

A GIS AND REMOTE SENSING APPROACH TO IDENTIFY SUITABLE SITES FOR IRRIGATION: A CASE STUDY OF KASUNGU DISTRICT

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DECLARATION

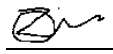
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ABSTRACT

This study investigates the integration of Geographic Information Systems (GIS) and Remote Sensing (RS) technologies for identifying suitable sites for irrigation development in Kasungu District, Malawi, a region increasingly affected by climate variability, declining rainfall, and agricultural challenges. With Malawi's agricultural sector largely reliant on rain-fed systems, the frequent occurrence of droughts and crop failures has underscored the urgency of adopting sustainable, data-driven planning tools. The research applied a Multi-Criteria Decision Analysis (MCDA) framework combined with the Analytical Hierarchy Process (AHP) to evaluate and weight biophysical factors critical to irrigation planning, including slope, soil texture, drainage, depth, land use/land cover, and proximity to water sources and road infrastructure. Supervised classification was performed using the Random Forest algorithm within Google Earth Engine to derive accurate land cover data, while Digital Elevation Models (DEMs) and detailed soil datasets were analysed using ArcGIS to assess terrain and soil suitability. Criteria weights were determined based on expert judgment, ensuring that highly influential factors such as slope and water access were emphasized in the final model. The study produced a spatially explicit irrigation suitability map that classified land into five categories ranging from highly suitable to highly unsuitable. Results indicated that large portions of Kasungu, particularly areas with flat terrain, deep well-drained soils, and close proximity to perennial rivers like Dwangwa and Bua, were ideal for irrigation development. Conversely, steep, flood-prone, or environmentally sensitive zones were deemed unsuitable. The research not only provides a practical framework for targeted investment in irrigation infrastructure but also highlights the scalability of the model for application in other regions with similar agro-ecological conditions. By leveraging cloud-based RS data and advanced GIS modelling techniques, the study offers a replicable and cost-effective approach for land use planning, supporting national efforts toward food security, climate resilience, and sustainable development. It further recommends piloting irrigation schemes in high-suitability zones, building local capacity in spatial technologies, and institutionalizing GIS-based tools for agricultural planning. This work aligns with Malawi's Vision 2063 and the Sustainable Development Goals (SDG's)

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ACRONYMS/ABBREVIATIONS

GIS	: Geographic Information Systems
LULC	: Land Use Land Cover
GEE	: Google Earth Engine
DEM	: Digital Elevation Model
USGS	: United States Geological Survey
SRTM	: Shuttle Radar
OLI	: Operational Land Imager
NDVI	: Normalized Difference Vegetation Index
TVDI	: Temperature Vegetation Dryness Index
AHP	: Analytical Hierarchy Process
MCDA	: Multi-Criteria Decision Analysis
CNN	: Convolutional Neural Networks
RF	: Random Forest
SMV	: Support Vector Machine
CART	: Classification and Regression Tress
LSTM	: Long Short-Term Memory
T/A	: Traditional Authority

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1. CHAPTER 1: INTRODUCTION

1.1. Background

Food security remains one of the most important concerns for Malawi's sustainable development (Food and Agriculture Organisation of United Nations, 2022). Unpredictable rainfall patterns and insufficient access to irrigation water present a notable challenge to agricultural productivity and also a threat to national food security. In addition to that, (CGIAR Initiative on Mixed Farming Systems, 2024) Agriculture players in Malawi have described the 2023/24 season as the toughest in a decade, with farmers facing drastically reduced and unstable rains. This has led to one of the highest crop failures and losses ever recorded, challenging traditional agricultural practices and highlighting the urgent need for new approaches and a deeper understanding of sustainable farming techniques. This research project aims at looking into the application of Geographic Information Systems (GIS) and remote sensing for identification of suitable site for irrigation.

Just like most of sub-Saharan countries, Malawi's agriculture is heavily dependent on rainfall, which makes it vulnerable to droughts and unpredictable weather patterns. These factors often lead to crop failure and food shortages. Irrigation which is described by application of water to smaller land portion, has come out as a promising solution to enhance agriculture resilience (Makwiza, et al., 2010). However, the success of these irrigation projects depends on the appropriate selection of a suitable location.

According to (Skidmore, Bijker, & Lalit, 2014), GIS and remote sensing provide useful tools for informed land and water resources management decisions. GIS offer functions such as digital maps, storing and analysing spatial data like soil characteristics, elevation and water resources. Remote sensing makes use of satellite imagery to monitor land cover, water availability and even crop health.

Previous research has established the efficacy of GIS and remote sensing in identifying suitable irrigation sites across various African countries. However, the application of these technologies within the unique context of Malawi necessitates further

investigation. Our research will account for Malawi-specific factors, including diverse landscapes, heterogeneous water sources, and the specific needs of smallholder farmers.

1.1.1. Problem Statement

According to (Chikabvumbwa, Sibale, & Chisale, 2021), There is over dependency on the use of traditional methods across Malawi when it comes to potential site selection for irrigation. The use of these traditional methods has had significant consequences on the environment such as pollution, soil erosion, siltation and land degradation. In addition to that, traditional site selection for irrigation is a complex task which consumes a lot of time and is prone to errors which result in suboptimal utilization of resources. Geographic information system is a computer system designed to allow users to collect, manage and analyse large volumes of spatially referenced and associated attribute data (Guptill, 2013). This research project aims to develop a GIS and remote sensing approach that can help to identify suitable site for irrigation tailored to the unique geographical and environmental conditions of the study area.

1.1.2. Main Objective

To assess potential sites suitable for irrigation development using Geographic Information Systems (GIS) and remote sensing techniques.

1.1.3. Specific Objectives

i. To map out key biophysical factors influencing irrigation suitability, which include
    - Soil characteristics (texture, drainage, depth, PH)
    - Topology(slope)
    - Land use

ii. To develop a model using ArcGIS Model Builder that can be adopted in other areas that are facing the same challenges.
iii. To create a weighted suitability map highlighting area with optimal conditions for irrigation considering the factors in objective 1.

1.1.4. Research Questions

i. How well does the developed weighted suitability map correlate with actual crop productivity in the study area?

ii. What weight should be assigned to each biophysical factor based on its relative importance for irrigation in the specific context of study area?

iii. How can the developed model, basing on the weighting factors, be adapted to other regions with different climatic and soil conditions?

iv. Based on the findings of the research, what additional biophysical factors, beyond those initially investigated, might be needed to be included in the model for application in new areas?

1.1.5. Significance of Study

This study of identifying suitable sites for irrigation holds an important value. By making use of GIS and remote sensing, it will highlight areas with favourable conditions for irrigation, resulting into increased agriculture productivity and food security. The study also promotes systematized water management and sustainable land use practices. The suitability map will also help investors, policy makers and local communities to make informed decisions, guiding the allocation of resources and infrastructure development for irrigation projects.

2. CHAPTER 2: LITERATURE REVIEW

Irrigation systems, consisting of plots ranging from a few hectares to tens of hectares, are critical for ensuring food security and enhancing agricultural productivity, particularly for small holder farmers. Traditionally in Malawi the selection of suitable sites for irrigation has relied on subjective assessment and time-consuming field surveys. However, Improvements is Geographic Information Systems and Remote sensing have revolutionized this process, providing powerful and objective approach for identifying areas with high potential for irrigation.

2.1. The Role of GIS and Remote Sensing in Irrigation Site Selection

Traditional methods for suitable site selection often rely on limited field data and subjective assessment. GIS and RS provide a powerful framework for overcoming these limitations. GIS provide an opportunity for the integration of various spatial datasets relevant to irrigation suitability, such as:

- **Topography**: Slope and elevation data derived from Digital Elevation Model (DEM) are very important for determining the water flow and to identify areas suitable for canal construction and gravity-fed irrigation systems. Digital Elevation Model represents continuous variation of topography over space that help assessing landscape characteristics (Naidu, Ghosh, & Giridhar, 2012). According to (FAO, 1999) The standard guidelines for the evaluation of slope gradient, slope which are less than 2% are very suitable for irrigation. But slopes which are greater than 8% are not generally recommended
- **Soil Properties:** Data and Maps portraying soil characteristics like drainage, texture, and organic matter content, obtained through survey and RS techniques, are useful for assessing soil suitability for crop growth and irrigation efficiency. Soil is an important factor to work out land suitability for sustainable surface irrigation. The consequences of soil for irrigation are primarily associated with soil fertility, toxicity, moisture content, depth and credibility (Wubalem, 2021).

- **Land Cover and Use:** Land cover and Land use maps derived from multispectral satellite imagery assist in identifying existing land use and vegetation cover which is considered to avoid disruption of ecosystems and agricultural practices. Land use maps can be generated from satellite images downloaded from USGS website (Wubalem, 2021). In most cases the land is categorized into highly suitable, suitable, marginally suitable and not suitable (Girma, 2022).

Remote sensing on the other hand offers valuable insights through analysis of satellite and aerial imagery. Spectral indices derived from these images can provide information on:

- **Soil Moisture:** Vegetation indices like NDVI (Normalized Difference Vegetation Index) and TVDI (Temperature Vegetation Dryness Index) can be used to assess soil moisture conditions and identify areas with potential for irrigation development (Ortiz, Musarella, Carmona, & Canas, 2022)

2.1.1. Multi-Criteria Decision Analysis: Considering the Right Factors

The analytical Feature of Geographic Information Science and remote sensing for irrigation site selection is the application of Multi-Criteria Decision Analysis (MCDA) techniques. MCDA structure allows individuals to include various factors with various important scores into the overall suitability analysis. This acknowledges that not all factors hold equal weight in determining suitability analysis.

The analytical Hierarchy Process (AHP) is one of the most used MCDA methods that help to assign weights to different criteria based on expert knowledge and data (Malczewski & Rinner, Multicriteria Decision Analysis in Geographic Information Science, 2015). For example, in a water scarce region, water sources available might be signed higher weight to soil type in the MCDA process

By integrating weighted criteria through spatial analysis in GIS, researchers can generate suitability maps that categorize areas based on their potential for small-scale

irrigation development. These maps provide valuable insights for decision-makers in selecting optimal locations for irrigation projects, considering the interplay of various biophysical factors.

2.1.2. Common Models for Irrigation Suitability Assessment

Several models exist to identify suitable irrigation sites, each with distinct strengths and weaknesses. A prevalent approach utilizes Geographic Information Systems (GIS) combined with Multi-Criteria Decision Analysis (MCDA). This method excels in its ability to integrate and analyse spatial data on various factors influencing irrigation success, like soil properties (texture, drainage), topography (slope), climate (precipitation, temperature), and water availability (surface and groundwater). Users can assign importance scores to each factor based on their specific needs, enabling the identification of areas with the most favourable combinations for irrigation. However, the effectiveness of this approach hinges on the quality and resolution of the data used (Malczewski & Rinner, Multiicriteria Decision Analysis in Geographic Information Science, 2015). Additionally, assigning weights to each factor can be subjective and require expert input, potentially introducing bias into the results.

For a more standardized and user-friendly approach, the Land Suitability for Irrigation (LSI) Index offers a readily available option (Cloud Publications, 2012). This index integrates soil characteristics (texture, electrical conductivity), climate (rainfall), and drainage into a single score representing irrigation suitability. Its strength lies in its simplicity and objectivity, making it a good choice for rapid evaluations. However, the LSI index may not be adaptable to all regions with varying soil types and climatic conditions (Cloud Publications, 2012). It also has limitations in capturing specific irrigation practices or the unique water requirements of different crops.

2.1.3. Limitations and Considerations for Sustainable Implementation

While GIS and remote sensing offer important advantages for irrigation site selection, it is necessary to acknowledge their limitations. The accuracy of the results is dependent on the quality and resolution of the data used. High-resolution data provides a more detailed picture of the landscape; however, it may also come at a

higher cost. Furthermore, ground-truthing data collected through field surveys is crucial for validating the interpretations derived from remotely sensed data (Mohammedshum, Maathuis, Mannaerts, & Teka, 2023). Inconsistencies between remotely sensed data and ground observations can lead to misleading results.
It is also important to recognize that social and economic factors extend beyond the realm of biophysical suitability and play a crucial role in the success of small-scale irrigation projects. Land tenure security, infrastructure availability (roads, markets), and access to financial

2.2. Land Use Land Cover Classification

Land Use Land Cover (LCLU) classification is a crucial process is a crucial process that help monitor environmental changes, urban expansion, deforestation, and agricultural activities (Lu & Weng, 2007). Traditionally LULC was performed using software's such as ENVI and ArcGIS; however, recent advancement in cloud computing and big data analytics have facilitated the use of platforms like Google Earth Engine (GEE) for large-scale and efficient classification (Gorelick, et al., 2017).

2.2.1. Google Earth Engine for LULC Classification

Google Earth Engine (GEE) is a cloud based geospatial analysis platform that provides access to a vast repository remote sensing datasets and computational tool. GEE has been increasingly used for LULC Classification due to its ability to process large datasets efficiently. It enables users to perform both supervised and unsupervised classification using machine learning algorithms.

2.2.2. Supervised and Unsupervised Classification in Google Earth Engine

Land Use Land Cover Classification in GGE is broadly categorized into supervised and unsupervised methods. Supervised method involves training a machine learning model using labelled references data, where each pixel in an imagery is assigned a known land cover category before being used to classify the entire image. Common machine learning classifiers in GEE for supervised classification include Random Forest (RF), Support Vector Machine (SMV), Classification and Regression Trees (CART),

and Naïve Bayes (Belgiu & Dragut, 2016). Among these, RF is widely used due high accuracy, robustness to overfitting and efficient handling of large datasets. Supervised Classification is advantageous because it allows better control over definition of classes and improves accuracy when there is availability of high-quality training data. However, it requires sufficient and accurately labelled training data, which is labour intensive and time consuming to collect (Lu & Weng, 2007).

On the other hand, Unsupervised Classification does not need prior knowledge of land cover types instead cluster image pixels into distinct groups based on spectral similarity. Techniques such as K-means Clustering and ISO Clustering are mostly used in GEE to put together pixels into classes, which are manually interpreted by the user (Jensen, 2014). While Unsupervised classification is use in exploratory analysis and regions with limited reference data, it often results in low accuracy due to the lack of ground truth to guide the process. Additionally, spectral similarities between land cover classes can cause misclassification, particularly in homogeneous landscapes. Although supervised classification is generally more accurate, a combination of both methods-such as using unsupervised classification to identify land cover patterns before refining them with supervised techniques-can enhance overall accuracy efficiency in GEE-based LULC mapping.

2.2.3. Challenges and Future Directions in GEE-Based Classification

Despite the advantages of Google Earth Engine in LULC classification, several challenges persist in its application. One major limitation is data processing constraints imposed by GEE's computational quota, which restricts the execution of large-scale analyses (Gorelick, et al., 2017). This can be a significant barrier for researchers working with high-resolution imagery or conducting long-term multi-temporal analyses. Additionally, the accuracy of supervised classification heavily relies on the quality and representativeness of training data, and poor training samples can lead to biased results and misclassification errors (Belgiu & Dragut, 2016). Another challenge is algorithmic bias, as different classifiers yield varying results, and selecting the optimal classifier requires extensive experimentation (Mountrakis, Im, & Ogole, 2011). Furthermore, cloud cover and atmospheric interference in optical

satellite imagery, such as Landsat and Sentinel-2, can affect classification performance, necessitating the integration of cloud-masking techniques and alternative datasets such as Synthetic Aperture Radar (SAR).

Looking ahead, future research in GEE-based LULC classification should focus on integrating deep learning models, such as Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks, which have demonstrated superior classification performance in remote sensing applications (Mohammady, Horadi, Heinivand, & Temme, 2014). Additionally, multi-sensor fusion approaches, combining optical and radar datasets, can enhance classification accuracy by mitigating cloud cover limitations and improving discrimination between spectrally similar land cover types. Another promising direction is automated training data generation using AI-assisted labelling techniques, which can reduce the dependency on manually collected ground truth data. As cloud computing capabilities continue to advance, GEE will play an increasingly vital role in large-scale environmental monitoring, enabling real-time LULC change detection and supporting data-driven policy decisions in land management and conservation

3. CHAPTER 3: METHODOLOGY

3.1. Research Design

The study employed a straightforward approach, which effectively met its core goals. Below is a simple flow of the whole research:

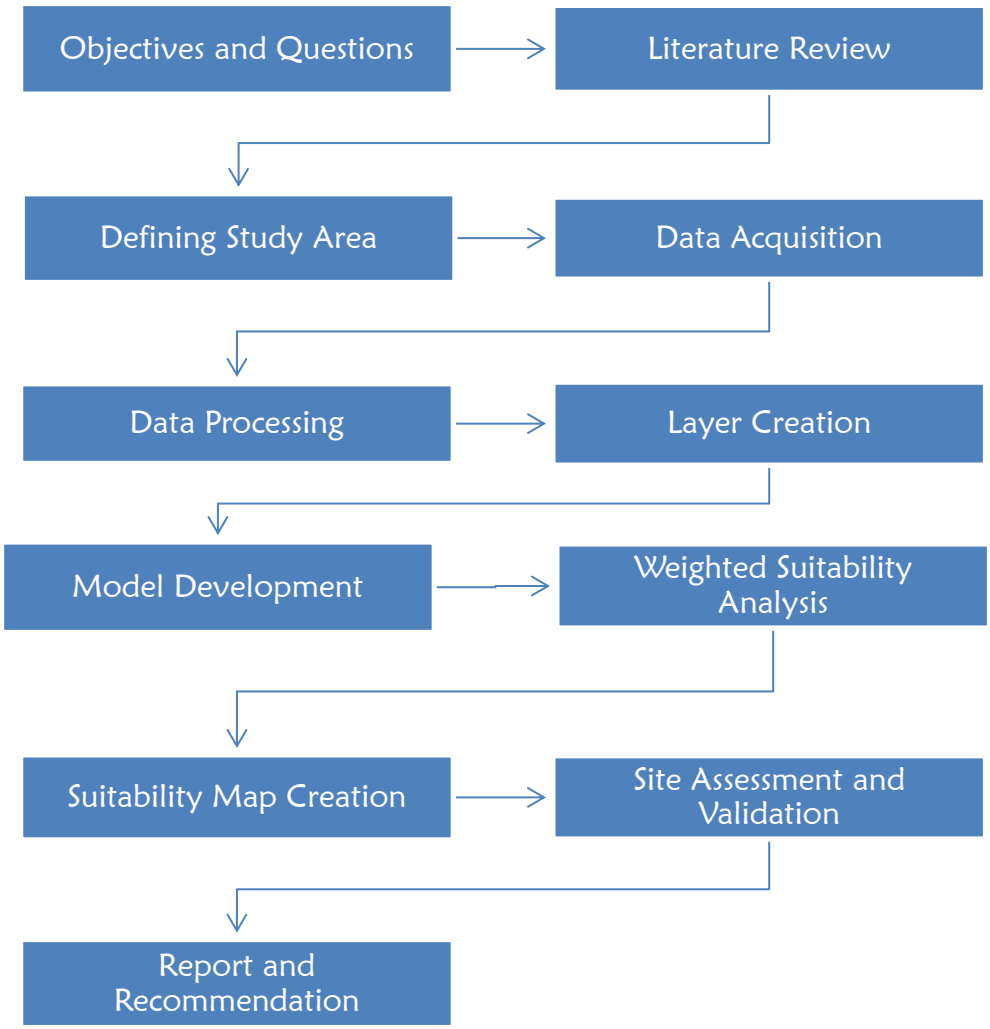


Figure 1: Flow Diagram of Research Design

3.1.1. Materials and Methods

3.1.2. Study Area

Due to population growth in Malawi and high demand for agriculture products for either consumption or as raw material, Kasungu was considered as the best area of study due to its geographical location, as is located on the Central Region Plateau

also called Lilongwe Plain which is good for agriculture. The broad valleys of the Lilongwe, Bua and Dwagwa rivers traverse the region in an east-northern direction. Their tributaries' spread out in dambos, offering little free-flowing water. Kasungu is found in central region of Malawi approximately 130 Kilometers north west of the capital of Malawi. The district covers an area of 7878 Km², borders Zambia and has population of 842,953.

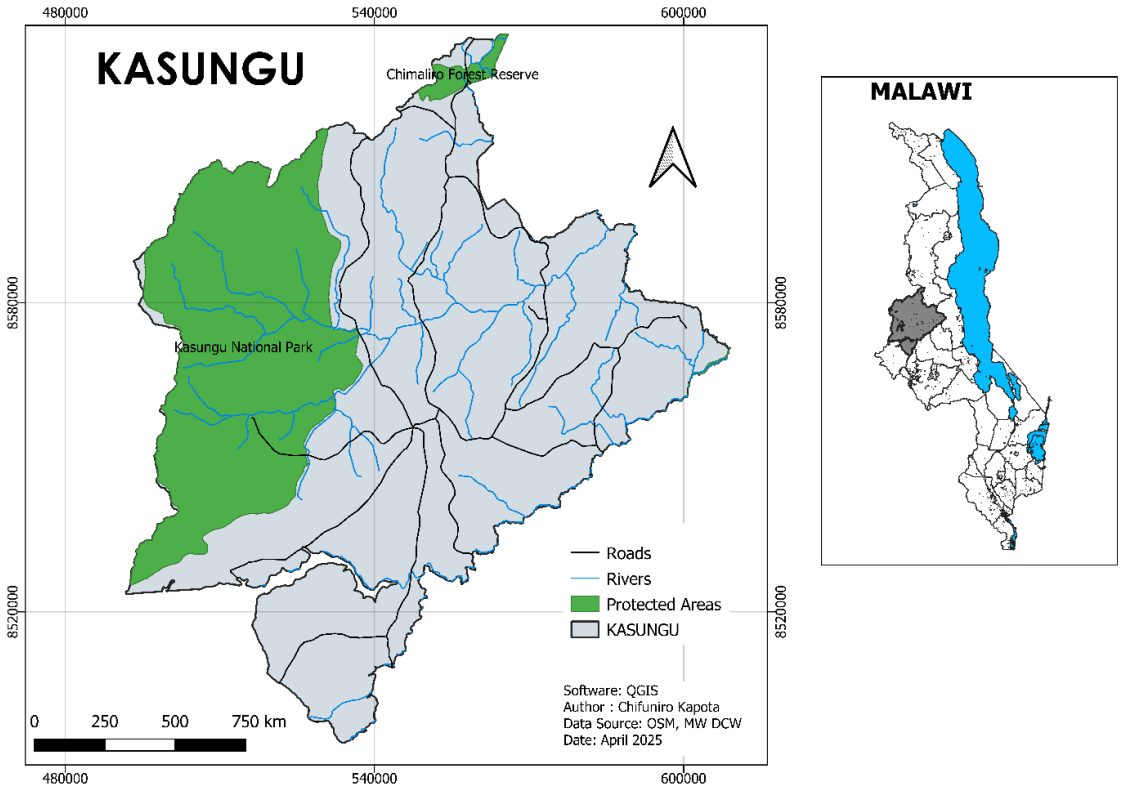


Figure 2: Study Area Map, Kasungu District, Malawi.

3.1.3. Data Acquisition

Data collection and evaluation are the first important steps in suitability analysis for Irrigation. The data that was used for this project was obtained from various sources. Administrative boundary and protected areas shape files were accessed from the Humanitarian Data Exchange Portal (https://data.humdata.org/). Roads and rivers shape files from were obtained from ArcGIS Hub (https://hub.arcgis.com/). Soil data was obtained from ISRIC Soil Data Hub (https://www.isric.org/explore/isric-soil-data-hub). The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was downloaded from USGS website (https//www.earthexplorer.usgs.gov). The study also used Landsat 8 operational Land Imager (OLI) which were cloud free

and downloaded from United States Geological Survey (USGS) through Google Earth Engine.

3.1.4. Land Use Land Cover Classification

The land use land cover classification used Google Earth Engine, starting from data collection to final processing. The method used was Supervised Classification, specifically employing Random Forest Classifier (RF). Below is a flow chart of that was used.

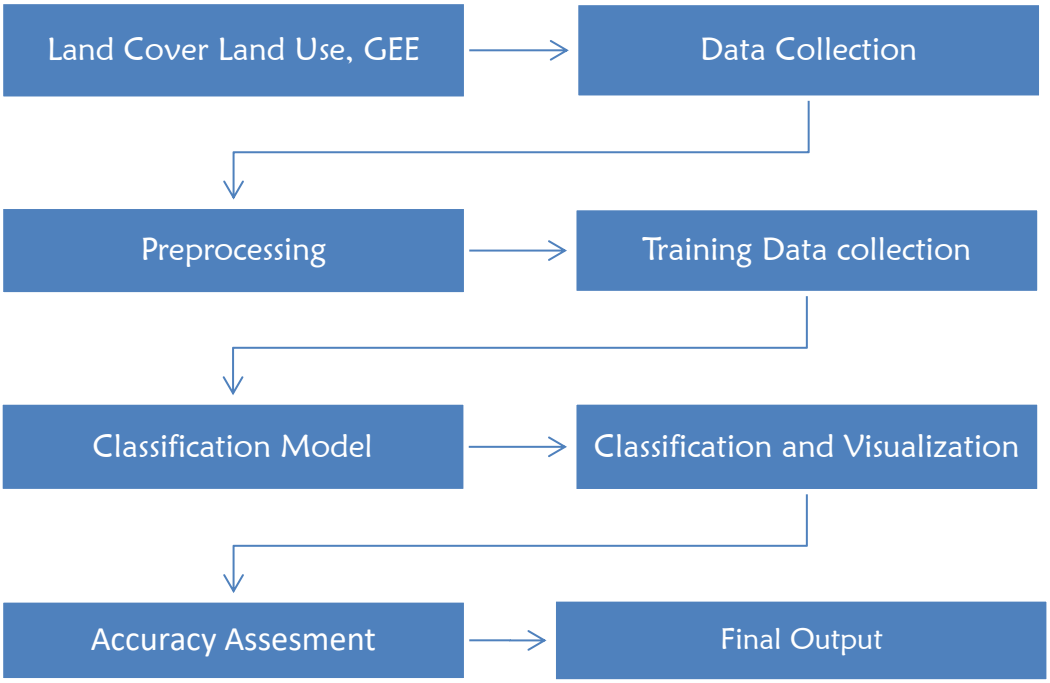


Figure 3: LULC Processes, Google Earth Engine.

3.1.5. Data Collection

Landsat 8 Operation Land Imager (OLI) and Thermal Infrared Sensor (TIRS) surface reflectance (SR) data, were downloaded from United States Geological Survey (USGS), were used for land cover classification (Earth Resources and Observation Science(EROS) Center., 2024). The dataset was filtered for a temporal period between May and October to ensure the inclusion of images captured during the dry season, a period of critical irrigation planning. Cloud cover was limited to less than 10% to enhance image quality and reduce classification errors (Chuvieco, 2016).

3.1.6. Pre-processing

To establish accuracy in spectral analysis, preprocessing steps were applied to Landsat 8 imagery. Scaling factors were utilized to correct for surface reflectance and thermal bands and thermal bands variations (Mather & Koch, 2022):

- Optical bands (SR_B2 to SR_B7) were adjusted using a scale factor of 0.0000275 and an offset of -0.2 to correct for sensor radiometric inconsistencies.
- The thermal bands (ST_10) were processed using a scale factor of 0.0034180 with an offset of 149.0 to improve temperature estimation accuracy.

A median composite of the rescaled images was generated to minimize noise and mitigate the effects of atmospheric disturbances, following established methodologies in remote sensing- based land cover classification (Jensen, 2014). The composed image was clipped to Kasungu region to refine the focus area for further analysis.

3.1.7. Training Data Collection

Supervised classification requires labeled training data which were manually collected through visual interpretation of high-resolution satellite imagery and existing landcover data sets. The study classified the landscape into five distinct land cover categories

Table 1: Land Use Land Cover Classes

LULC Class	Description
Water	Rivers and Dams
Settlement	Areas primarily characterized by human habitation and infrastructure, including, buildings, roads and associated land uses, such as residential, commercial and industrial zones
Forest	Protected forest, deciduous forest, mixed forest land and forests on customary land
Bare land	Area with little or no vegetation
Shrubs	Woody plants typically shorter than trees, usually less than 5-6 meters in height and often having multiple stems arising from the base

Training samples for each land cover were merged into single dataset overlaid on the preprocessing Landsat 8 Imagery. The sampleRegion function was applied to extract spectral values for training the classification model.

3.1.8. Classification Model

A supervised classification approach using Random Forest (RF) algorithm employed due to its capability in handling high dimensional datasets and its proven accuracy in land cover classification (Breiman, 2001). The RF model was trained using 80% of the labelled samples, while 20% were reserved for accuracy assessment to validate classification performance. Key spectral bands (SR_B1, SR_B2, SR_B3, SR_B4, SR_B5, SR_B6, SR_B7) were selected based on their relevance in distinguishing different land cover types.

3.1.9. Classification and Visualization

The Trained RF Classifier was applied to the study area to generate a land cover classification map. The classified images were visualized using predefined color palette to differentiate land cover types.

- Water
- Settlement
- Forest
- Cropland
- Shrubs

The classification results were clipped to the Kasungu study area and displayed within the Google Earth Engine interface for further spatial analysis and validation.

3.1.10. Accuracy Assessment

To evaluate the classification performance, an accuracy assessment was conducted using confusion matrix. The testing dataset (20% of the original samples) was classified and an error matrix was generated to compare predicted versus actual land classes. The following accuracy metrics were computed (Congalton & Green, 2019).

- Overall Accuracy (OA): Measures the proportion of correctly classified pixels
- Producers Accuracy (PA): Assesses omission errors by quantifying how well actual classes are represented in the classification.
- Users Accuracy (US): Evaluates commission errors by measuring reliability of assigned classes.

3.1.11. Exporting Final Output

The final classified map was exported to Google Drive for further analysis and integration into GIS-based irrigation site suitability modelling. The classification output was stored with a spatial resolution of 30 meters and maximum pixel count 1e13 to preserve the integrity of the land cover data.

3.1.12. Topography and Soil Characteristics Analysis

Topology and soil characteristics play a fundamental role in determining the suitability of land for irrigation. The physical properties of the terrain influence water flow, soil erosion and drainage, which in turn affect irrigation potential. Slope analysis is crucial as it determines the extent to which water will infiltrate or

run off, while soil properties such as texture, drainage, and depth impact water retention and nutrient availability (Food and Agriculture Organisation, 2015). A Systematic approach was adopted extract and analyze these parameters using ArcGIS 10.8.2

3.1.13. Topography Analysis (Slope Derivation and Classification)

Topology is a key determinant of irrigation feasibility, influencing both water distribution and soil stability. Areas with steep slope are generally unsuitable for irrigation due to high run off and soil erosion, whereas flatter areas allow for better water retention and infiltration (Chalumuri, 2006). To analyze topography a Digital Elevation Model (DEM) was used to derive slope information and classify into suitable categories.

The first step in topographical analysis was acquisition of a high-resolution DEM, which was sourced from Shuttle Radar Topology Mission (SRTM), USGS. The DEM was downloaded with a resolution of 30m which is sufficient for detailed topographic assessment. Once the DEM was acquired it was imported into ArcGIS 10.8.3 and preprocessed to remove errors such as sinks and spikes using ''Fill'' tool ensuring the accuracy of the terrain representation.

Following preprocessing, the "Slope" tool in ArcGIS Spatial Analyst was used to generate raster. This tool calculates the maximum rate of elevation between neighboring cells, providing a continuous surface representation of slope steepness. The output slope values were then classified into four categories according to (Chikabvumbwa, Sibale, & Chisale, 2021). The reclassification process was carried out using "Reclassify" tool, which assigns categorical values to the continuous slope date.

3.1.14.Soil Characteristics Analysis

As started area, the soil data was obtained from International Soil Reference and Information Centre (ISRIC). The soil data had texture, depth and drainage attributes. The soil data was the converted from vector data to raster data using Polygon to Rater tool. This was done in order to have grid cells where each cell represented a

value. The raster data were then resampled in order to set the pixel resolution the same for all the data.

3.1.15. Development of a Model

The study employed Multi-Criteria Decision Analysis (MCDA) approach to assess the varying levels of suitability analysis for irrigation. According to (Hussein, Woldu, & Birhanu, 2019) Multi criteria land analysis plays a crucial role in ensuring the sustainable management of limited resources such as land.

To facilitate the identification of suitable areas, spatial datasets were reclassified to standardize measurement scale. The weighting analysis was conducted following the FAO guidelines. A suitability scare was ranging from 1 to 4 was utilized, where 4 represented most suitable, while 1 indicate unsuitable location.

To assess the relative of the selected parameters in decision making, they were assigned to weights based on their relative importance. The Analytical Hierarchy Process was applied for parameter weighting and validation. Weighted parameters are considered reliable when consistency ration is less than 0.1 (Saaty, 2008).

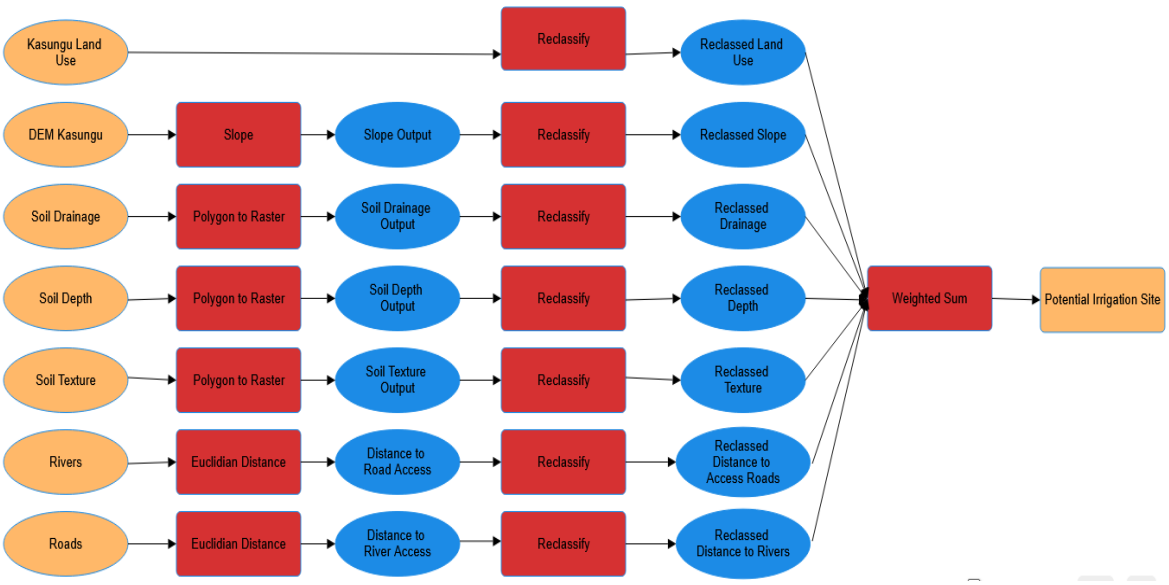


Figure 4: Irrigation Suitability Model

4. CHAPTER 4: RESULTS AND DISCUSSIONS

4.1. Results

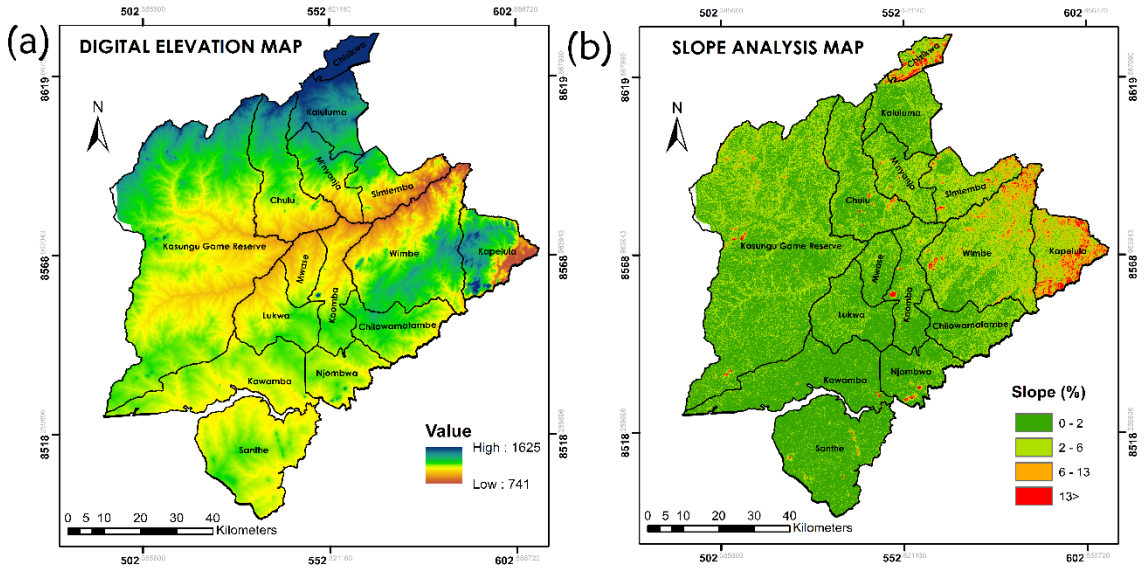


Figure 5: (a) Digital Elevation Model (b) Slope Map

The Digital Elevation Model reveals a significant variation in elevation across the different Traditional Authorities (T/A's). The northern part of the area, particularly T/A Chisikwa, Kaluluma and Mnyanja is characterized by high elevation. Similarly, T/A Simlemba, located in the northeast shows moderately high elevation with a mixture of green and yellow tones, reflecting steep slopes in certain areas. In contrast the central parts, including T/A Chulu, Mwaase and Kaomba, are marked by moderate elevation. Towards the southern and southeast regions, specifically in T/A Lukwa, Kawamba, Njombwa and santhe, the elevation decreases significantly, with predominant green shades suggesting flat terrain. Notably, Kapelula in the easternmost part features extensive low-lying area (Figure 5a).

In figure 6b, the slope map shows the flattest terrain (0-2% slope) is most common in southern T/A's like Santhe and parts of Kawamba and the Kasungu Game Reserve. These areas, along with TA Lukwa, also feature significant gentle slopes (2-6%). Central T/A's Njombwa, Mwase, and Chulu exhibit mixed slopes, transitioning to

the predominantly moderate (6-13%) and steep (>13%) terrain found in the northern and eastern TAs: Chisinga, Kaluluma, Simlemba, Wimbe, Kapelula, and Chilowamatambe.

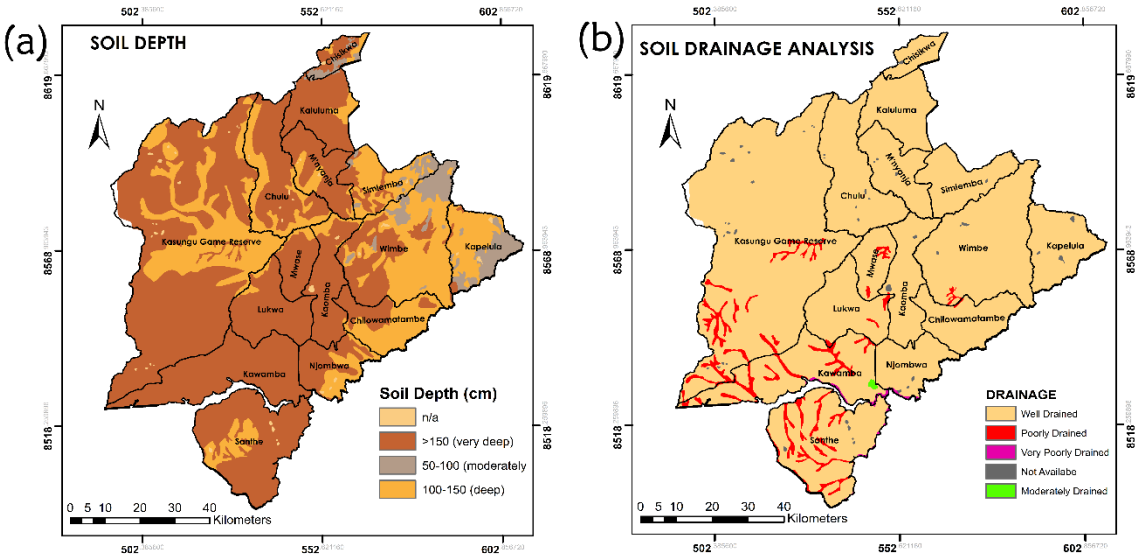


Figure 6: (a) Soil Depth *(b) Soil Drainage*

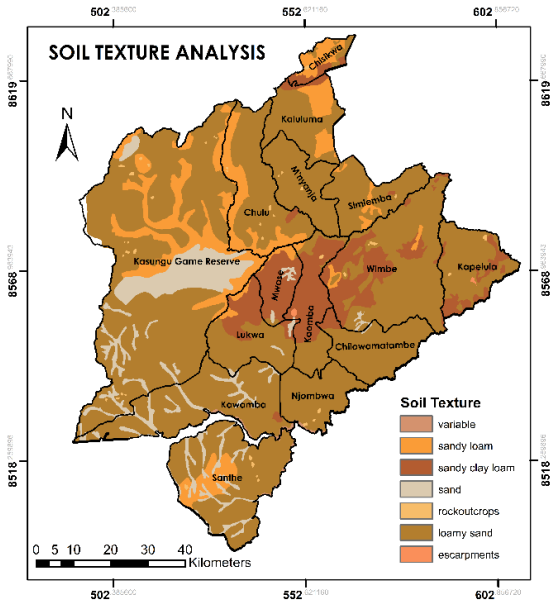


Figure 7: Soil Texture

The soil depth across the region varies considerably. Very deep soils exceeding 150 cm, the most extensive covering Kasungu Game Reserve Area and T/A Chulu, Lukwa, Kawamba, Kaomba, Santhe and extending towards Wimbe and Chilowamatambe.

Moderately deep soils, ranging from 50 to 100 cm are primarily found in the northeast around T/A Kapelula. Deep soils between 100-150 cm are present in smaller bands bordering the very deep soils in the northeast near Simlemba (Figure 6a).

Figure 6b shows that the region has a well-drained soils that are most widespread covering Kasungu game reserve, T/A Chulu, Lukwa, Kawamba, Njombwa, Santhe, Wimbe, Chilowamatambe, Kaluluma and Chisikwa. Very poorly drained conditions are observed smaller patches within the poorly drained zone in of the southern part. The area is also dominated by loamy sand texture, covering most of the T/A's. Sandy clay loam is distinctively presented in T/A Mwase, Kaomba and some parts of Wimbe (Figure 7).

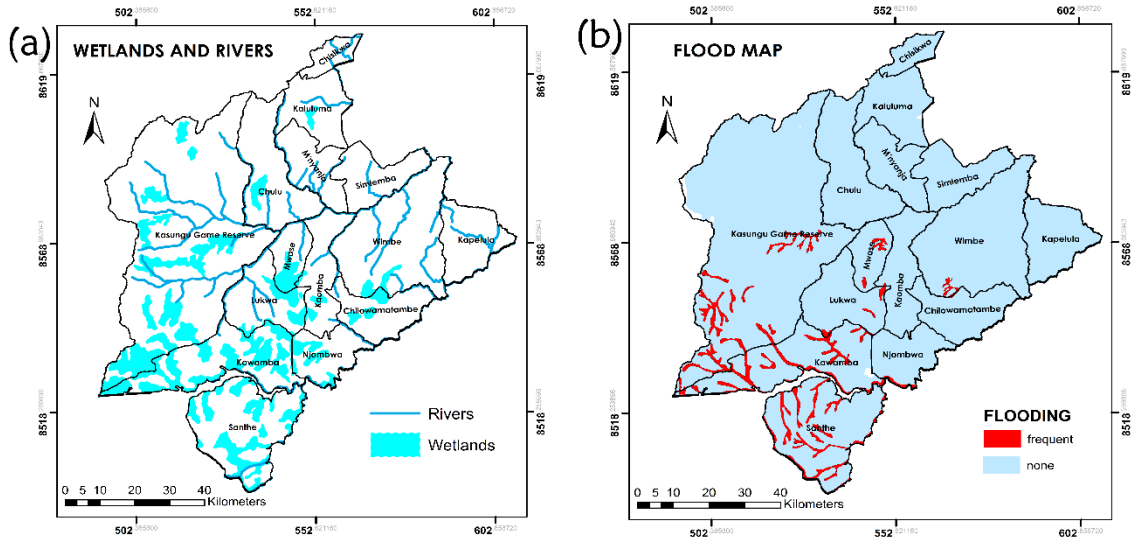


Figure 8: (a) Wetlands and Rivers (b) Flood Map

Figure 10a shows the wetlands are primarily concentrated to the southern region of Kasungu, specifically around T/A Santhe, Kaomba and Lukwa and Mwase. Rivers are distributed throughout most part of the area, forming a dense network particularly within the game reserve and extending towards the northern areas like Chulu, Kaluluma and Chisikwa. It is observed that frequent flooding is also experienced in the southern part, around Santhe and Kawamba extending northwards in linear pattern along low-lying areas. The rest of the area including

locations like Kasungu Game Reserve, T/A Chulu, Wimbe, Kapelula, Simlemba, Kaluluma and Chisikwe indicated have no frequent flooding. Therefore, the risk of frequent flooding appears to be concentrated in the southern low-lying areas of the district (Figure 8b).

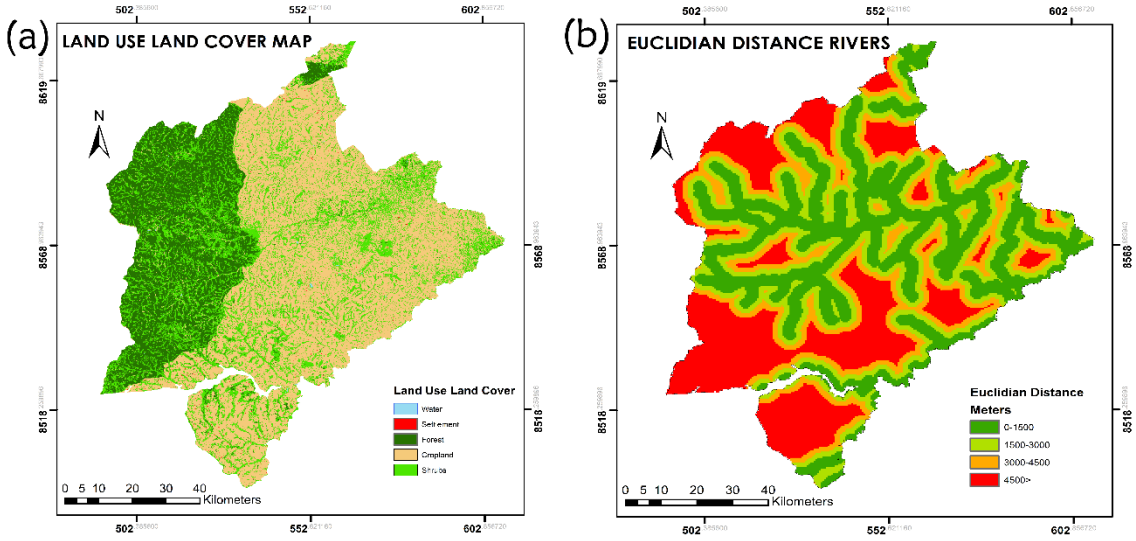


Figure 9: (a) Land Use Land Cover (b) Euclidian Distance Rivers

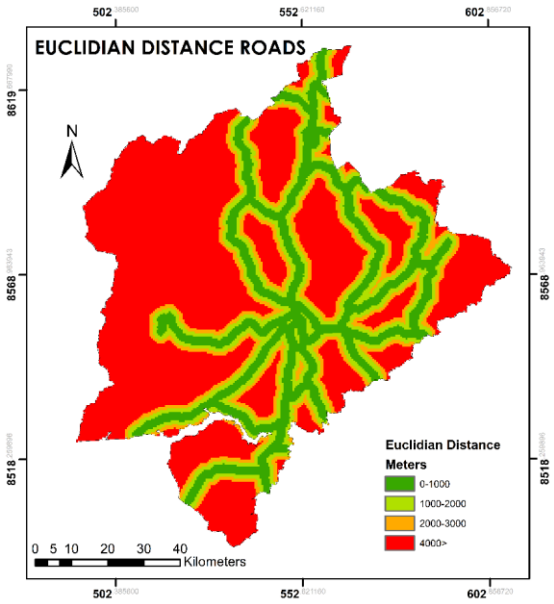


Figure 10: Distance from road access

Figure 9a the land use land cover across the area shows a clear spatial distribution. The western part is predominantly covered by forest. moving to the eastward, the dominant land cover transitions to cropland which extends across the large central and eastern portion. Shrubland land is also significant, particularly in the northeast and southeast interspersed with cropland. Settlements are indicated by red patches, appear scattered throughout the cropland areas with slightly higher concertation in the central region of the areas.

The Euclidian distance that varies across the area. Areas closest to the river, within 0-1500 meters, are presented in green and form a network along the river courses throughout the area. Moving away from the rivers, the distance increases. Areas between 1500-3000 meters from the river are shown in yellow, forming a buffer zone around the green areas. Further out, the areas between 3000-4500 meters are depicted in orange. The areas furthest from the rivers, at a distance greater than 4500 meters, are shown in red (Figure 9b).

Figure 10, the Euclidian distance from roads shows a network of accessibility across the area. Areas are closest to roads, with 0-1000 meters, are indicated in green, forming corridors along the road infrastructure. Moving away from these corridors, the distance increase, areas between 1000-2000 meters from the road are shown in yellow, creating buffer zones around the primary road network. Further away, areas between 2000-3000 meters are depicted in orange. The most Signiant portion of the area, shown in red, presents distances greater than 4000 meters from the road. These areas, particularly in the Northen, eastern and southwestern parts, indicate limited accessibility to major road network

4.1.1. Discussions

Figure 5a illustrates the elevation characteristics of Kasungu district, highlighting significant topographic variation across the area. The district reaches its highest elevation at approximately 1,625 meters above sea level, while the lowest point lies at around 714 above the sea level. Notably the northern portion of the district is

characterized by elevated terrain, forming a distinct contrast to the central region, which is predominantly flat and gently undulating. This variation in elevation has important implications for land use planning, water drainage and potential irrigation development within the district. Figure 5b presents the distribution of slope classes within Kasungu district. The majority of the area approximately 58.69% is characterized but nearly flat terrain with slopes ranging from 0-2%. This category of land is suitable for irrigation, particularly surface irrigation which are widely practiced by smallholder farmers due to their simplicity and cost effectiveness. Land with gentle slopes accounts ranging from 2-6% accounts for about 35.97%, while the moderate steep terrain (6-13%) makes up 4.27%. Steep areas with slopes greater than 13% represents 1.07%. According to (Food and Agriculture Organization, 2002) slopes less than 2% are optimal for irrigation development, especially for surface irrigation methods, which depend on gravitational water flow. These gentle surfaces minimize runoff and soil erosion risk making water distribution more uniform and efficient. This analysis supports findings by (Main & Raude, 2016) who emphasized that slope plays a significant role in influencing hydrological factors such as surface runoff, soil erosion and drainage. Therefore, the relative flat nature of Kasungu district as indicated in the slope analysis, is a key advantage in identifying and selecting appropriate location for irrigation schemes.

The drainage of Kasungu as shown in Figure 6b reveals that approximately 96.8% is composed of well drained soils with favourable physical properties. These properties allow efficient water percolation, reducing the risk of waterlogging and promoting healthy growth. This analysis aligns with spatial findings in Figure 8b which show the majority of the district is not prone to flooding. The low flood susceptibility can be attributed to the presence of well drained soils and minimal levels of erosion across the district. On the other hand, areas that experience frequent flooding often have poorly drained soils and are typically subjected to higher rates of soil erosion. Such conditions are unstable for surface irrigation systems, which are widely used in Malawi due to their affordability and adaptability to small holder farmers. These observations are consistent with the findings of (Nafesse & Kidanu, 2010) who reported that flooding is a consequence inadequate drainage, extensive

deforestation, and widespread soil degradation. Poorly management of catchment areas and vegetation loss can exacerbate runoff and reduce soil permeability, further contributing to flooding risk. Given the predominantly good drainage regime in Kasungu, the district presents favourable conditions for development of effective and sustainable irrigation structures. The availability of well drained land not only enhances the suitability of the area for surface irrigation but also provide valuable guidelines for engineers in the design and implementation of efficient drainage channels. Such considerations are essential to ensure long term functionality and resilience of irrigation schemes in the face of changing environmental conditions.

The river system of Kasungu district as depicted in Figure 8a is mainly dendritic in nature, with the general flow of water moving from the western to the eastern part of the district. This branching pattern is indicative of a well-integrated network of rivers, which include several perennial water sources such as Dwangwa, Bua, Lingazi, Rusa, Luwezi, Lupache and Milenje rivers. These rivers are known for their relatively good water quality, making them source for irrigation purposes throughout the year. Hydrological assessment of the district reveals that the minimum dry season flow, commonly referred to as Q80, ranges between 0.01 and 0.02 litres per second per square kilometre. Although these flows are relatively low, they are sufficient to support various irrigation techniques, particularly when combined with appropriate water storage or management intervention (Chikabvumbwa, Sibale, & Chisale, 2021).

The combination of slope data, as previously shown in figure 5b, with river flow patterns shows numerous opportunities for implementation of irrigation methods across the district. These may include surface irrigation, drip system, and sprinkler irrigation depending on soil conditions.

The assessment of soil characteristics in Kasungu district focused on three key properties: soil type, soil drainage and soil texture. These properties play a crucial role in determining the suitability of land for irrigation. Figure 7 provide a breakdown of soil texture classes across the district, showing that loamy sand, sandy clay, and sandy loam are the predominant soil types. These textures are generally favourable for irrigation, as they offer good balance between water retention and

drainage (United States Dapartment of Agriculture, 2017). Loamy soils, in particular, are well-regarded for their ability to hold adequate moisture while also allowing excess water to drain, reducing the risk of water-logging- a critical factor for many crops.

In terms of soil depth, Figure 6a reveals that the district is largely covered by deep soils, with depth ranging from 50 cm to over 150 cm. Deep soils are particularly advantageous for crop cultivation because they provide a larger rooting volume, allowing plants to access more nutrients and water. According to (Food and Agriculture Organization, 2006) this depth correspond to what is commonly considered an effective root zone for a wide variety of crops, thus enhancing plant health, productivity and resilience during dry period. Taken together, suitable soil texture, good soil drainage and substantial rooting depth suggest that soils in Kasungu district are well suited for irrigation development. These characteristics not only support crop growth but also facilitate the effective design and implementation of sustainable irrigation systems.

Figure 9a shows the land use land cover classification of Kasungu. The land use land cover reveals that the majority of the land (50.46%) is arable, making it suitable for agriculture activities. Forested area account for 22.44%, while vegetation is approximately 27.51 and the remaining portion of land is occupied by human settlement. However, a closer analysis of the cultivated area indicates that not all cropland is suitable for irrigation. This is primarily due to the distance of some agricultural plots from reliable water sources, limiting their accessibility for conventional irrigation methods.

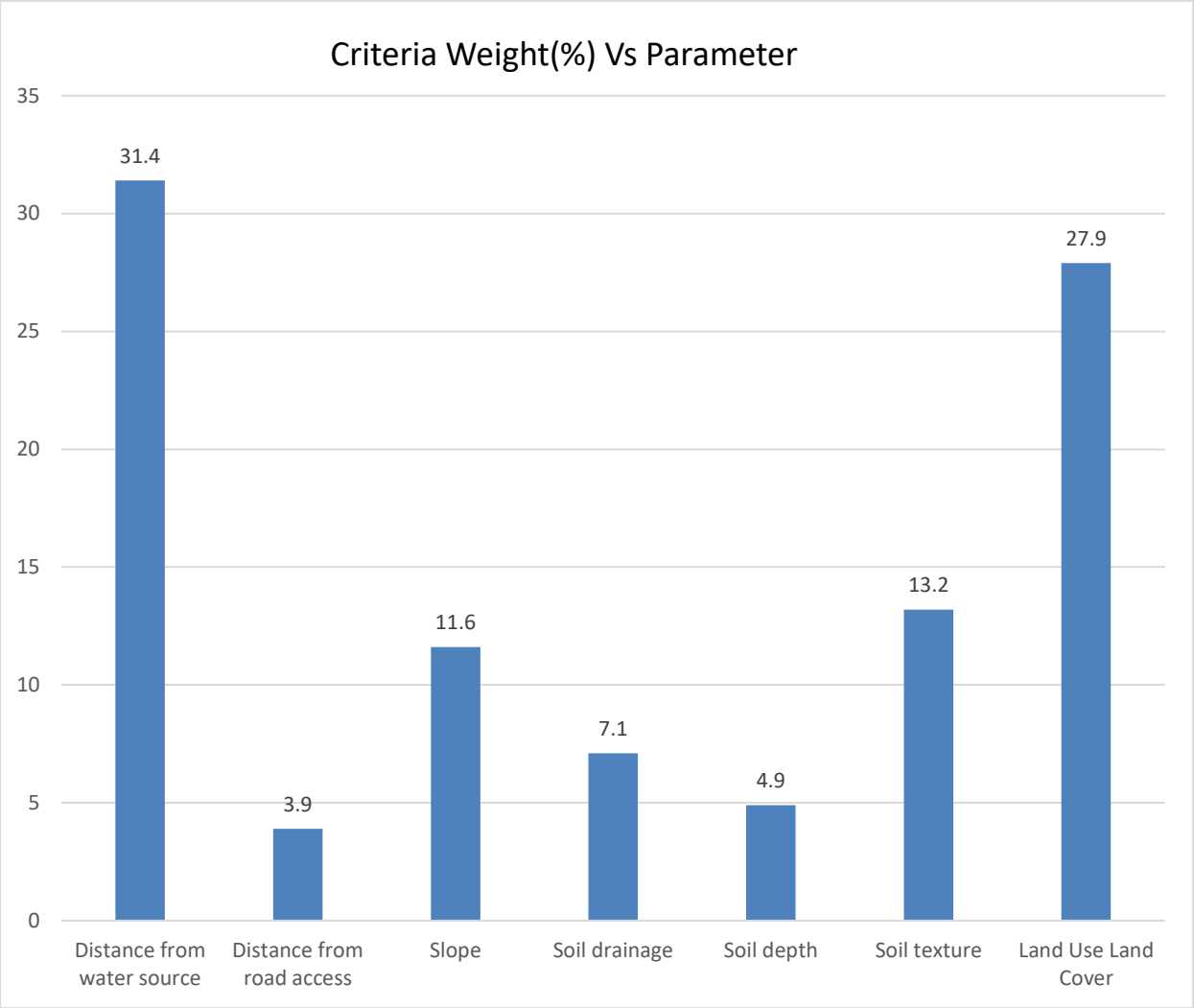


Figure 11:Criteria weights for irrigation site selection parameters

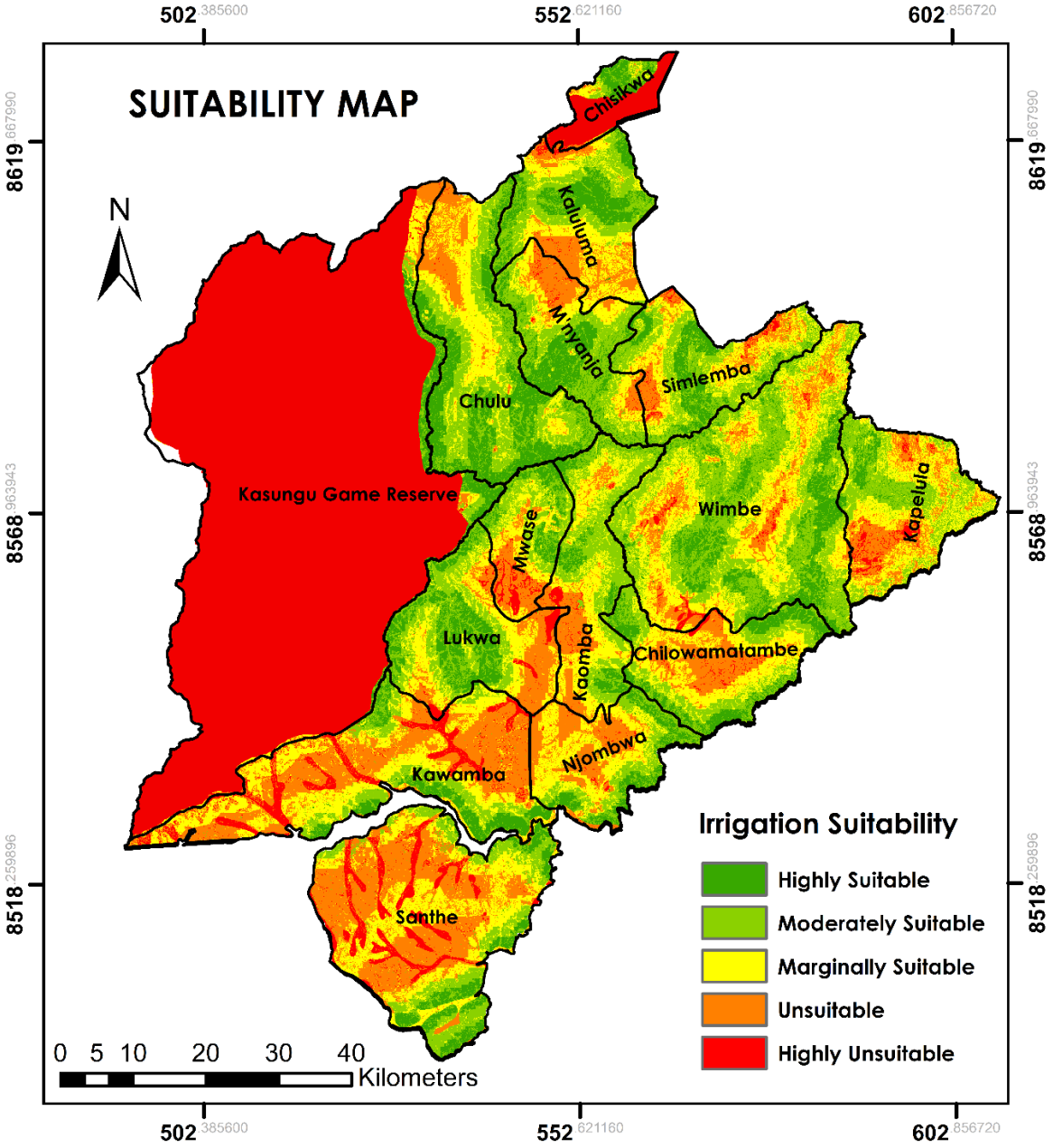


Figure 12: Irrigation Suitability Levels of Kasungu

Figure 11 Highlights the criteria weights that were used to assess the influence of each parameter, with their reliability confirmed by consistency level (CR=0.070), which falls within the acceptable limit of less than 0.1 as recommended by (Saaty, Decision making with the Analytical Hierarchy Process, 2008). The analysis showed that water source, slope and land use were the most influential factors in identifying suitable irrigation sites. Nonetheless, soil type, soil depth and proximity to water sources also

played a vital role in the decision making-process. By applying AHP method within ArcGIS, the most suitable areas for irrigation in Kasungu district were identified. These optimal zones were determined based on the intersection of all considered variables, emphasizing not just their presence, but their significance in influencing irrigation suitability.

From figure 12 the analysis revealed varying levels of suitability for irrigation across the study area. Specifically, the land was categorized as highly suitable, moderately suitable, marginally suitable, unsuitable and highly unsuitable. These classifications were derived from spatial data analysis and are clearly illustrated in the suitability map. Consistent with the findings of (Damitew, Getahun, & Babu, 2019), the use of GIS proved instrumental in enabling decision-makers to better comprehend and interpret spatial patterns, facilitating informed and strategic planning. Moreover, the timely processing and integration of satellite driven data using Remote Sensing and GIS aligns with the assertation that such technological application not only save time but also improves the accuracy and efficiency of identifying appropriate locations for development projects. This proves particularly useful regions where timely data-driven decisions are essential for sustainable resource management.

As demonstrated in figure 12 the outcomes of suitability analysis serve as a practical guide for irrigation experts in selecting the appropriate irrigation technologies and systems tailored to the specific suitability class of each area. This ensures that irrigation planning is both efficient and sustainable, promoting long term viability of water resource infrastructure. These findings are in agreement with those of (Rasooli & Kang, 2015) and (Kavurmaci & Apaydin, 2019), who highlighted that site suitability mapping supports planning and implementation of sustainable water infrastructure and target investment strategies

It is also worth noting that are deemed unsuitable for irrigation were primarily regions highly susceptible to flooding, protected areas, and landscapes characterized by escarpment. These environmental constraints pose significant risk or restrictions for irrigation development and must be carefully considered during planning to avoid degradation and ensure compliance with conservation regulations.

5. CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study successfully demonstrated the application of Geographic Information Systems (GIS) and Remote Sensing (RS) techniques in identifying suitable sites for irrigation development within Kasungu district, Malawi. Through integration of biophysical factors including topography(slope), soil characteristics (texture, depth, drainage), land use land cover, proximity to water resources, and road accessibility, the research effectively developed a weighted irrigation model using Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP).

The results indicated that a significant portion of Kasungu is highly suitable and moderately suitable for irrigation, particularly in areas of flat terrain, deep and well-drained soils, and close proximity to perennial rivers. The suitability analysis revealed spatial variability, allowing for detailed mapping and informed site-specific planning.

Furthermore, the use of supervised classification techniques in Google Earth Engine, combined with GIS-based spatial analysis in ArcGIS, proved effective in generating accurate land cover data and facilitating robust suitability assessment. The methodology adopted provides a replicable and scalable framework that can be applied in other regions facing the similar climatic and agricultural challenges

5.1.1. Recommendations

Based on the findings of this study, the following recommendations are proposed:

- Promote GIS-Based Irrigation Planning for Agriculture Transformation
  To improve food security and increase resilience, government agencies, NGO'S and private sector actors should institutionalize the use of GIS and Remote Sensing in the planning of irrigation projects. This supports sustainable agricultural intensification, efficient land use, and target investment in high-potential areas.
- Implement Pilot Irrigation Schemes to Enable Climate Resilience

The study identifies areas in Kasungu that are highly suitable for irrigation. These should be prioritized for pilot irrigation schemes to enhance smallholder farmer resilience against climate shocks such as drought and unstable rains which is increasingly affecting Malawi's agricultural sector.

- Build Local Capacity in Spatial Technologies
  To ensure sustainable application of GIS and RS technologies, targeted training and capacity development programs should be introduced for technical staff in local councils, agricultural extension officers and academic institutions. This will foster innovation and improve infrastructure planning.
- Avoid Irrigation Development in Ecological Sensitive Areas
  Planning should avoid areas with high flood risk, protected ecosystems, and steep escarpments. Environmental Impact Assessment must be a prerequisite for any irrigation intervention to maintain Malawi's biodiversity and ecological integrity.
- Establish Monitoring and Evaluation Systems for Land Use and Water Resource Management
  Regular monitoring through satellite data and ground truthing should be embedded in district-level environmental management plans. This supports sustainable land and water resource use, reduce or eliminate land degradation and ensure expansions aligns with ecosystems conservation goals.
- Scale and Replicate the GIS-based Irrigation Suitability Model Nationally
  The GIS model developed for Kasungu cab be used as a blueprint for other districts across Malawi. National scale application will improve coordination and guide strategic investment under initiatives such as the Malawi Irrigation Master Plan and Investment Framework.

By implementing these recommendations, Malawi can make significant progress towards achieving food securing, thereby contributing to achievement of SDG 2 and 13 and long-term aspirations of Malawi 2063 vision.

REFERENCES

Belgiu, M., & Dragut, L. (2016). Random forest in Remote Sensing: A Review of applications and future directions. *ISPRS Journal of Photogrametry and Remote Sensing*, 24-31.

Breiman, L. (2001). Random Forest. *Machine Learning*, 5-32.

CGIAR Initiative on Mixed Farming Systems. (2024). *Briging capacity gaps for sustainable farming systems in Malawi.*

Chalumuri, R. N. (2006). *Comprehensive Irrigation Planning using GIS and Remote Sensing.* ResearchGate.

Chikabvumbwa, S. R., Sibale, D., & Chisale, S. W. (2021). Irrigation Site Selection Using Hybrid GIS-based Approach. *International Journal of Human Capital in Urban Management*.

Chuvieco, E. (2016). *Fundamentals of Sattelite Remote Sensing: An Enviromental Approach.* CRC Press, Tyler & Francis Group.

Cloud Publications. (2012). International Journal of Advanced Remote Sensing and GIS.

Congalton, R. G., & Green, K. (2019). *Assessing Accuracy of Remotely Sensed Data: Principles and Practices.* Boca Raton: CRC Press.

Damitew, F. G., Getahun, K., & Babu, A. (2019). Assessment of Land Physical Suitability for Surface Irrigation by Using GIS AND RS, In Case of Loma District, South Western Ethiopia. *International Journal of Current Research and Academic Review*, 32-45.

Earth Resources and Observation Science(EROS) Center. (2024). *Landsat 8-9 Operational Land Image/ Thermal Infrared Sensor Level-2, Collection 2 [dataset].* U.S Geological Survey.

FAO. (1999). *The FAO Guidlines For Land Evaluation.* Rome.

Food and Agriculture Organisation. (2015). *Guidelines For Soil Description.* Rome.

Food and Agriculture Organisation of United Nations. (2022). *FAO IN MALAWI.*

Food and Agriculture Organization. (2002). Irrigation Manual: Planning, Development Monitoring and Evaluation of Irrigated Agriculture With Farmer Participation. *Module 7*, 168.

Food and Agriculture Organization. (2006). *Guidelines for Soil Desciption.* Rome.

Girma, D. (2022). Site Suitability Analysis for Surface Irrigation using GIS, Remote Sensing, and Analytical Hierarchy Process (AHP) Integration in Wama Watershed, Western Ethiopia. *Hydrospatial Analysis*.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 18-27.

Guptill, S. C. (2013). *A Process of Evaluating Geographical Systems.* U.S Department of Interior.

Hussein, K., Woldu, G., & Birhanu, S. (2019). A GIS- Based Multi-Critaria Land Suitability Analysis for Surface Irrigation Along the Erer Watershed, East Hararghe Zone, Ethiopia. *East African Journal of Sciences*.

Jensen, J. R. (2014). *Remote Sensing of the Environment: An Earth Resource Perspective.* Pearson.

Kavurmaci, M., & Apaydin, A. (2019). Assessment of irrigation water quality by a Geographic Information System–Multicriteria Decision Analysis-based model: A case study from Ankara, Turkey. *Water Environmental Research*, 1420-1432.

Lu, D., & Weng, Q. (2007). *A Survey of Image Classification Methods and Techniques for Improving Classification Perfomance.*

Main, C., & Raude, J. (2016). Assesing Land Suitability For Rainwater Harvest Using Geospatial Techniques: A Case Study of Njoro Catchment Kenya. *Applied and Environmental Soil Science*, 10.

Makwiza, C., Kadyampakeni, D., Mloza Banda, H. R., Ekwanu, A., Tusiime, G., & Najaiwa, J. (2010). Improving Smallholder Irrigation Perfomance in Malawi.

Malczewski, J., & Rinner, C. (2015). *Multicriteria Decision Analysis in Geographic Information Science.* Springer Berlin Heidelberg.

Mather, P. M., & Koch, M. (2022). *Computer Preprocessing of Remotely-Sensed Images.* Wiley.

Mohammady, M., Horadi, H. R., Heinivand, H., & Temme, A. (2014). A Comparison of Suprvised, Unsupervised and Sythetic Land Use Classification

Methods in the North of Iran. *International Journal of Environmental Science*.

Mohammedshum, A. A., Maathuis, B. H., Mannaerts, C. M., & Teka, D. (2023). *Mapping Small-Scale Irrigation Areas Using Expert Decision Rules and the Random Forest Classifier in Northern Ethiopia.*

Mountrakis, G., Im, J., & Ogole, C. (2011). Support Vector Machines in Remote Sensing. *ISPRS Journal of Photogrammetry and Remote Sensing*, 247-259.

Nafesse, N. T., & Kidanu, S. T. (2010). The Water Balance of May Nugus Catchmen, Tigray, Northern Ethiopia.

Naidu, R., Ghosh, S., & Giridhar, M. V. (2012). *Application of Remote Sensing And GIS For Identification And Assessment Of Crop Growth In Wazirab Command Area By Calculation of Irrigation Losses and Demand To Improve The Farming.*

Ortiz, A. C., Musarella, C. M., Carmona, C. E., & Canas, Q. R. (2022). *Vagetation Index and Dynamics.* IntechOpen.

Rasooli, A., & Kang, D. (2015). Assessment of Potential Dam Sites in Kabul River Basin Using GIS. *International Journal of Advanced Computer Science and Application*, 83-89.

Saaty, T. L. (2008). Decision making with the Analytical Hierarchy Process. *International Journal of Service Sciences*, 83-98.

Skidmore, A. K., Bijker, W., & Lalit, K. (2014). Use of remote sensing and GIS for sustainable land management.

United States Dapartment of Agriculture. (2017). Soil Survey Manual.

Wubalem, A. (2021). *GIS-based Land Suitability Analysis for Surface Irrigation Using Analytical Hierarchy Process Method in East and West Bellesa, Northwesten Ethiopia.* University of Gondar.