University of Nairobi

School of Engineering

Use of Geospatial Technologies in the Selection of Suitable Sites for a Wastewater Treatment Plant

Case Study: Loitokitok Town

BY

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Declaration

I, Duncan Nzula Sammy, 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.

DUNCAN NZULA SAMMY ……………………… ……………………………

Name of student Signature Date

This project has been submitted for examination with my approval as university supervisor.

MR. PETER C. WAKOLI ………………………. …………………………

Name of supervisor Signature Date

Abstract

The County Governments began operations in the year 2013 and this has led to rapid population growth in the county and sub-county headquarters. Due to the increased population, water, soil and air pollutions have been detected in some urban centers including Loitokitok town. The town does not have a sewerage system and the existing methods of handling wastewater, including solid-waste by use of pit-latrines, soak pits and septic tanks are proving inefficient.

This research project used geospatial technologies such as GIS modeling processes and Multi criteria decision analysis to locate suitable areas for a wastewater treatment plant in Loitokitok town. The study considered ten variables; major roads, dwelling houses, soils, slope, altitude of the town, distance from the town, water bodies, land use land cover, location of the airstrip and the country borderline with Tanzania. The relevant datasets were collected and processed to cover the study area. The relative weights of the variables where determined through questionnaire responses from experts. Nineteen respondents participated and the resultant weights were computed through the Analytic Hierarchy process. Water bodies' variable was found to have the highest level of significance at 21%, the country borderline had the lowest at 4% while the other variables had varying significance levels ranging from 5% to 17%. The site location criteria were identified from existing sewerage and sanitation manuals and other previous researches. GIS modeling and analysis were executed to determine the suitability maps for each criterion and the overall suitability map. The overall suitability map depicted that, out of the 246km^2 area coverage of the study area; 88.6% of the study area was found to be unsuitable for siting the plant, 10.7% had high suitability level, 0.5% had very high suitability level and 0.2% had moderate suitability level. Eight most suitable sites (Site1 to Site8) were realized and they fall within Kimana, Loolopon and Kuku sub locations in Loitokitok sub-county.

The selected sites were compared with previously proposed sites by Wanjohi Consulting Engineers in 2009 and Runji & Partners Consulting Engineers in 2015. Site 5 was found to be near the two sites and the best location for siting the plant. The study achieved it overall objective of determining the most suitable site(s) for a wastewater treatment plant for Loitokitok town.

Acknowledgement

I appreciate all the course lecturers and support staff from the Department of Geospatial and Space Technology for knowledge dispensed and guidance through the various courses that i have undertaken so far. I sincerely thank my supervisor, Mr. P.C Wakoli for his robust guidance and support during the execution of this research project.

I further appreciate my colleagues for the unity, love and guidance during the study period. I also acknowledge the love, support and encouragement from my family. I also thank my workmates for their support and advice on sewerage studies.

Finally, i thank the Almighty God for the gift of life and blessings offered to me.

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Dedication

I dedicate this project to my grandmother, Mary Wambua who has given me courage and support during my studies from primary school to the University level.

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List of Abbreviations and Acronyms

AHP: Analytic Hierarchy Process

BOD: Biological Oxygen Demand

DEM: Digital Elevation Model

ESRI: Environmental Systems Research Institute

GIS: Geographic Information System

ILRI: International Livestock Research Institute

KARLO: Kenya Agricultural and Livestock Research Organization

KeNHA: Kenya National Highways Authority

KNBS: Kenya National Bureau of Statistics

MCDA: Multi Criteria Decision Analysis

MOWI: Ministry of Water and Irrigation

NOLWASCO: Nol-Turesh Loitokitok Water and Sewerage Company Limited

SRTM: Shuttle Radar Topography Mission

USGS: United States Geological Survey

UTM: Universal Transverse Mercator

WSP: Water Service Provider

WRMA: Water Resource Management Authority

WWTP: WasteWater Treatment Plant

1. INTRODUCTION

1.1. Background Information

The rapid increase in population of certain small towns poses the merits and demerits associated with urbanization. Wastewater disposal problem has been a major concern in many developing countries because of the high rate of increase in population. Most of the industrial, domestic, commercial or agricultural activities cause production of wastewater which if not handled with care, would cause considerable harm to the environment. Kenya's Vision 2030 pillar on infrastructure has envisaged a country that will be firmly interconnected through a network of water and sanitation systems. Therefore location of appropriate sites for wastewater treatment systems must be done to avoid contamination of the surface and groundwater channels, especially those used as a source of drinking water and irrigation. The sites should also be away from human settlements and other sensitive areas.

The design of a sewerage system should ensure a comprehensive treatment of wastewater according to the limits allowable by the National Environment Management Authority (NEMA) in Kenya, the standards of the World Health Organization (WHO) and the guidelines of the World Bank Environmental Health and Safety, before releasing it into the river (Kamau, 2012). A sewerage system is comprised of collection points for sewage from buildings, which is then conveyed by sewer lines to a sewage treatment plant. A sewerage system is normally designed to facilitate sewage flow by gravity to avoid prohibitive cost.

The GIS-based tools and processes have been extensively used to address the challenges of optimizing sewer lines, site selection and route networks based on the collection, processing and analysis of spatial data such as topography, vegetation, soil type, land use, geology and population densities. Site selection of such crucial sites can be successfully achieved by multi criteria decision analysis tool used in Geographical Information System. Analytic Hierarchy Process (AHP) is a widely used method in decision-making. AHP was introduced by Saaty (1972), with the basic assumption that comparison of two elements is derived from their relative importance. The decision-making in AHP is a continuous process starting from analyzing the decision environment to understand and arrange the criteria into different groups and levels to evaluating the criteria in its decision outputs. Saaty (2000) developed pair wise comparison matrix in order to perform any difficult task in a simpler manner.

1.2. Problem Statement

Loitokitok town is one of the rapidly growing towns in Kenya. Multi-storey buildings and numerous business and residential houses characterize this town. Water provision in the town is managed by Nol-Turesh Loitokitok Water and Sewerage Company Limited (NOLWASCO). The area doesn't have a sewerage system and the existing methods of handling wastewater, including solid-waste by use of pit-latrines, soak pits and septic tanks are proving inefficient. The steep rise in population has exerted too much pressure on the existing sanitation systems. The pit-latrines soak pits and septic tanks are poorly maintained, with some overflowing and /or seeping underground. This poses a huge environmental risk in the form of soil, air and water pollution. Such latrines are also insanitary due to the foul smell they produce by acting as breeding grounds for flies, leading to possible outbreak(s) of diseases. This calls for identification and construction of a waterborne sewerage system to mitigate these challenges.

Traditional methods that were employed in determining sites for wastewater treatment ponds involved large volumes of paper based maps and data, numerous site visits, trekking on all the sites, continuous data collections and numerous consultations with various experts. These methods were tedious, costly, inefficient, protracted and took very long time to conclude. These old methods also led to delays in developing physical development plans and water and sanitation master plans for various towns hence the need to adopt modern technologies like GIS.

1.3. Objectives

1.3.1. Overall Objective

To determine the best site for a wastewater treatment plant to serve Loitokitok town using Geospatial technologies.

1.3.2. Specific Objectives

i) To identify the siting criteria for a wastewater treatment plant and determine their relative weights.

ii) To develop suitability maps based on each criterion.

iii) To develop a suitable site(s) map for the WWTP through multicriteria analysis and GIS modeling processes.
iv) To analyze the obtained results and generate conclusions and recommendations

1.4. Justification of the Study

Developing countries have trailed behind in embracing technologies to promote effective waste water management due to factors such as cost challenges and lack of proper planning and management. It is not affordable anymore to do so with the increasing call for environmental improvement strategies all across the globe.

Thus this study that promotes the adaptation of more effective methods of liquid waste management is in line with the current global trends and can promote sustainable development and effective environmental management in Loitokitok town and the larger Kajiado County.

This project is a milestone in the facilitation of proper collection and safe disposal of the sewage which is legally recognized as a necessity in an urbanized and industrialized society. Since wastewater produced in most households and commercial set ups remains untreated and exposed, outbreak of waterborne diseases is common. Kenya's Vision 2030 pillar on infrastructure envisages a country that will be firmly interconnected through a network of water and sanitation systems. Access to safe drinking water, basic sanitation and proper hygiene can prevent waterborne diseases by nearly 90% and lead to improved health, poverty reduction and socio-economic development

This project is inexpensive and efficient since it only requires available data, GIS and remote sensing tools to determine the best site for putting up the WWTP. The project can be replicated in other towns across the country and can form a strong basis for undertaking site suitability analysis for other infrastructure installations like in the transport sector and telecommunications.

The Physical Planners and Engineers can easily develop physical development plans of towns and master plans for water and sewerage which are accurate, fast and reliable through use of these geospatial technologies.

1.5. Scope of the Study

This study will mainly target the development of site suitability map for wastewater treatment plant that will optimally serve Loitokitok town, identify the siting criteria to be considered, determine the suitable weights for each criteria, develop suitability maps based on each criterion and compare the selected site(s) with those from previous studies; Wanjohi Consulting Engineers (2009) and Runji & Partners Consulting Engineers (2015) and finally draw conclusions and recommendations. The study therefore relies on the expert input from other professions dealing with water and sanitation such as environmentalists, sociologists, water and sanitation experts and civil engineers. The deliverables will be limited on the previously collected and available data from different organizations and websites and due to the timelines, minimal field data collection is anticipated.

1.6. Organization of the Report

This report is organized into five chapters. Chapter one tackles the introduction to the concept of sewerage system, the problems that led to the study and the objectives of the study. Chapter two is a literature review of academic and research findings that relate to the sewerage system, the Analytic Hierarchy process and the GIS modeling and analysis processes. Chapter three covers the methodology used in achieving the final results. This includes a detailed explanation of all the processes involved. Chapter four contains the results and findings of the research and chapter five covers the conclusion and recommendations.

2. LITERATURE REVIEW

2.1. Sewerage System

A sewerage system comprises a network of pipelines and technical installations (e.g. pumping stations and treatment plants). The system collects and transports wastewater and storm water from more than one source to a wastewater treatment plant and then to the receiving waters.

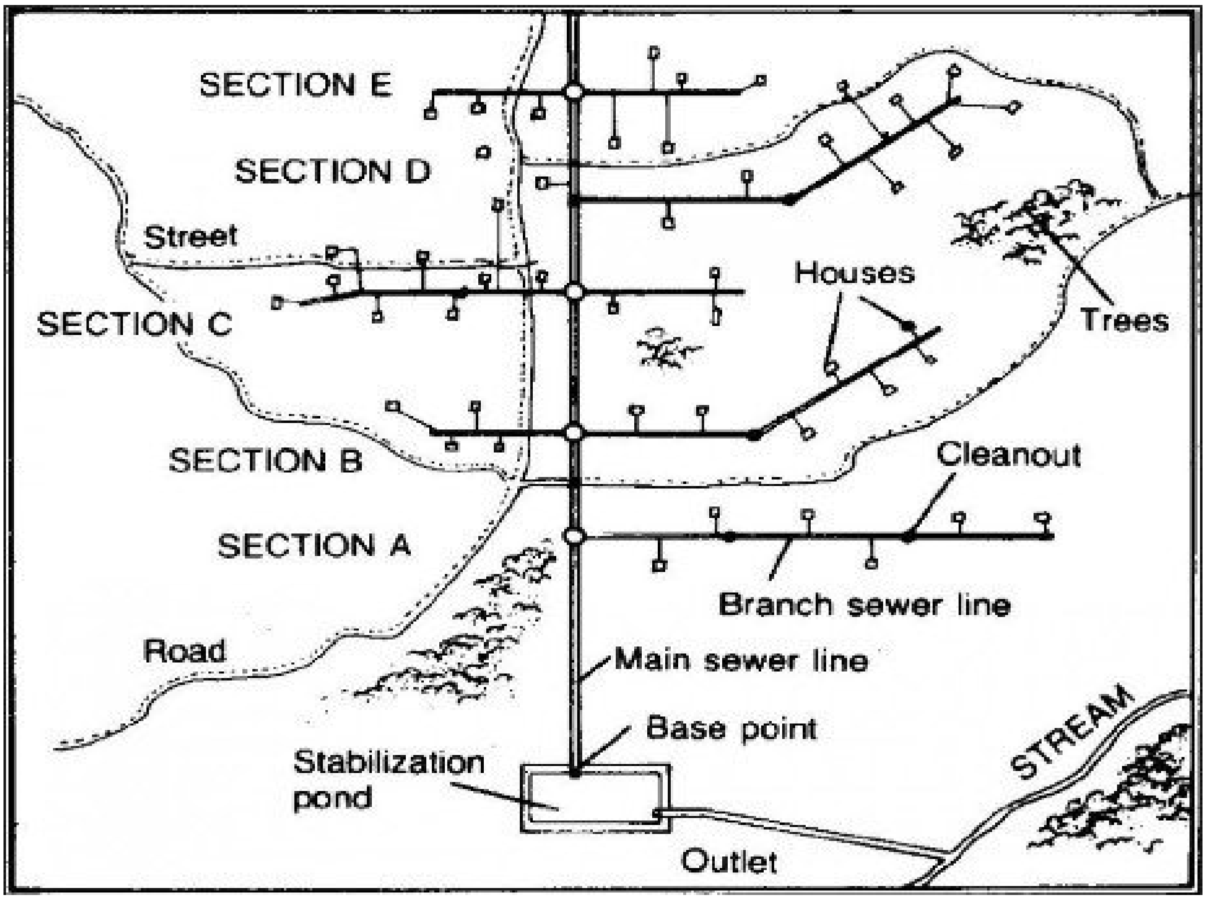

Figure 1: Sewer Sanitary System Layout, Source: https://theconstructor.org/building/set-up-sewer-sanitary-system-layout/17956/ [accessed on 12th May, 2018]

There are two types of sewerage collection systems; the combined and separate sewerage systems. The combined sewer system transports both sanitary wastewater (liquid and waterborne wastes from residences, commercial buildings, industrial complexes etc.) and surface/storm water in the same pipeline. The separate sewer system transports wastewater in separate sanitary sewer pipeline and storm water in another pipeline called the storm sewer (MOWI, 2008).

Figure 2: Sewerage System Layout, Source: https://www.slideshare.net/reddyas/sewerage-system-56376402 [Accessed on 13th May, 2018]

Sewer lines are grouped into four main categories: building, lateral, branch and trunk. Building sewer lines convey sewage from buildings and drain it into the lateral sewer lines; branch sewer lines collect sewage from lateral sewer lines and drain it into the trunk sewer lines. A trunk sewer line is the main sewer line from the start node to the end node at the treatment works. Manholes are situated at every node where two sewer lines connect (Wanjama and Odera, 2017). They are provided for cleaning, maintenance and repair purposes at the head of the sewer line, at the sewer line junction, at points where there is a change in sewer pipe size, slope or alignment and at the specified intervals along a straight sewer line reach (Nagoshe et al., 2014).

Sewerage treatment is quite crucial in ensuring the undesirable characteristic in sewage that is usually the suspended solids and its BOD are reduced to the acceptable standards that don't pollute the water resources into which it's discharged (MOWI, 2008).

There are various options of wastewater treatment technologies, these include; Trickling Filters system, Activated Sludge system, Facultative Aerated lagoons and Wastewater Stabilization ponds.

Trickling filters system technology has been in use for a long time. The technology is very efficient in the reduction of BOD but has little effect on the Faecal Coliform except with the incorporation of disinfection system. The system has the disadvantage that a lot of pumping systems will be required for sludge management such as pumping into the digester and also to the sludge drying bed. Furthermore, more power is required in the running of the trickle filter itself. The systems will require high power costs to run which is a big challenge in developing countries like Kenya.

Activated Sludge System technology is a highly mechanized system with aeration and requires sophisticated process control. Due to this, the treatment technology is not considered feasible for the present technological development in the country.

Facultative Aerated lagoons technology requires the use of mechanical aerators for the facultative ponds which is costly in installation and maintenance. This technology involves placing floating surface aerators on the facultative ponds to make up for the oxygen deficit. There are two types of aerated lagoons; partially mixed aerated lagoons and completely mixed aerated lagoons (MOWI, 2008).

Wastewater Stabilization Ponds technology considers the use of wastewater stabilization ponds consisting of Anaerobic, Facultative and Maturation ponds in series. The technology has numerous advantages among them being; low maintenance costs as there is no power requirement, ease of operation and requires low level skills among others. They are used for sewage treatment in temperate and tropical climates and represent one of the most cost-effective, reliable and easily-operated methods for treating domestic and industrial wastewater. This treatment technology however has the disadvantage of high land requirement. Elaborate displacement and resettlement plan have to be worked out and the community persuaded to accept the development in areas where there is no reserved land. In developing countries and especially in the tropical and equatorial regions sewage treatment by Wastewater Stabilization Ponds has been considered an ideal way of using natural processes to improve sewage effluents (MOWI, 2008).

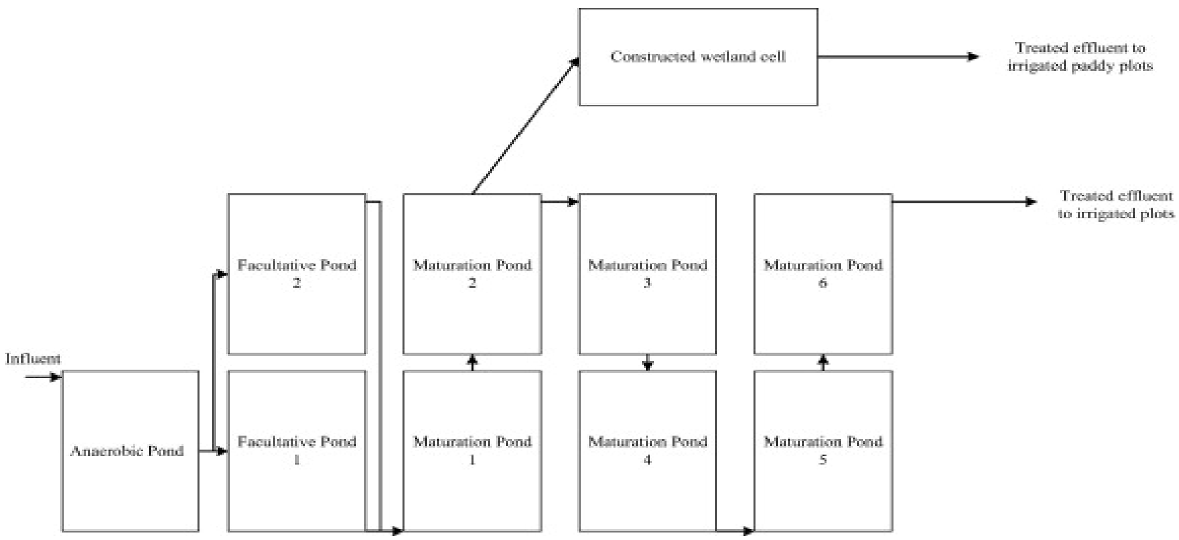

Figure 3: Wastewater Stabilization Ponds Layout, Source: Kihila et al, 2014

Figure 4: Schematic flow chart of waste stabilization ponds of Mathura III in India, Source: Amerasinghe et al, 2013

2.2. Multi Criteria Decision Analysis

Multi Criteria Decision Analysis (MCDA) is a useful tool that is applied in many complex decisions. It's mostly used in solving problems that are characterized as a choice among alternatives. Decision making involves choosing among alternatives based on multiple criteria. In each decision we have several factors or criteria to consider and several alternatives or choices to choose. These alternatives and criteria are usually determined first in group decision making before giving some evaluation or judgment score to them. At its core, MCDA is useful for:

a) Dividing the decision into smaller, more understandable parts
b) Analyzing each part
c) Integrating the parts to produce a meaningful solution

MCDA provides a unique ability for people to consider and talk about complex trade-offs among alternatives. In effect, it helps people think, re-think, query, adjust, decide, rethink some more, test, adjust and finally decide. MCDA tool allows for multiple objectives, for the use of different types of data and the involvement of different stakeholders.

MCDA problems are comprised of five components:

i) Goal
ii) Decision maker or group of decision makers with opinions (preferences)
iii) Decision alternatives
iv) Evaluation criteria (interests)
v) Outcomes or consequences associated with alternative/interest combination

There are various MCDA methods which have been researched on and used in different applications: Multiple attribute value theory (MAUT),Analytic hierarchy process (AHP), Evaluation matrix (Evamix), ELECTRE III, Regime, Novel approach to imprecise assessment and decision environments (NAIADE), and programming methods (Multi-Objective programming ,Goal Programming and their variants) (Montis et al, 2000).

MCDA is a very useful tool in finding the most suitable location for construction a facility. The location of the site for the facility is a multiple criteria decision making issues inclusive of quantitative and qualitative criteria. For instance fuzzy weighted average method has been used to determine a suitable location for a sewerage treatment plant. Ten different criteria are defined and then fuzzy weighted average method is applied to rank the best location for the plant (Diallo et al, 2009).

2.2.1. Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is one of the multi-criteria decision making approach introduced by Thomas Saaty in 1970s. The AHP has attracted the interest of many researchers mainly due to the nice mathematical properties of the method and the fact that the required input data are rather easy to obtain. It is a method of deriving priority scales from paired comparisons based on judgments' of experts. The AHP can be summarized into four steps: construct a suitable decision hierarchy; evaluate the relative importance of each factor or criteria; evaluate each alternative and calculate its overall weight in regard to each criteria and check the consistency of the subjective evaluations (Ouma and Tateishi, 2014).

In constructing the suitable decision hierarchies, the human mind recognizes objects and concepts and identifies existing relations between them. The simplest model of a hierarchy of AHP consists of three steps: step one is the goal of the decision, step two is the criteria and step three is the alternatives. However more complex hierarchies can be developed with more levels which include a certain number of sub criteria.

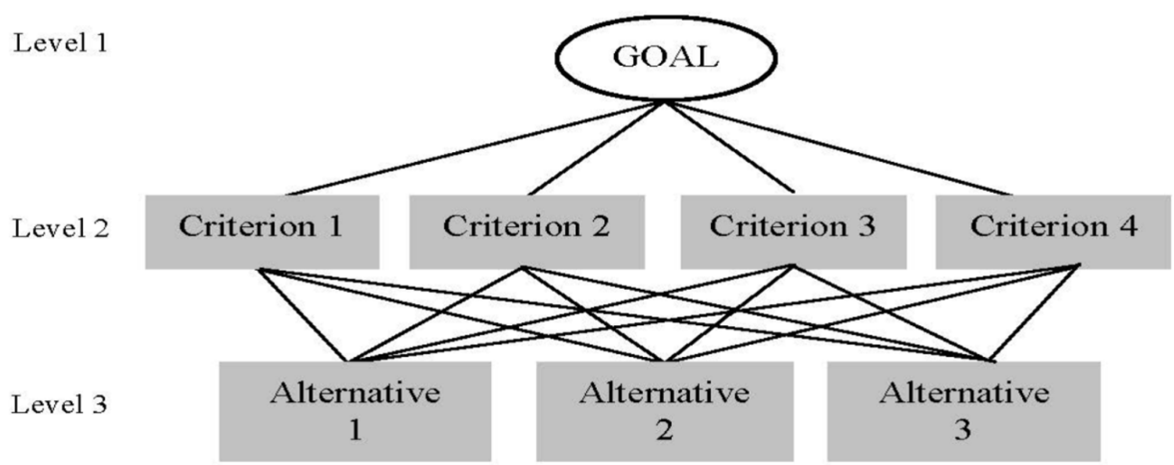

Figure 5: A typical hierarchy of AHP, Source: Ouma and Tateishi, 2014

To achieve satisfactory results, hierarchies should be large enough to accommodate all major crucial factors to the decision making. After constructing the suitable hierarchy, pairwise comparison is then undertaken to establish priorities or weights among elements of the same hierarchical level. They are compared in pairs with respect to the corresponding elements in the next higher level, obtaining a matrix of pairwise comparisons. For representing the relative importance of one element over another, a suitable evaluation scale was introduced by Saaty (2008). It defines and explains the values 1 to 9 assigned to judgments in comparing pairs of elements in each level with respect to a criterion in the next higher level.

Table 2-1: The fundamental scale of absolute numbers (Saaty, 2008)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice.
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then j has the reciprocal value compared with *i*.	A reasonable assumption
1.1-1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities

When element *i* compared with *j* is assigned one of the above numbers, then element *j* compared with *i* is assigned its reciprocal.

After determining the relative importance of the factors or criteria, the weight of each factor is calculated based on the pair wise comparisons. In particular, for each criterion C, an *n*-by-*n* matrix A of pair wise comparisons is constructed. The components a_{ij} (i, j = 1, 2… n) of the matrix A are numerical entries, which express (by means of Saaty's scale) the relative importance of the element *i* over the element *j* with respect to the corresponding element in the next higher level.

Thus the matrix A has the form:

$$A \equiv \begin{pmatrix} a_{11} & a_{12} & .... & a_{1n} \\ a_{21} & a_{22} & .... & a_{2n} \\ .... & .... & .... & .... \\ a_{n1} & a_{n2} & .... & a_{nn} \end{pmatrix} \text{Where: } aii=1,\ a_{ji=}\frac{1}{a_{ij}},\ a_{ij} \neq 0 \qquad (2.1)$$

The principal eigen value and the corresponding normalised right eigen-vector of the comparison matrix give the relative importance of the various criteria being compared. The elements of the normalised eigenvector are termed weights with respect to the criteria or sub-criteria and ratings with respect to the alternatives.

The relative weights of each matrix are given by the right eigenvector (*w*) corresponding to the largest eigen value (λ_{max}) as in Equation (2.2).

$$A_w = \lambda_{max} w \qquad (2.2)$$

If the pairwise comparisons are completely consistent, the matrix A has rank 1 and $\lambda_{max} = n$. The quality of the output of the AHP is strictly related to the consistency of the pairwise comparison judgments. The consistency is defined by the relation between the entries of A: $aij \times a_{jk} = a_{ik.}$ The consistency index CI is given by Equation (2.3):

$$CI= (\lambda_{max}-n)/ (n- 1) \qquad (2.3)$$

The final consistency ratio (CR), which lets the user to conclude whether the evaluations are sufficiently consistent, is calculated as the ratio of the CI and the random index (RI), as expressed in Equation (2.4). The values of RI are tabulated in Table 2.2.

$$CR=CI/RI \quad (2.4)$$

Table 2-2: Random Consistency Index (Saaty and Forman, 1993)

N	1	2	3	4	5	6	7	8	9	10
Random Index (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The random index in Table 2-2 is obtained by averaging the CI of a randomly generated reciprocal matrix.

The maximum threshold of the CR is 10%.A CR greater than 10% would mean that the pairwise judgments are just about random and are completely untrustworthy. In this case, comparisons should be repeated. The measurement of consistency can be used to evaluate the consistency of decision makers as well as the consistency of overall hierarchy (Ouma and Tateishi, 2014).

In many industrial engineering applications the final decision is based on the evaluation of a number of alternatives in terms of a number of criteria. This problem may become very difficult when the criteria are expressed in different units or the pertinent data are difficult to be quantified. The Analytic Hierarchy Process (AHP) is therefore an effective approach in dealing with this kind of decision problems as it enables explicit ranking of tangible and intangible criteria against each other for the purpose of selecting priorities (Saaty, 1994). AHP allows group decision-making, where group members can use their expertise, experience and knowledge to break down a problem into a hierarchy and solve it by the AHP steps. Comparisons are made based on standards established by experience (Saaty, 1990).

2.2.2. ELECTRE III

ELECTRE III is a one of the software packages developed by Roy (1985). There are other versions in the ELECTRE family which include; ELECTRE I, II, IV, IS and TR1. ELECTRE III is a remarkable version because it takes explicitly into account the indifference and the preference thresholds. The system solves ranking problems by dividing the set of actions into equivalence classes.

2.2.3. Regime

This method was developed by Hinloopen et al (1983), assessed and refined by Hinloopen (1985) and Hinloopen and Nijkamp (1990). Regime is a qualitative multiple criteria method hence provides a tool that analyses complex situations which cannot be modeled by means of quantitative information.

2.2.4. Programming Methods

The programming methods used in MCDA include Goal Programming (GP) and Multi-Objective Programming (MOP). They are usually categorized as continuous multiple criteria methods. Programming methods are different from the other methods outlined above in that, they don't rank or sort a finite number of alternatives but generate the alternatives during the solution process based on the mathematical model formulated (Montis et al, 2000).

2.3. Geospatial Technologies

Geospatial technologies are a term used often to collectively describe the modern tools and techniques applied in geographic mapping and analysis of the earth. These technologies have rapid grown from the times of static maps to dynamic maps supported by a network of operating space borne satellites, airborne remote sensing platforms, sophisticated softwares, high quality hardware and large volumes of spatial data. This development has led to increased research and productivity in industrial engineering, agriculture, biodiversity and academic studies among others.

The following are the main types of Geospatial technologies currently being applied;

2.3.1. Remote Sensing

This technology enables data and information collection about objects on the earth through sensors on aircrafts, drones and satellites without getting into contact with them. The sensors collect the data in form of images and provide capabilities of processing, manipulating, analyzing and presentation in various formats that can be understood by the users. This has led to increased usage in fields like security, environmental monitoring and agricultural production among others. The availability of the remotely sensed data has increased with other agencies issuing the data for free like the Landsat imagery which can be accessed online for free.

2.3.2. Global Navigation Satellite System (GNSS)

This is a satellite navigation system composed of a constellation of satellites that provides autonomous geo-spatial positioning over the whole earth surface through transmitting signals from space to GNSS receivers on the earth surface to determine location of objects on the surface. The GNSS includes the USA's NAVSTAR Global Positioning System (GPS), Russia's Global Navigation Satellite System (GLONASS), China's BeiDou Navigation satellite system, Europe's Galileo Navigation satellite system and other regional systems

2.3.3. Web Mapping Technologies

These technologies have enabled a wide audience who are not GIS experts to view and share dynamic maps of the earth via the internet. The user interface has been made user friendly and easily understandable hence software programs like Google Earth and Microsoft Virtual Earth have actualized the dream of viewing the whole earth on the mobile phones. The traditional GIS have been left to the specialists as more advancements and researches are being worked out these web based mapping technologies.

2.3.4. Geographic Information System (GIS)

GIS is a system capable of gathering, manipulating, managing, analyzing and presenting all types of geographical data. GIS is composed of data (spatial and attribute data), software, hardware, people and methods to effectively meet its objectives. GIS is vital tool that is used in communicating, solving complex problems, decision making and visualization of mapped objects. GIS is currently being practiced by communities, government agencies, Planners, Surveyors, Engineers, Environmentalists and other experts in various fields like agriculture, environmental monitoring, crime management, engineering works, land use planning, disaster management, wastewater management among other fields. There are various tools that are incorporated in the software that enable integration of all types of data and performance of analysis and modeling processes easier and effective: CLIP tool, Spatial Analyst tool, 3D Analyst tool, Analysis tool, weighted overlay tool among others.

a) Data Collection

In executing any application in GIS, data is core component. Spatial data and attribute data in either raster or vector format have to be gathered from various sources. Currently many agencies like ILRI have gathered sufficient data and are available on their websites and /or in their offices. Field data collection to supplement existing data can also be undertaken using the geospatial technologies discussed earlier. Depending on the expected outputs, the user ought to check on the accuracy, resolution, date acquired among others factors. The metadata is key to getting these details if it exists. For Land use land cover mapping, Landsat 8 imagery provides upto date imagery and it's free from the USGS explorer website, Global datasets for DEM are also available from SRTM and Aster, other datasets covering Kenya in shapefiles can be downloaded from ILRI website. Field data collection can be undertaken using the GNSS receivers like the Handheld GPS gadgets.

b) GIS Analysis and Modeling

GIS analysis involves combining and modeling different types of GIS data in GIS software platforms, processing the combined data and deriving new information that enables users make wise decisions and to solve complex problems. Some of GIS analysis methods include;

i) Spatial Analysis

This process involves examining the location, attributes and relationships of features in spatial data through overlays and other analytical techniques to extract new information. This method has proven to be useful in identifying suitable sites for specific purposes, predicting outcomes, change detection and much more. There are various methods of spatial analysis which include overlay analysis, spatial modeling, surface analysis, point pattern analysis among others.

ii) Overlay analysis

It is useful for site selection studies whereby multiple layers of different data sets are combined at a common scale through various methodologies to achieve an integrated analysis.

This analysis often involves different factors or datasets considered in the site selection. The following general steps are involved in overlay analysis: defining the problem; breaking the problem into sub models; determining significant layers; reclassifying the data within a layer; weighting the input layers; combining the layers and analyzing. During the step of combining the layers based on the weights of the input layers attained, the weighted overlay tool comes in handy. The weighted overlay is available in the spatial analyst tool in ArcGIS and overlays raster layers using a common measurement scale and weights each layer based on its level of importance.

iii) Proximity Analysis

This is a GIS analytical technique that features (points, lines, polygons or raster cells) are selected based on the distance from other features or cells. They help answer the question 'which geographic features are nearest?' It's very useful for market planning and site selection applications. Some of the tools most used in these analyses are the Buffer tool which creates area features or polygons at the specified distance around the reference geographic features, the other tools are Near, Thiessen polygons, multiple ring buffers, point distance among others.

iv) Network Analysis

This is GIS analysis technique of solving complex routing problems through the usage of a configurable transportation network data model. The available types of network analysis are shortest path analysis, best route, closest facility, allocation, location- allocation, OD-cost matrix, and network partitioning-trace analysis.

2.4. GIS Application in Optimal Site Selection

Optimal site selection or suitability modeling is a kind of GIS analysis applied when determining the most suitable site to carry out a specific project. Potential sites of various infrastructure facilities like schools, landfills, hospitals or telecommunication masts among others can be quickly and effectively selected using the geospatial technologies. When carrying out site selection analysis, the person involved must state specific criteria based on the factors from which GIS can rate the best site. The selection can be carried out using raster or vector data. However, one of the most commonly used types of weighted site selection uses raster data. It allows users to perform ranking of raster cells and assign a relative crucial value to each layer. The outcome is a suitability surface ranking potential sites from 1 to 5, where sites with value of 1 are denoted least suitable and those with a value of 5 denoted most suitable (ESRI, 2014).

The use of geospatial technologies in suitability mapping of engineering projects has been studied by several authors: Gipps et al., 2001(transport route); Balogun et al., 2012 (oil pipeline route); Macharia and Mundia, 2014 (oil pipeline route); Abuga and Mundia, 2015 (sewage management system and sewer-line extension); Kathuo and Mubea, 2016 (water utility route); Ibrahim et al, 2011 (waste water lift station). Some of the factors considered for determining the optimal routes and sites are applicable in the siting of wastewater treatment plant, though with different weightages. Similar factors have been considered though different analysis criteria have been applied. Most of these researchers have used the Analytic Hierarchy Process (AHP) together with GIS application to derive the suitable sites and optimal routes.

For determination of suitable sites for wastewater treatment projects, use of geospatial technologies have been studied by several researchers. Deepa and Krishnaveni used analytic hierarchy process (AHP) method and GIS to determine a suitable site for decentralized wastewater treatment plant in Shollinganallur region in South Chennai City. In their study, they used five criteria: topography, slope, land use, population and soil (Deepa and Krishnaveni,2012), Shahmoradi and Isalou used an integrated fuzzy logic and multicriteria decision model together with GIS to select a suitable site for establishing wastewater treatment plant in Kahak, Iran. They found out that combining these two models yielded better results. They considered twelve criteria which were categorized in the form of two general groups of discrete and continuous indices, such that discrete indices included six criteria (soil, slope, topography, geology, land use and wind) and continuous indices included six criteria (distance from main city, underground water, surface water, roads and settlements) (B. Shahmoradi and A. Isalou, 2013), Benujah and Gevi in their research of selecting potential sites for sewage treatment plant in Tamil Nadu in India considered four constraints: ground slope, land use pattern, distance to river and roads then used the weighted index overlay analysis and weightage in ArcGIS software to select and classify the areas into good, moderate and poorly suitable areas (Benujah and Devi, 2012), Di Zhao with other researchers used analytic hierarchy process and GIS in optimal site selection for a sewage treatment plant for

Guangyuan city in China, then developed a GIS-Based Multi Criteria Analysis (MCA) model. They considered six factors: altitude, existing buildings, roads, vegetation, water body and slope (Zhao et al, 2015).

2.5. Influencing Factors

The factors that ought to be considered in locating a suitable site for wastewater treatment plant are many and various based on the area of interest. The following factors were identified based on the literature reviews of previous researches.

i) Distance to dwelling houses or residential areas

WWTP site should be located away from residential areas. Mara recommends that no part of the system should be within 200 m (preferably 500 m) of any dwelling house to minimize impact of the residents' lives (Mara, D. et al, 1992). The greater the distance from a potential complainant the better and should be away from any likely area of future expansion. This is mainly to avoid challenges of odour releases, flies nuisance, land acquisition, compensation and disruption of people's lives. The requirements concerning distance from residences are naturally dependent on local customs, climate and type of treatment process planned. In India, it's considered at least 150m from small residential colonies and 450m from large residential areas. In USA, a distance of 0.5-1km between pond and housing development is customary.

ii) Major Roads

WWTP should be located at a minimum distance of 300m from major roads according to Mara, D (1997) but the other minor roads are not treated as constraining features since they offer ease of accessibility and transportation to the WWTP during construction and operation. This buffer distance helps in safety and pollution risks to people driving or walking on these major roads which are mostly busy. Moreover, economic factors must be taken into consideration and a WWTP site should be located within a reasonable distance of existing roads in order to reduce the cost of constructing roads to the site in future. The presence of a wastewater treatment plant have no influence on traffic as is in the case of sanitary landfills which goes with solid particles and attracting birds that might influence transportation in one way or the other.

iii) Land use land cover

Land use refers to the different activities for which the land is put under for the benefit of man like agricultural and transportation whereas land cover refers to the physical conditions of the land like forests and water bodies. Different land use land cover categories vary in suitability when locating a WWTP based on the impact resulting from construction and operation of the plant. WWTP should not be placed on water bodies, wetlands, transportation routes and settlement areas due to the environmental hazards associated. Sitting in an open area is recommended so as to take advantage of the sun and wind, which assist the efficient operation of the facultative pond and thus improve the quality of the discharge. Bare lands or grasslands are considered most suitable for sitting the WWTP.

iv) Ground Slope

The ground slope is a very important factor to be considered so as to avoid huge costs during construction and operation stages. To minimize earthworks, the site should be flat or gently sloping. Steep slopes results into high excavations, run offs, high soil erosion rates and difficulties during the operation and maintenance period. A slope of less than or equal to 15% is preferable. It is generally recommended that slopes greater than 35% should not be used for land application of effluent due to the high risk of surface runoff. If the slope is too high, runoff and erosion is increased and the soil condition becomes unstable when the soil is saturated. Steep slopes can also make grass planting more difficult and the wastewater application can be more expensive (Meinzinger, 2003).

v) Airstrip

Ponds should not be located within 2 km of airports and airstrips, as any birds attracted to the ponds may constitute a risk to air navigation. It also helps in mitigating safety and pollution risks to people and aircrafts.

vi) Distance to rivers

The distance to rivers should be well thought considering the vulnerability of the streams and rivers to ground and surface water pollution from the WWTP. The need for draining the treated effluent to a natural water body or a drainage channel that can sufficiently dilute and re-oxygenate the treated effluent should be considered. According to the EU directives, a 500m buffer zone should be maintained around significant surface water bodies. This buffer also keeps it away from areas likely to flood and reduces the length of pipeline for the treated effluent. In order to protect natural resources, Anagnostopoulos and Vavatsikos (2007) identified minimum 500 meters and maximum 3 kilometers from main rivers as a suitable area for constructing wastewater refinery. Shahmoradi and Isalou (2013) also considered same distances to main rivers.

vii) Distance to drinking water sources (springs and wells)

These are key sources of drinking water. According to the EU directives, wastewater plants must not be close to any source of drinking water, due to pollution risks. The same buffer zone as for rivers was maintained in the present study around the drinking water sources. Shahmoradi and Isalou also considered 500m to 3500m as suitable distances to wells and springs (Shahmoradi, B., and Isalou, A. A., 2013). Existing springs and wells used as sources of drinking water in the study area were found to fall along the rivers hence the 500m buffer would also protect them from pollution. NEMA regulations also emphasize on preservation of water bodies and ensuring that any activity that may affect water bodies be undertaken at safe distances away from them.

viii) Distance from town center

WWTP sites should not be far from the town center or the targeted connection area but should be at least 500m away from town or large residential area. If located very far from the town, huge costs will arise from the acquisition of numerous trunk sewerline pipes to be laid from the town center to the WWTP. Land acquisition will also increase for the sewerline routes. The distance should be well chosen such that it also doesn’t hinder the town expansion.

Many researchers suggested that the appropriate distance from the borders of urban areas to a WWTP site should be at a suitable distance due to the economic factors and impact on the general public. The cost of the land as well as health and safety laws often prevents siting of a WWTP within the boundaries of an urban area. Important factors to consider are decreases in property value, odor, aesthetics as well as ensuring that the urban area retains the potential to expand in the future.

ix) Altitude of the town center

The suitable site for the WWTP should be at lower heights compared to the town center to enable a gravity system of the sewerage system. Higher elevations than those of town center leads to a pumping system which is difficult to operate and maintain due to high power bills and maintenance costs of the pumping systems. The lowest altitude of the town extents ought to be higher than the altitude of the WWTP. Mara, D. recommends that lagoons be located downgrade and downwind from the homes they serve, when possible, to avoid the extra cost of pumping the wastewater uphill (Mara, D. et al, 1992).

x) Distance from country borders (Kenya-Tanzania border)

The study area borders Tanzania to the south hence to avoid conflicts over any adverse effects from the WWTP a buffer zone of 1000m specified by Gemitzi et al (2007) was adopted. Effects of odour releases, flies nuisance, water pollutions and disruption of people's lives are key concern to neighboring states. Social, cultural and political issues of the neighboring states ought to be considered.

xi) Soils

Soil is key factor in the selection of a site for a sewerage treatment plant. Detailed study has to be undertaken on soil characteristics; soil type, soil depth, soil drainage and so on. These aspects affect the rate of seepage of waste water which poses a great threat to the groundwater. Soils should be heavy and impermeable and the water table should be deep (Mara, D. et al, 1992). Silt or clay soils are ideal for pond foundations and construction. Building ponds over coarse sands, gravels, fractured rock or other materials, that will allow effluent to seep out of the pond or allow groundwater to enter in, should be avoided. If there is no suitable local soil with which at least a stable and impermeable embankment core can be formed, it must be brought to the site at extra cost and the local soil, if suitable, used for the embankment slopes. Mara D. recommends that if soil is permeable ($>10^{-6}$ m/s), a plastic membrane plastic may be used to line the pond. Ponds must be artificially lined with clay, bentonite, LOPE sheets, concrete, or other materials to prevent groundwater pollution (Mara, D.et al, 1992). The soil needs to be permeable enough to pass the water and yet capable of retaining the water so that treatment occurs.

xii) Lithology

On lithology, the characteristics of existing rocks and faulty lines should be investigated as they determine the rate of seepage and excavation costs during construction. The main kinds of rocks that exist on the ground are sedimentary, metamorphic, igneous and unconsolidated rock. Areas with hard rocks should be avoided as the excavation costs are high. In terms of rock hardness, the hardest is igneous rock followed by metamorphic then sedimentary and finally unconsolidated rocks which are the soft rocks.

3. MATERIALS AND METHODS

3.1. Introduction

This chapter deals with definition and explanation of the study area, the required datasets and their sources, the used tools and materials, adopted methodology, identification of the sitting criteria, determination of relative weights of the various variables and allocation of their respective influence in the weighted overlay analysis and the GIS modelling and analysis processes.

3.2. Study area

Loitokitok town is located about 200km south-east of Nairobi in Kajiado County in Kenya. The town can easily be accessed from the capital city (Nairobi) via Mombasa road (A109), and Emali-Loitokitok Road (C102). The two roads are tarmacked and in a good state. The town is well served by a number of well tarmacked streets with good storm water drainage facilities.

The intended study area measures about 246 km2 and extends upto the Kenya-Tanzania border. The township is located between Kimana and the llassit market centres. The geographic co-ordinates of Loitokitok town are; $2^0$55’30’’S, $37^0$30’36’’E. The town altitude ranges between 1,700 to 1,900 meters above mean sea level. The ground slopes gently toward the East. The town is characterized by the existence of a number of medium rise (2-4 storey) buildings and bungalows. The economic activities in the area are mainly agricultural and various small scale businesses. Sectors of agriculture; horticulture, food crop farming, livestock production, dairy and beef production, hides and skins and poultry farming are among the important investments, just like the rest of the Kajiado County.

Loitokitok town is the headquarters of the Loitokitok Sub County of Kajiado County hence it hosts major County and National Governments offices. Loitokitok Sub County comprises of three wards namely; Kuku, Entonet and Kimana. According to the 2009 National Census, the human population at that time stood at about 137,496 divided as 122,749 for the Rural and 14,747 for urban (Loitokitok, Kimana, Rombo and Ilassit towns) population. The average temperature in Loitokitok is 17.8 °C. Loitokitok’s climate is classified as warm and temperate with the area receiving an annual average rainfall of 894 mm. There are varying rainfall distribution patterns due to the presence of Mt. Kilimanjaro at the border of Tanzania that causes the lowest elevation to receive about 500 mm while the mountain slopes record an average rainfall of 1250 mm per annum.

Loitokitok town has sufficient and stable water supply from the Nol Turesh Springs but lacks a sewerage system. The town also has a consistent electricity supply connected to the national electricity grid and is used to pump the treated bulk water from the springs to storage tanks near the town.

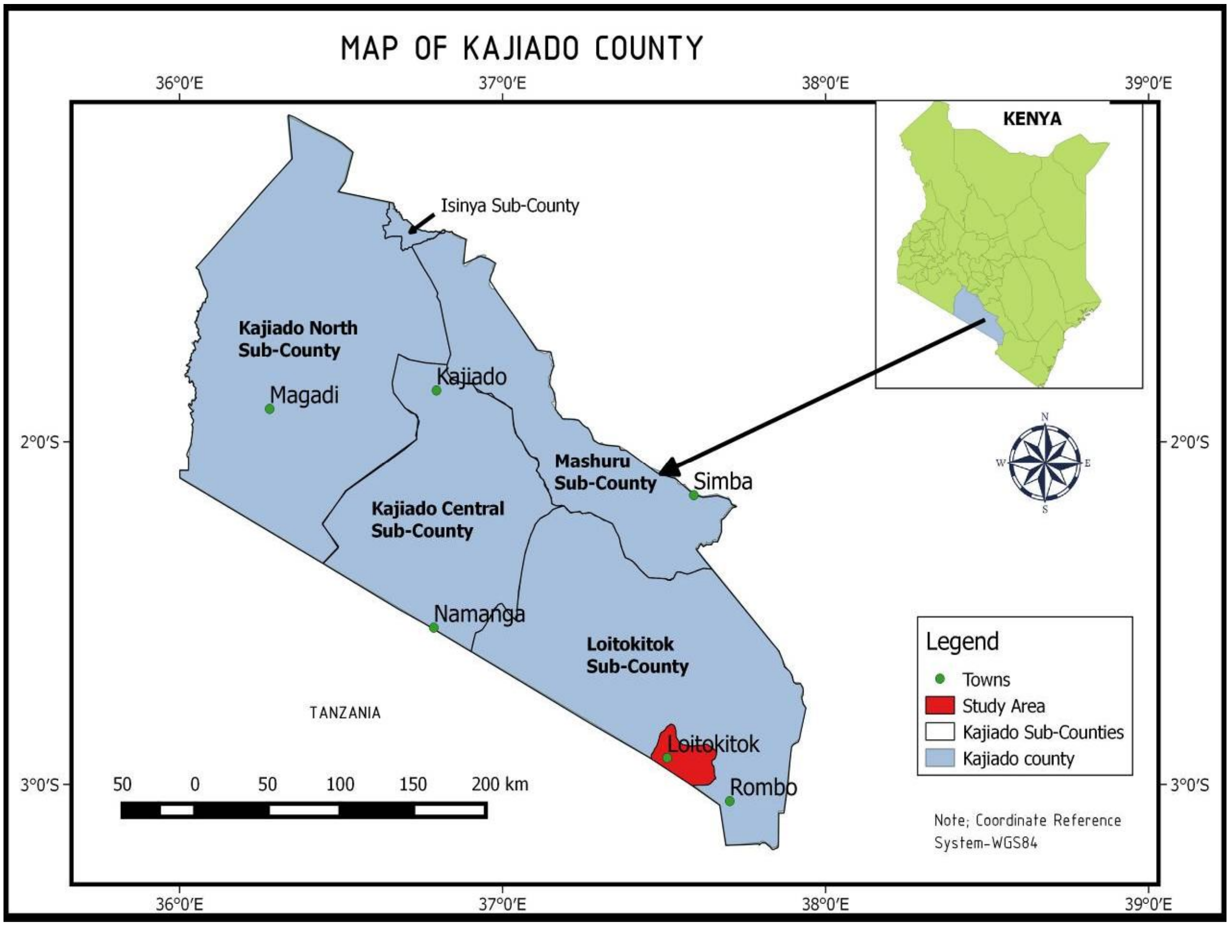

Figure 6: Location of the study area in Kajiado County of Kenya

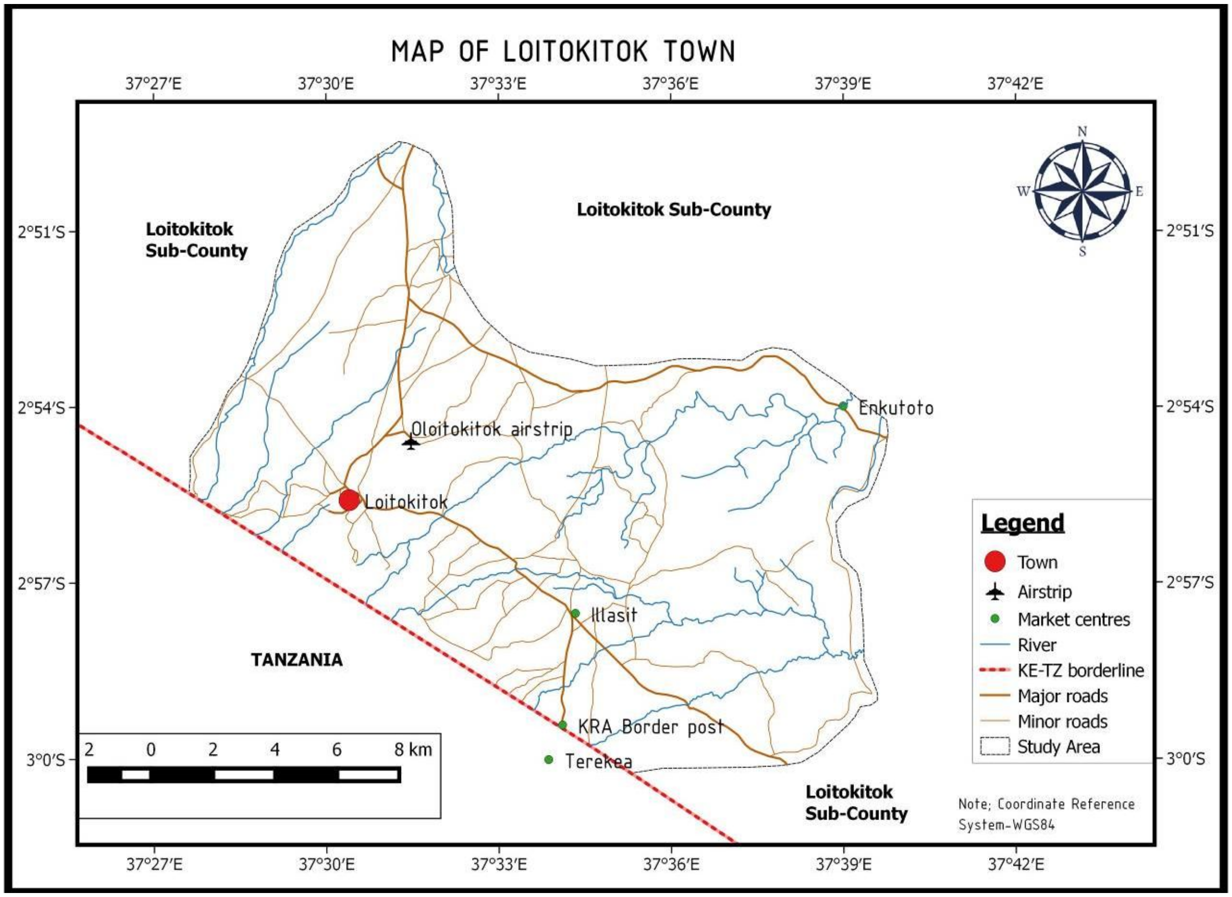

Figure 7: Study Area of Loitokitok town in Loitokitok Sub-County

3.3. Overview of methodology

The first step was to identify the relevant available datasets based on the influencing factors detailed in the literature review section. For this research, the relevant datasets are on Land Use Land Cover, Soils, lithology, roads, water bodies (rivers, wells and springs), buildings, town center, topography (DEM and slope) and airstrip location. The data were collected from different sources and a project geo-database created in ARCGIS. Some of the data were edited and others processed further before analysis. The criteria weights were also computed from experts' response on the questionnaires. The next step was to develop a model in ARCGIS to carry out the analysis and determine suitable sites.

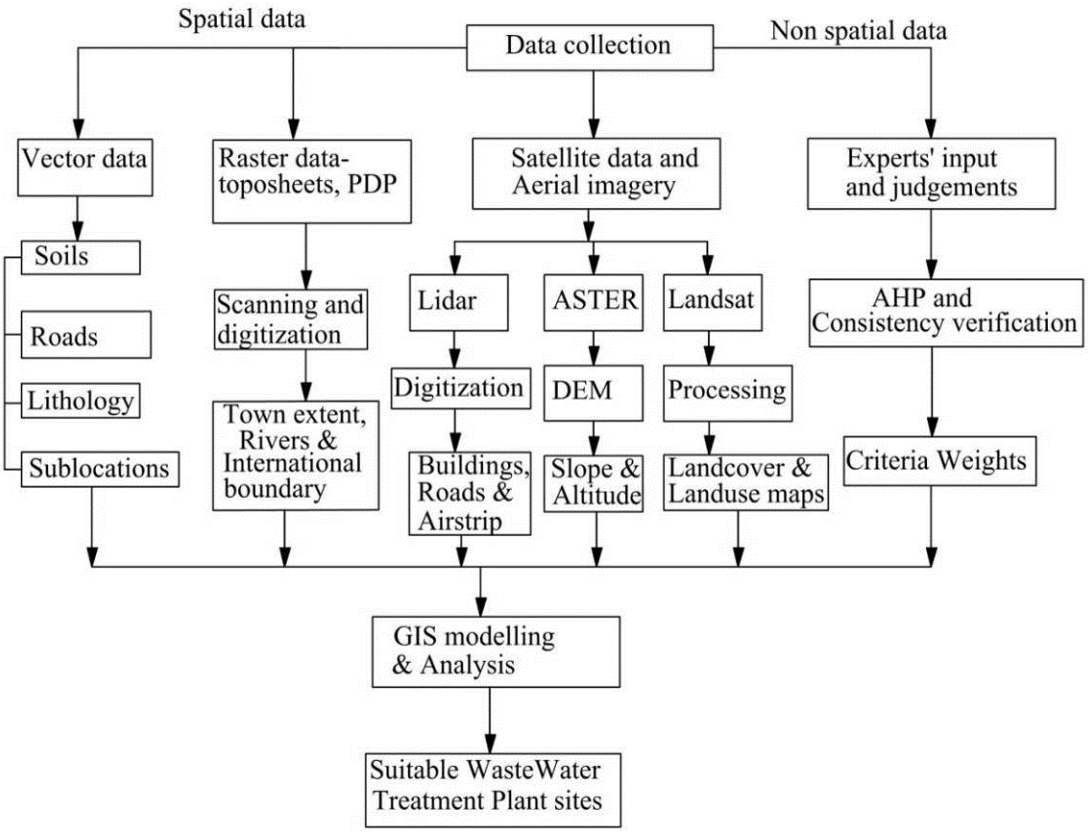

Figure 8: Methodology Flow Chart

3.4. Identification of the sitting criteria

The site location criteria were identified based on the opinions of experts in this field, literature reviews on previous researches and data available in the study area. Guided by the Draft Practice Manual for Sewerage and Sanitation Services in Kenya from the Ministry of Water and Irrigation (2008), Design Manual for Eastern Africa (Mara, D. et al, 1992) and other previous researches, the following siting criteria for a Waste Water treatment plant were adopted:

i) WWTP site should be atleast 200m from any existing dwelling house.

ii) It should be atleast 2km away from airports and airstrips.

iii) It should be on level to gently sloping ground.

iv) It should be located on areas with clayey soils permeable enough to pass the water and yet capable of retaining some water so that treatment occurs.

v) It should at least 500m away from large residential areas or towns.

vi) It should be located away from water sources to avoid pollution

vii) It should be located downgrade or at lower altitudes from the homes they serve, when possible, to avoid the extra cost of pumping the wastewater uphill.

viii) It should be located at convenient distances away from major roads to avoid pollution and enable ease of access.

ix) It should be located away from international boundaries to avoid any conflicts due to any arising hazards.

x) It should be located on soft rocks that allow water infiltration and reduce excavation costs.

3.5. Data Identification

In consideration of the sitting criteria identified above, the relevant data to be acquired was identified and used to create map layers in ARCGIS. The required map layers are listed below;

Table 3-1: Identified map layers

Map layer	**Factor(s) considered**
Dwelling houses	Distance to dwelling houses or residential areas
Major Roads	Distance to major roads
Land use land cover (LULC)	Areas with water bodies, settlements and transportation network
DEM	Ground slope and altitude of the town center
Airstrip	Distance to airstrip
Rivers	Distance to rivers
Springs and wells	Distance to springs and wells
Town extent	Distance from town center
Kenya –Tanzania Borderline	Distance from country border
Soils	Areas with clayey soils
Lithology	Rock hardness factor

3.6. Data and tools acquisition

The required data were acquired from different sources and in different formats.

Table 3-2: Acquired Datasets

Data	Format	Source	Year	Resolution
Landsat 8 satellite imagery	Raster	USGS: http://earthexplorer.usgs.gov/	2018	30m
Lidar imagery	Raster	GeoMaps International	2013	
World imagery	Raster	Global Mapper	2017	
DEM (Aster GDEM V2)	Raster	USGS: http://earthexplorer.usgs.gov/	2016	30m
Toposheets; 182/3(Oloitokitok)& 181/4 (Rongai)	Raster	Survey of Kenya	1974	1:50,000
Springs and wells	Vector	WRMA , ILRI	2014	
Transport (Roads) Network Shape file	Vector	Kenya Roads Board (KRB)	2013	
Soil data	Vector	KARLO, ILRI	1997	
Lithology	Vector	KARLO, ILRI		
Sub locations	Vector	ILRI		
Towns	Vector	ILRI	2000	

The relevant tools for execution of the project were identified and acquired. The tools are as listed below.

Hardware

- Computer with specifications of 1TB memory, 8GB RAM and 2.67 GHz of speed.
- A flash disk of 8 GB memory space
- A handheld GPS (Garmin GPSMAP64s)
- A HP Printer
- A digital camera

Software

- ArcGIS 10.1
- Global Mapper v11
- QGIS 2.10.1
- IDRISI 17.0
- Mozilla Firefox
- Microsoft Office 2010 suite

3.7. Data Collection and Processing

After downloading and acquiring the above datasets from different sources, the datasets were further processed as follows;

a) Landsat 8 Imagery

The satellite imagery LANDSAT 8 was downloaded from the USGS website, the imagery was well selected in consideration of the cloud cover and date captured, imagery with cloud cover less than one percent was chosen. The imagery selected was acquired on 29th January 2018 with a cloud cover of 0.86 percent. The imagery was then processed using IDRISI 17.0 software. Image classification was done to categorize the image to different classes through supervised classification. General land cover of the area was derived and five land cover classes were identified namely: forests, settlements, agricultural land, bare land grassland and shrubs, rocky outcrop and other lands. This provided the land cover land use layer for GIS analysis.

b) **Lidar Imagery and world imagery**

The dwelling houses data and airstrip were digitized from the Lidar imagery in ARCGIS software and for areas in the study area that fall outside the available Lidar imagery, the world imagery was used to digitize those houses. Due to the large number of houses, at least a house was captured in each homestead.

The Lidar and World imagery mosaic was also used to check the rivers, roads and international boundary data obtained from the other sources. The mosaic is attached in Appendix B for reference.

c) **DEM**

The ASTER GDEM V2 data was downloaded from the USGS website, clipped to the study area and processed in ARCGIS software to obtain slope data and altitude ranges covering the study area and the Loitokitok town extents. The resultant DEM is attached in Appendix B.

d) **Toposheets: 182/3 (Oloitokitok) and 181/4 (Rongai)**

The toposheets were scanned, georeferenced and digitized in ARCGIS to obtain vector layers of rivers, springs and the Kenya –Tanzania Border line.

e) **Soils**

The vector data obtained from the ILRI website was clipped to the study area and soil type and characteristics investigated for the suitability analysis.

f) **Lithology**

The lithology data obtained from ILRI website was also clipped to the study area and the rock type and characteristics investigated for the suitability analysis. These study area was found to be wholly composed of igneous rocks hence this factor was not considered in the suitability analysis.

g) **Springs and wells**

Vector data for springs and wells was obtained from the ILRI website and the local WARMA offices, the data was then clipped to the study area for analysis. The wells and springs were found to fall within the rivers hence the river layer was used for suitability analysis.

h) **The town extent and it's altitude**

The development plan of Loitokitok town was obtained from the Physical Planning offices of the Kajiado County which showed the town was planned in 1993 and has not been updated. The development plan was scanned, georeferenced and digitized to obtain the map layer on town extent. This map layer was then overlaid on the study area map for the suitability analysis. The scanned development plan is attached in Appendix B for reference.

Some of the processes executed

a) Clipping

This involved extracting only datasets that fall within my study area for further analysis. This was done using the clip tool in Arc toolbox.

b) Reprojection/ Transformation

This involved conversion of datasets with different coordinate projections and systems to a uniform coordinate projection to ease the GIS analysis processes. Global Mapper and ARCGIS software were mostly used for this process.

c) Multiple Ring Buffering

This involved creating area rings (buffers) at specified distances from the relevant input features. This was done using the multiple ring buffer tools in the Arc toolbox of ArcGIS software.

d) Rasterization

This involved conversion of vector data to raster format for GIS analysis using the conversion tools in the Arc toolbox.

e) Model Building

The model was built through creation of a new tool box in Arc catalog and was named 'WWTP *siting*'. Then inside the new toolbox a model was created using the model builder. All the relevant tools and dataset for the processing of the expected deliverables were incorporated in this model.

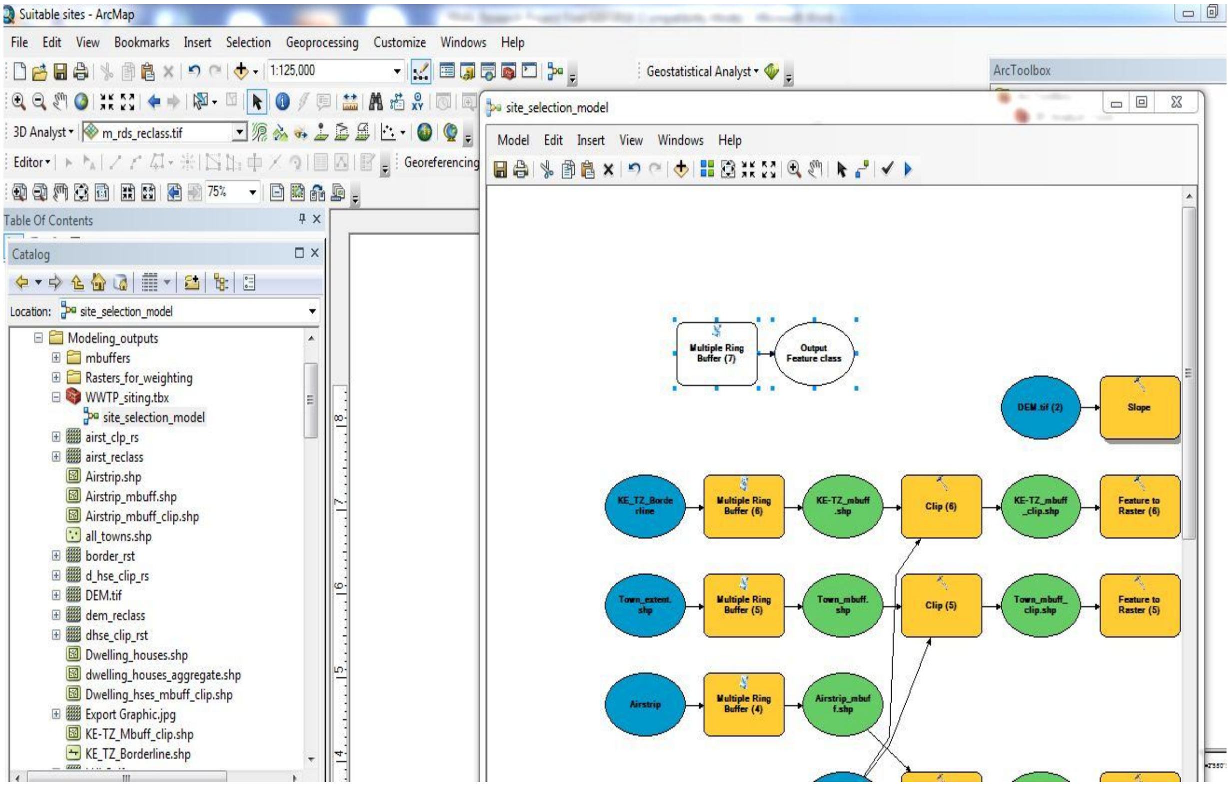

Figure 9: Model building for the site selection

3.8. Determination of Weights

The weights of the factors considered were determined through pairwise comparison in the Analytical Hierarchy process. This method was preferred because the required input data are rather easy to obtain and it can deal with inconsistent experts' judgments and provides a relative measure of the inconsistencies. Questionnaires were developed capturing all the ten factors identified and were issued to Engineers, Environmentalists, Sociologists and Government officials to give their judgments on the relative importance of all those factors in respect to Saaty's 9-point scale. Twenty eight questionnaires were issued equally to the proposed categories of respondents' i.e seven to Engineers, seven for Sociologists, seven for Environmentalists and seven for Government officials. The filled questionnaires are attached in Appendix C for reference.

3.9. GIS Modeling and Analysis

After ensuring all relevant datasets are available and clipped to the study area in the geodatabase, a model was developed in ARC GIS covering all required processes using the ARC toolbox.

The siting was then divided into factor and constraint criteria. Factor criterion enabled the selection of the best site considering suitability levels while constraint criterion represented the areas unsuitable for siting a WWTP. The various criteria that were created as a layer in ARCGIS environment are as shown below;

Table 3-3: Acceptable minimum separation distance to a suitable WWTP site

Spatial data/ Feature	**Minimum Separation distance**	
	Distance(m)	**Source**
Dwelling houses	200	Mara, D. et al(1992), Mara, D. (1997), MOWI(2008)
Major roads	300	Msangi, Y. and Liwa, E (2014)
Airports and airstrips	2000	Mara, D et al(1992), Mara D(1997), MOWI(2008)
Rivers	500	Msangi, Y. and Liwa, E. (2014),Gemitzi, A. et al (2007)
Springs and wells	500	Shahmoradi, B. and Isalou, A.(2013), Anagnostopoulos K.P. and Vavatsikos A.P. (2007).
Country border	1000	Gemitzi, A. et al (2007)

Table 3-4: Constraint criteria table

Criteria	Unsuitable areas
Distance to dwelling houses	Less than 200m
Distance to major roads	Less than 300m
Land use land cover	Areas with water bodies, settlements and transportation network
Ground slope	Areas with slope greater than 35%
Distance to airstrip	Less than 2000m
Distance to rivers	Less than 500m
Distance to springs and wells	Less than 500m
Distance to town	Less than 500m
Distance from country border	Less than 1000m

For the factors; dwelling houses, major roads, water bodies, distance to town, distance to Airstrip and distance to Kenya-Tanzania borderline, multiple ring buffers were created based on the criteria set on *Table 3-5* on each of these input features, the obtained buffer rings were clipped using the polygon of the study area. The clipped buffer map of each factor was converted to raster and then reclassified to a common scale. It was then added to weighted overlay tool ready for weighted overlay analysis.

The factors which were in raster format like LULC and Altitude of town, the datasets were reclassified to a common scale of 0-5 then added to weighted overlay tool ready for weighted overlay analysis.

For the factor on ground slope, the Aster GDEM data was used to generate slope of the study area through the spatial analyst tools in ARC GIS software. The slope map generated which was in raster format was reclassified to a common scale of 0-5 then added to weighted overlay tool ready for weighted overlay analysis.

Reclassification was a key process in all datasets as it involved allocating the variables a common scale of 0-5 based on the proposed suitability scales shown below which were standardized across all datasets for the weighted overlay analysis to be executed efficiently

All the reclassified datasets were then combined using the weighted overlay tool. The weighted overlay analysis involved also incorporating weights of each variable previously determined from the experts' inputs using AHP. After execution of the weighted overlay analysis, the suitable areas were identified from the output raster map.

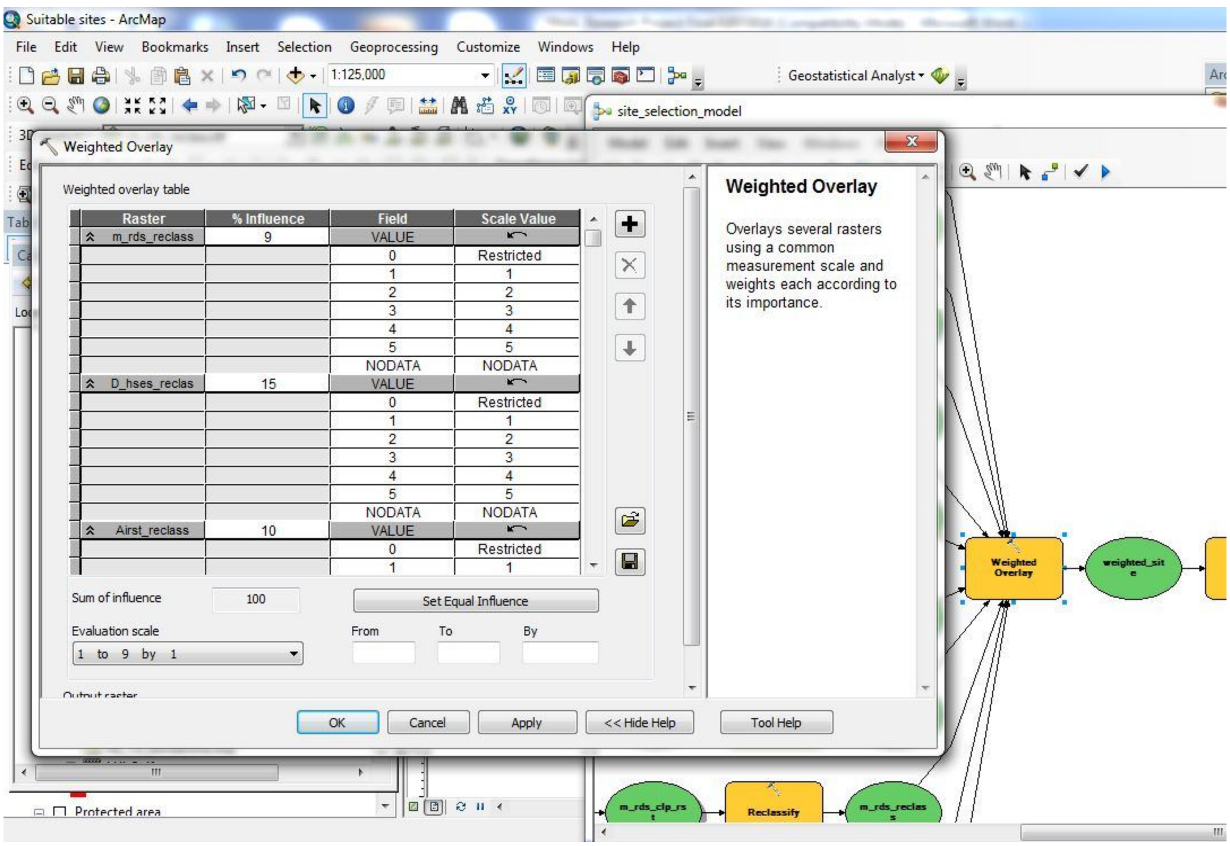

Figure 10: The Weighted Overlay tool used

The raster map was then converted to vector format for extraction of optimal sites and further analysis. All processes above were done using a model developed which incorporated all the relevant tools provided in the Arc tool box.

Presentation of the final results was in constraint-criterion maps showing the different suitability maps for each criterion and the overall suitability map.

Table 3-5: Attribute scores and weights for the factors used in the WWTP site selection

Factor	Layer	Criteria	Suitability Scale	Weight (% influence)
Distance to dwelling house	Dwelling houses	Buffer 200m	0	9
		Buffer 500m	2	
		Buffer 1000m	4	
		Buffer 1500m	5	
Distance to major roads	Major roads	Buffer 300m	0	5
		Buffer 1000m	5	
		Buffer 2000m	4	
		Buffer 3000m	3	
		Buffer 5000m	2	
		Buffer 10000m	1	
Distance to water bodies	Rivers	Buffer 500m	0	21
		Buffer 1000m	5	
		Buffer 2000m	4	
		Buffer 3000m	3	
		Buffer 5000m	1	
Land use land cover	LULC	Settlements	0	5
		Farmland	4	
		Forests	2	
		Bareground, grasslands and shrubs	5	
		Rock outcrop	1	
		Other lands	3	

Factor	Layer	Criteria	Suitability Scale	Weight (% influence)
Distance to airstrip	Airstrip	Buffer 2000m	0	9
		Buffer 3000m	1	
		Buffer 4000m	2	
		Buffer 5000m	3	
		Buffer 10000m	4	
		Buffer 20000m	5	
Distance to town	Town extent	Buffer 500m	0	10
		Buffer 2000m	2	
		Buffer 5000m	3	
		Buffer 8000m	4	
		Buffer 10000m	5	
		Buffer 20000m	1	
Altitude of town	DEM	1293m-1717m	5	17
		1717m-1969m	1	
Distance to Kenya-Tanzania border	KE-TZ Borderline	Buffer 1000m	0	4
		Buffer 2000m	1	
		Buffer 3000m	2	
		Buffer 5000m	3	
		Buffer 10000m	4	
		Buffer 15000m	5	
Soils	Soils	Slow drained Kaolinitic clayey	5	9
		Well drained Montmorillonitic clayey	4	

Factor	Layer	Criteria	Suitability Scale	Weight (% influence)
Ground slope	Slope	0-2%	3	11
		2-5%	4	
		5-15%	5	
		15-25%	2	
		25-35%	1	
		>35%	0	

A scale of 0-5 is used to show suitability levels where 0 is unsuitable, 1 least suitable and 5 is most suitable. As shown in Table 3-6.

Table 3-6: Suitability Scale

Scale	Suitability Level
0	Unsuitable
1	Very low
2	Low
3	Moderate
4	High
5	Very High

4. RESULTS AND DISCUSSIONS

4.1. Introduction

This chapter presents the results and findings realised after application of the methodology discussed above. The deliverables include the thematic maps of the various factors considered, the constraint criterion maps for each of the criteria considered and a suitability map showing of the most suitable sites for a WWTP.

4.2. Determination of Weights

From the twenty eight questionnaires issued to respondents, only nineteen were returned i.e seven from Engineers, four from Sociologists, four from Environmentalists and four from Government officials.

After receiving the filled in questionnaires, the questionnaires were processed using AHP Excel Template with multiple Inputs downloaded from the website; http://bpmsg.com and authored by Dr. Klaus D. Goepel (Goepel, 2013) to produce the consolidated weights shown on Table 4-1 below.

The filled in questionnaires, excel sheets for pairwise comparison matrices and summary of calculations are provided in the Appendix C for the purpose of reference.

Table 4-1: Consolidated Criteria Weights obtained

Criterion		**Variable**	**Weights**	**Rank**
1	Criterion 1	Dwelling houses	9%	7
2	Criterion 2	Major roads	5%	9
3	Criterion 3	Land Use Land Cover	5%	8
4	Criterion 4	Slope	11%	3
5	Criterion 5	Airstrip	9%	5
6	Criterion 6	Water bodies	21%	1
7	Criterion 7	Distance to town	10%	4
8	Criterion 8	Altitude of town	17%	2
9	Criterion 9	Kenya-Tanzania Borderline	4%	10
10	Criterion 10	Soils	9%	6
		Total	**100%**	

The obtained criteria weights are also represented in a graph below;

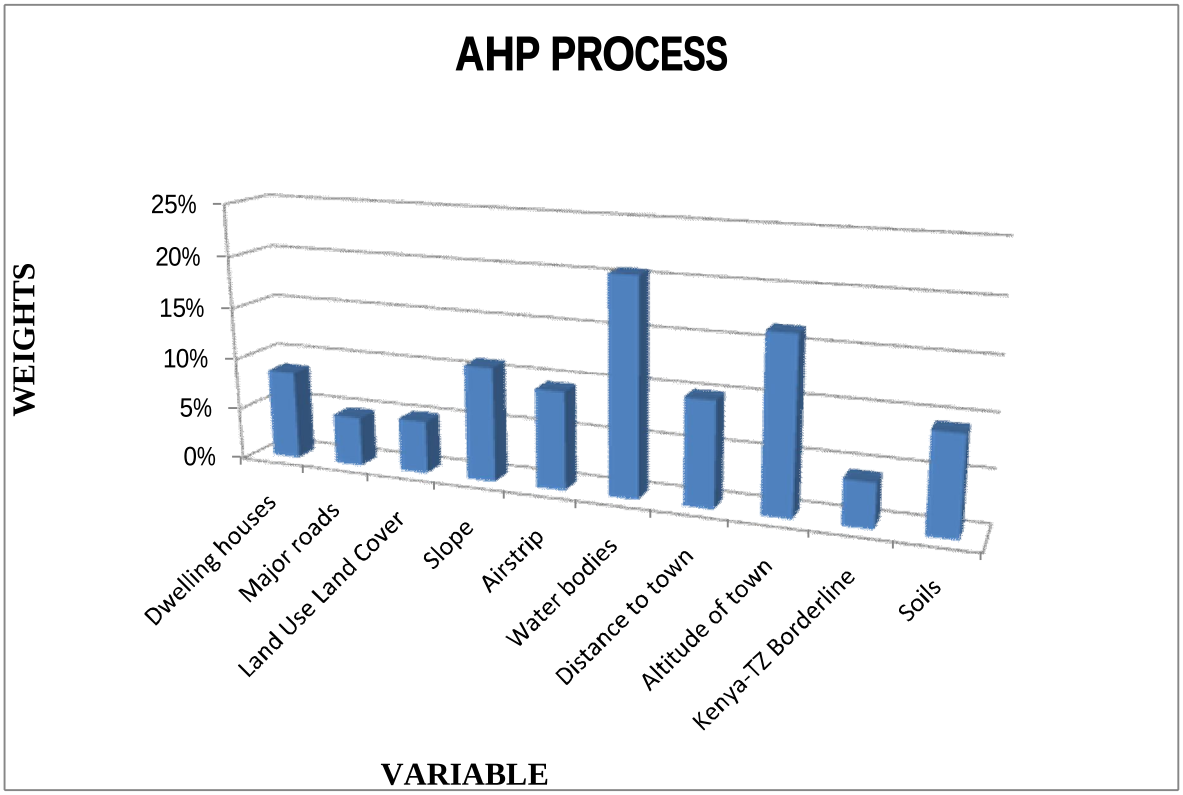

Figure 11: A graph showing the criteria weights

The experts put more significance on water bodies' variable with 21% significance level, followed by altitude-of-the-town variable with 17% significance level then ground slope with 11% as shown on the graph above. The least significant variable according to the experts' judgments is the country border between Kenya and Tanzania with 4% followed by Land use and major roads variables which tie at 5% significance level.

The resultant Consistency Ratio (CR) of 2.7% as shown in Appendix C was obtained which is less than the maximum threshold of 10% required. Hence these pair wise comparisons were found to be adequately consistent. These weights were then used in the weighted overlay analysis to derive suitable sites for a wastewater treatment plant.

4.3. Model Building

The model was successfully built for execution of the GIS modeling and analysis process. The resultant model captured all required processes discussed in the methodology. The resultant model is shown in Appendix D for purposes of reference.

4.4. Suitability Maps for Each Criterion

The suitability maps realised for each of the ten variables are displayed in this section and discussed briefly on their output. The maps for each criterion define the influence that each criterion has on the selection of a suitable site for a wastewater treatment plant. The reclassified maps are in raster format and display the suitability levels of the various parts of the study area according to the suitability scale.

The constraint criterion maps of each variable are presented below.

4.4.1. Dwelling-houses Constraint Criterion map

Distance to dwelling houses is a key factor which has been considered by many researchers and organizations dealing with water and sanitation infrastructure. The population within the study is growing rapidly hence many dwelling houses were identified after digitization.

The resultant buffer map from the dwelling houses and the reclassified map are shown on figures12 and 13 respectively.

The 200m buffer area shown on the figures in yellow color is categorized as unsuitable as it’s near the dwelling houses while the 1500m buffer area in blue color has a very high suitability level for site location of the WWTP.

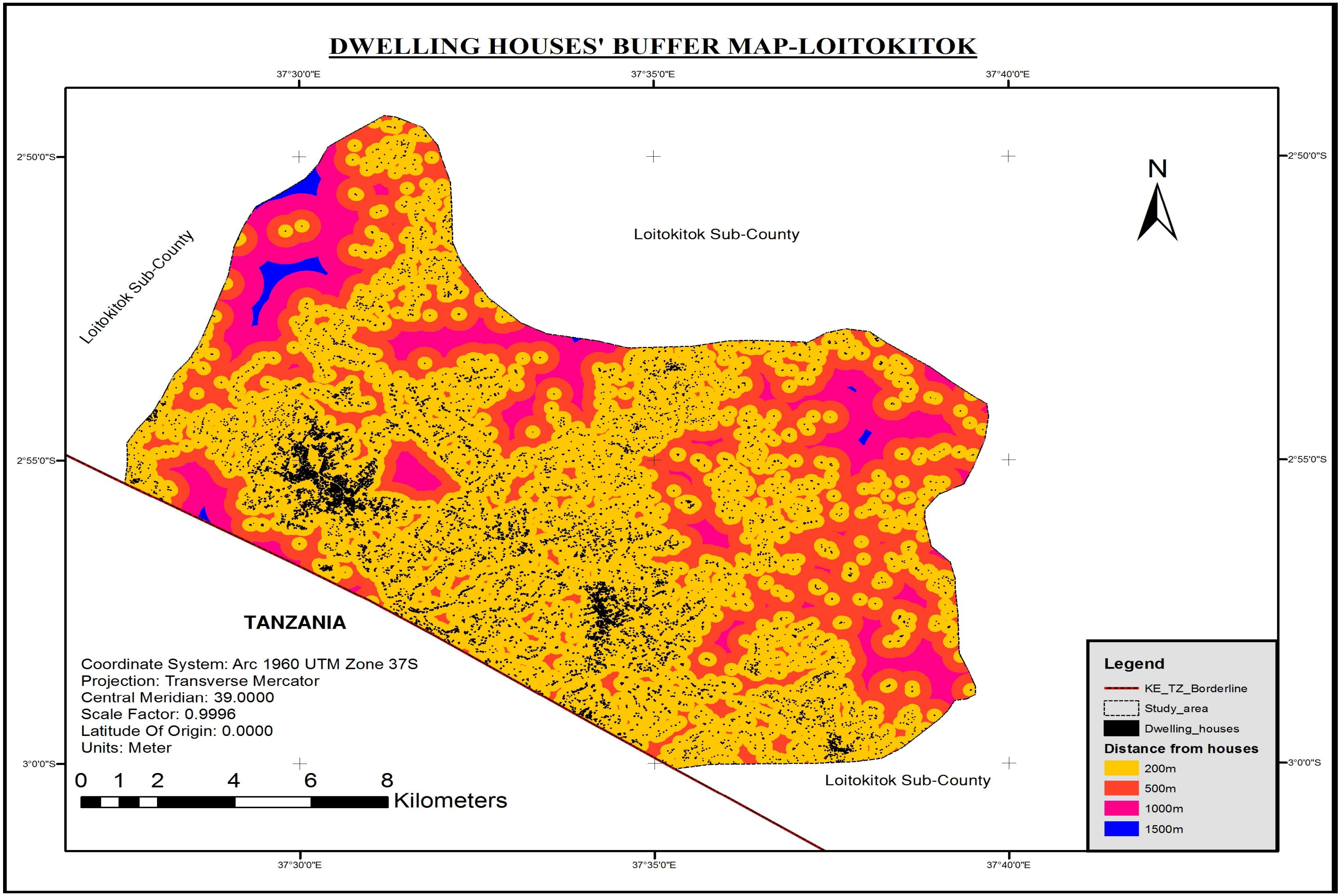

Figure 12: Dwelling houses' buffer map

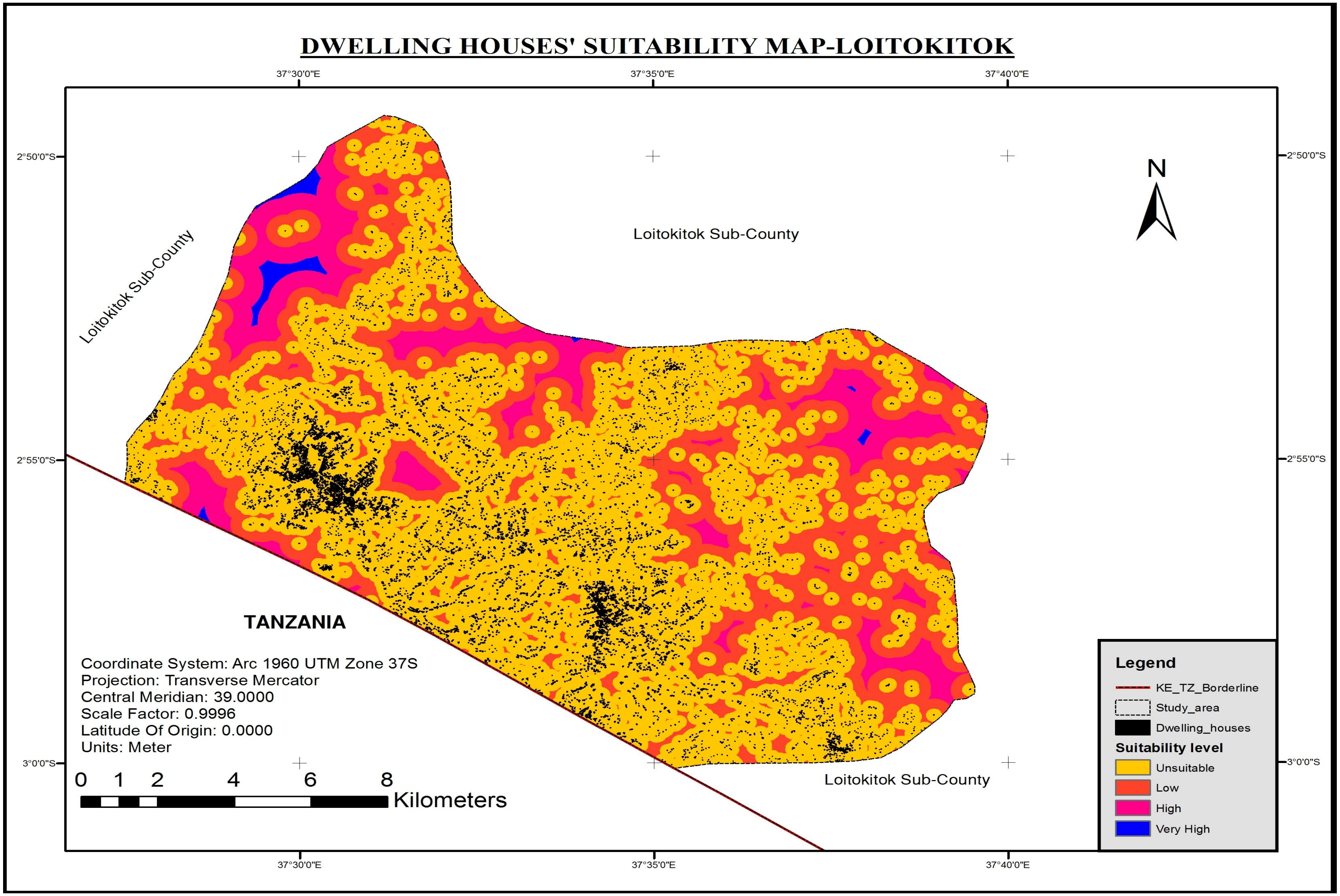

Figure 13: Dwelling houses' suitability map

4.4.2. Major-roads Constraint Criterion map

Major roads are usually busy with traffic and also enable accessibility to various parts of the county and country at large. The major roads that were identified that exist within the study area are E2023, E1824, E703, D536, C102 and C103. Distance to major roads is key factor as it determines ease of access to the site whilst ensuring safety and pollution risks on road users are avoided.

The resultant buffer map at the specified distances from the major roads and the reclassified map showing the suitability levels are shown on figures14 and 15 respectively.

The 300m buffer area was categorized as unsuitable site due to the safety and pollution risks on people driving or walking on these major roads. The 1000m buffer area which next to the restricted area has very high suitability level as it enables ease of access to the WWTP.

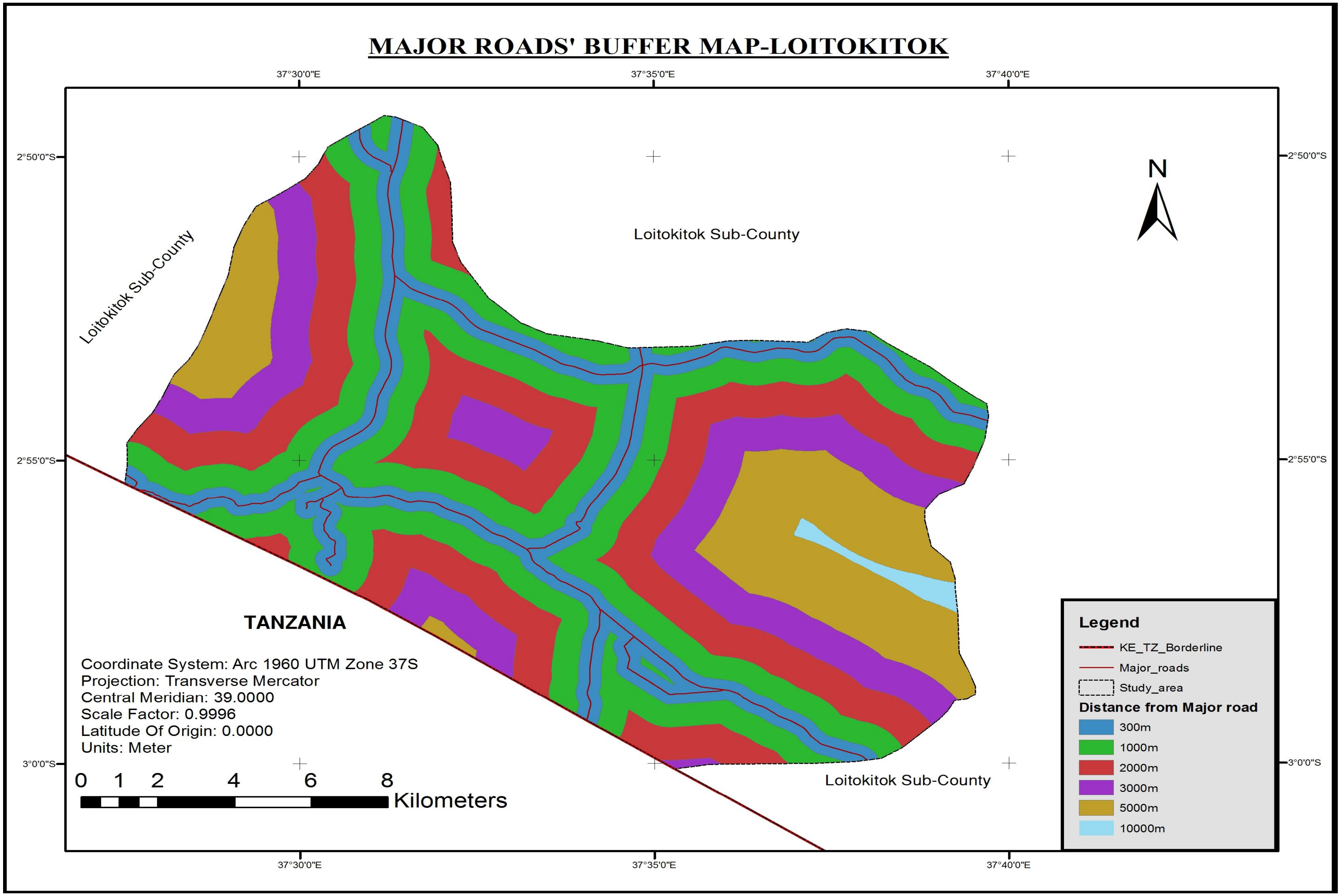

Figure 14: Major roads buffer map

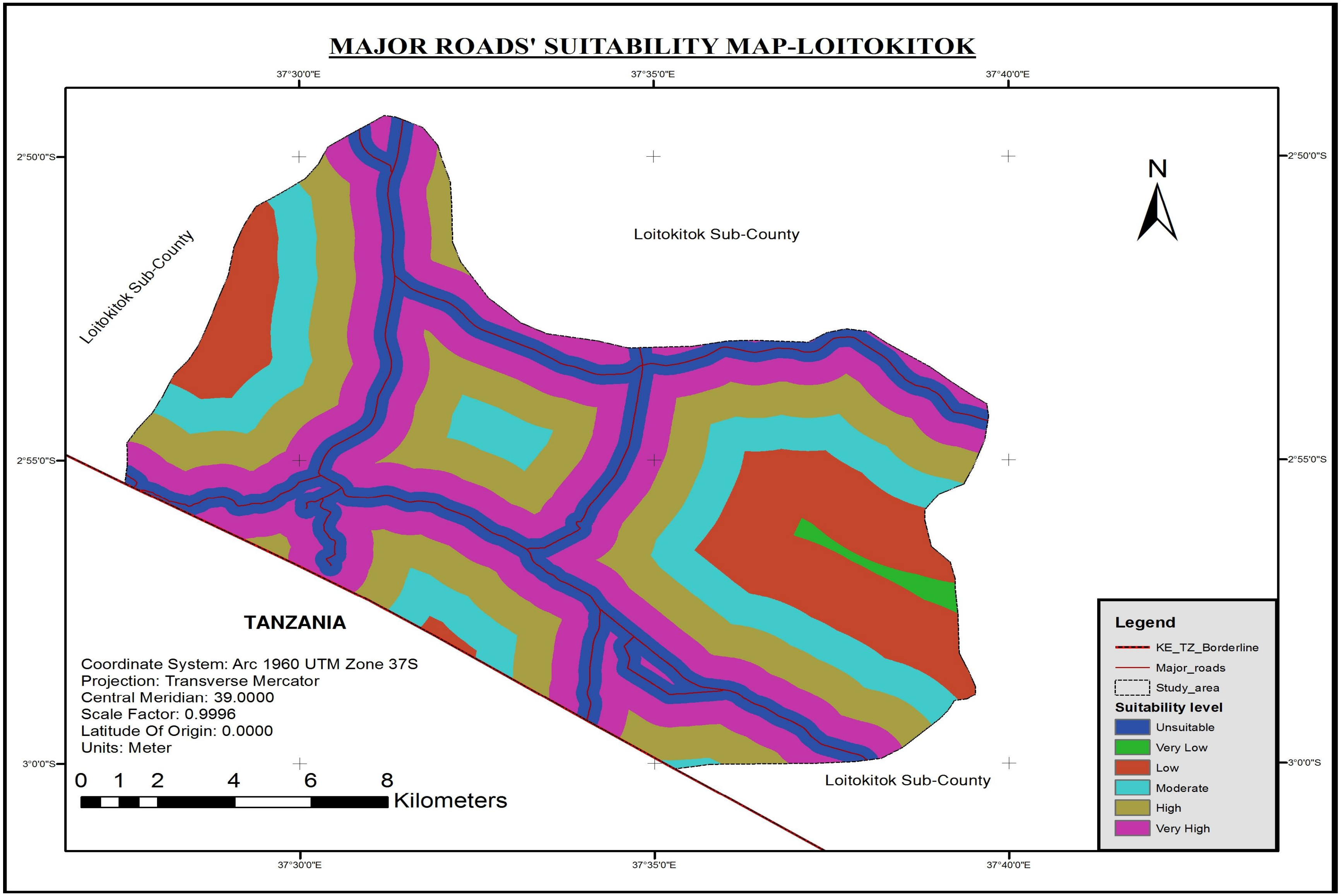

Figure 15: Major roads suitability map

4.4.3. Water bodies (Rivers, springs and wells) Constraint Criterion map

The existing springs and wells within the study area were found to fall along the rivers hence the river layer was used for the multi ring buffering process.

The resultant buffer map and suitability map are shown on figures 16 and17 respectively.

The 500m buffer area in dark green colour from the rivers protects these water sources from ground and surface water pollution from the WWTP hence it’s unsuitable for the plant set up.

The 1000m buffer area next to the restricted area has a very high suitability level as a shorter effluent disposal channel to the rivers would be achieved hence saving construction costs.

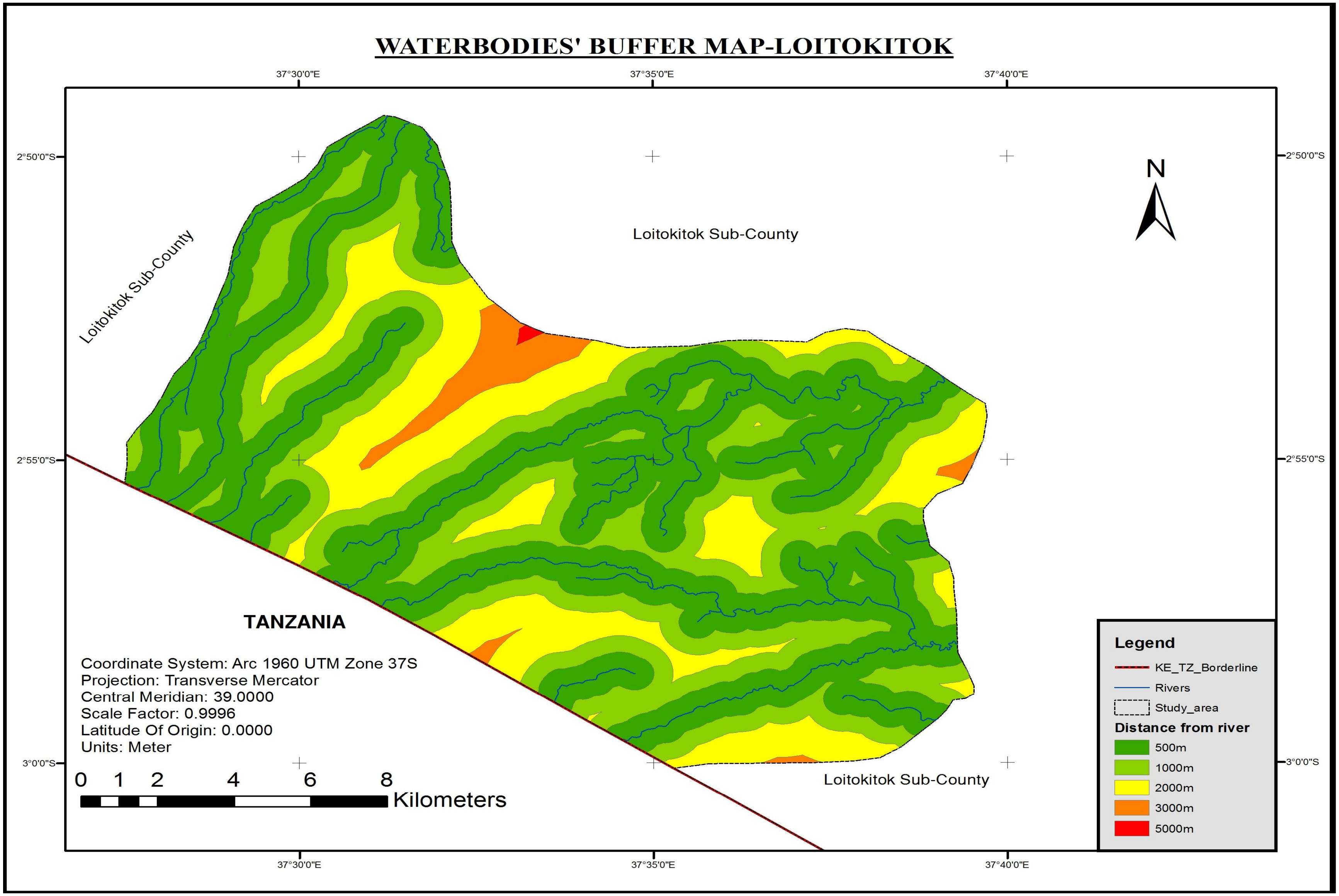

Figure 16: Water bodies buffer map

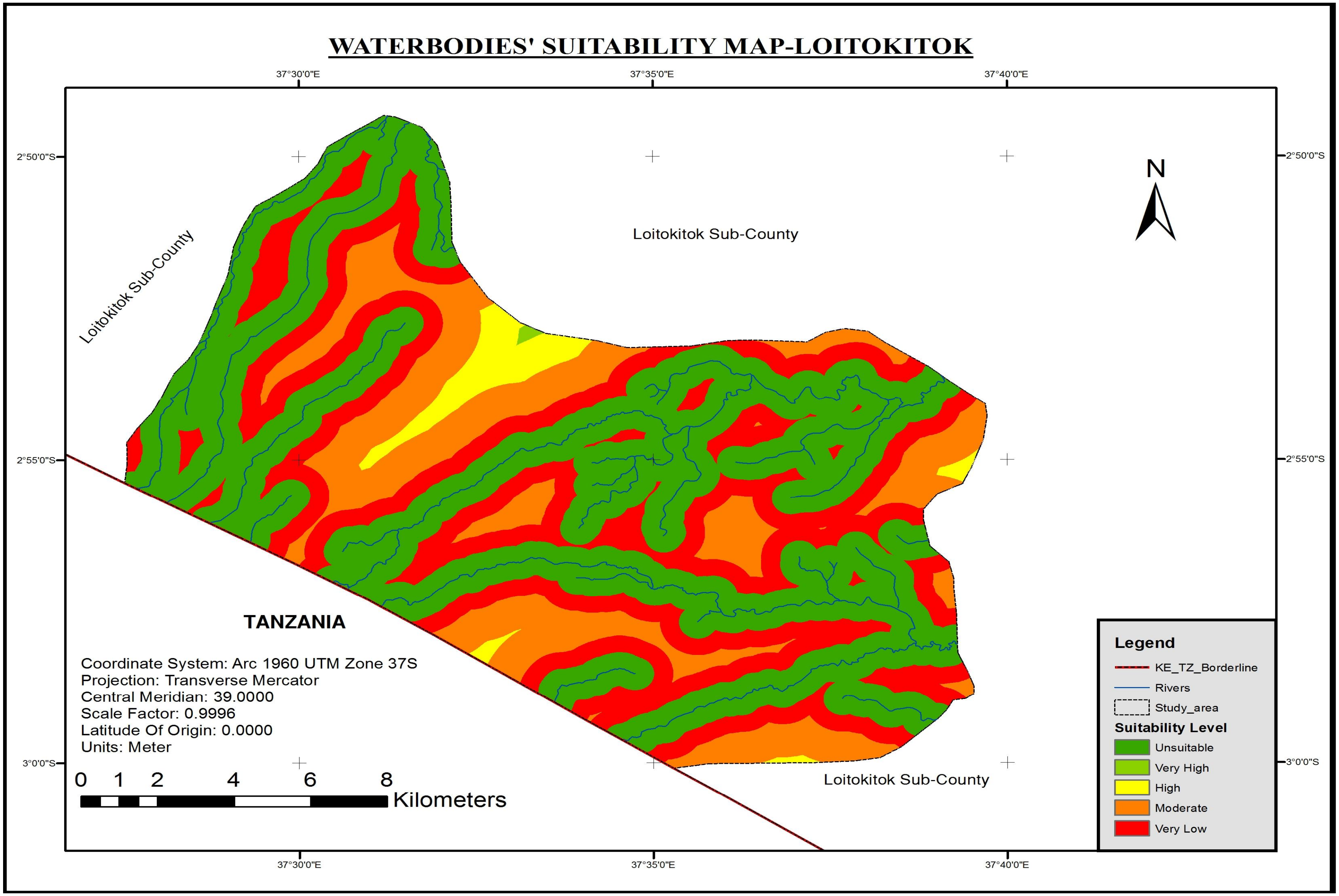

Figure 17: Water bodies suitability map

4.4.4. Airstrip Constraint Criterion map

Airstrips and airports are regarded as key installations that ought to be considered when siting a WWTP due to the fact that birds are usually attracted to waste water disposals on these sites. The study area has no airport but has an airstrip called Loitokitok Airstrip.

The resultant buffer map and a suitability map are shown on figure 18and 19 respectively.

The 2000m buffer area from the airstrip is a restricted area for safety of the aircrafts hence unsuitable. The further the site of the WWTP the better as it provides room for expansion of the airstrip and guarantee safety.

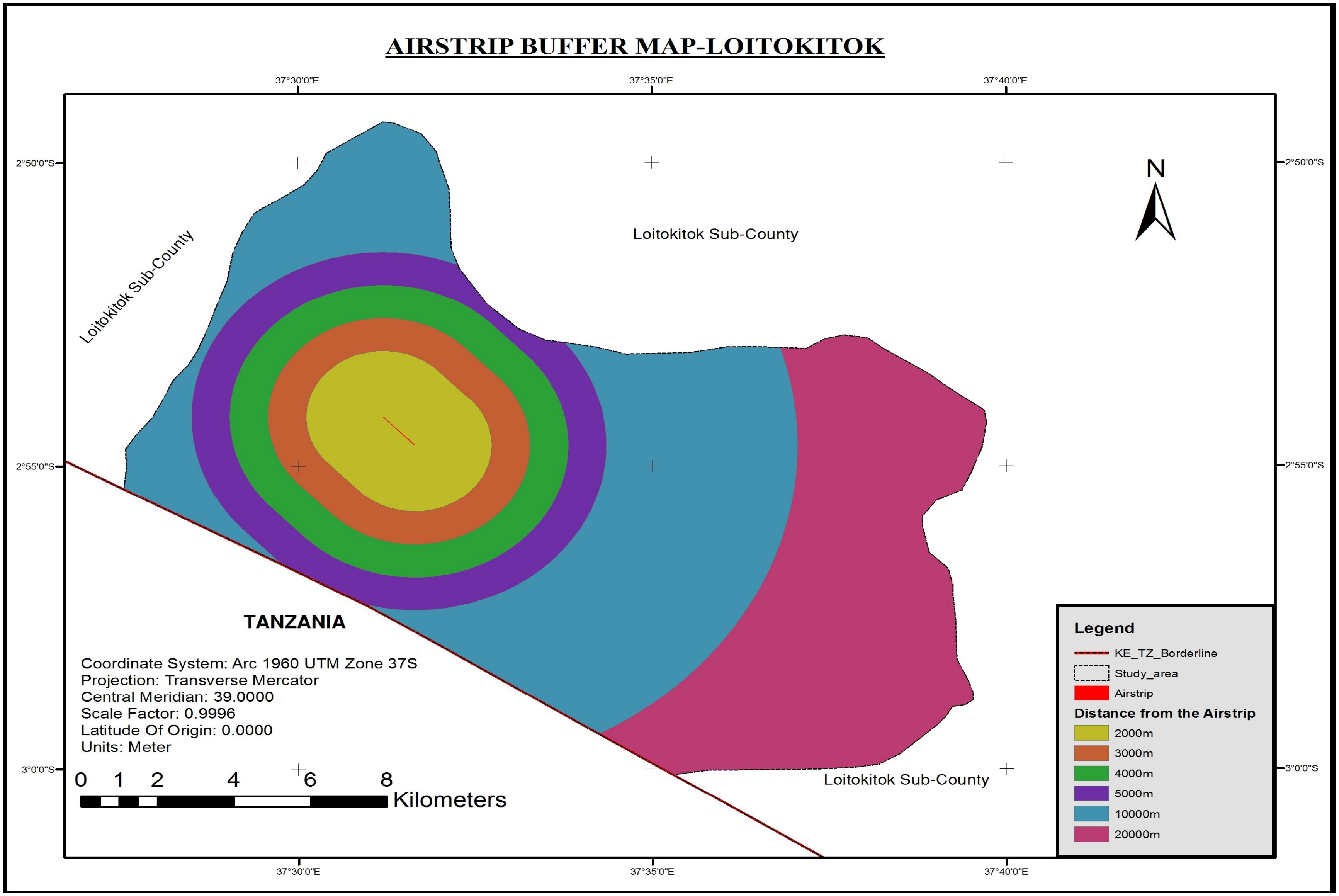

Figure 18: Airstrip buffer map

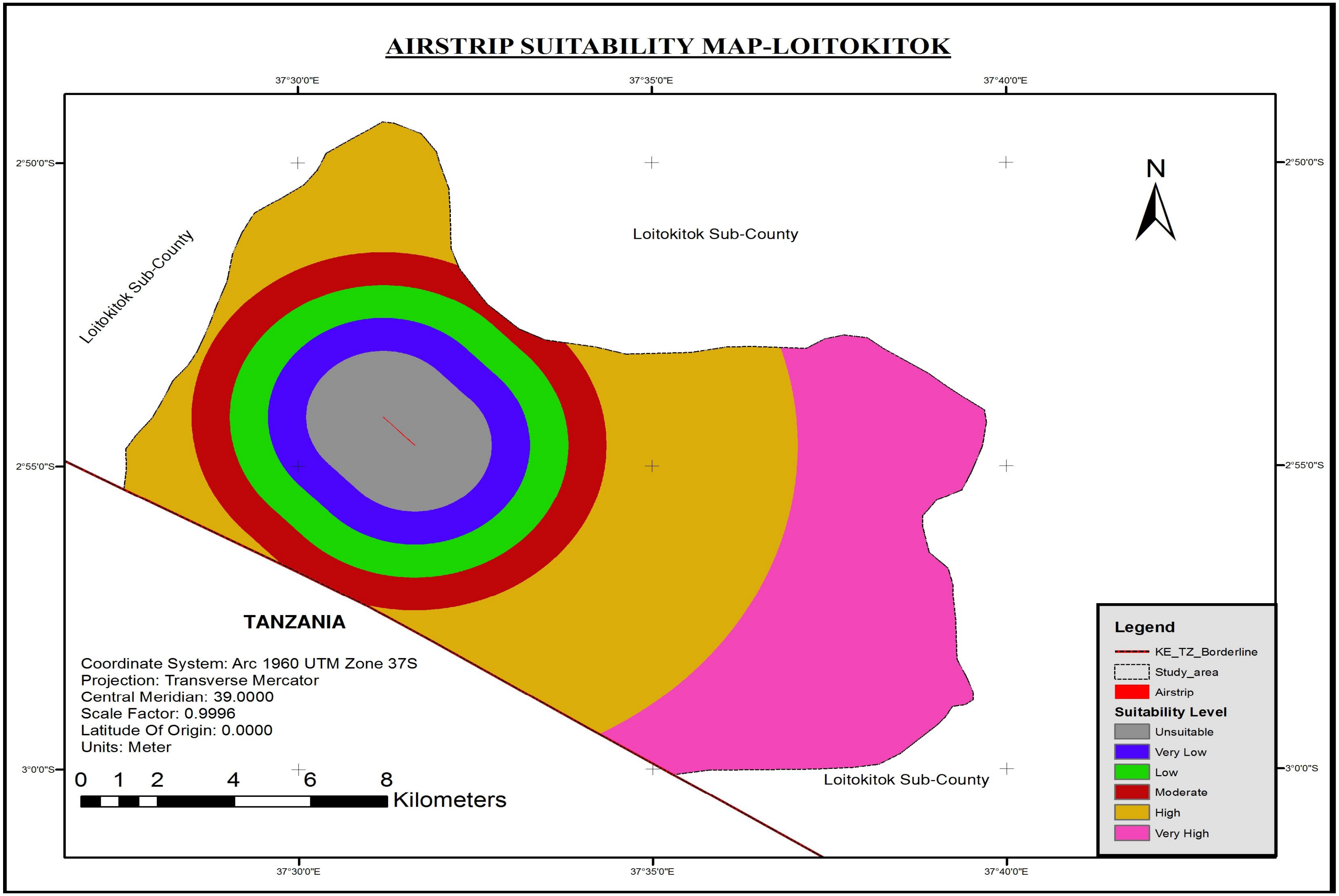

Figure 19: Airstrip suitability map

4.4.5. Kenya –Tanzania Borderline Constraint Criterion map

International borders are also considered during siting of WWTP due to challenges of odour releases, flies nuisance, water pollutions and disruption of people's lives of the neighbouring states. Social, cultural and political issues of the neighboring states ought to be considered. The resultant buffer map and suitability map are shown on figures 20 and 21 respectively. A 1000m buffer area from the borderline was considered as unsuitable and the further the WWTP is located the better hence the 15000m buffer area has a very high suitability level.

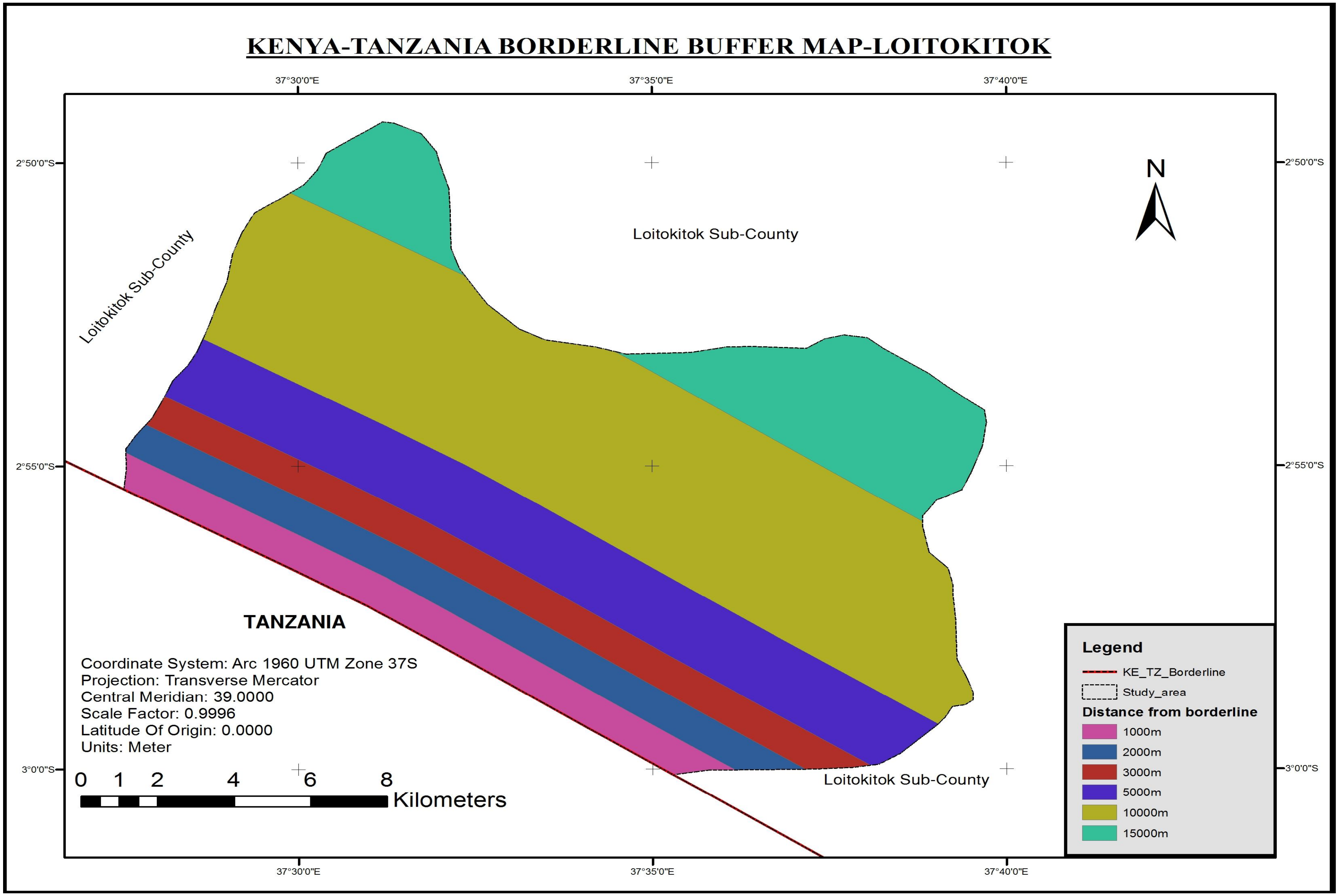

Figure 20: Kenya-Tanzania borderline Buffer map

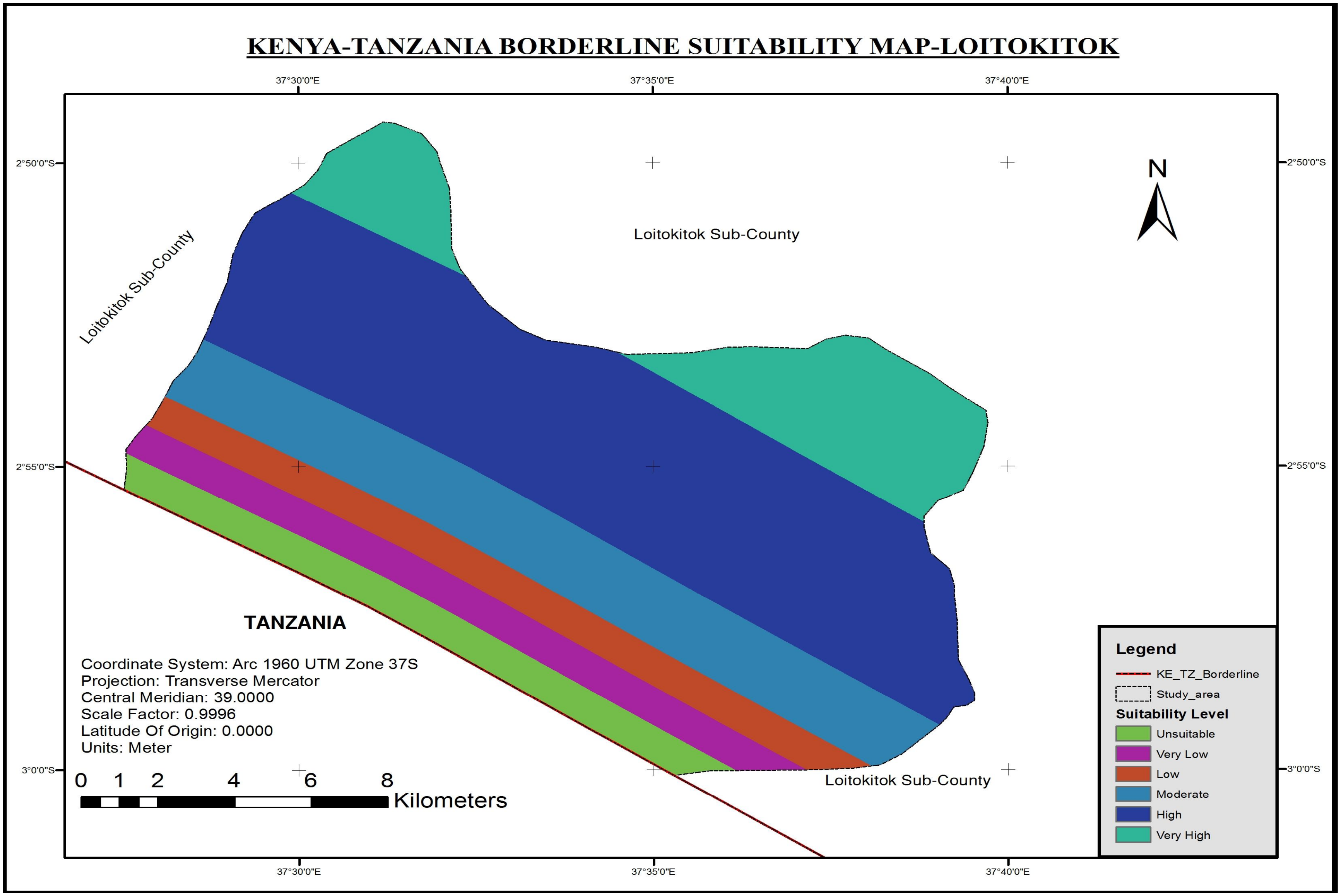

Figure 21: Kenya- Tanzania Borderline Suitability map

4.4.6. Distance-to-town Constraint Criterion map

The distance to targeted town or community that ought to be served by the WWTP was considered as this will determine the costs of trunk sewerlines to be laid from the town to the WWTP. Loitokitok town was lastly planned in 1993 according to the Physical Planning officials of the Kajiado County but from the lidar imagery the town has grown beyond the planned extents.

The 500m buffer area was considered as unsuitable site while the 2km buffer has a low suitability level because it will hinder town expansion and result to the nuisance effects previously discussed. The 10km buffer area has a very high suitability since it will balance the costs of trunk sewerlines' construction against the community to serve and further allow for town expansion.

The resultant buffer map and suitability map are displayed in figures 22 and 23 respectively.

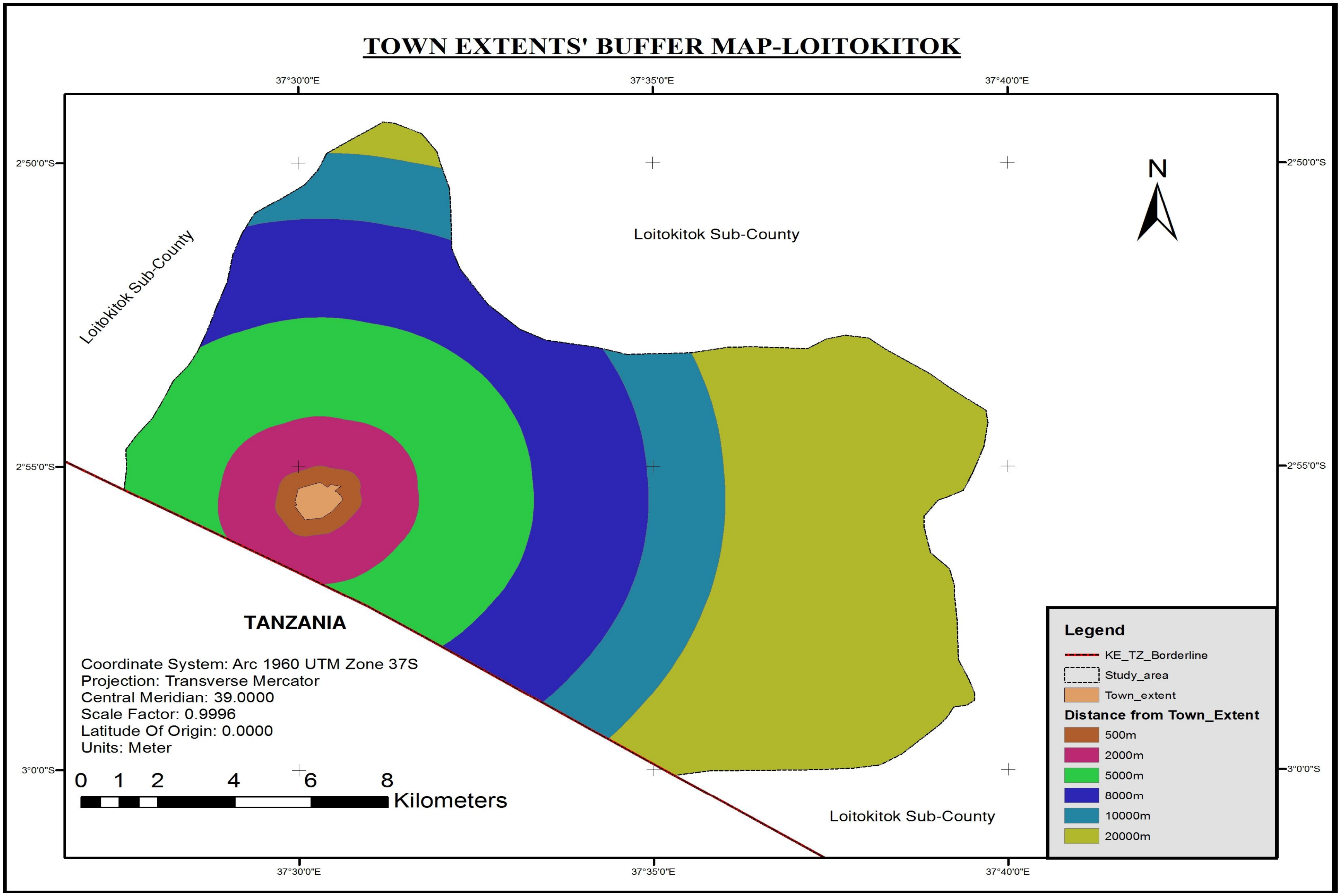

Figure 22: Distance to town buffer map

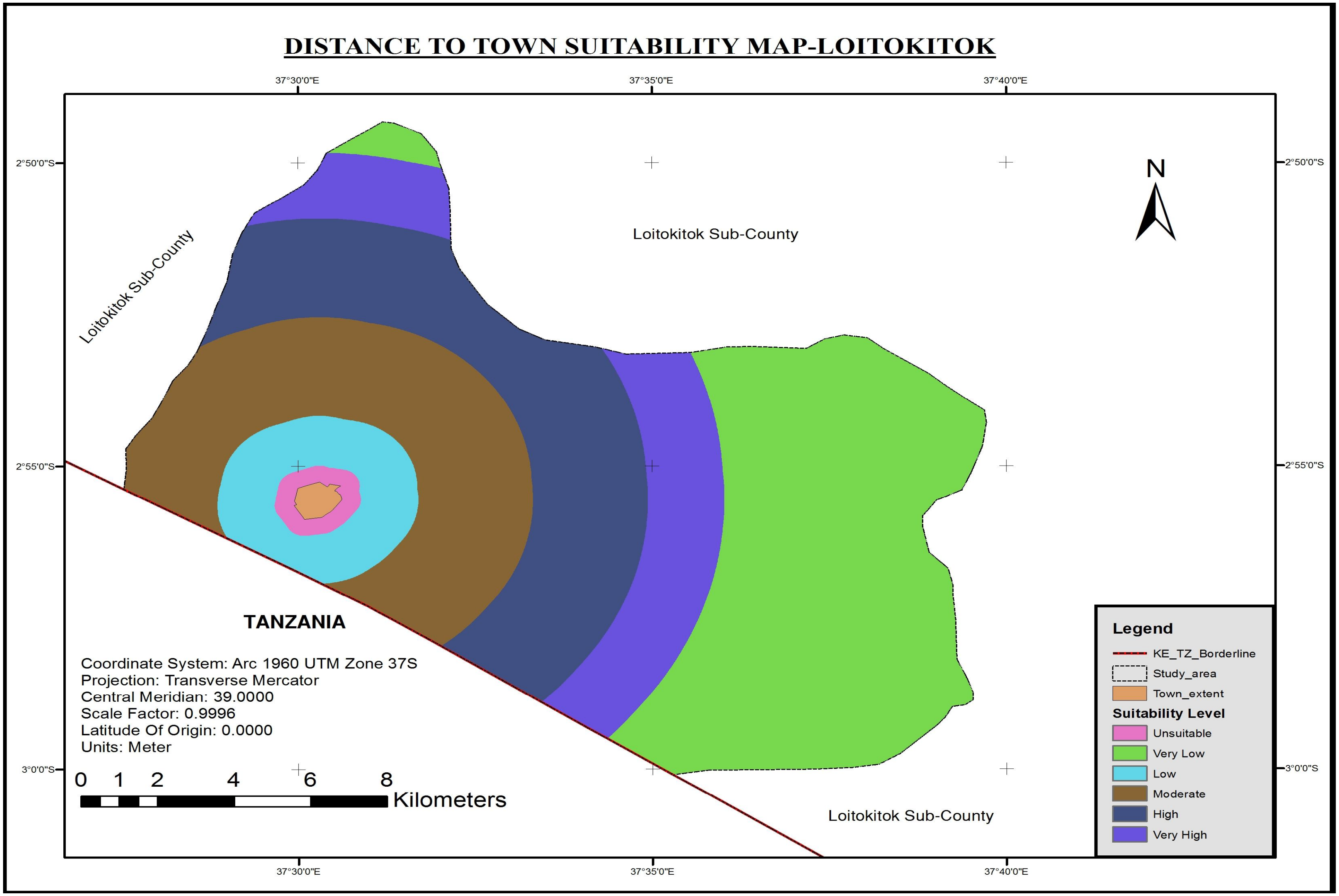

Figure 23: Distance to town suitability map

4.4.7. Land Use Land Cover (LULC) Constraint Criterion map

LULC is also another factor that is considered as it identifies areas that will be highly affected by the installation of a WWTP. Most researchers and organizations like NEMA recommend that WWTP should not be placed on water bodies, wetlands, transportation routes and settlement areas due to the environmental hazards associated. Most suitable areas are bare lands and grassland since the openness provides adequate provision of sun and wind that aid in the treatment process.

The LULC groups realized from the Landsat imagery were settlements, forests, farmlands, bare ground and grassland with shrubs, rock outcrop and other lands. Water bodies could not be depicted due to the tree canopy along the rivers and some of the rivers were dry during the image acquisition.

Settlement areas are the unsuitable areas and rock outcrop have very low suitability level while bare ground and grassland with shrubs have very high suitability level.

The resultant LULC thematic map and the reclassified map based on the suitability levels are shown on figures 24 and 25 respectively.

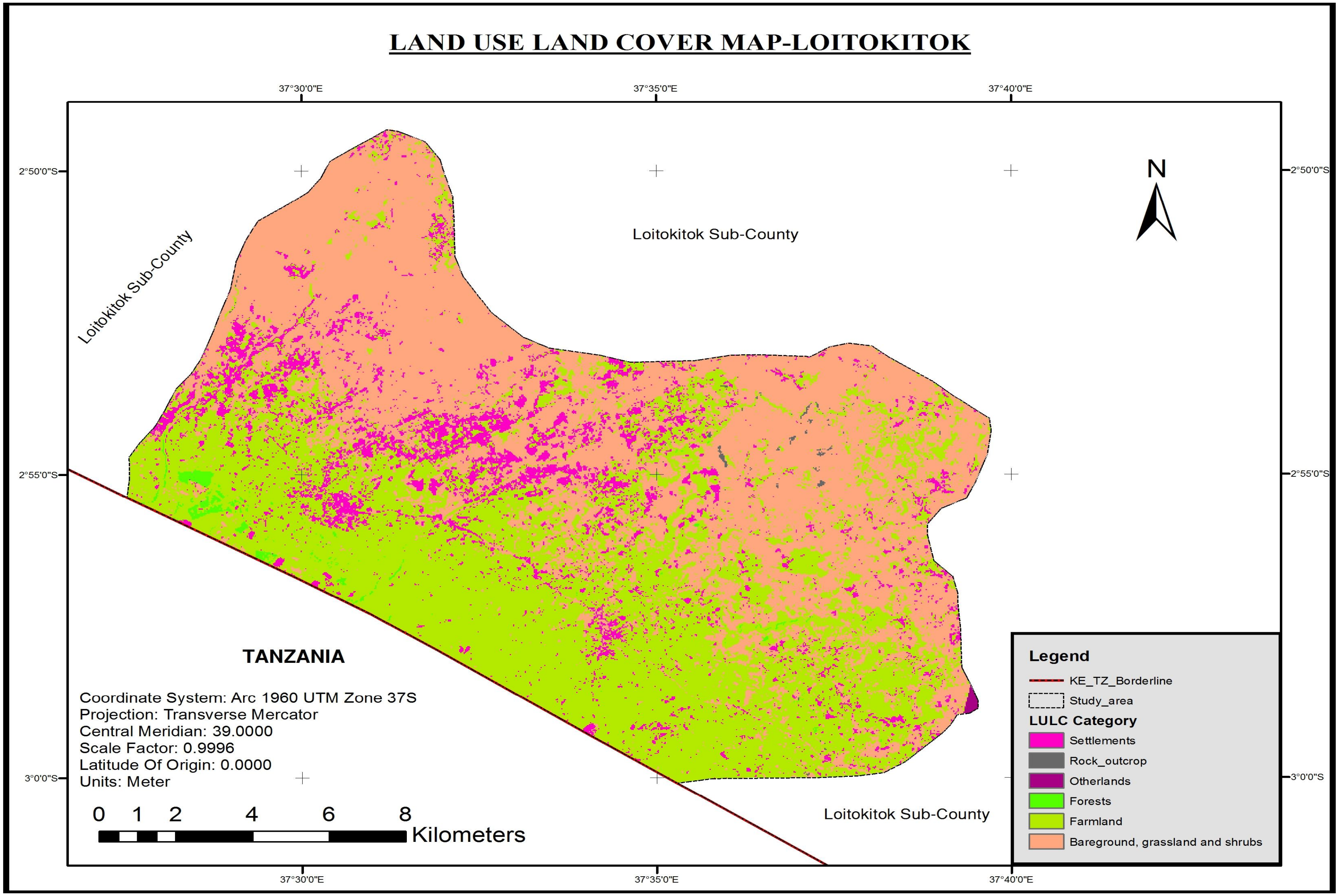

Figure 24: Land Use Land Cover Thematic map

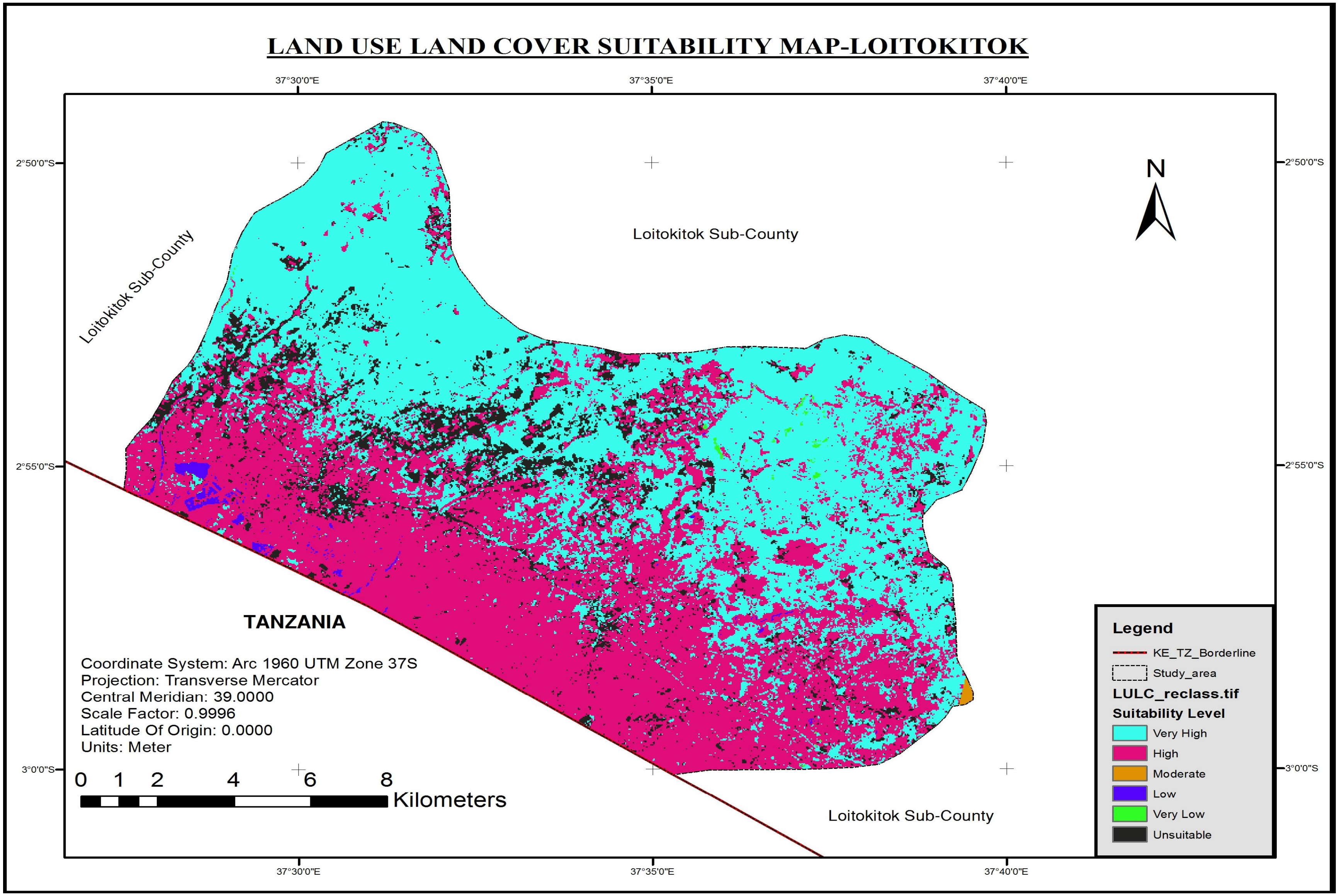

Figure 25: Land Use Land Cover Suitability map

4.4.8. Soils Suitability map

Soil is a key factor on locating a suitable site for the WWTP. Experts emphasize on availability of permeable soils enough to pass the water and yet capable of retaining the water so that treatment occurs.

Clayey texture soils are highly recommended as they are heavy and impermeable. Other key characteristics of soils that should be considered are soil depth, soil drainage, among others. The study area was found to be only composed of Montmorillonitic clayey which covers 24% of the whole area and Kaolinitic clayey soils which covers 76% of the whole area. However the Montmorillonitic clayey soil was found to be well drained within a short period compared to the Kaolinitic clayey soils. Kaolinitic clayey soils areas have a very high suitability level due to its slow draining characteristics compared to Montmorillonitic clayey areas which have a high suitability level.

The Soils thematic map and suitability map are shown on figures 26 and27 respectively.

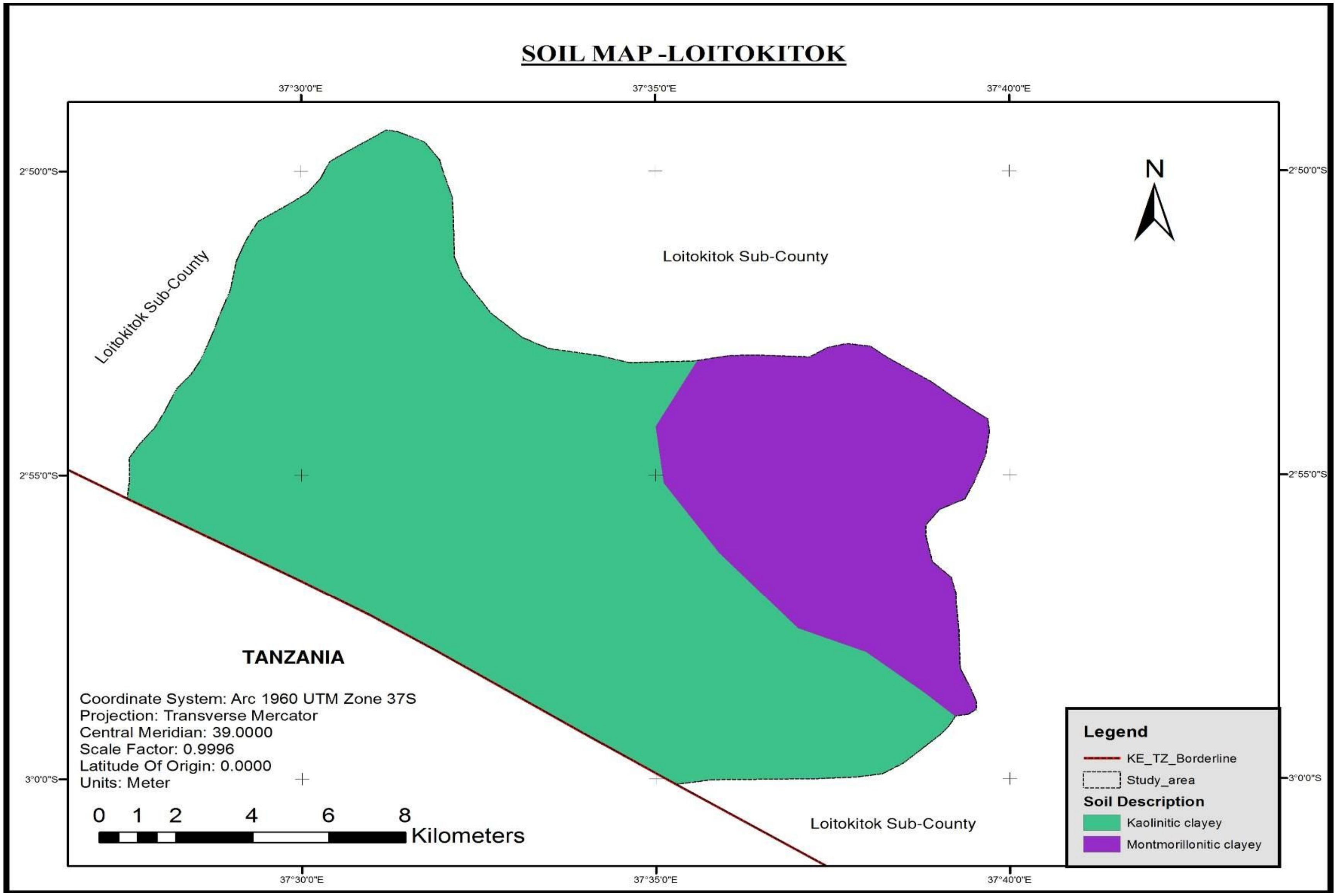

Figure 26: Soil map of the study area

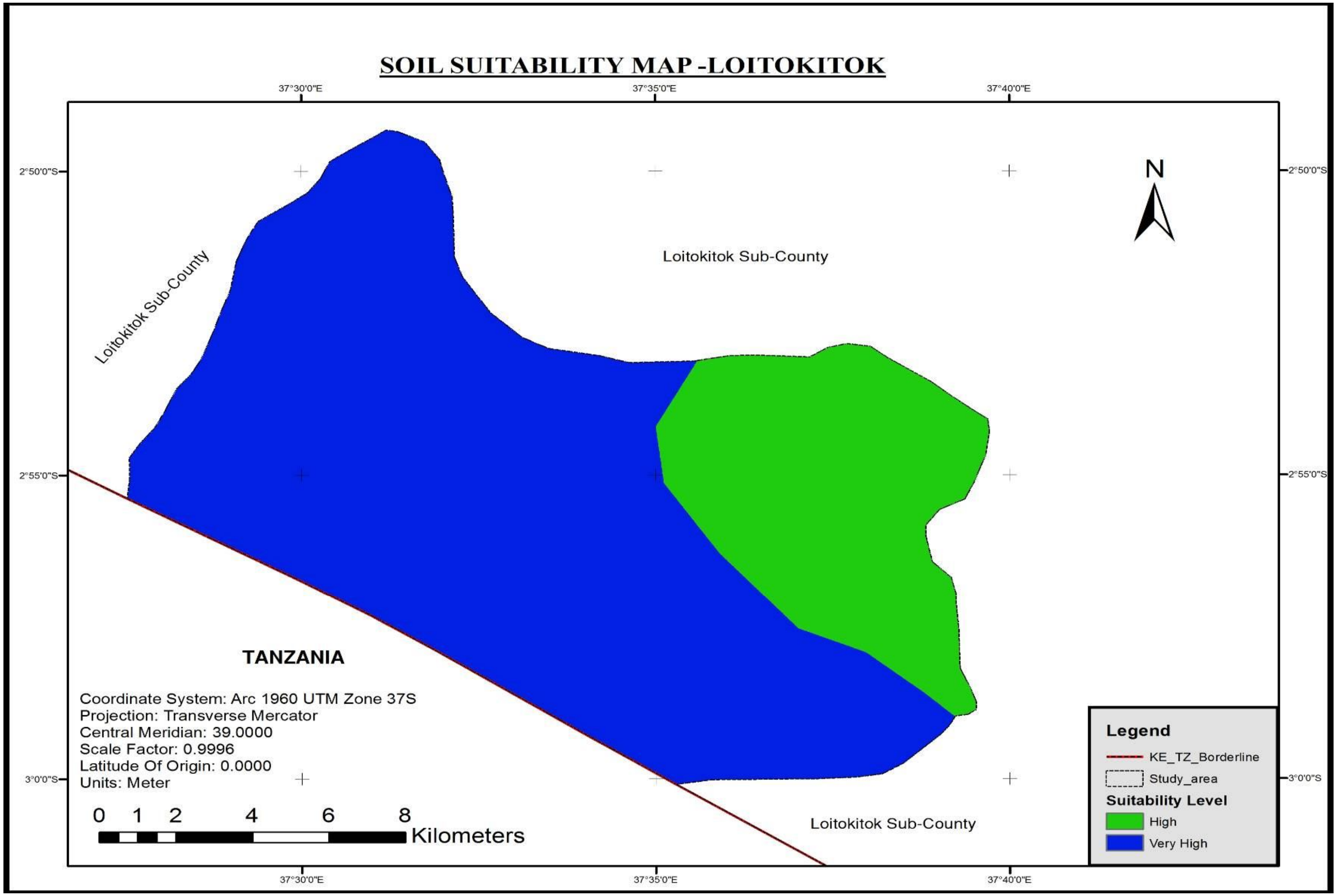

Figure 27: Soil suitability map

4.4.9. Altitude-of-the-town Suitability map

The altitude of the town or of the targeted area to be connected is a key factor which enables one to decide either to go for a gravity system or a pumping system. It's economically feasible to go for a gravity fed WWTP than the pumping system due to the cost of power and of the mechanized system.

From the DEM generated, the town extents' altitude was found to range from 1719m to 1814m above mean sea level while the range of the study area was 1969m to 1293m above mean sea level. The resultant altitude ranges obtained after provision of 2m deep manhole for the trunk sewer line were; 1293m-1717m and 1717m-1969m. The former range represented on figure 28 has a very high suitability level because it would allow a gravity system while the latter has a very low suitability level because a pumping system would be the only option.

The altitude map and the suitability map are shown on figures 28 and29 respectively.

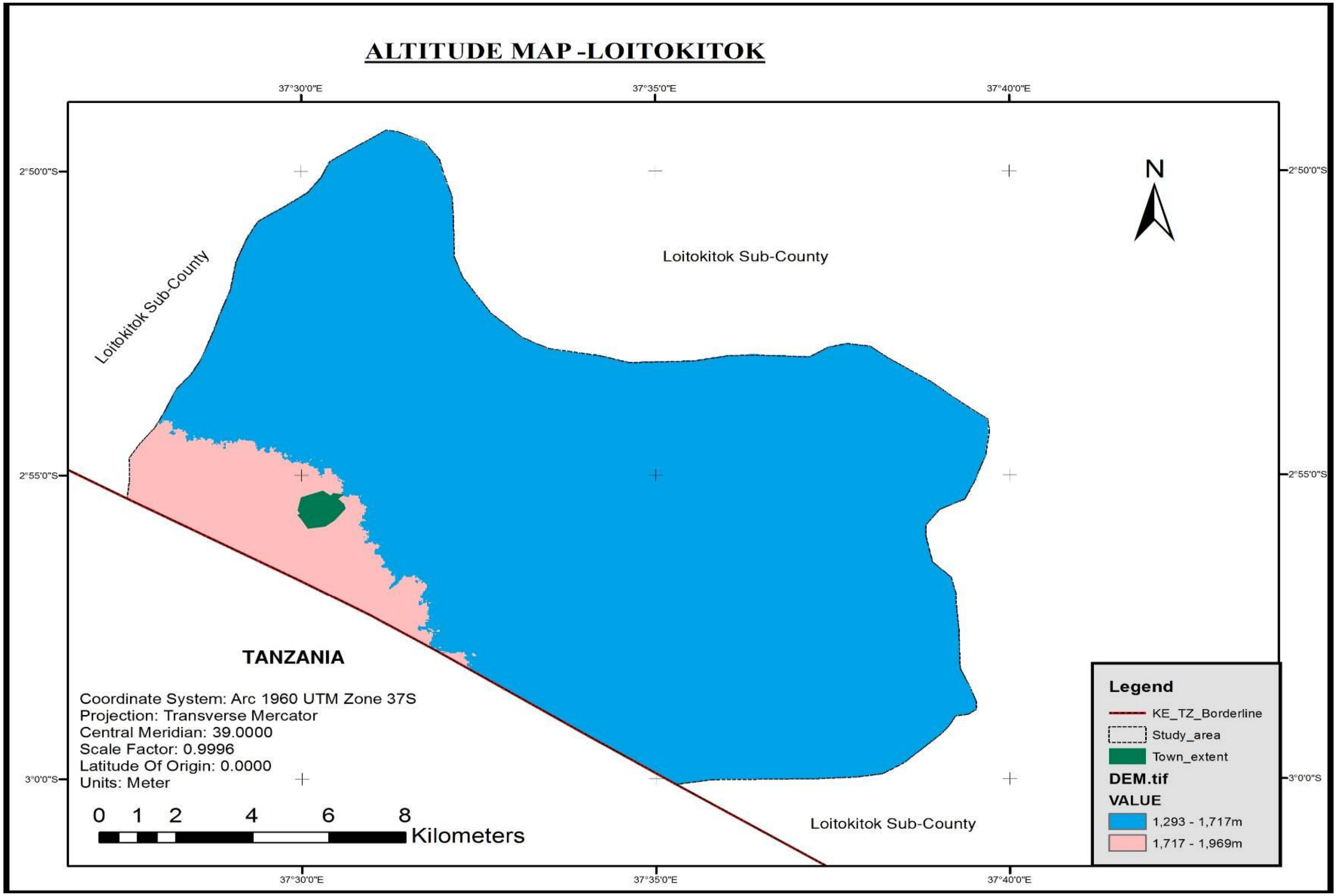

Figure 28: Altitude map of the study area

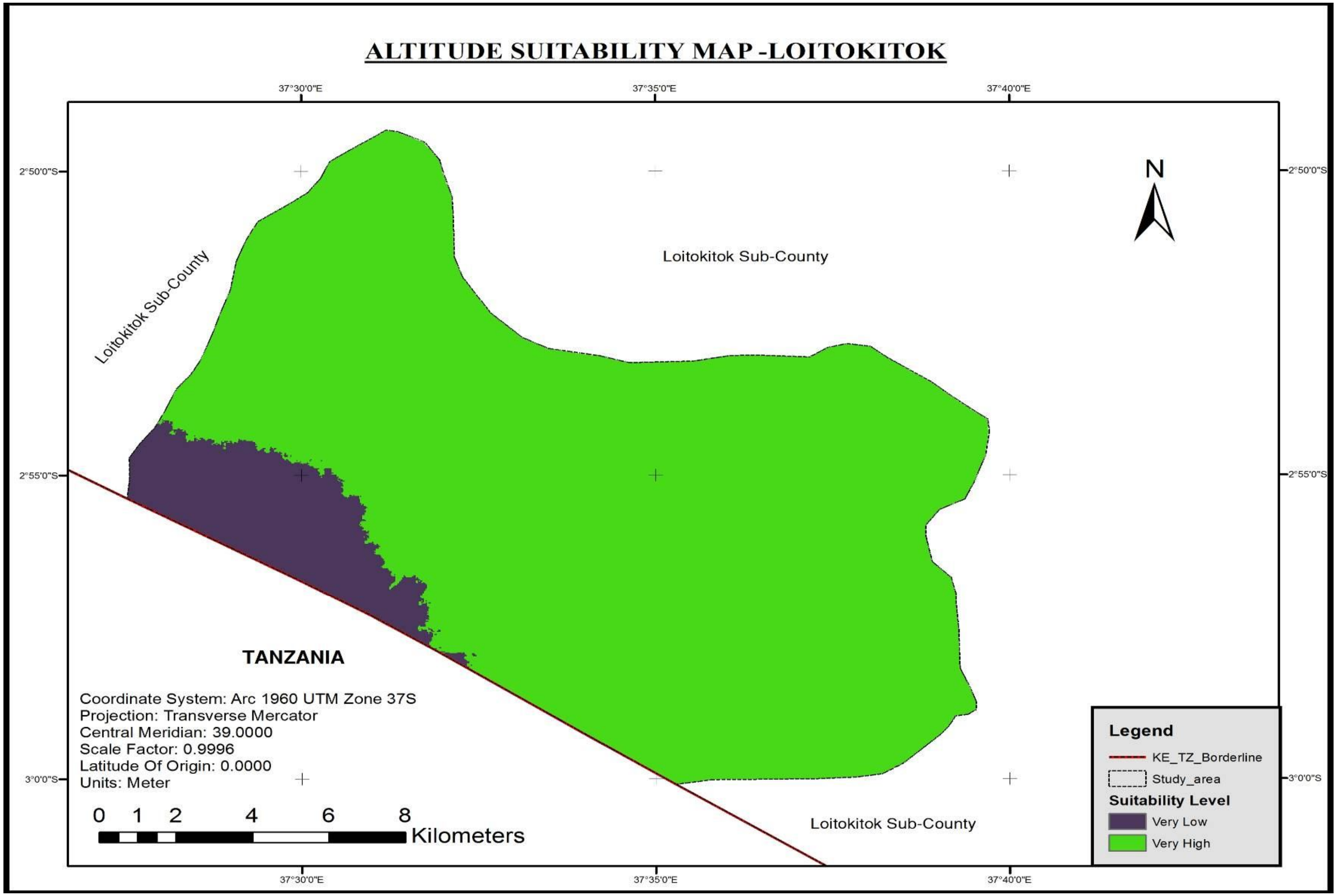

Figure 29: Altitude Suitability map

4.4.10. Ground Slope Constraint Criterion map

The ground slope is another key factor considered so as to avoid huge costs during construction and operation stages. A slope of less than or equal to 15% is preferable but slopes greater than 35% are unsuitable. The generated slope map which was classified into six groups; 0-2%, 2-5%, 5-15%, 15-25%, 25-35% and >35% is shown on figure 28.

Figure 29 shows the suitability map of the study area which indicates that areas with a slope of 0-2% have a moderate suitability, 2-5% have a high suitability, 5-15% have a very high suitability level, 15-25% have a low suitability level , 25-35% have a very low suitability and areas with slopes greater than 35% are the unsuitable areas. Slopes of 5-15% have very high suitability level because it reduces excavation works and also ensures easy flow of the wastewater within the ponds and the treated effluent to the river.

The resultant slope map and reclassified map are shown on figures 30 and 31 respectively.

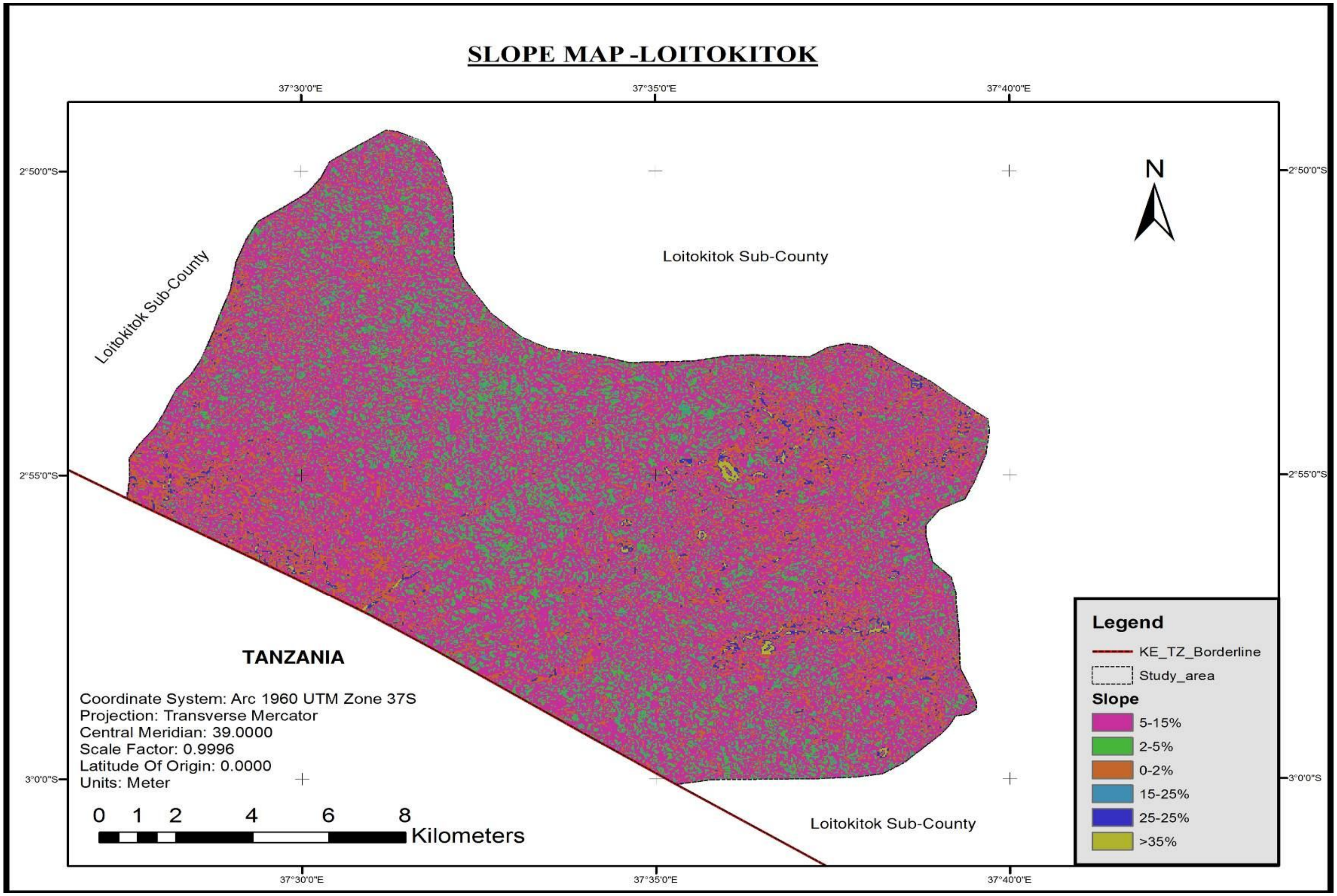

Figure 30: Slope map of the study area

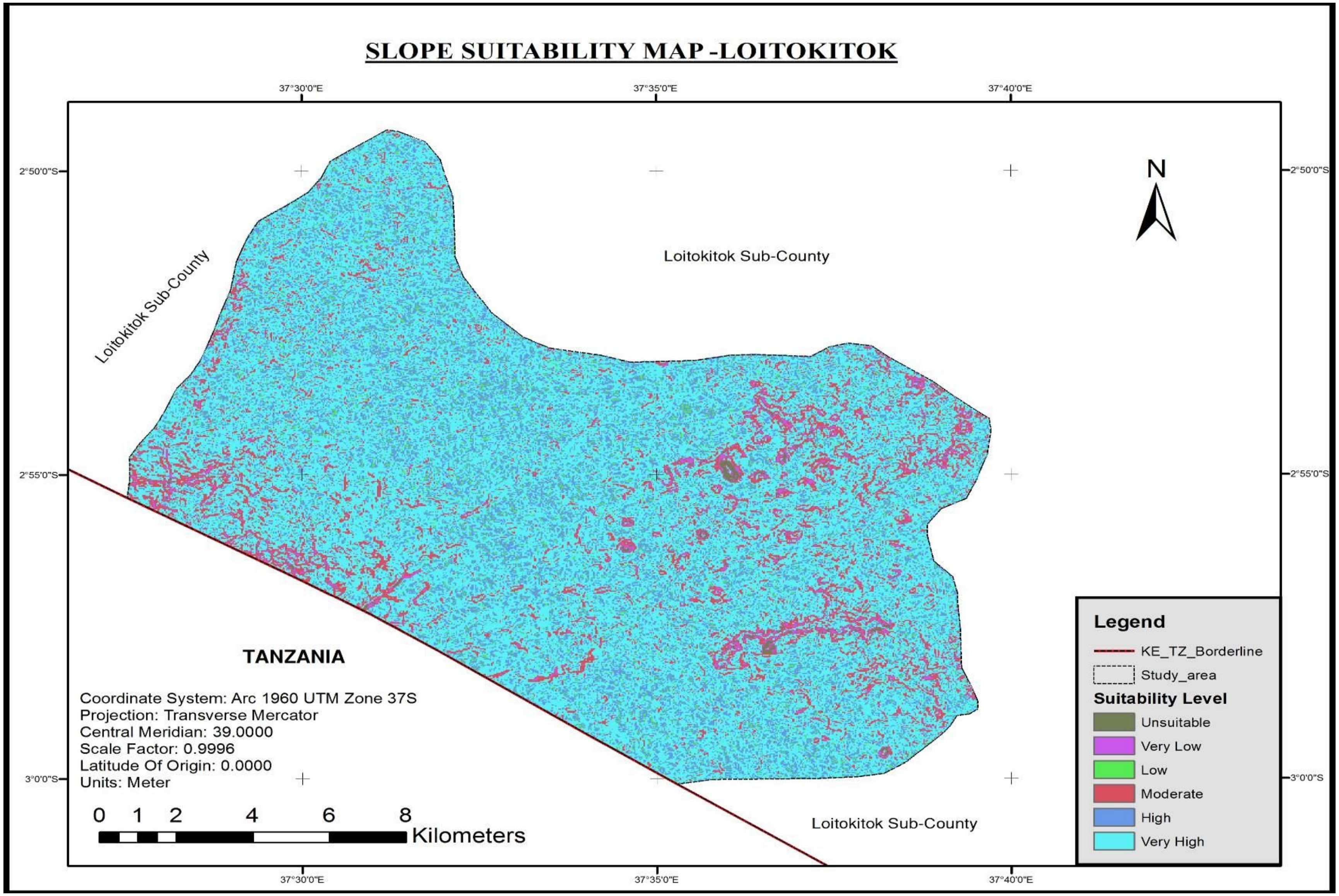

Figure 31: Slope suitability map

4.5. Overall Suitability Map

After execution of the weighted overlay analysis where all variables were combined with respect to their weights, the suitable sites were identified from the output in raster format. The resultant raster map is shown on figure 33.

The extracted areas with very high suitability levels are shown on figure 34. The administrative boundaries of the sub-locations shown defined the sub locations were these most suitable sites are located for further studies. Majority of the most suitable sites were found within Kimana Sub location, then others in Loolopon Sub location and the least in Kuku sub location. None of the most suitable site was found on Entarara and Entonet sub locations of the study area.

The resultant areas in the overall suitability map based on suitability levels are tabulated below.

Table 4-2: Resultant areas in the overall suitability map

Suitability scale	Area(m^2)	Remarks
0	218,232,096	Unsuitable areas
3	408,842	Moderate suitability areas
4	26,333,210	High Suitability areas
5	1,241,738	Very High Suitability areas
Total area	**246,215,886**	

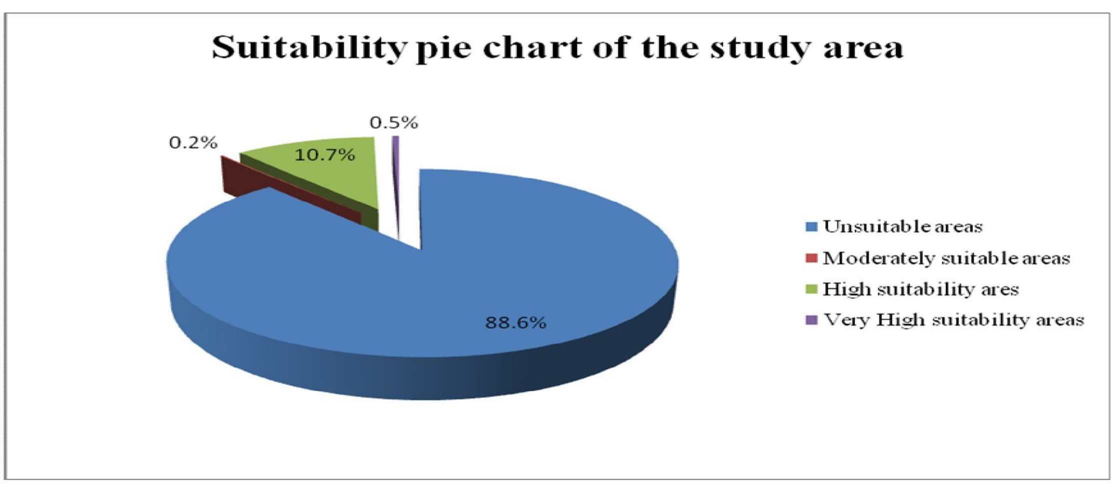

Figure 32: Resultant Suitability Pie Chart of the Study Area

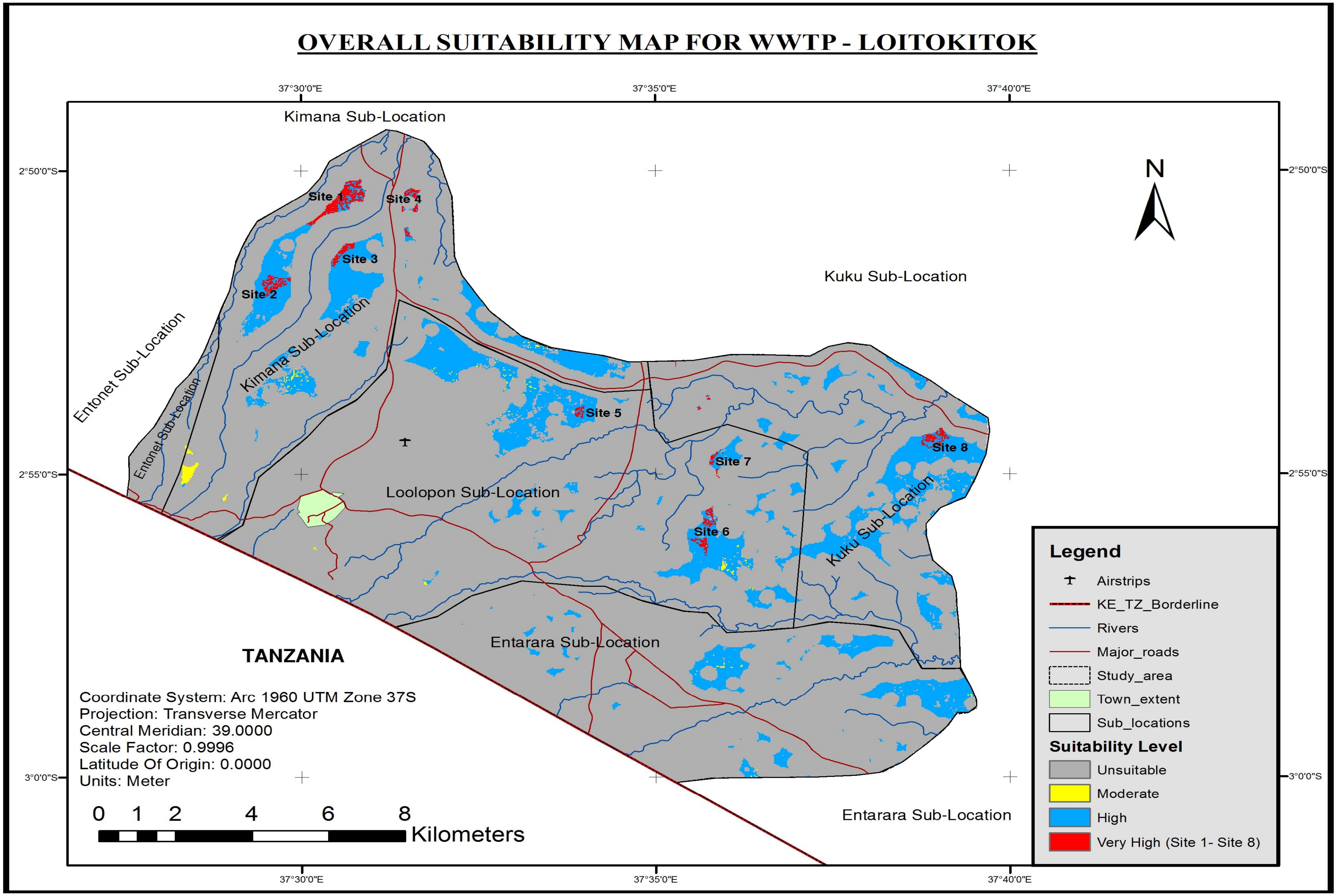

Figure 33: The overall suitability map for waste water treatment sites

4.6. Final results

The most suitable areas were realized after considering all the ten variables and applying the determined weights. The most suitable sites are numbered; Site 1, Site 2, Site 3, Site 4, Site 5, Site 6, Site 7 and Site 8 as shown on Figure 34.

Details of the sites inclusive of their approximate coordinates in UTM 37S Arc 1960 system were extracted and are listed below.

Table 4-3: Location and details of the most suitable sites

Site Name	Easting (m)	Northing (m)	Average Height (m)	Distance from Loitokitok town	Approximate Consolidated Area (Ha)	Sub-Location
Site 1	334349	9685925	1415	9.3 km	53	Kimana
Site 2	332506	9683317	1525	6.8 km	25	Kimana
Site 3	334366	9684231	1460	7.6 km	13	Kimana
Site 4	336093	9685609	1393	9.2 km	15	Kimana
Site 5	340578	9679431	1525	7.3 km	6	Loolopon
Site 6	343909	9675868	1490	10.1 km	26	Loolopon
Site 7	344075	9677927	1455	10.3km	7	Loolopon
Site 8	350026	9678501	1328	16.3 km	27	Kuku

Table 4-4: Location and Elevation of town

Name	Easting (m)	Northing (m)	Lowest Height (m)	Height considered for effective sewer line connection(m)
Loitokitok town	333869	9676664	1719	1717

On comparison of the elevations, all sites were found capable of receiving the sewage from town through gravity. Site 2 was found to be the nearest to town while Site 8 was found to be the furthest. Site 5 has the smallest consolidated area while Site 1 has the largest area. Assuming the trunk sewerline route will be a direct line from town to the most suitable WWTP sites, all the sites except site 5 would require a river crossing(s) and /or a major road crossing(s) of the trunk sewerline which is costly and might pose some technical challenges during construction and maintenance.

Site 5 was therefore found to be the best location for a WWTP site that would optimally serve the Loitokitok town. Despite the area being small it can be extended to the surrounding areas that have high suitability levels to obtain an area of more than 30 Ha which can serve the town for many years. The treated effluent can be easily drained into the Naromoru River on southern side and the site can be easily accessed from major roads; C103 on the northern side and E703 on the eastern side.

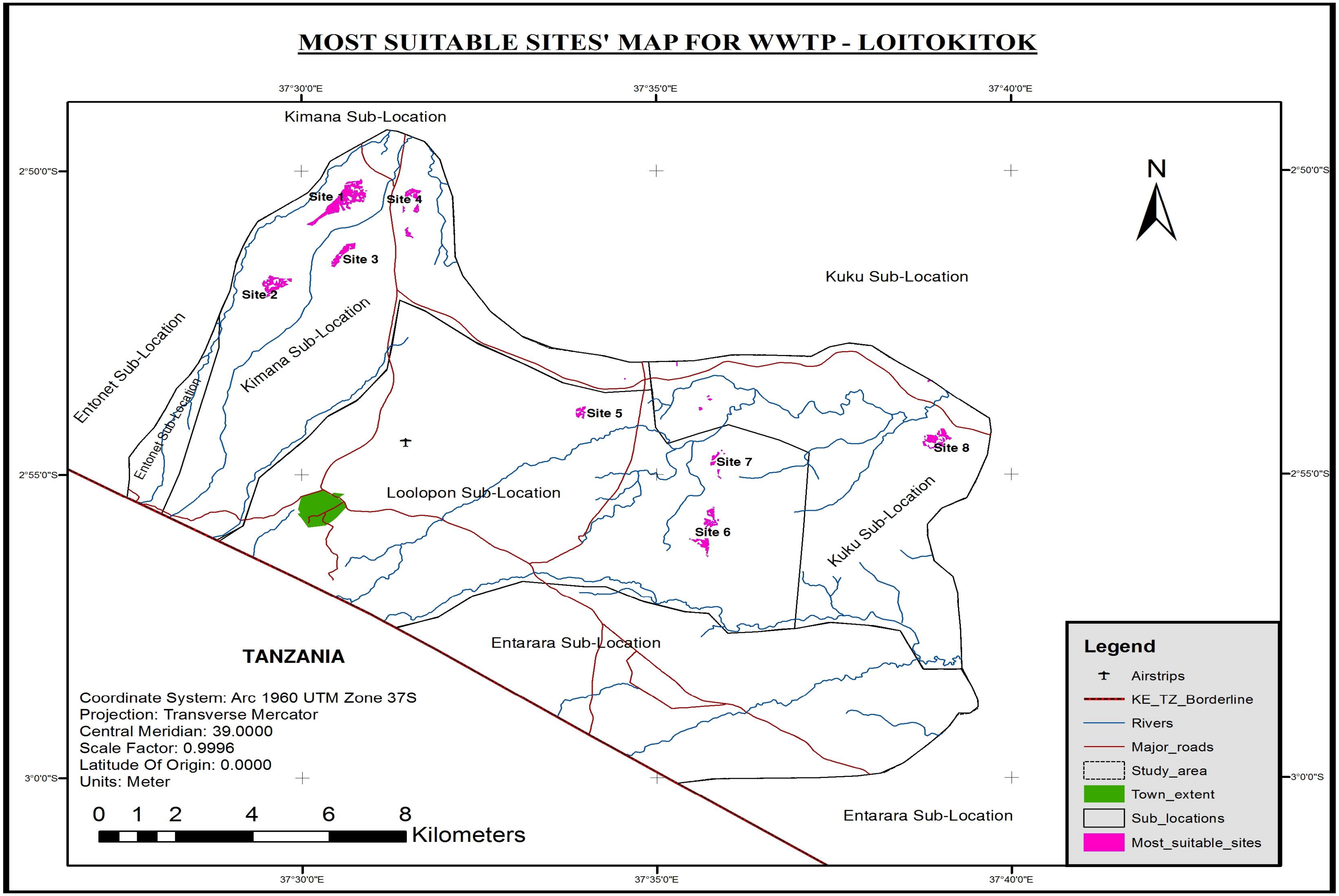

Figure 34: Most suitable sites 1-8 for WWTP

4.7. Results Validation and Comparison with previous studies

The two previously proposed sites overlaid on the most suitable sites map are shown on figure 35. One of the studies was a feasibility study for water and sanitation of Loitokitok project done by Wanjohi Consulting Engineers in 2009 and another was detailed design of water and sewerage system for Loitokitok town done by Runji and Partners Consulting Engineers in 2015. The maps of these two previous studies are attached in Appendix A.

On Wanjohi's proposed WWTP site, 20% coverage of the site lies on the areas of high suitability but 80% lies on restricted area (unsuitable areas) due the 2km buffer from the airstrip and some dwelling houses lies within the proposed site. Possibly the houses never existed during the study. The Wanjohi's proposed WWTP site has been named 'WWTP_Site-Wanjohi' as shown on figure 35.

On Runji's proposed WWTP site, the whole area falls within the unsuitable area category mostly because they never considered a 500m buffer from the river and some houses are seen to exist in the neighborhood. However site 5 is approximately 1km away and also areas of high suitability levels borders these previously identified sites. The Runji's proposed WWTP site has been named 'WWTP_Site-Runji' as shown on figure 35.

Table 4-5: Location of proposed WWTP sites from previous studies

Name	Easting (m)	Northing (m)	Distance to town (km)	Area (Ha)
Wanjohi site	338041	9678356	4.3	72
Runji site	339731	9678251	6	23

The thematic layers of major roads, rivers, airstrip and town extent were also shown on the overall suitability map and clearly the most suitable sites fall at safe distances away from these feature factors.

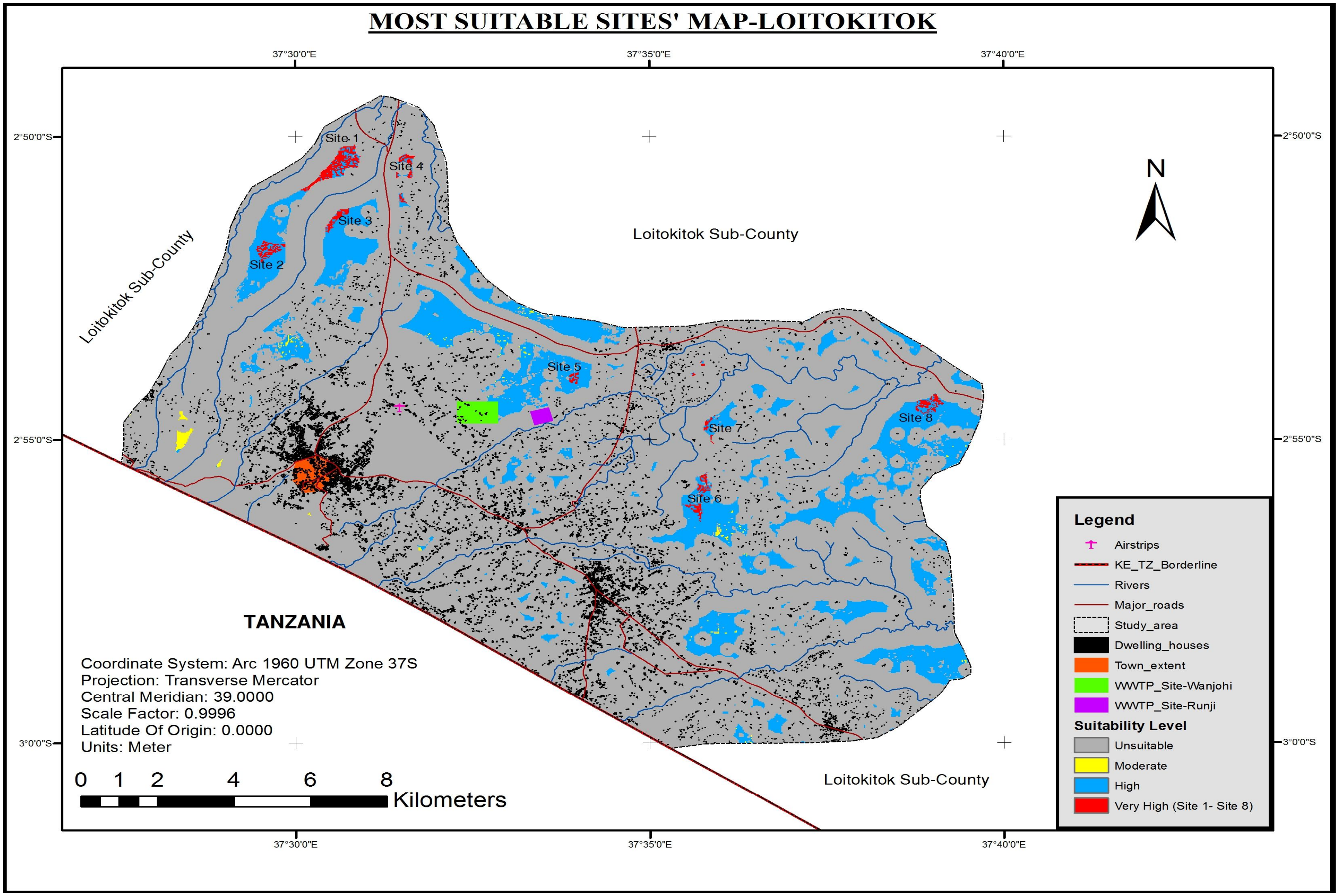

Figure 35: Comparison map of previously proposed sites and current results

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The Analytic Hierarchy Process was found to be a robust method of multi-criteria decision making. The weightages of the ten criteria used in the study; dwelling houses, major roads, water bodies, LULC, distance to airstrip, distance to town, altitude of town, distance from Kenya-Tanzania border line, soils and ground slope, were successfully processed using the AHP method. Based on experts' responses, the most significant criterion was the water bodies with a significance level of 21%, followed by Altitude-of-the-town criterion at 17%, Slope at 11%, distance to town at 10% while Kenya-Tanzania border variable had the lowest level of 4%. The other factors had the level of significance ranging from 4% to 10%.

The resultant suitability maps based on each criterion were useful in depicting the unsuitable areas and areas of very low, low, moderate, high and very high suitability levels. The resultant overall suitability map clearly depicted the most suitable sites for a wastewater treatment. In consideration of the study area which is $246km^2$, 88.6% falls under the unsuitable areas' category, 10.7% under high suitability areas' category, 0.5% under very high suitability areas' category and 0.2% under moderate suitability areas' category. The most suitable sites were found to be eight in number and they are all fall within the very high suitability areas' category. Site 2 was found to be the nearest to Loitokitok town at an approximate distance of 6.8km, Site 5 was second nearest to town at distance of 7.3km,Site 8 was the farthest from town at a distance of 16.3km while the other sites' distance from town was ranging from 7.6km to 10.3km. Further evaluation and comparison revealed that Site 5 can easily be served with a trunk sewerline that doesn't cross a major road and/ or a river unlike the other sites hence the best site for a wastewater treatment plant. The previously identified sites were found to be near Site 5. The site identified by Runji & Partners Consulting Engineers in 2015 was found to be approximately one kilometer away from Site 5 but it entirely falls within the unsuitable areas' category because it is within the 500m unsuitable areas' buffer zone from the water bodies which has been adopted for this study. The site identified by Wanjohi Consulting Engineers in 2009 was found to be approximately two kilometers away from site 5 but the site partly falls within the unsuitable sites' category and the high suitability areas' category. The Wanjohi site partly falls within the unsuitable areas' category due the 2km unsuitable areas' buffer zone from the airstrip and the 200m unsuitable areas' buffer zone from dwelling houses which are the constraint criteria adopted for this study.

This study has proved Geospatial technologies as an effective tool for selection of suitable site(s) for a wastewater treatment plant. The spatial analyst tools in Arc toolbox of ArcGIS software were found to be very useful for suitability analysis. The overall objective of this study on selection of suitable sites for a wastewater treatment plant site was met.

5.2. Recommendations

The study will be very useful in identification of most suitable sites for towns that do not have a sewage treatment plant. The Geospatial technologies will greatly help Engineers, Physical planners, Environmentalists and other experts involved in sitting suitable areas for WWTP and other related infrastructures.

Additional factors which were proposed by the respondents in the questionnaires like wind direction, land cost, cost of the sewerage system among others need to be included in the next study to validate the results. The number of respondents or experts can also be increased during the next study to ensure redundant expert judgments' are collected and analyzed. The local community living within the study area should also be involved to give their opinions since they play a vital role to the success of the actual project implementation.

A different MCDA method of determining the relative weights of the variables like the Fuzzy Logic and Analytic Network Process (ANP) need to be used in the next study to validate the results obtained.

Collection of up to date data and additional detailed studies of the identified suitable sites on the ground ought to be undertaken before actualization of the project. These additional studies shall include ground topographical surveys, soils investigations, hydrology and drainage investigations, environmental and social impact assessment (ESIA) among others.

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APPENDICES

Appendix A: Previous Studies' Maps

Appendix B: Raw Data

Appendix C: Relative Weights Calculations and Filled Questionnaires

Appendix D: Resultant Model Built

Appendix A: Previous Studies' Maps

a) Wanjohi Consulting Engineers' proposed site

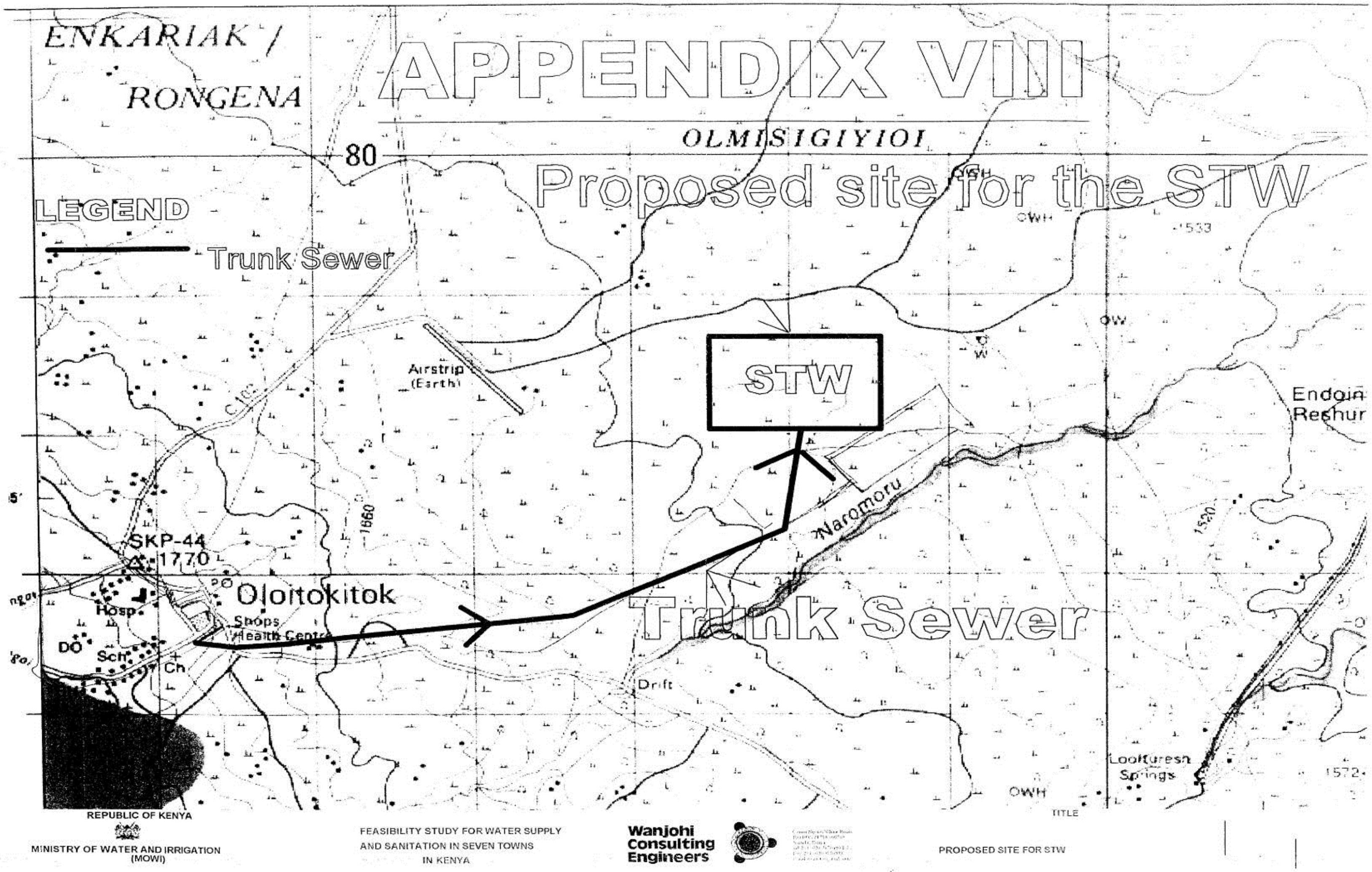

Figure 36: Wanjohi Consulting Engineers' proposed site map

b) Runji & Partners Consulting Engineers' proposed site

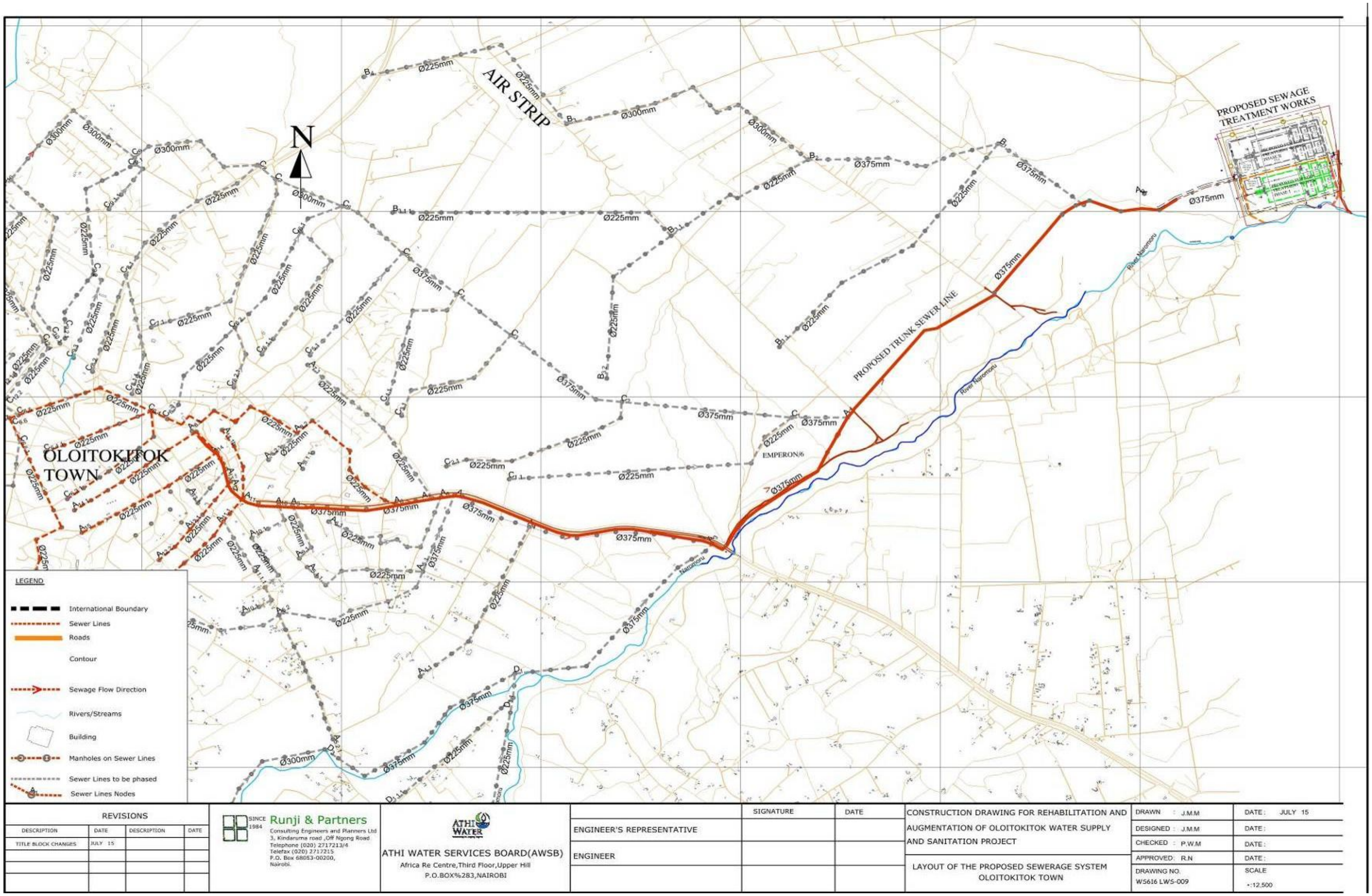

Figure 37: Runji& Partners Consulting Engineers' proposed site map

Appendix B: Raw Data

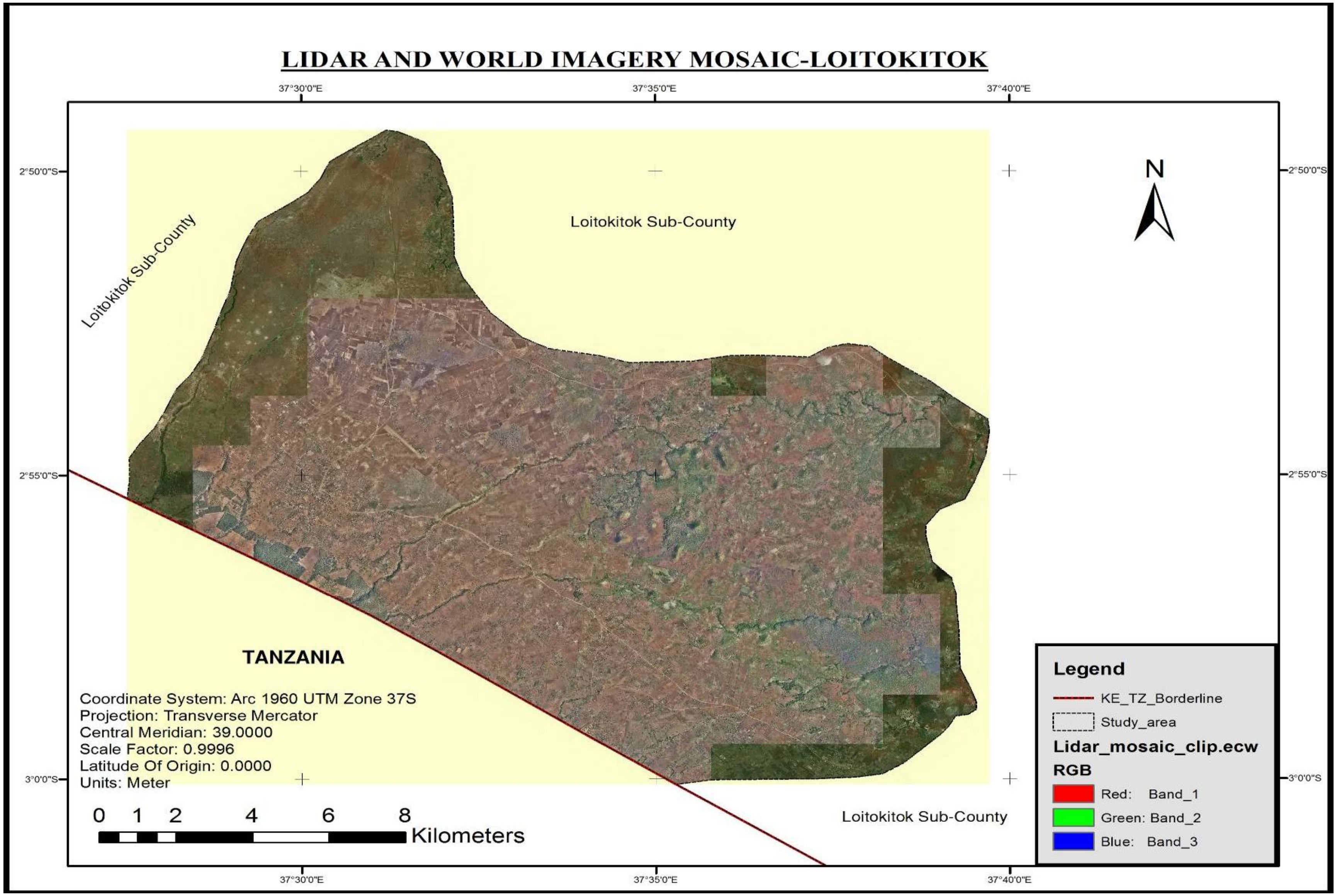

Figure 38: Lidar -World imagery mosaic of the study area

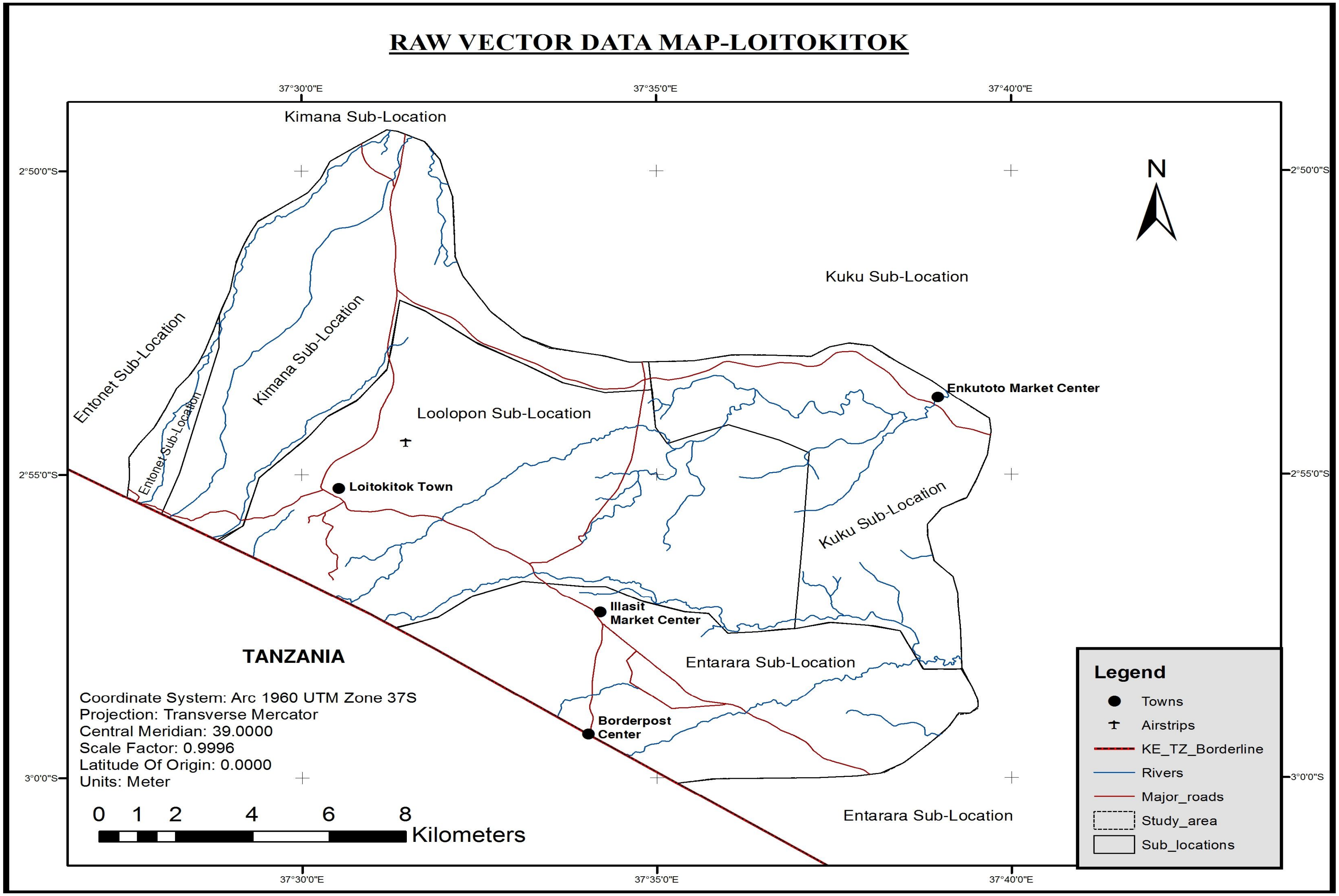

Figure 39: Raw Vector Data of the study area

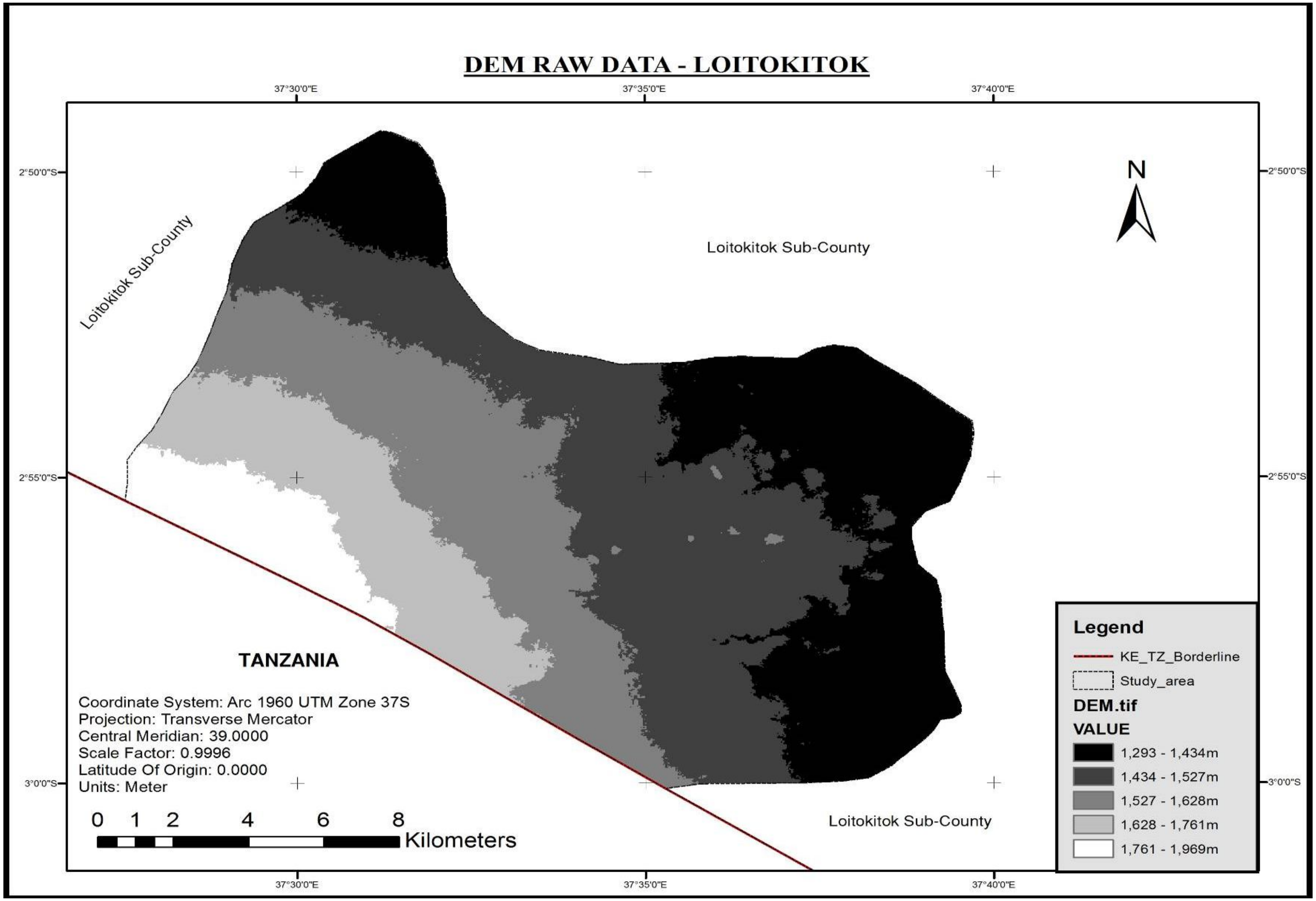

Figure 40: DEM Raw Data for the study area

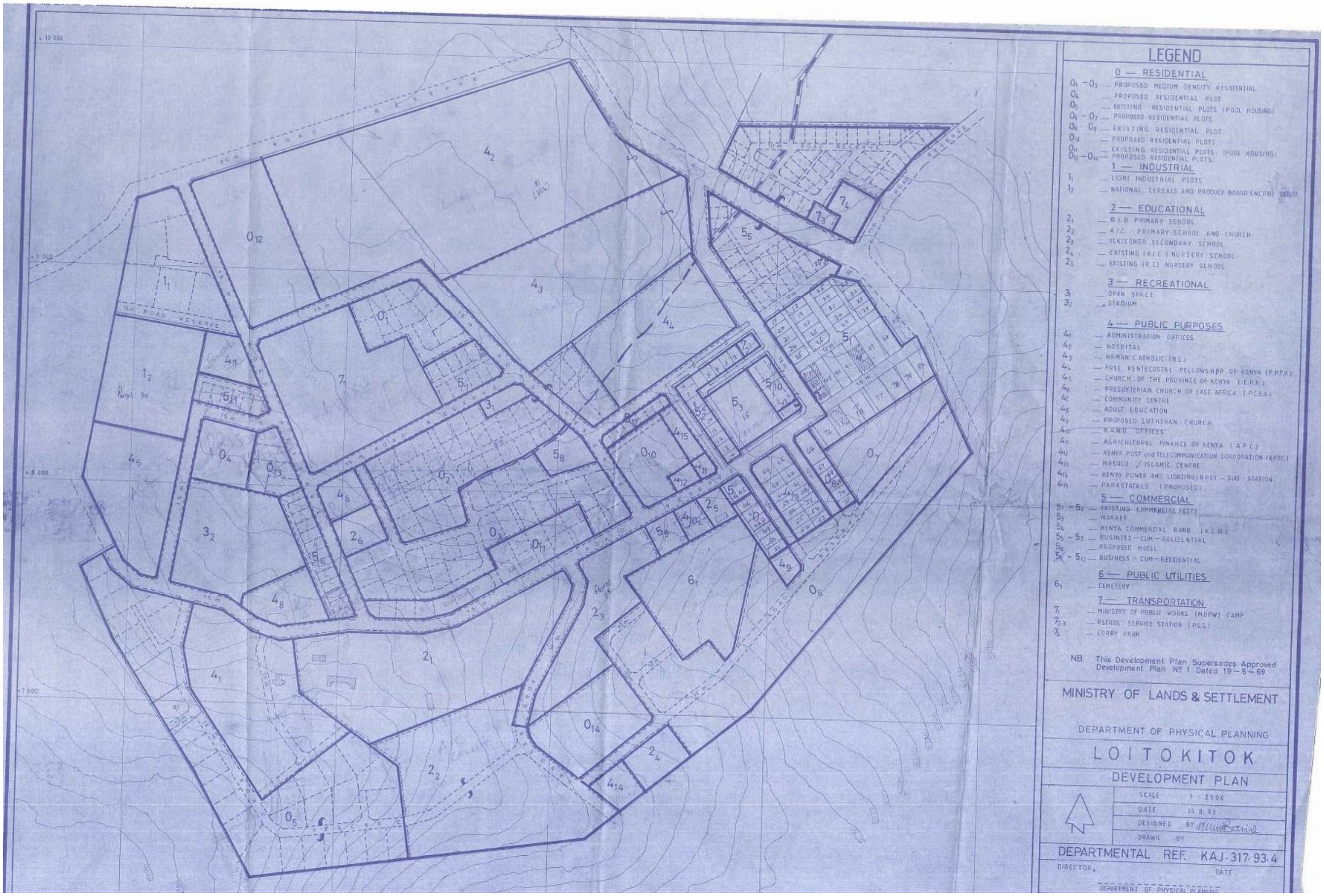

Figure 41: Loitokitok Town Development Plan

Appendix C: Relative Weights Calculations and Filled Questionnaires

http://bpmsg.com AHP 04-07-18

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 11.10.2017 Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n= 10	Number of criteria (2 to 10)	Scale: 1		AHP 1-9
N= 19	Number of Participants (1 to 20)	α: 0.1	Consensus:	45.6%
p= 0	selected Participant (0=consol.)	2	7	Consolidated

Objective Derivation of relative weights of factors considered for selecting WWTP location using AHP Method

Author K.D. Goepel

Date 23-Jun-18 Thresh: 1E-07 Iterations: 3 EVM check: 5.6E-08

Table

	Criterion	Comment	Weights	Rk
1	Criterion 1	Dwelling houses	9%	7
2	Criterion 2	Major roads	5%	9
3	Criterion 3	Land Use Land Cover	5%	8
4	Criterion 4	Slope	11%	3
5	Criterion 5	Airstrip	9%	5
6	Criterion 6	Water bodies	21%	1
7	Criterion 7	Distance to town	10%	4
8	Criterion 8	Altitude of town	17%	2
9	Criterion 9	Kenya-Tanzania Borderline	4%	10
10	Criterion 10	Soils	9%	6

Result

Eigenvalue lambda: 10.364

Consistency Ratio 0.37 GCI: 0.10 CR: 2.7%

Matrix

		Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Criterion 10	normalized principal Eigenvector
		1	2	3	4	5	6	7	8	9	10	
Criterion 1	1	-	3 1/8	1 2/7	3/5	1	2/7	1	1/3	2 2/5	1 2/7	8.62%
Criterion 2	2	1/3	-	1 4/7	1/3	3/7	2/9	3/8	2/9	1 2/3	3/4	4.79%
Criterion 3	3	7/9	5/8	-	5/9	3/5	1/4	2/5	2/7	1 1/2	2/3	5.15%
Criterion 4	4	1 5/7	3	1 4/5	-	1	1/2	1	1	2	1 1/4	11.05%
Criterion 5	5	1	2 1/3	1 2/3	1	-	1/3	1 3/8	2/3	2 4/9	3/4	9.44%
Criterion 6	6	3 5/8	4 3/7	4	2	3	-	2 2/3	1	3 1/7	1 3/5	20.65%
Criterion 7	7	1	2 2/3	2 2/5	1 1/9	5/7	3/8	-	3/4	1 4/7	1 5/9	10.05%
Criterion 8	8	3	4 5/8	3 1/3	1	1 4/7	1	1 3/8	-	3 3/5	1 1/4	16.61%
Criterion 9	9	2/5	3/5	2/3	1/2	2/5	1/3	5/8	2/7	-	1/3	4.26%
Criterion 10	10	7/9	1 1/3	1 5/9	4/5	1 1/3	5/8	2/3	4/5	3	-	9.38%

by K. Goepel AHPcalc-2018-6-23-nzula-Summary

Figure 42: Summary of the weights determination

AHP
bpmsg.com

Analytic Hierarchy Process
Multiple Input Summary Sheet

Consolidated = Weighted geometric mean off participants

19 = k number of participants
10 = n number of criteria

C Consolidated

	1	2	3	4	5	6	7	8	9	10
1		3.124	1.284	0.584	0.982	0.276	1	0.324	2.405	1.283
2	0.32		1.575	0.342	0.424	0.226	0.374	0.216	1.662	0.756
3	0.779	0.635		0.558	0.605	0.245	0.416	0.299	1.493	0.643
4	1.713	2.923	1.791		1.027	0.501	0.906	0.953	2.03	1.261
5	1.018	2.361	1.653	0.973		0.34	1.377	0.638	2.446	0.762
6	3.62	4.422	4.081	1.995	2.938		2.652	0.914	3.138	1.595
7	1	2.675	2.404	1.103	0.726	0.377		0.732	1.582	1.554
8	3.083	4.623	3.342	1.05	1.567	1.094	1.366		3.588	1.238
9	0.416	0.602	0.67	0.493	0.409	0.319	0.632	0.279		0.333
10	0.779	1.324	1.555	0.793	1.313	0.627	0.644	0.808	3.005	

1 ENG1 1 17-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	1	9	1/7	1/7	7	1	1/5	9	7
2	1	1	5	1	1/9	5	1	1/5	3	5
3	1/9	1/5	1	1/7	1/9	1/3	1/5	1/5	1	1
4	7	1	7	1	1/9	3	3	1	7	7
5	7	9	9	9	1	9	9	9	9	9
6	1/7	1/5	3	1/3	1/9	1	1/3	1/3	3	5
7	1	1	5	1/3	1/9	3	1	1	3	5
8	5	5	5	1	1/9	3	1	1	5	5
9	1/9	1/3	1	1/7	1/9	1/3	1/3	1/5	1	1
10	1/7	1/5	1	1/7	1/9	1/5	1/5	1/5	1	1

2 ENG2 1 22-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	3	1/3	1/7	9	1/7	1/7	1/7	1	1/7
2	1/3	1	7	1/7	7	1/7	1/7	1/7	1	1/7
3	3	1/7	1	1/7	7	1/7	1/7	1/7	1	1/7
4	7	7	7	1	7	1/3	1/3	1/7	1	1
5	1/9	1/7	1/7	1/7	1	1/7	1/7	1/7	1	1/7
6	7	7	7	3	7	1	1	1/5	1	1/3
7	7	7	7	3	7	1	1	1/5	1	3
8	7	7	7	7	7	5	5	1	1	5
9	1	1	1	1	1	1	1	1	1	1/3
10	7	7	7	1	7	3	1/3	1/5	3	1

3 ENG3 1 15-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1/9	1/9	1	1/9	1/9	1	1
2	1	1	1	1/9	1/9	1	1/9	1/9	1	1
3	1	1	1	1/9	1/9	1	1/9	1/9	1	1
4	9	9	9	1	9	9	9	9	9	9
5	9	9	9	1/9	1	9	9	9	9	9
6	1	1	1	1/9	1/9	1	1/9	1/9	9	1/9
7	9	9	9	1/9	1/9	9	1	1	9	9
8	9	9	9	1/9	1/9	9	1	1	9	9
9	1	1	1	1/9	1/9	1/9	1/9	1/9	1	1/9
10	1	1	1	1/9	1/9	9	1/9	1/9	9	1

4 ENG4 1 18-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	1	9	9	1/9	1/9	9	1/9	1/9	1
2	1	1	5	5	1/5	1/9	9	1/9	1/9	1
3	1/9	1/5	1	1/5	1/9	1/9	1	1/9	1/9	1
4	1/9	1/5	5	1	1	1	9	1/9	1/9	1
5	9	5	9	1	1	1/9	5	1/9	1/9	1
6	9	9	9	1	9	1	9	1/9	1/9	7
7	1/9	1/9	1	1/9	1/5	1/9	1	1/9	1/9	7
8	9	9	9	9	9	9	9	1	9	9
9	9	9	9	9	9	9	9	1/9	1	9
10	1	1	1	1	1	1/7	1/7	1/9	1/9	1

5 ENG5 1 18-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	7	1/3	5	5	1/5	3	9	1	1/3
2	1/7	1	1/7	1/3	1/5	1/7	3	1	5	1/5
3	3	7	1	5	3	1/5	1	3	1	1/7
4	1/5	3	1/5	1	1/3	1/5	3	5	1	1/5
5	1/5	5	1/3	3	1	1/5	3	5	1	1/7
6	5	7	5	5	5	1	5	7	1	3
7	1/3	1/3	1	1/3	1/3	1/5	1	3	1	1/7
8	1/9	1	1/3	1/5	1/5	1/7	1/3	1	3	1/5
9	1	1/5	1	1	1	1	1	1/3	1	1/7
10	3	5	7	5	7	1/3	7	5	7	1

6 ENG6 1 20-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	9	5	1/5	9	5	5	5	9	5
2	1/9	1	1/5	1/9	5	1/5	1/7	1/5	5	1/7
3	1/5	5	1	7	7	5	7	1	7	7
4	5	9	1/7	1	5	5	5	1	5	5
5	1/9	1/5	1/7	1/5	1	1/5	1/5	1/5	3	1/5
6	1/5	5	1/5	1/5	5	1	1	1/5	3	1/5
7	1/5	7	1/7	1/5	5	1	1	3	3	1/3
8	1/5	5	1	1	5	5	1/3	1	5	5
9	1/9	1/5	1/7	1/5	1/3	1/3	1/3	1/5	1	1/5
10	1/5	7	1/7	1/5	5	5	3	1/5	5	1

7 SO1 1 14-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	3	5	1/3	3	1/7	3	1/3	7	3
2	1/3	1	3	1/3	1/7	1/9	1/3	1/3	7	5
3	1/5	1/3	1	1/3	1/7	1/9	1/3	1/5	5	1/3
4	3	3	3	1	3	1/5	3	5	7	3
5	1/3	7	7	1/3	1	1/5	3	1/3	7	1
6	7	9	9	5	5	1	5	3	9	7
7	1/3	3	3	1/3	1/3	1/5	1	1/3	5	3
8	3	3	5	1/5	3	1/3	3	1	5	3
9	1/7	1/7	1/5	1/7	1/7	1/9	1/5	1/5	1	1/5
10	1/3	1/5	3	1/3	1	1/7	1/3	1/3	5	1

8 SO2 1 15-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	9	1	1/9	9	1/9	1/7	1/9	9	3
2	1/9	1	1	1/9	5	1/9	1/7	1/9	5	3
3	1	1	1	1/9	7	1/9	1/7	1/9	9	1
4	9	9	9	1	9	1	1	1	9	7
5	1/9	1/5	1/7	1/9	1	1/9	1/9	1/9	3	1/3
6	9	9	9	1	9	1	5	5	9	9
7	7	7	7	1	9	1/5	1	1	9	9
8	9	9	9	1	9	1/5	1	1	9	9
9	1/9	1/5	1/9	1/9	1/3	1/9	1/9	1/9	1	1/5
10	1/3	1/3	1	1/7	3	1/9	1/9	1/9	5	1

9 SO3 1 20-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	5	3	1	3	1/5	1	1/5	5	7
2	1/5	1	9	1	3	1/5	1/3	1	5	1
3	1/3	1/9	1	5	3	1/3	1/3	1	3	1
4	1	1	1/5	1	1/3	1/5	3	1	3	1/3
5	1/3	1/3	1/3	3	1	1/3	3	1/3	7	9
6	5	5	3	5	3	1	9	1/3	7	5
7	1	3	3	1/3	1/3	1/9	1	9	7	5
8	5	1	1	1	3	3	1/9	1	9	1
9	1/5	1/5	1/3	1/3	1/7	1/7	1/7	1/9	1	1/3
10	1/7	1	1	3	1/9	1/5	1/5	1	3	1

10 ENV1 1 14-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	3	1/3	5	1/3	1/9	3	1/3	5	1
2	1/3	1	1/7	3	1/7	1/9	1/5	1/3	5	1/5
3	3	7	1	1/3	1	1/9	1/3	1/5	5	3
4	1/5	1/3	3	1	1	1/7	1/5	1/3	5	1/3
5	3	7	1	1	1	1/7	1/3	1	5	1/5
6	9	9	9	7	7	1	7	7	9	3
7	1/3	5	3	5	3	1/7	1	1/5	1/7	1/3
8	3	3	5	3	1	1/7	5	1	5	1/3
9	1/5	1/5	1/5	1/5	1/5	1/9	7	1/5	1	1/5
10	1	5	1/3	3	5	1/3	3	3	5	1

11 ENV2 1 19-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	1/3	1/7	1/9	1/9	1/7	1/7	1/7	1/5	1/9
2	3	1	9	1/7	1/7	7	1/9	1/9	1/7	5
3	7	1/9	1	1/3	7	9	1/3	5	1/7	1/5
4	9	7	3	1	1/9	1	1/3	1	1/9	1/3
5	9	7	1/7	9	1	1/9	1/3	1/9	1/7	1/5
6	7	1/7	1/9	1	9	1	7	3	1/3	1/3
7	7	9	3	3	3	1/7	1	1	1/3	1
8	7	9	1/5	1	9	1/3	1	1	1/3	1/3
9	5	7	7	9	7	3	3	3	1	1/3
10	9	1/5	5	3	5	3	1	3	3	1

Figure 43: Pairwise Comparison matrices

12 ENV3 1 20-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	1	1/3	1/9	1	1/7	1/5	1/9	5	1/5
2	1	1	1	3	1	1/9	1	1/9	5	1/3
3	3	1	1	3	3	1/5	3	1/9	5	1
4	9	1/3	1/3	1	1/3	1/5	1/3	1/9	3	1/3
5	1	1	1/3	3	1	1/3	1	1/9	3	1/3
6	7	9	5	5	3	1	3	1/5	3	1
7	5	1	1/3	3	1	1/3	1	1/9	3	3
8	9	9	9	9	9	5	9	1	9	3
9	1/5	1/5	1/5	1/3	1/3	1/3	1/3	1/9	1	1/5
10	5	3	1	3	3	1	1/3	1/3	5	1

13 ENV4 1 17-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	3	5	1	1	1/7	1	1/5	1	1/5
2	1/3	1	1/3	1/7	1/7	1/7	1/3	1/7	1	1/7
3	1/5	3	1	1	1/7	1/7	1/3	1/7	1	1/9
4	1	7	1	1	1/5	1/7	1/7	1/3	1/5	1/7
5	1	7	7	5	1	1/7	7	1	3	1/7
6	7	7	7	7	7	1	7	7	9	3
7	1	3	3	7	1/7	1/7	1	1/3	3	1/7
8	5	7	7	3	1	1/7	3	1	3	1/7
9	1	1	1	5	1/3	1/9	1/3	1/3	1	1/9
10	5	7	9	7	7	1/3	7	7	9	1

14 GO1 1 20-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	3	1	7	3	1/5	1	1/3	5	3
2	1/3	1	7	1/5	1/3	1/9	1/3	1/5	1	3
3	1	1/7	1	1/3	1/7	1/9	1/3	1/5	3	1/5
4	1/7	5	3	1	1/7	1/5	1/3	3	7	3
5	1/3	3	7	7	1	1/5	1	3	7	3
6	5	9	9	5	5	1	5	1/5	7	3
7	1	3	3	3	1	1/5	1	1/5	5	1/3
8	3	5	5	1/3	1/3	5	5	1	3	1/5
9	1/5	1	1/3	1/7	1/7	1/7	1/5	1/3	1	1/5
10	1/3	1/3	5	1/3	1/3	1/3	3	5	5	1

15 GO2 1 15-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	3	1/3	1	1	1/3	3	1/3	7	5
2	1/3	1	5	1/5	1/7	1/9	1/5	1/7	3	1/5
3	3	1/5	1	1/7	1/9	1/7	1/3	1/5	3	1/5
4	1	5	7	1	5	1	1/5	3	1	1
5	1	7	9	1/5	1	1/5	1	1/3	5	1/3
6	3	9	7	1	5	1	5	1	5	1/5
7	1/3	5	3	5	1	1/5	1	5	1	3
8	3	7	5	1/3	3	1	1/5	1	3	5
9	1/7	1/3	1/3	1	1/5	1/5	1	1/3	1	1/5
10	1/5	5	5	1	3	5	1/3	1/5	5	1

16 GO3 1 20-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	9	1/7	1/9	1	1/5	1/5	1/3	1	1/3
2	1/9	1	5	1/9	1	1/5	1/5	1/3	1	3
3	7	1/5	1	9	1	1/7	1/5	1/3	1	3
4	9	9	1/9	1	9	1/7	1/5	1/3	1	3
5	1	1	1	1/9	1	1/9	1/5	1/3	1	3
6	5	5	7	7	9	1	1/7	1/5	1	1/5
7	5	5	5	5	5	7	1	9	1	3
8	3	3	3	3	3	5	1/9	1	7	1/3
9	1	1	1	1	1	1	1	1/7	1	1
10	3	1/3	1/3	1/3	1/3	5	1/3	3	1	1

17 GO4 1 16-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	5	9	1/3	1	1/7	3	1	5	7
2	1/5	1	5	1	1	1/5	5	1	3	5
3	1/9	1/5	1	1/3	1/5	1/7	1/3	1/5	3	1/3
4	3	1	3	1	3	1/7	1/3	3	9	7
5	1	1	5	1/3	1	1/5	3	1/3	1	3
6	7	5	7	7	5	1	9	3	7	3
7	1/3	1/5	3	3	1/3	1/9	1	1/5	3	5
8	1	1	5	1/3	3	1/3	5	1	5	1/5
9	1/5	1/3	1/3	1/9	1	1/7	1/3	1/5	1	1/3
10	1/7	1/5	3	1/7	1/3	1/3	1/5	5	3	1

18 ENG7 1 25-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	9	5	3	1	1	7	1	7	7
2	1/9	1	1	1/7	1/7	1/7	1/7	1/7	1/3	1/3
3	1/5	1	1	1/9	1/9	1/9	1/5	1/9	1/5	1/5
4	1/3	7	9	1	1	3	1	1	5	5
5	1	7	9	1	1	5	3	1	3	3
6	1	7	9	1/3	1/5	1	1	1	3	3
7	1/7	7	5	1	1/3	1	1	1/3	1/3	3
8	1	7	9	1	1	1	3	1	1	3
9	1/7	3	5	1/5	1/3	1/3	3	1	1	3
10	1/7	3	5	1/5	1/3	1/3	1/3	1/3	1/3	1

19 SO4 1 25-06-18

	1	2	3	4	5	6	7	8	9	10
1	1	9	1	1	1/9	1/9	1	1/9	1	1
2	1/9	1	1/9	1/9	1/9	1/9	1/9	1/9	1	1/9
3	1	9	1	1	1/9	1/9	1	1	1	9
4	1	9	1	1	1/9	1/9	1	1	1	1/9
5	9	9	9	9	1	1	9	9	9	1/9
6	9	9	9	9	1	1	9	9	9	9
7	1	9	1	1	1/9	1/9	1	1	1	1/9
8	9	9	1	1	1/9	1/9	1	1	1	1/9
9	1	1	1	1	1/9	1/9	1	1	1	1/9
10	1	9	1/9	9	9	1/9	9	9	9	1

Figure 44: Pairwise Comparison matrices continued

The Filled Questionnaires

Appendix D: Resultant Model Built