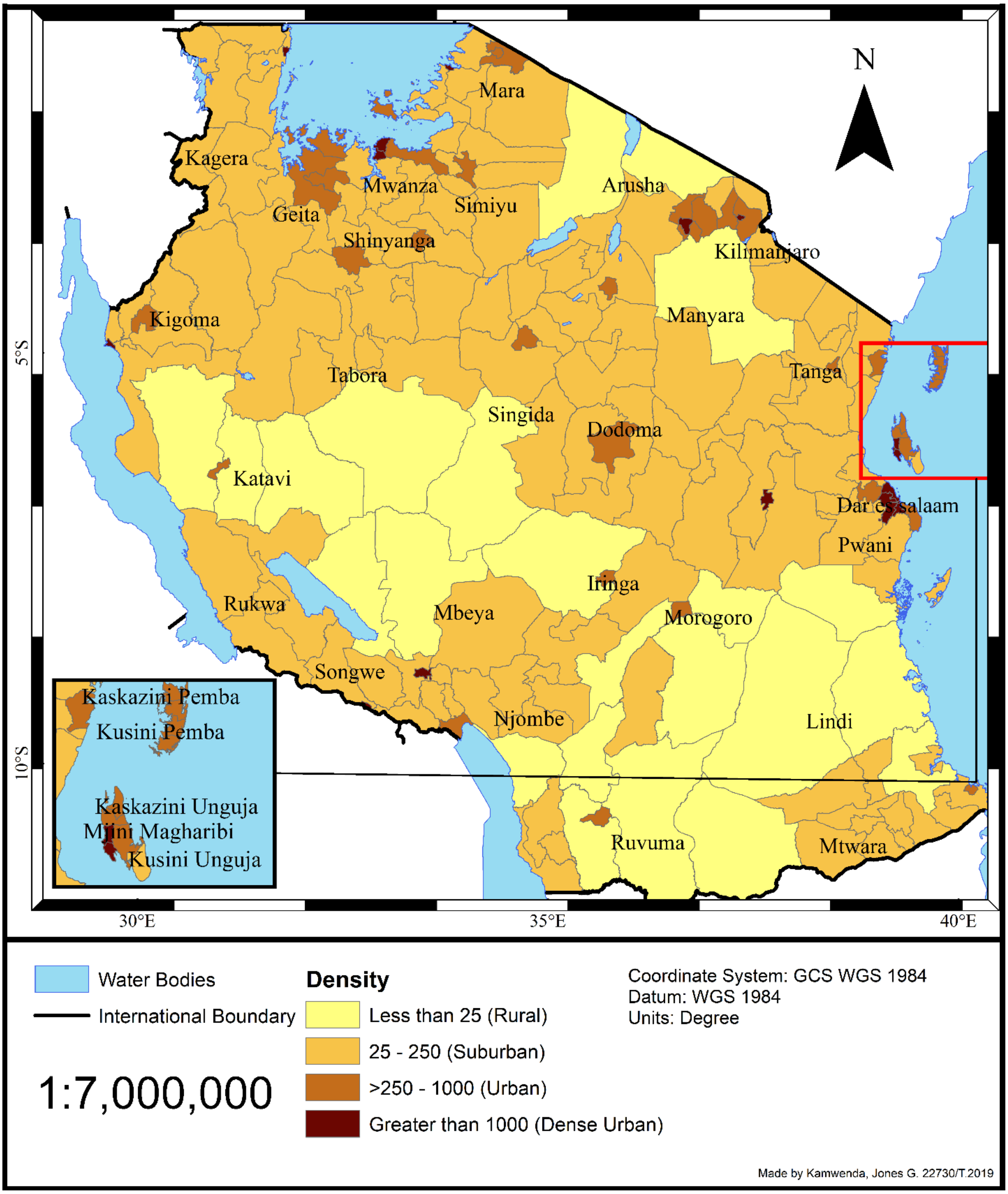

Figure 4-7: Population density in Tanzania districts as of 2022 census.

4.2.3 K-function Plot

As shown in figure 4-8, the plotting of the three lines (border corrected estimate Kbord, translation-corrected estimate Ktrans and the isotropic correction estimate Kiso) above the theoretical Poisson (Kpois) line indicates spatial clustering. Thus, this confirms the existence of high seismic activity zones (clustering).

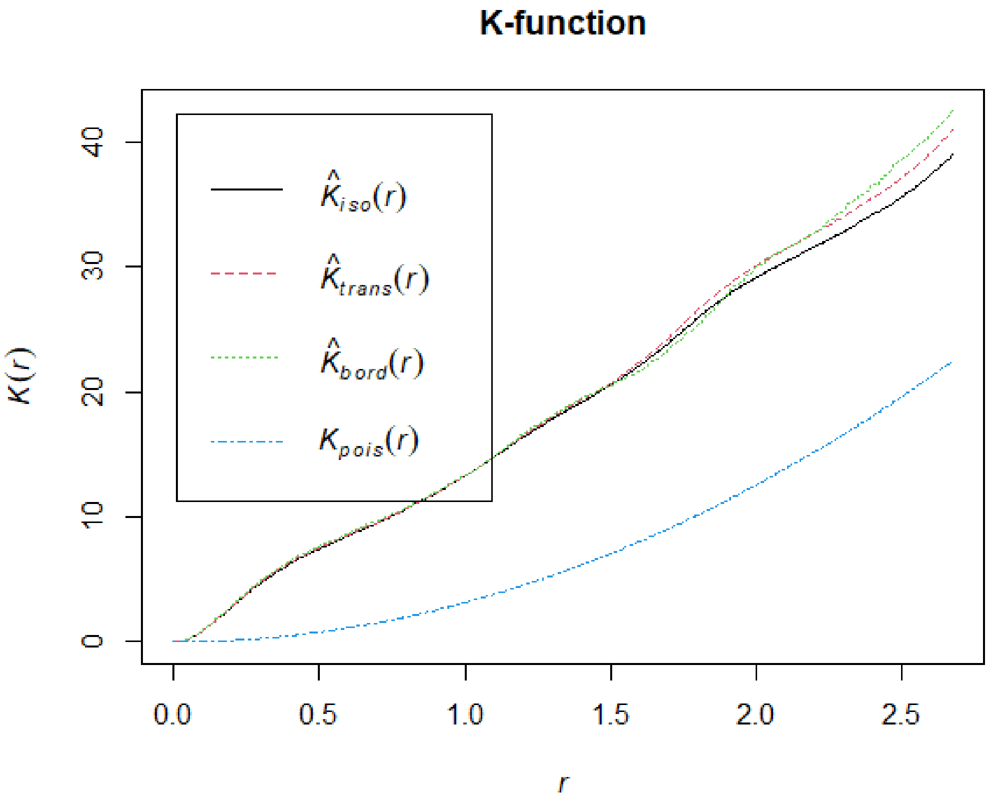

Figure 4-8: K-function plot indicating spatial aggregation (clustering) of the earthquake data.

4.2.4 Kernel Density Estimation

From the kernel density map (figure 4-9) classified according to the natural breaks (Jenks) algorithm into five classes of ranges of density values. The map indicates the coastal region of Lake Tanganyika and North Eastern region of Tanzania as having relatively higher density values of earthquake occurrences.

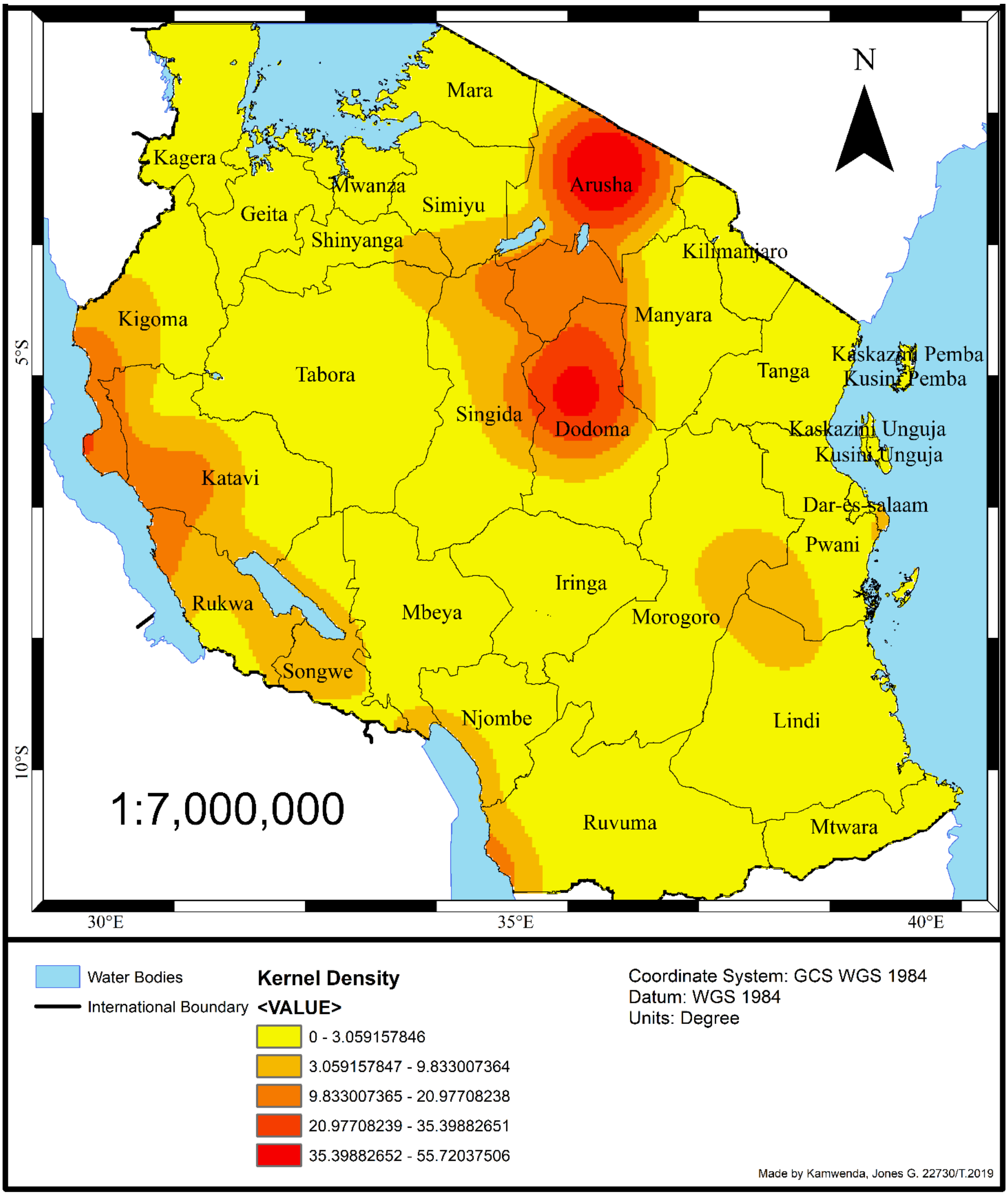

Figure 4-9: Earthquake occurrence kernel density map

4.2.5 Zones of Seismic activities

As observed from the figures 4-10 to 4-12 which entail the Density maps of earthquake occurrences based on different magnitude ranges, namely 3 to 3.9, 4 to 4.9 and those with magnitudes greater than 5 respectively. The zones of high density of point occurrence are observed to lie within the Great East African Rift Valley System as shown in figure 4-13.

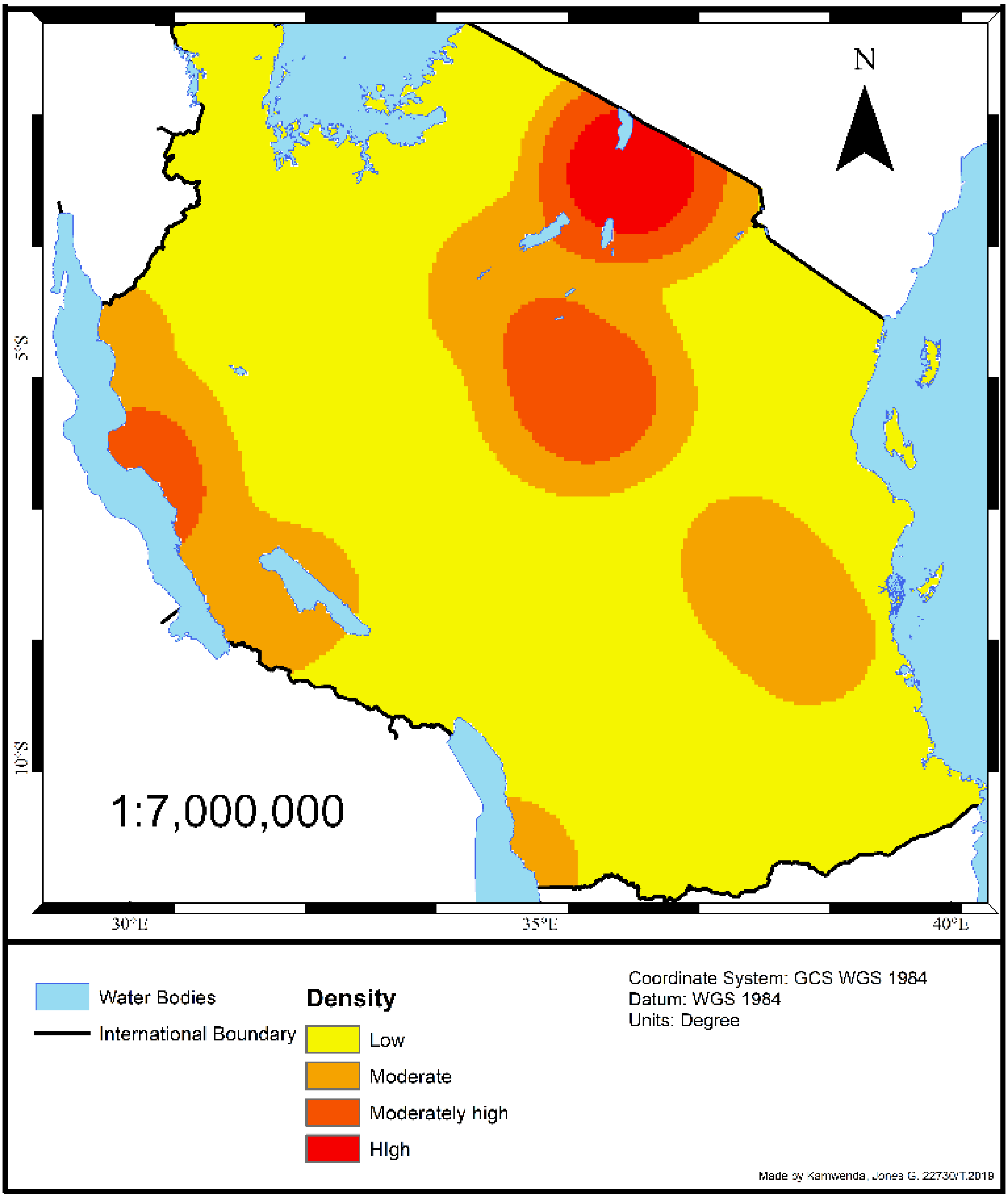

Figure 4-10: Earthquake density map of magnitude 3 to 3.9 occurrence in Tanzania

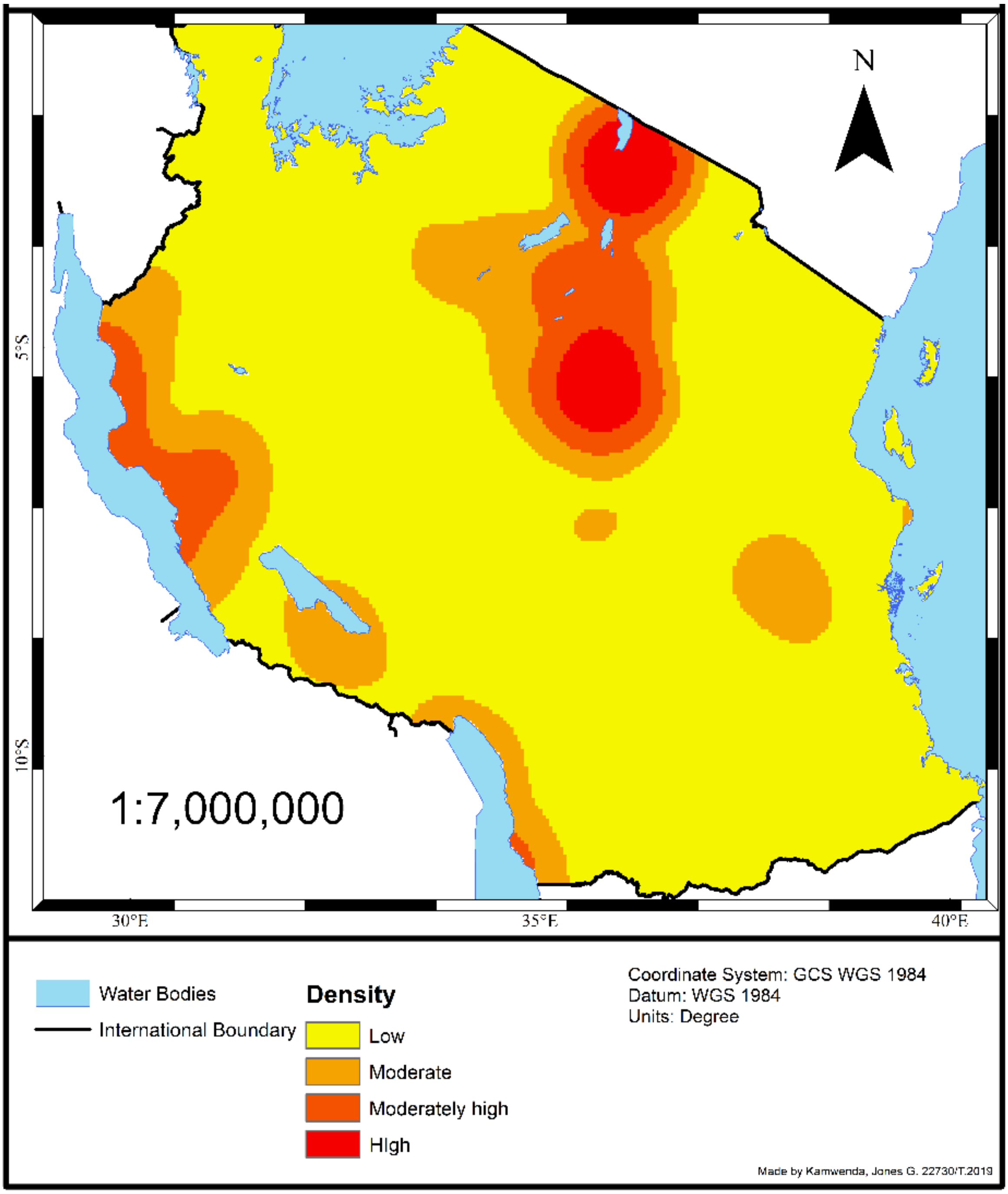

Figure 4-11: Earthquake density map of magnitude 4 to 4.9 occurrence in Tanzania

The earthquakes of magnitude 4 to 4.9 high density zones are less extensive compared to the high-density zones of magnitudes 3 to 3.9 as shown in figure 4-10 and 4-11 respectively. While the magnitudes greater than 5 earthquakes high density zones are much less extensive as shown in figure 4-12. This indicates that the lower magnitude earthquakes mostly occur around high magnitude earthquakes over space.

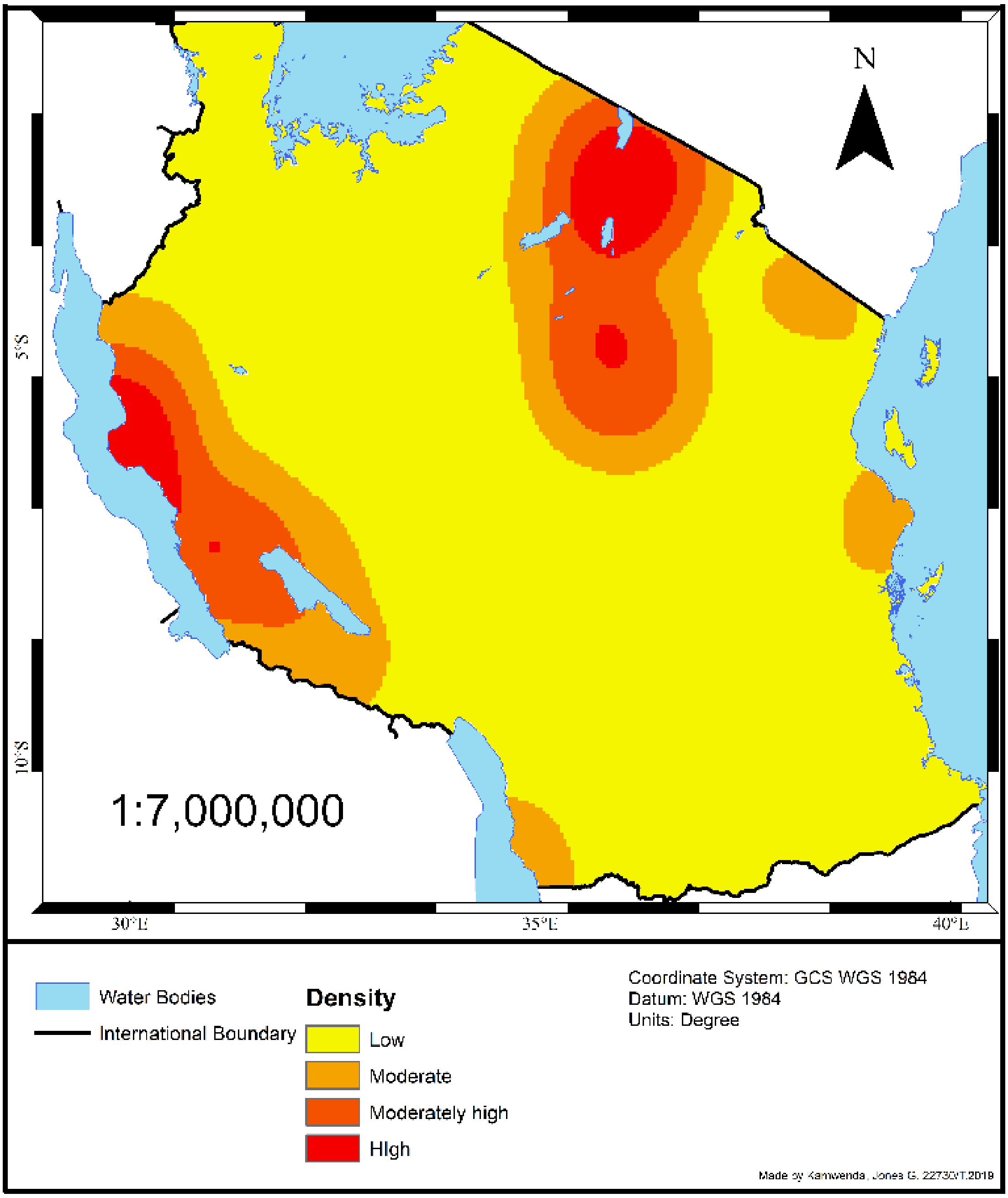

Figure 4-12: Earthquake density map of magnitude 5 and above occurrence in Tanzania

From the Earthquake occurrence density maps in figure 4-10 to figure 4-12, an overall density map is established, designating the seismic zones in accordance to the hierarchy of risk meaning areas of high earthquake density occurrence are considered to be of higher risk than area of low to zero density which are considered to be relatively safe. And considering from the suggestion that High magnitude Earthquakes are surrounded by lower magnitude earthquakes it is a supportive justification that these high-density zones can be designated as Seismic hazard zones as shown in the figure 4-14.

From figure 4-13 a presentation of the East African Rift Valley system is illustrated, though not part of the result but a complimentary to the results, as visually observed from figure 4-10 to figure 4-12 the areas of relatively high seismic activity coincide with the Rift valley system (indicated as red in the figure 4-13). Since faulted areas are more susceptible to slip or movement of landmasses along the faults resulting to tremors precepted as earthquakes.

Figure 4-13: The Great East African Rift Valley System (PIXELRZ, 2018)

Also, observing the identified seismic zones based on all magnitudes as shown in figure 4-14, It is clearly perceived that the three zones (located in Arusha, Dodoma and Kigoma regions) all coincide with the Rift valley system presented in figure 4-13 thus, further consolidating that the zones of seismic activity identified are the actual existing seismic zones.

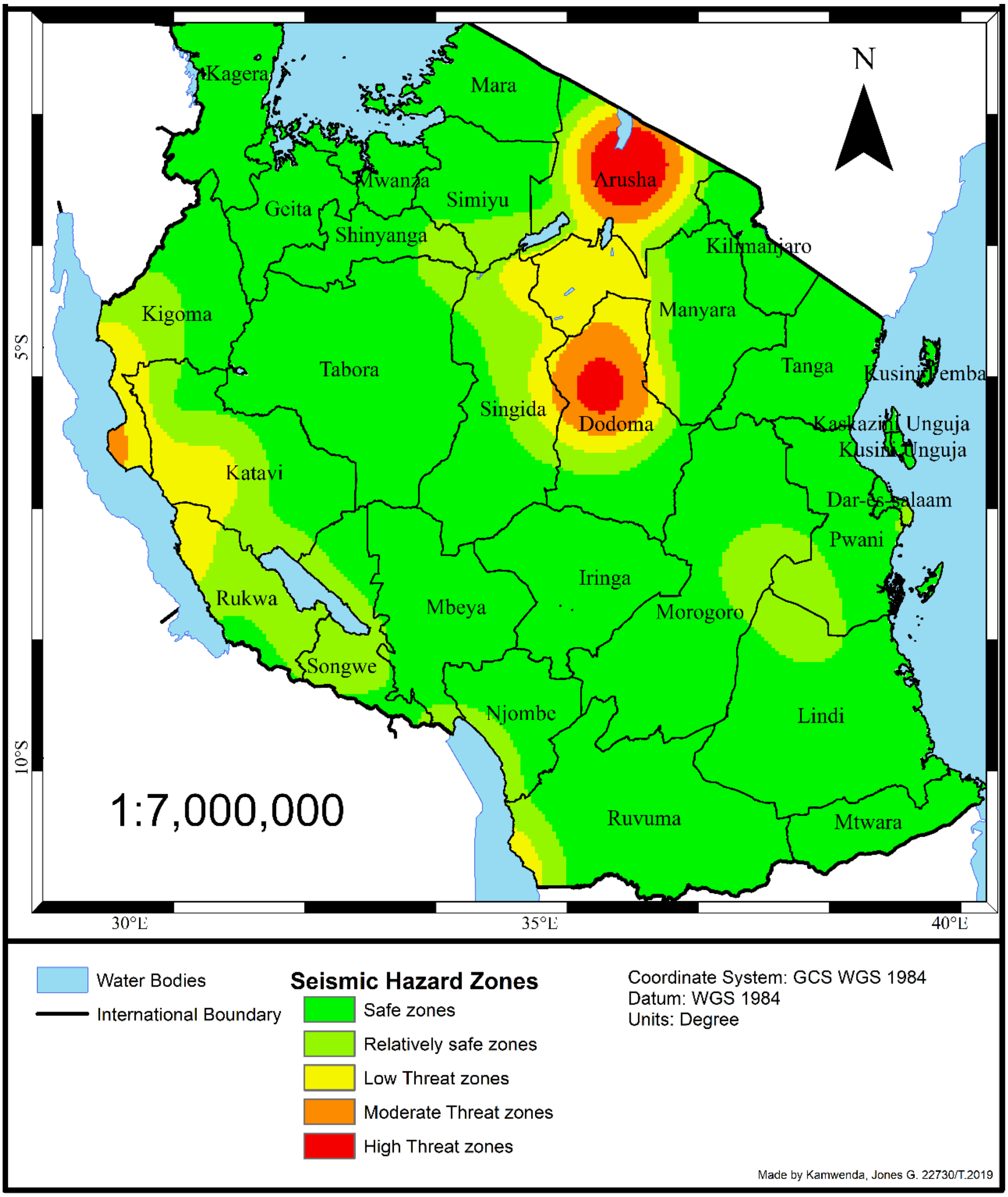

Figure 4-14: The designated Seismic Hazard zones in Tanzania.

From the Seismic hazard zones map three regions come to interest as appearing to fall within the high to moderate threat zones, the regions are Arusha, Dodoma (and a small eastern section of Singida) and Kigoma Regions as seen in the figure 4-14. While the remaining regions are considered to be relatively low threat to safe zones which is coupled by the figure 4-3 entailing the earthquake count in regions over the past fifty (50) years. Such that areas like Geita, Dar es salaam, Njombe and Mtwara have never experienced an earthquake occurrence over the past fifty (50) years.

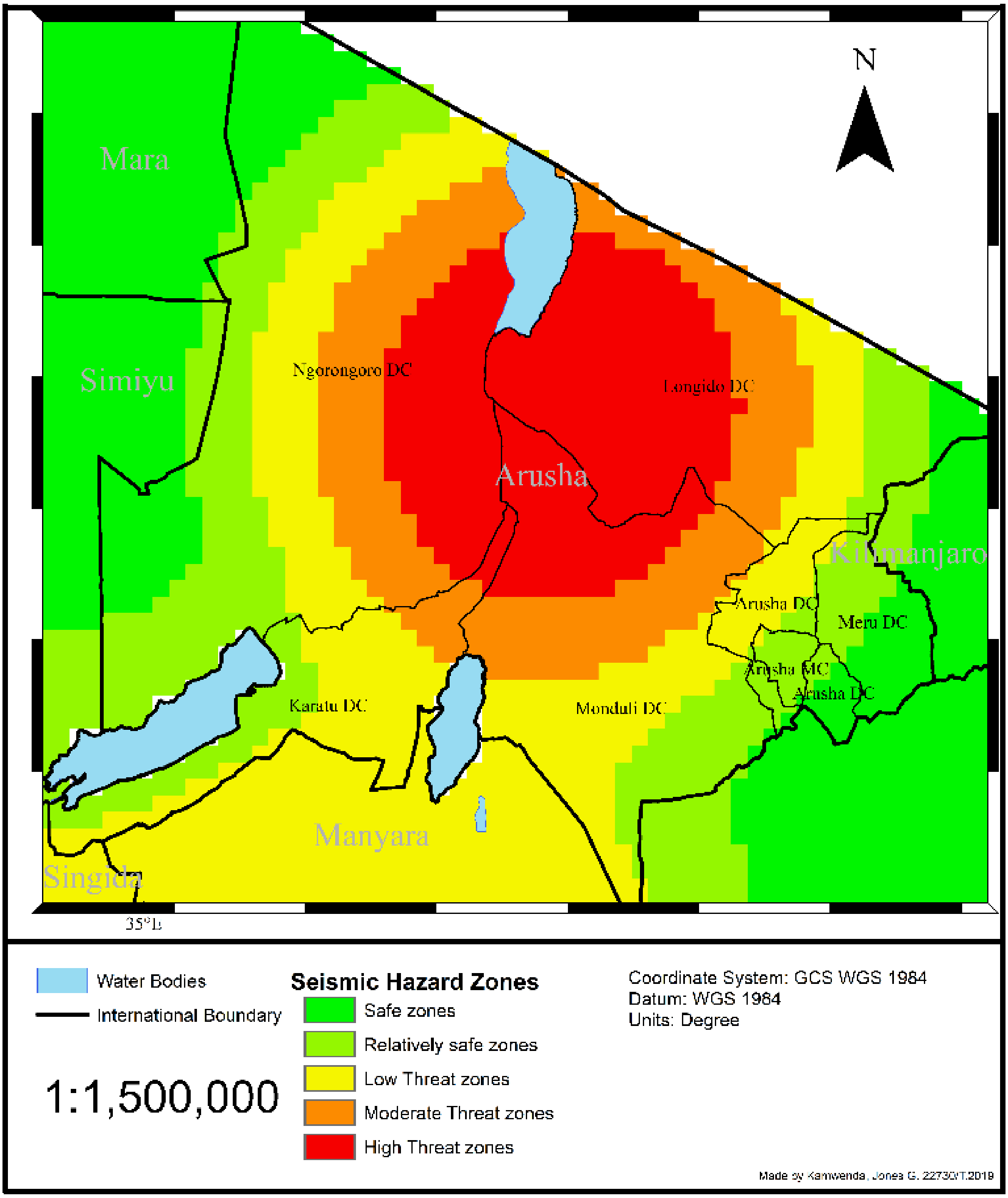

Figure 4-15: Seismic hazard zones in Arusha districts

From the figure 4-15 the seismic hazard zone appears to be allocated at the centre of the region, nearly encompassing all the Arusha districts with the exception of Meru DC and Arusha DC located at the South east sections of Arusha. While the low threat zones extending to Northern sections of Manyara region as well as Singida in the South west section of the map.

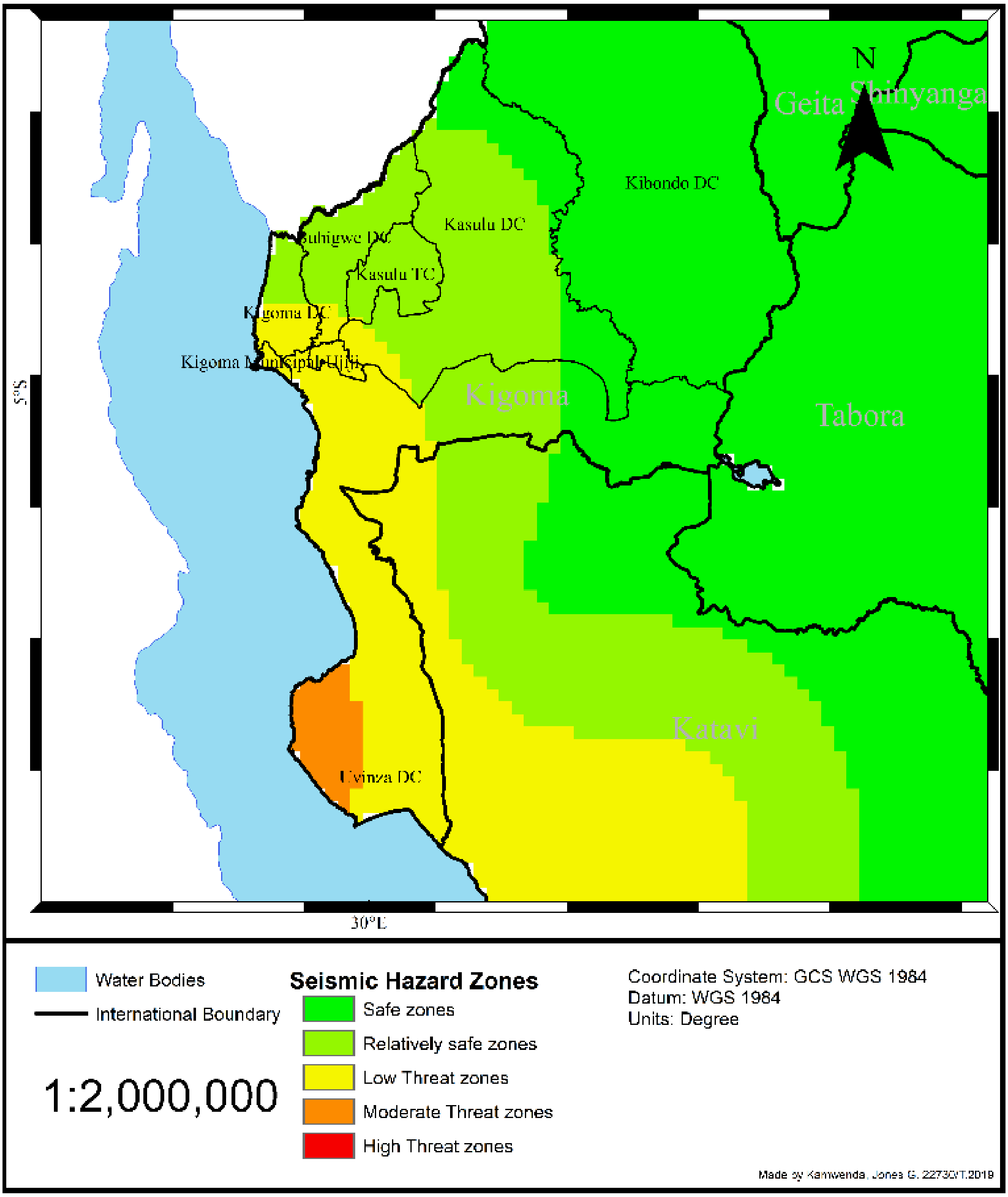

Figure 4-16: Seismic Hazard Zones in Kigoma districts

In the figure 4-16 the Low threat zones is extended along the coast of Lake Tanganyika as it is among the lakes located within the Eastern Africa Rift Valley System. While moderate threat zones fall within the Katavi DC district and the Low Threat zone extending to Western parts of the Katavi region.

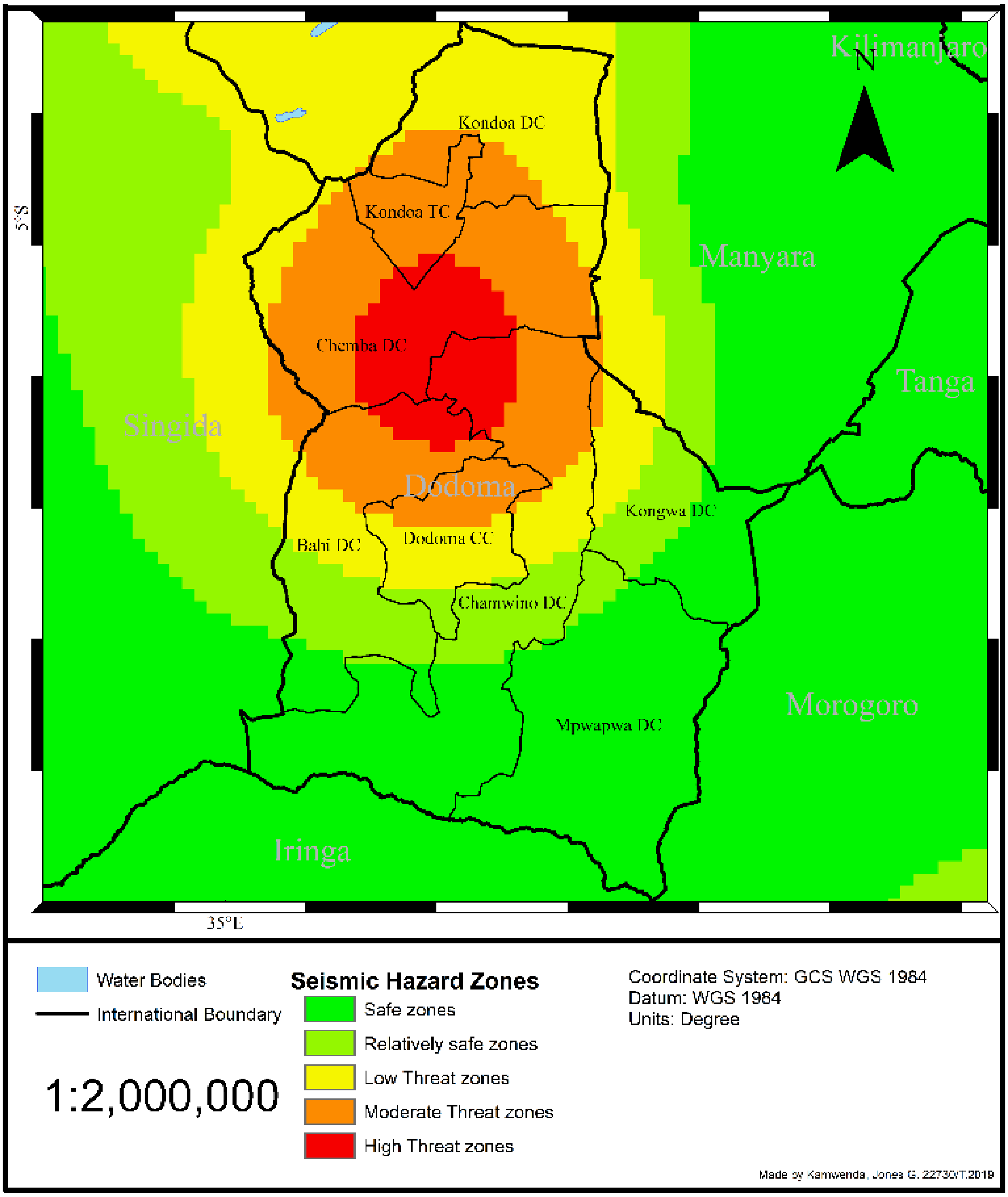

Figure 4-17: Seismic hazard zones in Dodoma region districts

From the figure 4-17, the seismic hazard zone falls on the northern and central parts of Dodoma region, encompassing Kondoa DC, Kondoa TC, Chemba DC, Dodoma DC, northern parts of Bahi DC, northern parts of Chamwino DC as well as north western parts of Kongwa DC. While the Low threat zone extending toward the north western part of Manyara region.

4.2.6 Time series plots

Several time series plots were made to understand the distribution of these earthquake occurrences over time as it was shown in the previous section the distribution of the earthquake events over space. Thus, achieving the understanding of the distribution in both space and time.

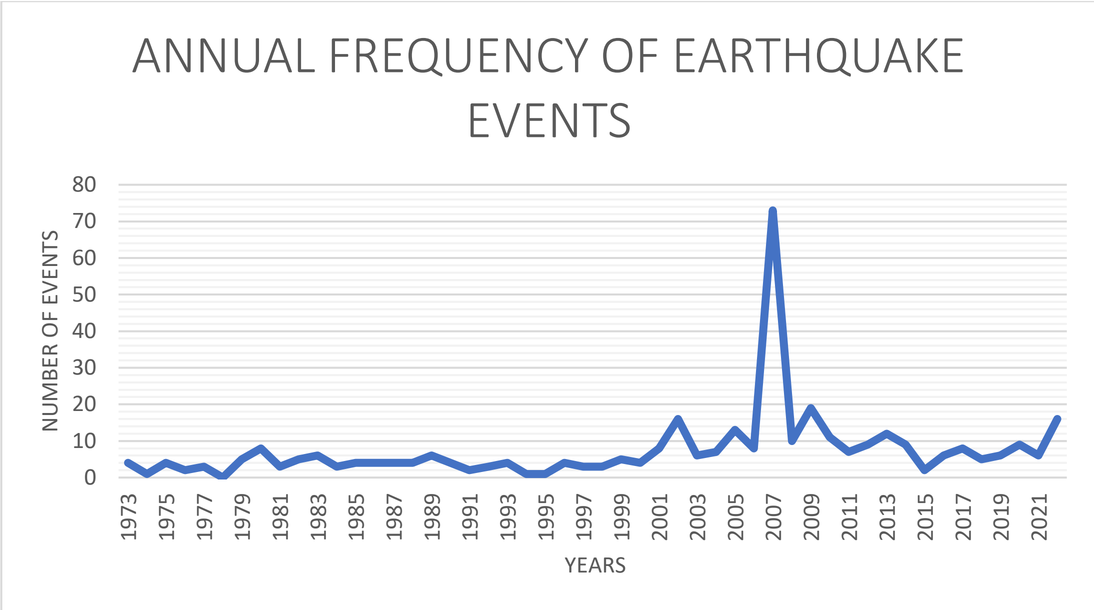

Figure 4-18: Annual frequency of Earthquake occurrence over the past 50 years

From the figure 4-18 suggests that the earthquake occurrences regularly occur at a frequency of around 10 per year with the exception of the year 2007 where there were relatively so much more earthquake occurrences that totalled to around 70. While further up of 2021 hinting on a similar rise in frequency as seen in 2001 to 2009.

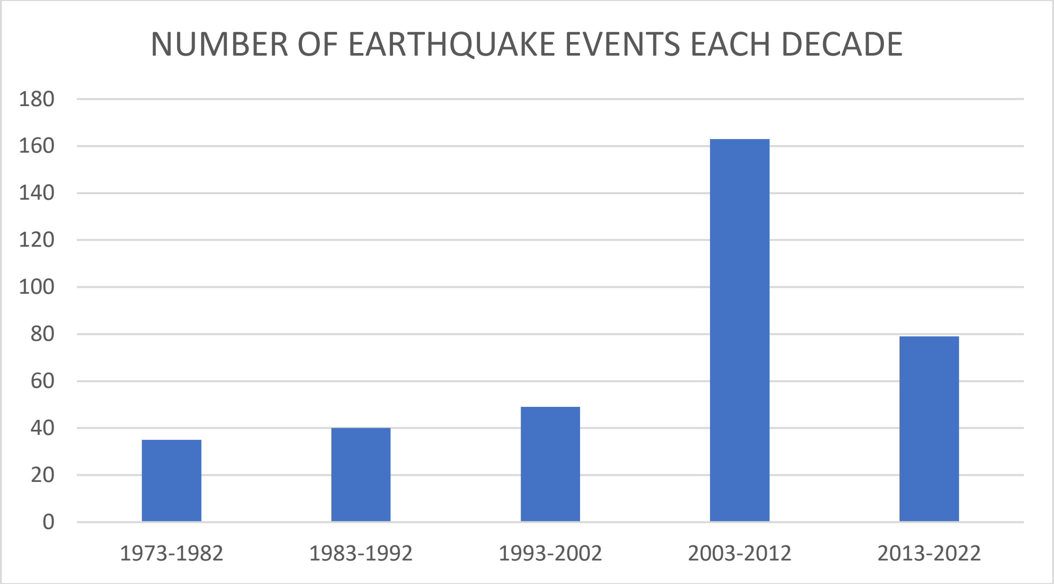

Figure 4-19: Frequency of earthquake occurrences per decades

From the figure 4-19, It shows a slow rise in total frequency of earthquake occurrence only then to spike during the fourth decade (2003 to 2012) and then dropping back again to the normal rise in frequency in comparison to the early three decades. This hints a steady rise in the number of earthquake occurrence each decade and that the sudden spike in number of earthquake occurrences in the third decade could have resulted in a consecutive release of pressures throughout the third decade then reverting back to the original gradual rising trend of earthquake occurrences.

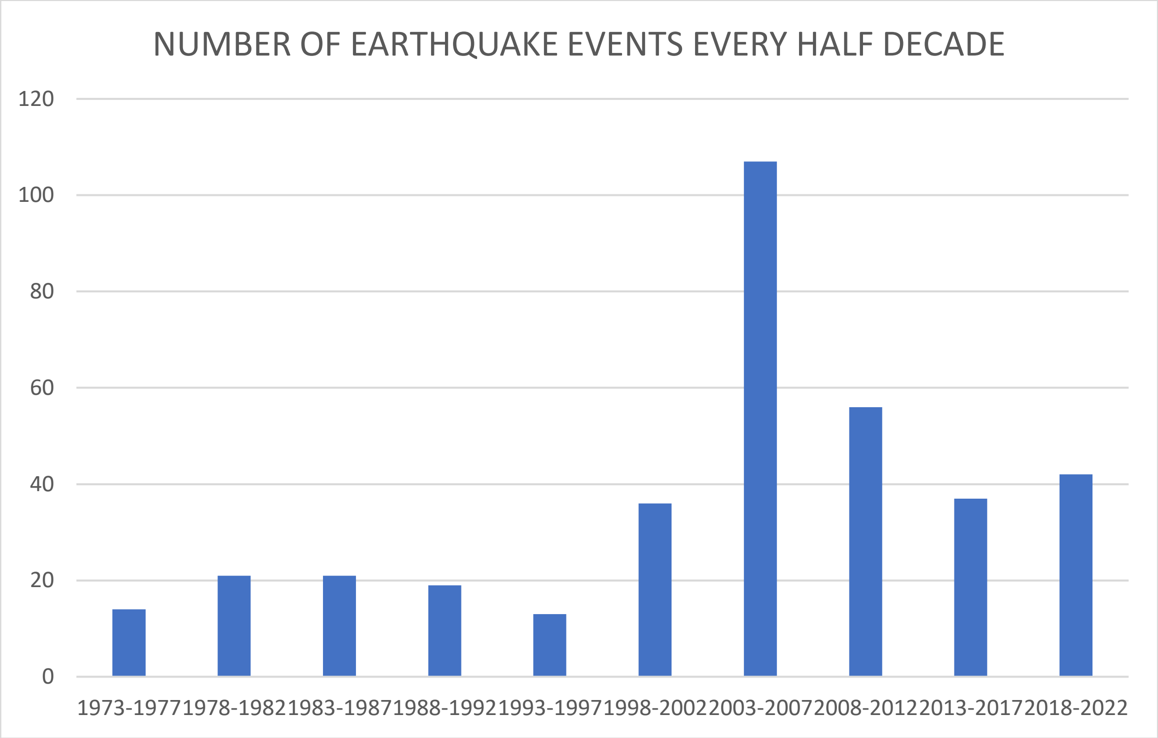

Figure 4-20: Frequency of earthquake occurrences per semi decade (5 years)

Similarly, the figure 4-20 shows a change in the trend of total frequency of earthquake occurrences in a semi decade for every 15years. Such as the was a rise in the first three (3) semi decades (15years) then changed to a gradual drop later to a rise then fall and so on all these changes in trends occurring within a 15-year window. Thus, hinting that the next 5 years will have a higher frequency of earthquake occurrences in comparison to the previous 5 years.

From the figure 4-21, entailing that the period between 2000 and 2010 experienced earthquakes of the highest magnitudes in all the 50 years of the research study. Subsequently, as seen in the previous figures this period is also with the highest occurrences of earthquakes. Also, from the same figure denoting a trending rise and fall in earthquake magnitudes over time suggesting a seasonal or pattern trend over time in the magnitude of the Earthquakes.

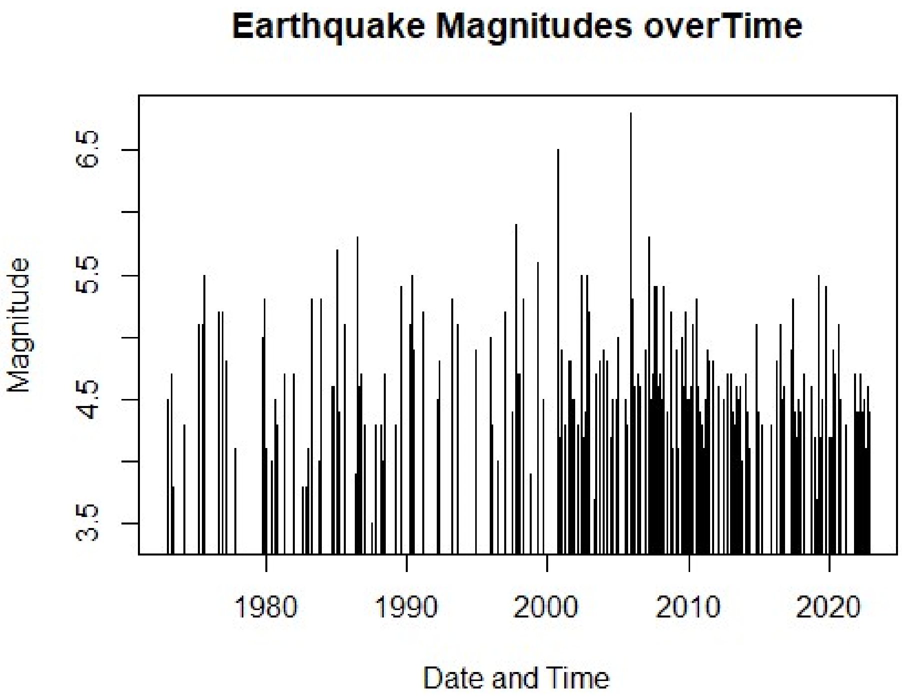

Figure 4-21: Vertical line graph Showing Earthquake magnitudes over time

From the figure 4-22, further visualizing the occurrence of high magnitude earthquakes (over 5.5 magnitude) to occur between the period around 1990 to 2010. While suggesting that magnitudes between 4 to 5.5 occurring as prevalent magnitudes throughout the 50years of the research study period as shown in the figure 4-22.

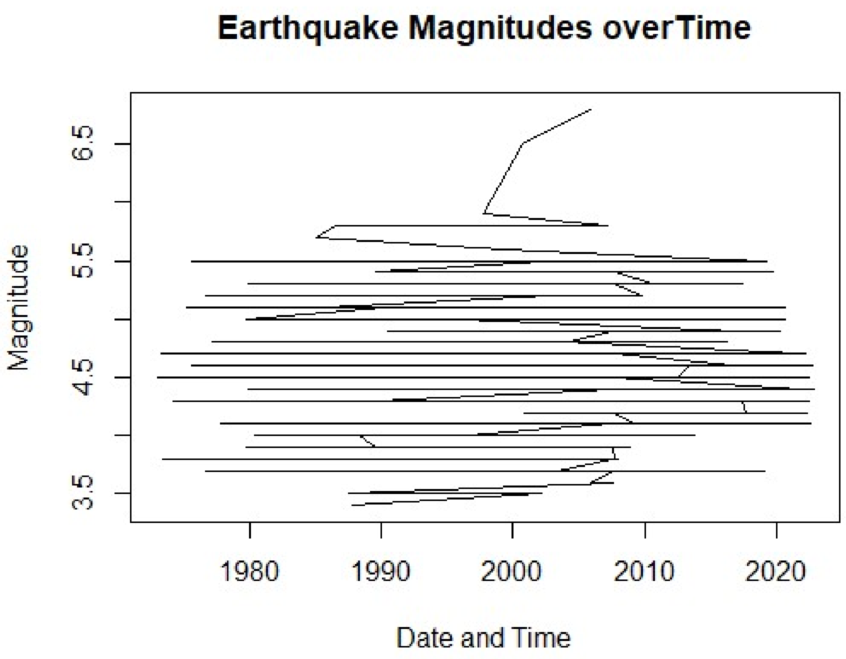

Figure 4-22: Line chart showing earthquake magnitudes over time

From the figure 4-23, further visualization of the depth attribute of the earthquake data portrays that most of the earthquake occur at a depth of 10km which is relatively very close to the surface hence magnifying the effects of earthquake magnitudes. Observing the overall plot entails that all of the earthquake in the time scope of the research study fall within the shallow depth categorization of earthquakes with earthquakes occurring before 1980 having a common depth of around 30km in contrast to those after 1980 having a common depth of 10km.

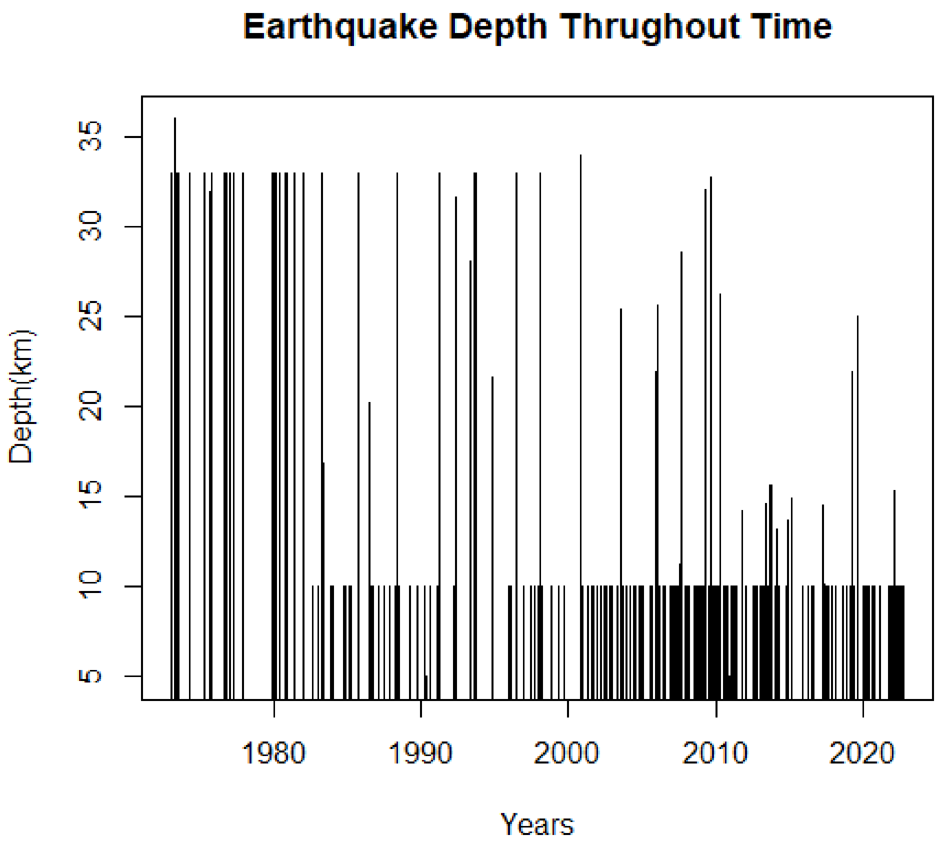

Figure 4-23: Earthquake depths throughout time

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The research study intended to assess the nature of the seismic events to have a much more advantageous grasp on the behaviours of these seismic activities within our study area (United Republic of Tanzania). Thus, the results of this study have denoted areas in Tanzania that are most affected by the seismic events, as well as the periodical behaviour and trend of occurrences with their respective prevalent magnitudes in the study area. The seismic zones identified fall on the regions Arusha, Dodoma and Kigoma with further description of the districts within those regions entailed in chapter 4.

In conclusion, this research study aimed to gain a better understanding of the nature of seismic events in the United Republic of Tanzania. The study successfully identified the areas in Tanzania (central areas of Arusha, northern areas of Dodoma and coastal areas of Kigoma) that are most affected by seismic events and determined the periodic behaviour and trend of occurrences, along with their respective magnitudes in the study area.

5.2 Recommendations

Further forecasting and early earthquake warning systems; Based on the results, it is recommended that further research should be conducted focusing on the designated seismic hazard zones. These smaller windows of research should utilize recent forecasting algorithms such as Random Forest, Naive Bayes as well as Logistic Regression to name a few to enhance our understanding of seismic activity in these specific areas. By narrowing down the scope of study, researchers can gather more detailed information and insights.

Public awareness; Furthermore, public awareness and education regarding earthquake preparedness are crucial. Increasing knowledge among the general population about the risks associated with earthquakes and the necessary safety measures can significantly reduce casualties and damages. It is essential to disseminate information about earthquake preparedness through various channels, such as educational campaigns, community outreach programs, and media platforms.

By combining these recommendations with ongoing research efforts, it is possible to improve the overall understanding of seismic events in Tanzania, enhance preparedness measures, and ultimately reduce the impact of earthquakes on society.

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