DEVELOPING A CLIMATE-RESILIENT GIS-BASED FRAMEWORK FOR IRRIGATION SITE SELECTION IN DEDZA DISTRICT

A MASTER OF SCIENCE THESIS IN GEOINFORMATICS

DINGANI JOMO MKANDAWIRE

MZUZU UNIVERSITY

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DINGANI JOMO MKANDAWIRE

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DECLARATION

I, DINGANI JOMO MKANDAWIRE, hereby declare that the work presented in this thesis is a result of my own research effort and that, to the best of my knowledge, it has not been submitted previously to Mzuzu University or any other institution of higher learning for the award of any academic qualification.

Where other sources of information have been used, acknowledgement has been made accordingly by means of references.

Signature_________________________ Date___________________________

CERTIFICATE OF APPROVAL

I, the undersigned, certify that this thesis is a result of the author's own work and that, to the best of my knowledge, it has not been submitted for any academic qualification within Mzuzu University or elsewhere. The thesis is acceptable in form and content, and satisfactory knowledge of the field covered herein was demonstrated by the candidate through an oral examination held on

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Supervisor: Dr. Brighton Austin Chunga (PhD)

Signature: ------------------------------------

Date: --

DEDICATION

To God Almighty, thank you for the gift of life, wisdom and determination.

To my wife, daughter, parents and sisters, thank you for your support and prayers.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Dr. Brighton Austin Chunga, for his invaluable guidance and encouragement throughout this study. I also appreciate the support rendered to me by Mr. Dominic Kamlomo and Dr. Webster Sambo, Postgraduate Coordinators, Department of Built Environment, for providing the necessary support in my postgraduate studies. My thanks also go to the Dedza District Agriculture Office for their support during fieldwork. I am grateful to the farmers and stakeholders who participated in interviews and discussions. Lastly, I thank my family and friends for their unwavering support.

ABSTRACT

Climate change poses a significant threat to agricultural sustainability in Malawi, particularly in Dedza District, where rainfed farming systems are highly vulnerable to erratic rainfall and rising temperatures. While irrigation offers a pathway to resilience, current site-selection approaches remain fragmented, relying on outdated datasets, coarse-scale assessments, and expert opinion, with limited integration of climate projections or socio-economic realities. This study developed and validated a climate-resilient irrigation site selection framework for Dedza District using an integrated Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) approach, guided by the Analytic Hierarchy Process (AHP) and informed by both qualitative and quantitative data. Key factors influencing suitability included proximity to rivers (19%), land use/cover (15%), landform (15%), and rainfall deficit (14%), with stakeholder insights reinforcing the importance of water access, infrastructure, and climate variability. The framework integrated 12 reclassified and weighted spatial layers, achieved strong internal consistency (CR = 0.08), and was validated, with 97% of existing irrigation sites falling within areas classified as suitable. Future climate projections under SSP5-8.5 revealed a sharp decline in highly suitable land from 37.25 km² (2000–2020) to 0 km² by the 2070s, highlighting the urgency of adaptive irrigation planning. The novelty of the framework lies in combining literature and stakeholder-derived qualitative inputs with climate projections to produce forward-looking suitability maps, bridging a critical gap in Malawi's irrigation planning. Limitations include the exclusion of groundwater due to data constraints, reliance on coarse-resolution climate datasets, and the absence of crop-specific modelling, which should be addressed in future studies. The study recommends integrating this framework into district and national irrigation planning, prioritising moderately suitable zones, strengthening institutional capacity, and extending the model to other districts, thereby advancing Malawi 2063's vision for climate-smart, food-secure agriculture.

Keywords: *Analytic-Hierarchy-Process (AHP), Climate-Resilience, GIS-Based MCDA, Irrigation Suitability, Climate Projections, Sustainable-Agriculture*

ACRONYMS AND ABRBREVIATIONS

AfDB	African Development Bank
AfSIS	Africa Soil Information Service
AHP	Analytical Hierarchy Process
CMIP6	Coupled Model Intercomparison Project Phase 6
CR	Consistency Ratio
DCCMS	Department of Climate Change and Meteorological Services
DEM	Digital Elevation Model
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FGD	Focus Group Discussions
GIS	Geographic Information System
GoM	Government of Malawi
IPCC	International Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
LULC	Land Use/ Land Cover
LST	Land Surface Temperature
MCDA	Multi-Criteria Decision Analysis
MZUNI-REC	Mzuzu University Research Ethics Committee
NDVI	Normalized Difference Vegetation Index
NIP	National Irrigation Policy
NGO	Non-Governmental Organizations
PET	Monthly potential evapotranspiration
RS	Remote Sensing
SSP	Shared Socioeconomic Pathways
SRTM	Shuttle Radar Topography Mission
USGS	United States Geological Survey

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CHAPTER 1: INTRODUCTION

1.1. Background

Climate change poses a significant and growing threat to agriculture worldwide, with developing countries especially vulnerable due to their dependence on rainfed farming systems (Dawit et al., 2020; Duy, 2020; IPCC, 2021, 2022; Todd et al., 2011). Increasingly erratic rainfall, rising temperatures, and shifting seasonal patterns undermine agricultural productivity and heighten food insecurity (Coulibaly et al., 2015; World Bank, 2021). In Malawi, agriculture underpins livelihoods and the economy, employing over 80% of the population and contributing significantly to GDP (AfDB, 2011; GoM, 2014). Yet, climate shocks—shortened growing seasons, prolonged dry spells, and pest and disease outbreaks—continue to erode food production, leaving rural households increasingly vulnerable to hunger and poverty (Coulibaly et al., 2015; World Bank, 2021).

Irrigation has long been recognised as a critical adaptation strategy to climate shocks, but its expansion has been constrained by weak planning, poor targeting, and sustainability challenges. Effective irrigation planning requires a structured, forward-looking framework that integrates biophysical suitability, socio-economic conditions, and climate projections. Without such integration, irrigation investments risk being inefficient and unsustainable in the long term (GoM, 2014).

Geographic Information Systems (GIS) and Remote Sensing (RS) offer powerful tools for building such a framework. GIS enables spatial analysis of land, water, and infrastructure, while RS provides dynamic environmental data. Together, they support evidence-based site selection that prioritises areas likely to remain viable under future climate scenarios (Ambika et al., 2016; Cai et al., 2017; Khatami & Khazaei, 2014; Massari et al., 2021). Globally, GIS-based approaches have been used to map and identify irrigation potential for irrigation planning (Gao et al., 2018; Ozdogan et al., 2010). In Africa, Mabhaudhi et al. (2022) demonstrated their potential for analysing irrigation suitability across multiple countries, including Malawi. Yet, many studies did not incorporate climate change impacts, reducing their long-term relevance. Within Malawi, Chikabvumbwa et al. (2021) highlighted the limited use of integrated GIS approaches in Malawi's irrigation planning framework, with a notable absence of structured decision-support systems at the district level (GoM, 2014).

This study thus focuses on Dedza District, a climate-vulnerable area where rainfed farming dominates and irrigation potential remains underutilised. By applying a GIS-based Multi-Criteria Decision Analysis (MCDA) model, the research demonstrates how geospatial tools and stakeholder knowledge can be combined to improve irrigation planning. Rather than presenting irrigation expansion as a general solution, the study emphasises the importance of spatially explicit, climate-informed analysis for guiding investment decisions. This framing provides a foundation for examining the specific challenges of irrigation site selection in Malawi, which are detailed in the following Problem Statement.

1.2. Problem Statement

Despite the recognised importance of irrigation for strengthening agricultural resilience, Malawi's irrigation development has not kept pace with the scale of climate-related risks. In districts such as Dedza, where farming systems depend heavily on rainfall, farmers face declining yields and heightened food insecurity due to prolonged dry spells, erratic rainfall, and rising temperatures (Coulibaly et al., 2015; Jury & Gwazantini, 2002; Kumambala, 2010; World Bank, 2021). While irrigation is acknowledged as a critical adaptation strategy (AfDB, 2011; Coulibaly et al., 2015; GoM, 2014; World Bank, 2021), its expansion has often been poorly targeted and unsustainable, limiting its effectiveness in reducing vulnerability.

The problem is not only climate variability, but also poor integration of spatial tools in planning, reliance on outdated datasets, lack of climate-informed frameworks, and limited capacity for district-level irrigation planning (Chikabvumbwa et al., 2021). Nationally, site selection often depends on coarse-scale data, historical averages, and expert opinion, with minimal integration of future climate variability or localised socio-economic constraints (GoM, 2014). This leads to irrigation schemes being developed in suboptimal areas, resulting in underutilised infrastructure, inefficient systems, low investment returns, and continued vulnerability to climate stress (Bwambale et al., 2022; Mabhaudhi et al., 2022).

This gap underscores the urgent need for a climate-resilient planning framework that systematically integrates climate projections, biophysical suitability, and socio-economic considerations through geospatial analysis with stakeholder input to identify sustainable irrigation sites. This study responds to that need by developing and applying a GIS-based Multi-Criteria Decision Analysis (MCDA) model for Dedza District. Beyond contributing to academic discourse, the framework provides practical, data-driven tools for planners and policymakers at the district and national levels, supporting Malawi's transition toward climate-smart agriculture in line with the Malawi 2063 Vision.

1.3. Main Objective

The main objective of this study is to develop a climate-resilient GIS-based framework for irrigation site selection in Dedza District.

1.3.1. Specific Objectives

The study aims to achieve the following specific objectives:

i. To evaluate key factors that affect irrigation suitability.
ii. To develop a GIS-based Multi-Criteria Decision Analysis (MCDA) framework, for irrigation site selection.
iii. To apply the developed framework in Dedza District to generate spatially explicit irrigation suitability maps.
iv. To evaluate long-term irrigation potential and resilience by integrating future climate scenarios into the framework

1.4. Research Questions

i. What biophysical, socio-economic, and climatic factors influence irrigation suitability?
ii. How can a GIS-based MCDA framework, informed by AHP, be developed for irrigation site selection?
iii. How can this framework be applied to generate suitability maps for Dedza District?
iv. How will future climate scenarios affect irrigation suitability, and how can these be incorporated into the framework to enhance long-term resilience?

1.5. Significance of the study

This study is significant in both academic and policy terms. It advances scholarship by integrating climate projections and stakeholder input into a GIS-based MCDA framework for irrigation planning, an approach rarely applied at district level in Malawi. The framework demonstrates how qualitative insights can be systematically incorporated into spatial analysis, producing suitability maps that are both technically robust and socially relevant. For policymakers, the study offers practical decision-support tools that can improve targeting of irrigation investments, reduce maladaptation, and strengthen resilience against climate shocks. The framework directly supports the National Irrigation Policy (2014), contributes to the Dedza District Development Plan (2022–2027), and aligns with the Malawi 2063 Vision, which emphasises climate-smart agriculture and sustainable water management (GoM, 2022, 2024). By identifying not only current but also future suitability zones, the study provides a forward-looking approach that can guide both district-level planning and national strategies for climate-resilient irrigation development.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Irrigation is increasingly recognised as a cornerstone of climate-resilient agriculture, particularly in regions such as sub-Saharan Africa, where rainfed farming dominates (IPCC, 2021; Mabhaudhi et al., 2022). Expanding irrigation can help stabilise yields, reduce vulnerability to rainfall variability, and support long-term food security. However, effective irrigation planning requires more than identifying land and water availability: it demands structured frameworks that integrate climate projections, biophysical conditions, and socio-economic realities (Hussien et al., 2019; Worqlul et al., 2019).

Existing studies highlight three major domains shaping irrigation site suitability. First, biophysical factors such as soils, slope, and hydrology determine whether irrigation is technically feasible. Second, climatic conditions influence water availability and long-term system viability, especially under scenarios of rising temperatures and rainfall deficits. Third, socio-economic and institutional factors, including road access, market proximity, and governance capacity, affect adoption and sustainability. Studies that address only one domain risk produce outputs that are technically accurate but socially or climatically irrelevant.

Geographic Information Systems (GIS) and Remote Sensing (RS) have provided powerful tools to integrate such datasets, while Multi-Criteria Decision Analysis (MCDA) approaches—especially the Analytic Hierarchy Process (AHP)—allow for structured weighting of diverse criteria. Globally, these tools have been used to identify irrigation potential with varying degrees of success (Akpoti et al., 2023; Gao et al., 2018). In Malawi, however, applications remain limited and fragmented. National irrigation planning often depends on coarse-scale data, expert opinion, and historical averages, with little systematic integration of climate change scenarios or local socio-economic knowledge (Chikabvumbwa et al., 2021).

This review critically examines global and African literature on GIS- and MCDA-based irrigation site selection, with particular attention to how these approaches have (or have not) incorporated climate and socio-economic dimensions. By synthesising lessons from existing studies and highlighting gaps in Malawi's current approaches, the review provides the foundation for developing a climate-resilient, GIS-based framework for irrigation planning in Dedza District.

2.2. GIS and Remote Sensing in Irrigation Site Selection

GIS and Remote Sensing (RS) are indispensable tools for assessing irrigation potential because they enable the spatial integration of diverse datasets, such as slope, soils, land cover, and hydrology. GIS provides the analytical framework for overlaying and reclassifying these datasets, while RS supplies high-resolution imagery for monitoring vegetation health, land-use dynamics, and surface water availability (Bastiaanssen et al., 2000; ESRI, 2023; Khatami & Khazaei, 2014). Together, these tools enable planners to visualise spatial constraints and opportunities, improving the accuracy and efficiency of irrigation planning (Ambika et al., 2016; Atzberger, 2013; Ban et al., 2017).

In contexts where on-the-ground data are scarce, as in much of sub-Saharan Africa, RS-derived indicators such as Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) have been particularly valuable for assessing vegetation stress, crop performance, and water demand (Adrian et al., 2021; Munghemezulu et al., 2021; Okal et al., 2020). DEM-derived slope data also help assess the technical feasibility of irrigation infrastructure, especially gravity-fed systems (FAO, 2002, 2020).

However, most applications remain biophysically focused, with limited integration of socio-economic realities such as road access, market proximity, or land tenure. This reduces the practical value of GIS–RS analyses for district-level planning, where adoption and sustainability depend on more than technical suitability. In Malawi, while tools like GIS have been used to map irrigation potential (Chikabvumbwa et al., 2021), their uptake into decision-support systems is still fragmented, and systematic incorporation of climate change projections is largely absent.

2.3. Multi-Criteria Decision Analysis (MCDA) and AHP in Irrigation Suitability Mapping

2.3.1. Conceptual Background

Multi-Criteria Decision Analysis (MCDA) provides a structured approach for evaluating irrigation suitability when multiple, sometimes conflicting, factors must be considered. The Analytic Hierarchy Process (AHP) is one of the most widely applied MCDA methods, enabling systematic weighting of factors through pairwise comparisons (Saaty, 2008). In irrigation studies, AHP has been used to integrate soils, slope, rainfall, water access, and infrastructure into suitability maps, often within GIS platforms (Akpoti et al., 2023; Chikabvumbwa et al., 2021; Hussien et al., 2019; Mabhaudhi et al., 2022; Worqlul et al., 2017, 2019). Its key strengths are transparency, replicability, and the ability to blend expert judgment with empirical data.

Despite these advantages, AHP is not without limitations. Results depend heavily on expert inputs, which may introduce subjectivity, and many studies have excluded socio-economic and climate-change dimensions, reducing long-term policy relevance (Mabhaudhi et al., 2022; Worqlul et al., 2019).

2.3.2. Applications in Sub-Saharan Africa

African case studies across Sub-Saharan Africa have demonstrated the promise and limitations of GIS–MCDA approaches in irrigation site selection. In Ethiopia, Hussien et al. (2019) applied AHP to rank slope, rainfall, soils, and water proximity, improving infrastructure planning. Worqlul et al. (2017) extended this by integrating groundwater availability, while Worqlul et al. (2019) further included socio-economic variables such as market and road access in Ghana, making the model more inclusive. Similarly, Akpoti et al. (2023) combined climate projections with groundwater and infrastructure data to plan irrigation for cocoa production, while Mdemu et al. (2020) in Tanzania incorporated rainfall variability into national irrigation zoning. Collectively, these studies show the strength of MCDA lies in making explicit the trade-offs between factors and in providing a transparent, replicable weighting process, which adds climate and socio-economic dimensions, enhancing model robustness and policy relevance.

2.3.3. Applications in Malawi

In Malawi, applications remain at an early stage. Chikabvumbwa et al. (2021) demonstrated the use of AHP for generating high-resolution irrigation suitability maps, but their work highlighted challenges of inconsistent datasets and a lack of climate integration. Mabhaudhi et al. (2022), through the CGIAR Ukama Ustawi initiative, applied a GIS-MCDA approach across several countries, including Malawi, classifying suitability based on FAO standards. While valuable, the model focused mainly on physical criteria and only later acknowledged the importance of socio-economic dimensions.

These limitations have contributed to irrigation schemes being placed in suboptimal areas, resulting in underutilization, low efficiency, and weak resilience to climate shocks (Bwambale et al., 2022). A key gap is the absence of a comprehensive, district-level framework that systematically integrates climate projections, socio-economic conditions, and local knowledge into site selection. This would align with the African Union's Irrigation Development and Agricultural Water Management (IDAWM) strategy (Mabhaudhi et al., 2022).

2.3.4. Summary and Implications

In summary, Multi-Criteria Decision Analysis (MCDA)—particularly when operationalized through the Analytic Hierarchy Process (AHP)—offers a robust, transparent, and adaptable framework for irrigation suitability assessment. When integrated within GIS platforms, this approach enables spatially explicit, context-sensitive planning that accommodates both current biophysical realities and future climate uncertainties. However, its potential has not been fully realized in Malawi. International examples highlight the benefits of integrating groundwater, climate projections, and socio-economic factors, yet national approaches continue to rely on coarse datasets and expert opinion. Addressing these shortcomings requires frameworks that are spatially explicit, climate-informed, and grounded in local realities. The present study responds directly to this need by developing a GIS–AHP framework tailored to Dedza District.

2.4. Integrating Climate Change in GIS-Based Irrigation Planning

Climate change is reshaping water availability and land suitability, making the integration of climate data into GIS-based irrigation planning essential. Studies have shown that rainfall shifts, rising temperatures, and prolonged dry spells directly influence irrigation demand and long-term feasibility (Akhtar et al., 2021; Dai et al., 2004). Incorporating projections from CMIP6 scenarios (e.g., SSP5-8.5) into suitability models enables forward-looking planning by identifying areas likely to remain viable under future climate conditions (Gaznayee et al., 2023; Ozdogan et al., 2010; Worqlul et al., 2019).

Case studies from Ethiopia and Ghana illustrate the benefits of integrating climate variables into suitability mapping. For instance, Akpoti et al. (2023) demonstrated that combining future climate scenarios with groundwater availability and crop water demand data led to more sustainable and targeted irrigation development in Ghana’s cocoa-growing regions. Additionally, Worqlul et al. (2019) provided a holistic approach that facilitated more inclusive planning by identifying resilient, socially viable irrigation zones. The study also highlighted the dynamic nature of suitability under changing climate scenarios, reinforcing the value of integrating future projections. Hussien et al. (2019) incorporated rainfall and temperature projections into irrigation site selection in Ethiopia's Erer Watershed, resulting in spatially explicit plans that accounted for both current feasibility and long-term climate resilience. These approaches provide strong evidence that climate integration strengthens resilience and reduces investment risk.

In Malawi, however, climate data is rarely embedded into irrigation planning at district level. Despite the availability of projections from the Department of Climate Change and Meteorological Services (DCCMS), limited technical capacity constrains their use. As a result, irrigation infrastructure is often designed for current or historical hydrological conditions, overlooking future risks. This has led to systems being established in areas likely to face water stress, undermining efficiency and sustainability (Bwambale et al., 2022; Chikabvumbwa et al., 2021; GoM, 2014; Mabhaudhi et al., 2022).

2.5. Conclusion

This review shows that GIS, RS, and MCDA provide a strong methodological foundation for irrigation site selection, but existing applications often exclude socio-economic realities and future climate variability. In Malawi, reliance on outdated datasets and expert opinion has resulted in fragmented and suboptimal irrigation development. Bridging this gap requires a framework that integrates geospatial analysis, stakeholder input, and climate projections at district scale. The present study addresses this need by applying a GIS–MCDA model in Dedza District, offering a replicable and climate-resilient approach for national irrigation planning

CHAPTER 3: MATERIALS AND METHODS

3.1. Introduction

This chapter outlines the methodological framework established to support climate-resilient irrigation site selection within Dedza District, using a Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) approach. The methodology integrates both quantitative and qualitative data to assess the spatial suitability for irrigation, guided by the Analytical Hierarchy Process (AHP) and future climate projections under the Shared Socioeconomic Pathway 585 (SSP585) scenario. Each method was chosen and applied to address specific research objectives, culminating in spatial outputs—including suitability maps and constraint overlays—that form the basis for key findings.

3.2. Study Area

The study was conducted in Dedza District, located in Central Malawi (*see Figure 3-1*), covering approximately 3,624 km² with 4,206ha currently under irrigation against a total developed area of 5,639.4ha. Dedza features diverse topography, including the Lilongwe Plain (1,100–1,300 m), Dedza Highlands (1,200–2,200 m), and Escarpments (1,000–1,500 m), with a subtropical highland climate. The district receives annual rainfall between 800–1200 mm and experiences mean temperatures ranging from 14°C to 21°C (Kottek et al., 2006).

3.2.1. Justification for Selecting Dedza District

Malawi has increasingly experienced adverse climatic hazards, including droughts, floods, dry spells, and intense rainfall events, which threaten food and water security in rural, rain-fed agricultural zones (NIDOS, 2009; World Bank, 2021). Dedza is particularly vulnerable due to its heavy reliance on rain-fed farming (GoM, 2014; Jury & Gwazantini, 2002; Kumambala, 2010) and recent land use changes that have transformed wetlands and forests into farmland and settlements (Munthali et al., 2019). These trends have intensified land pressure and pushed cultivation into marginal areas, highlighting the urgent need for strategic, climate-resilient irrigation planning. Dedza's diverse topography, soil types, and microclimates, along with strong institutional support for sustainable agriculture and irrigation development, as outlined in the Dedza District Development Plan (GoM, 2022), the district offers a relevant and strategic case study for applying a GIS-MCDA-based irrigation suitability framework (Hussien et al., 2019; Mabhaudhi et al., 2022), allowing for robust analysis of how environmental and climatic variables interact to affect irrigation potential.

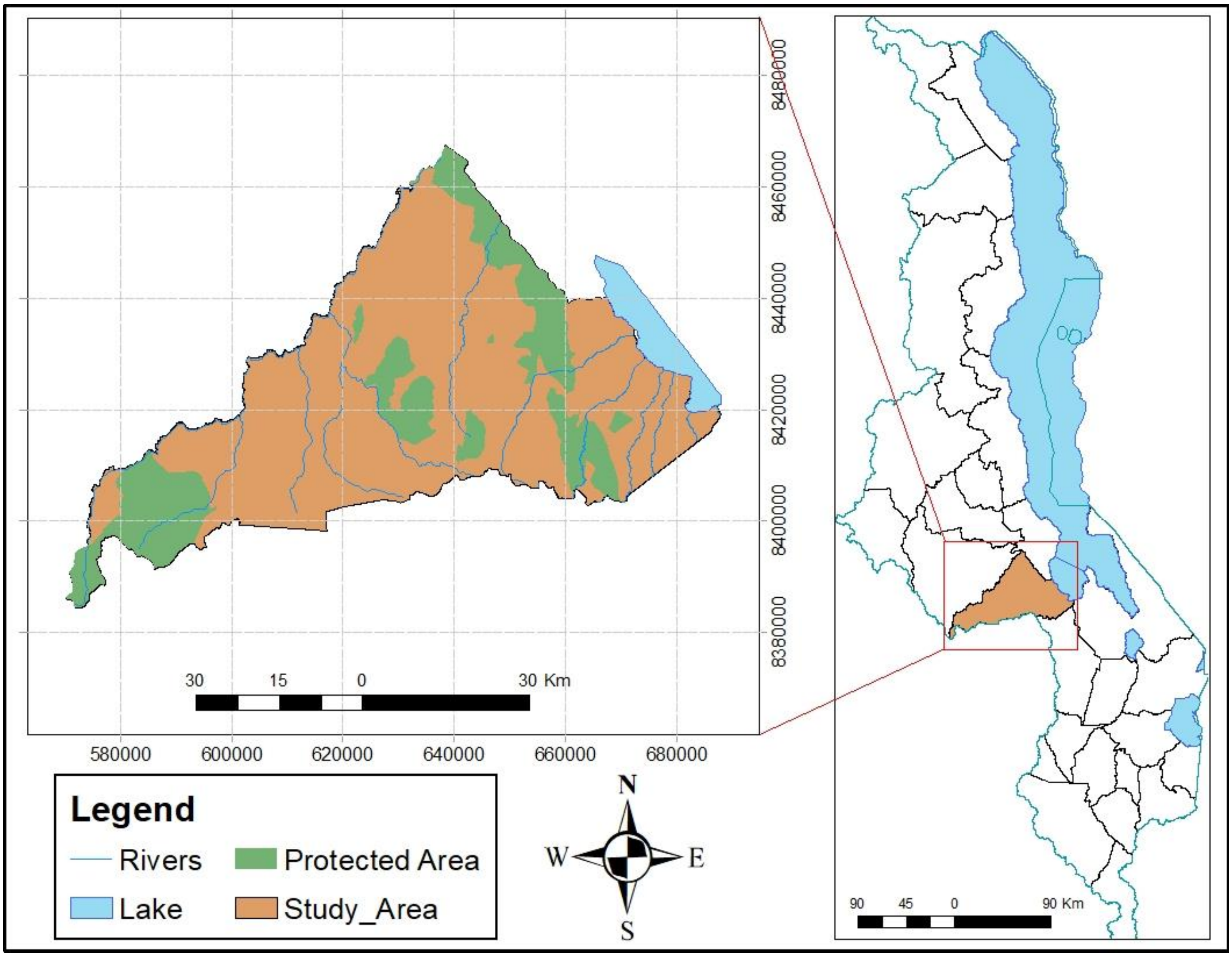


Figure 3-1: Study Area

3.3. Research Methodological Framework

This study adopted a sequential mixed-methods design, where qualitative data collection and analysis preceded and informed the quantitative modelling process. The framework combined participatory stakeholder engagement with GIS-based Multi-Criteria Decision Analysis (MCDA) to ensure that both scientific evidence and local knowledge shaped irrigation site selection.

Step 1: Identification of Factors (Qualitative Phase)

Key factors influencing irrigation suitability were first identified through stakeholder consultations, including focus group discussions (FGDs) with farmers and interviews with district agricultural officers. These qualitative insights highlighted practical constraints — such as water access, road networks, and land tenure —which were subsequently incorporated into the analytical framework.

Step 2: Data Preprocessing

To ensure analytical accuracy and comparability, all spatial datasets underwent cleaning and preprocessing. This process involved checking for missing or inconsistent values, correcting attribute errors, and aligning spatial boundaries to avoid overlaps or gaps. For spatial consistency, all datasets were standardised to a common projection, WGS 1984 UTM Zone 36S, which is suitable for Malawi's location. Vector and raster datasets were converted into a uniform raster format and resampled to a consistent 30 × 30 m pixel cell size. This resolution was selected to balance computational efficiency with the level of spatial detail required for irrigation suitability analysis.

Step 3: Criteria Structuring and Weighting (Qualitative to Quantitative Link)

Insights from stakeholders and literature reviews were systematically translated into a set of twelve spatial factors grouped under biophysical, climatic, and socio-economic domains. The transition from qualitative insights to quantitative weighting was achieved in three stages.

i. **Factor Grouping:** Stakeholder consultations (interviews and FGDs) and literature review were jointly used to identify criteria influencing irrigation suitability. These were organised into three domains—biophysical (e.g., soils, slope, land use/cover), climatic (e.g., rainfall deficit, temperature), and socio-economic (e.g., proximity to markets, roads, settlements).

ii. **Translation of Stakeholder Priorities:** During FGDs, participants ranked and discussed the relative importance of different factors based on their lived experiences of water scarcity, infrastructure access, and farming challenges. These rankings were cross-checked against literature-based criteria to avoid bias or omission.

iii. **Application of AHP:** The combined list of twelve factors was entered into the Analytic Hierarchy Process (AHP). Pairwise comparisons were made, assigning relative weights based on both stakeholder priorities (qualitative evidence) and literature-derived importance (scientific evidence). For example, stakeholders emphasised proximity to rivers as critical, which corresponded with literature highlighting water availability as the most limiting factor. The consistency ratio (CR) was calculated to confirm the reliability of these weights.

Through this process, qualitative insights were systematically quantified, ensuring that the final weighting reflected both scientific rigour and local realities.

Step 4a-b: Spatial Analysis (Quantitative Phase)

Each factor was reclassified into suitability classes and converted into standardised raster layers. Weighted overlay analysis was conducted in ArcGIS to integrate the reclassified factors into composite irrigation suitability maps. Constraint areas, such as forests, wetlands, and urban zones, were excluded to refine the outputs.

Step 4c: Validation and Refinement

The model outputs were validated against existing irrigation schemes in Dedza District, achieving a 97% alignment. This validation demonstrated the robustness of the framework while highlighting areas for improvement—such as integrating groundwater data—that would strengthen its applicability.

Step 5: Integration of Climate Projections

Downscaled climate data under the SSP5-8.5 scenario were incorporated to evaluate long-term changes in rainfall and temperature. This allowed the framework to generate suitability maps not only for the baseline period (2000–2020) but also for future horizons (2030s, 2050s, and 2070s).

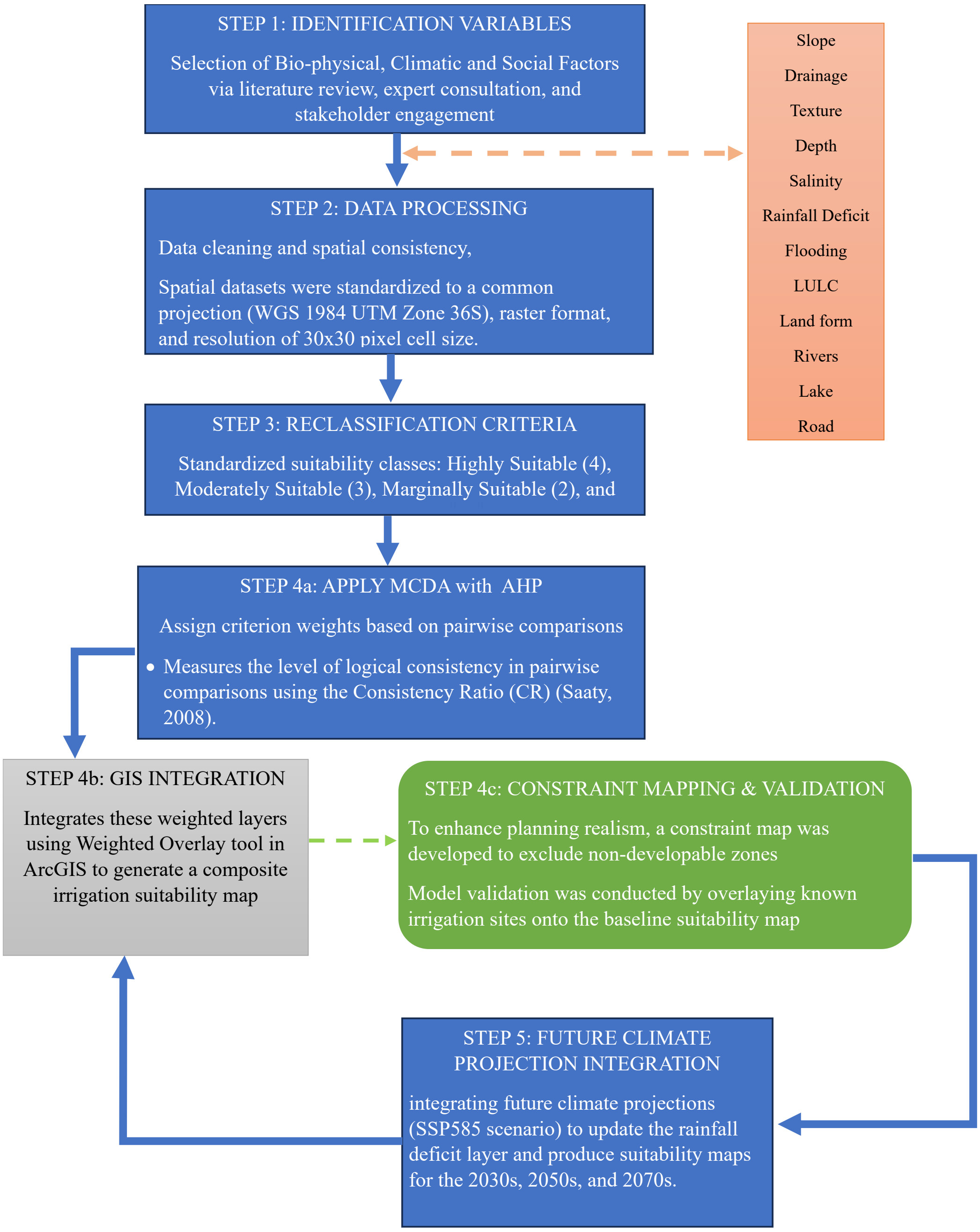


Figure 3-2: Research Methodological Framework Flowchart

3.4. Tools and Software

The study utilized multiple tools to support data collection, analysis, and visualization (*see* ***Table 3-1***). ArcGIS was central to spatial analysis, while stakeholder engagement was facilitated through field interviews and GPS mapping. Microsoft Excel and Word supported documentation and AHP calculations.

Table 3-1: Tools and Software employed in the study

Category	Tools/Software	Purpose
Data Collection	Climate databases (WorldClim, CRU-TS)	Acquisition of historical and projected climate datasets
	Remote sensing/GIS repositories (USGS, FAO GeoNetwork)	Access to satellite imagery and spatial datasets (DEM, land cover, etc.)
Data Processing and Analysis	ArcGIS (Desktop and Spatial Analyst extension)	Spatial analysis, map generation, reclassification, and overlay operations
	Analytical Hierarchy Process (AHP) in ArcGIS MCDA toolbox	Weighting and prioritization of criteria for suitability analysis
Mapping and Visualization	GPS devices (handheld units, smartphones)	Ground-truthing and collection of georeferenced field data
Community and Expert Engagement	Structured stakeholder consultations and key informant interviews	Integration of local knowledge and validation of criteria and results
Documentation and Reporting	Microsoft Office Suite (Word, Excel, PowerPoint)	Report writing, data tabulation, and result presentation

3.5. Data Collection and Analysis

A combination of primary and secondary data sources was employed to evaluate irrigation suitability in Dedza District. This mixed-methods design ensured integration of biophysical, climatic, and socio-economic datasets, enabling robust analysis through GIS-based Multi-Criteria Decision Analysis (MCDA).

3.5.1. Primary Data Collection

3.5.1.1. Field Surveys and Ground-Truthing

Field visits were conducted across selected Extension Planning Areas (EPAs) to collect georeferenced data on water access points, existing irrigation schemes, and land cover. GPS-enabled devices were used to validate spatial datasets, including soil, elevation, and land-use data. Observed irrigation sites were mapped and later used to validate the suitability model outputs in ArcGIS.

3.5.1.2. Stakeholder Engagement

Qualitative data were collected through 10 semi-structured interviews and 3 focus group discussions (FGDs) involving 32 participants, including farmers, district agricultural officers, NGO staff, and government representatives. Using structured guides tailored to each stakeholder group, discussions explored perceived irrigation challenges, climate variability, land use changes, and criteria for site selection. Farmers emphasized declining rainfall, frequent dry spells, and inadequate infrastructure, while institutional actors highlighted policy alignment, participatory planning, and the importance of climate projections. Data were transcribed, coded thematically, and analyzed in Microsoft Excel. Insights from this process—combined with literature review findings—shaped the selection of twelve criteria and informed the weighting process in the Analytic Hierarchy Process (AHP), ensuring that both scientific evidence and local knowledge were reflected in the model.

3.5.2. Secondary Data Collection

Secondary data provided the foundation for spatial analysis and modelling in this study. Secondary datasets were sourced from global, regional, and national repositories, covering biophysical, climatic, and infrastructural variables. *Table 3-2* provides a summary of the sources and resolutions of each dataset.

3.5.2.1. Climate Data

Baseline data (2000–2021) were obtained from WorldClim v2.1, downscaled from CRU-TS 4.06 (~85 km^2) (Fick & Hijmans, 2017; Harris et al., 2020). Future projections were derived from the Coupled Model Intercomparison Project - Phase 6 (CMIP6) HadGEM3-GC31-LL model under Shared Socioeconomic Pathway (SSP)5-8.5 for the 2030s, 2050s, and 2070s. This high-emissions scenario was selected to stress-test irrigation suitability under severe climate risks (IPCC, 2021). Climate values were sampled at 35 sites across Dedza and used to calculate rainfall deficit (Rainfall – PET), where PET was estimated using the Thornthwaite method (Hafeez et al., 2020; Thornthwaite, 1948). Rainfall deficit was then used as a proxy for water availability.

Thornthwaite's formula calculates monthly potential evapotranspiration (PET), which is often used as an approximation for ETo. The formula is expressed as:

$$\text{PET} = 16\left(\frac{10 * T}{I}\right)^{a} \qquad \textbf{(1)}$$

Where:

- PET: Monthly potential evapotranspiration (mm/month)
- *T*: Mean monthly temperature (°C), where T > 0
- *I*: Heat index, calculated as the sum of monthly heat indices (*i*) for a given year
- *a*: An empirical exponent dependent on *I*

Heat Index (*I*)

The heat index *I* is calculated as:

$$I = \sum_{m=1}^{12} i_m \quad \text{..........} \quad \textbf{(2)}$$

$$i = \left(\frac{T}{5}\right)^{1.514}$$

Where:

- i: Monthly heat index
- m: Index for each month (1 to 12)

Exponent (a)

The value of a is derived from the heat index (I) using the following relationship:

$$a = (6.75\times10^{-7} * I3^{-7}) * (7.71\times10^{-5} * I^2) + (1.792\times10^{-2} * I + 0.49239) \quad \text{..........} \quad \textbf{(3)}$$

3.5.2.2. Remote Sensing and Elevation

A 30 m Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) from United States Geological Survey (USGS)'s imagery website, was used to derive elevation and slope. Sentinel-2 imagery (10 m) supported high-precision land use/cover classification.

3.5.2.3. Soil Data

Soil parameters (texture, depth, drainage, salinity, flooding risk) were obtained from the Africa Soil Information Service (AfSIS) and the International Soil Reference and Information Centre (ISRIC) databases (250 m). These were reclassified into suitability classes using FAO (2006) guidelines and expert input.

3.5.2.4. Hydrology and Infrastructure

Rivers, lakes, and road network shapefiles were extracted from the Malawi Department of Water Resources, Digital Chart of the World (DCW), and World Bank GIS archives (2017). Proximity analyses were performed to assess accessibility to water and transport networks.

Table 3-2: Spatial Data Sources and Resolutions

Factor	Source	Spatial Resolution
Rainfall	WorldClim version 2.1, downscaled from CRU-TS 4.06	~85 km^2
Temperature	WorldClim version 2.1, downscaled from CRU-TS 4.06	~85 km^2
Rainfall Deficit	Calculated from Rainfall - Evapotranspiration (ETo) derived from Temperature data	~85 km^2
Land Use / Land Cover (LULC)	Sentinel-2 Land Use/Land Cover Time Series	10 m
Landform	Africa Soil Information from ISRIC & DEM (SRTM 1 Arc-Second Global)	250 m
Soil Texture	Africa Soil Information from ISRIC	250 m
Soil Depth	Africa Soil Information from ISRIC	250 m
Soil Drainage	Africa Soil Information from ISRIC	250 m
Soil Salinity	Africa Soil Information from ISRIC	250 m
Flooding Potential	Africa Soil Information from ISRIC	250 m
Elevation	Digital Elevation Model (SRTM 1 Arc-Second Global)	30 m
Slope	Derived from DEM	30 m
Proximity to Road	Digital Chart of the World (DCW), World Bank	N/A
Distance to River	Calculated from river location data	N/A

3.6. Data Processing and Analysis

This section describes the procedures used to prepare, weight, and analyze spatial datasets for developing irrigation suitability maps. Using MCDA and AHP, the data were standardized and integrated to generate current and future suitability outputs aligned with the study objectives.

3.6.1. Data Cleaning and Reclassification

All datasets were projected to WGS 1984 UTM Zone 36S, standardised to raster format, and resampled to a uniform resolution. Climate data were interpolated using Inverse Distance Weighting (IDW), a reliable method for estimating spatial rainfall and temperature (Chen & Liu, 2012; Ndiaye et al., 2021).. Each criterion was reclassified into four suitability classes— Highly Suitable = 4, Moderately Suitable = 3, Lowly Suitable = 2, Not Suitable = 1—based on FAO (2020) guidelines and expert consultation. *Table 3-3* shows the reclassification scheme of all factors.

Table 3-3:Factor Reclassification Scheme

Factor	Class	Weight	Description
Slope (% slope)	0 – 2	4	Highly Suitable
	0 – 7	3	Moderately Suitable
	7 – 16	2	Lowly Suitable
	More than 16	1	Not Suitable
Soil Depth (cm)	> 150 (Very Deep)	4	Highly Suitable
	100 - 150 (Deep)	3	Moderately Suitable
	50 - 100 (Moderately Deep)	2	Lowly Suitable
	0 - 50 (Shallow)	1	Not Suitable
Soil Drainage	> 150 (Very Deep)	4	Well Drained
	100 - 150 (Deep)	3	Moderately Drained
	50 - 100 (Moderately Deep)	2	Poorly Drained
	0 - 50 (Shallow)	1	Very Poorly Drained
Soil Texture	Loamy Sand	4	Highly Suitable
	Sandy Loam	3	Moderately Suitable
	Sandy Clay	2	Lowly Suitable
	Sand	1	Not Suitable
Soil Salinity	5.5 – 7.0	4	Highly Suitable
	7.0 – 8.0	3	Moderately Suitable
	4.5 – 5.5	2	Lowly Suitable
	> 8.0 or < 4.5	1	Not Suitable
Distance to Perennial Rivers (km)	0 - 1.5	4	Highly Suitable
	1.5 – 3	3	Moderately Suitable
	3 - 4.5	2	Lowly Suitable
	More than 4.5	1	Not Suitable
Distance to Access Roads (km)	0 – 1	4	Highly Suitable
	1 – 2	3	Moderately Suitable
	2 – 3	2	Lowly Suitable
	More than 3	1	Not Suitable
Flooding Potential	None	4	Highly Suitable
	None to except	3	Moderately Suitable
	Exceptional	2	Lowly Suitable
	Frequent	1	Not Suitable
LULC	Crops	4	Highly Suitable
	Rangeland/Flooded vegetation	3	Moderately Suitable
	Bare Ground	2	Lowly Suitable
	Water/Trees/Built Area	1	Not Suitable
Landscape	plains/uplands/dambo/alluvial plains	4	Highly Suitable
	marshes/outwash plains/bottomlands/valleys in upland	3	Moderately Suitable
	floodplains/foot slopes/lake margin plain/depressions	2	Lowly Suitable
	rock outcrops/hillsides/escarpments	1	Not Suitable
Proximity to lake (km)	0 - 1.5	4	Highly Suitable
	1.5 – 3	3	Moderately Suitable
	3 – 5	2	Lowly Suitable
	More than 5	1	Not Suitable
Rainfall Deficit (mm)	> 163	4	Highly Suitable
	18 – 163	3	Moderately Suitable
	- 163 – 18	2	Lowly Suitable
	<-271	1	Not Suitable

3.6.2. AHP Weighting and Overlay Analysis

The relative importance of the twelve factors was determined using AHP pairwise comparison matrices, with stakeholder-informed judgments supported by literature. Weights were derived from the normalized eigenvector of the matrix, and consistency was validated using the Consistency Ratio (CR), a standard AHP metric introduced by Saaty (2008). The CR measures the level of logical consistency in pairwise comparisons and is calculated as:

$$\mathrm{CR} = \frac{CI}{RI} \quad \textbf{(4)}$$

where CI is the Consistency Index and RI is the Random Index, a benchmark value dependent on the matrix size. The CI is calculated using:

$$\mathrm{CI} = \gamma - \frac{n}{n-1} \quad \textbf{(5)}$$

Here, γ is the maximum eigenvalue of the PCM and n is the number of comparisons. A CR value $\leq$ 0.10 indicates acceptable consistency, while higher values suggest inconsistency in the matrix and the need to re-evaluate inputs (Saaty, 2008; Worqlul et al., 2019).

After validation of CR, the weighted overlay tool in ArcGIS integrated all reclassified layers into composite suitability maps for the baseline period (2000–2021). The output map was categorized into four standard classes—Highly Suitable, Moderately Suitable, Lowly Suitable, and Not Suitable—in accordance with FAO guidelines (FAO, 2020).

3.6.3. Constraint Mapping and Validation

Non-developable zones (e.g., wetlands, forest reserves, urban areas) were masked (constraint map) to enhance planning realism and ensure environmental compliance. Model accuracy was assessed by overlaying known irrigation sites provided by the Dedza District Agriculture Office, with 97% alignment between observed sites and areas classified as suitable.

3.6.4. Climate Scenario Integration

Projected rainfall deficit layers for the 2030s, 2050s, and 2070s (SSP5-8.5) were incorporated into the weighted overlay, generating suitability maps for future periods. These outputs enabled assessment of climate change impacts on irrigation potential over time.

3.7. Ethical Considerations

The study received ethical clearance from the Mzuzu University Research Ethics Committee (MZUNIREC), Protocol Ref. MZUNIREC/DOR/24/53 (*See Appendix 1)* All participants were informed of the research purpose, assured of voluntary participation, and signed consent forms prior to interviews or FGDs.

3.8. Conclusion

This chapter outlined the sequential mixed-methods framework used in the study, integrating stakeholder insights with geospatial analysis to identify, weight, and evaluate irrigation suitability factors. The GIS-AHP-MCDA approach produced current and future suitability maps, ensuring both technical robustness and local relevance.

CHAPTER 4: RESULTS

4.1. Introduction

This chapter presents the results derived from spatial and qualitative analyses conducted in Dedza District. The findings are organized according to the stakeholder engagement insights and the study's three objectives. Visual outputs, including thematic maps and analytical overlays, form the basis of this analysis.

4.2. Stakeholder Engagement Insights

Qualitative data from semi-structured interviews and focus group discussions (FGDs) with farmers, district officers, and NGO representatives were analyzed thematically to inform the development and validation of the irrigation suitability model in Dedza District. These insights guided the selection and weighting of criteria in the GIS-based AHP framework.

4.2.1. Water Access and Climate Variability

Stakeholders consistently reported declining water availability, drying streams, and erratic rainfall. This information was used to justify the inclusion of water availability and rainfall variability as key criteria in the GIS-AHP model. For example, areas near perennial water sources were assigned higher suitability scores, while regions prone to seasonal water shortages were assigned lower scores. Similar challenges are documented in Malawi (Coulibaly et al., 2015; GoM, 2014; Kumambala, 2010; World Bank, 2021).

4.2.2. Land Suitability and Environmental Factors

Participants highlighted soil depth, slope, drainage, and land degradation as critical determinants of irrigation feasibility. These observations informed the selection of soil and topographic layers in the GIS model. Weightings in the AHP reflected stakeholder emphasis on land quality, ensuring that flatter, well-drained, and fertile areas received higher suitability ratings. Munthali et al. (2019) support these considerations.

4.2.3. Infrastructure and Market Access

Stakeholders stressed that proximity to roads and markets is essential for input delivery and produce marketing. This feedback was used to include road network layers as socio-economic criteria in the GIS model, with AHP weights reflecting their relative importance in enabling sustainable irrigation. These findings are consistent with Worqlul et al. (2017) and Chikabvumbwa et al. (2021). Similarly, the FAO (2002) underscores that infrastructure—such as roads, storage, and market access—is essential for improving the economic viability and performance of irrigation systems.

4.2.4. Climate Resilience and Future Planning

Government and NGO representatives emphasized integrating future climate scenarios and promoting water-efficient technologies. This input informed the incorporation of climate projection layers (SSP5-8.5) in the GIS-AHP analysis, allowing the model to account for anticipated changes in rainfall and temperature, enhancing the long-term resilience of selected sites.

4.2.5. Community Participation and Inclusion

Stakeholders recommended participatory approaches that incorporate local knowledge, gender considerations, and traditional water management practices. These insights guided the validation of AHP pairwise comparisons, ensuring that the model reflected local priorities, social acceptability, and technical suitability.

In summary, the qualitative data from interviews and FGDs was used in two main ways:

a) Criterion selection: Identifying the most relevant biophysical, socio-economic, and climate-related factors for irrigation suitability.

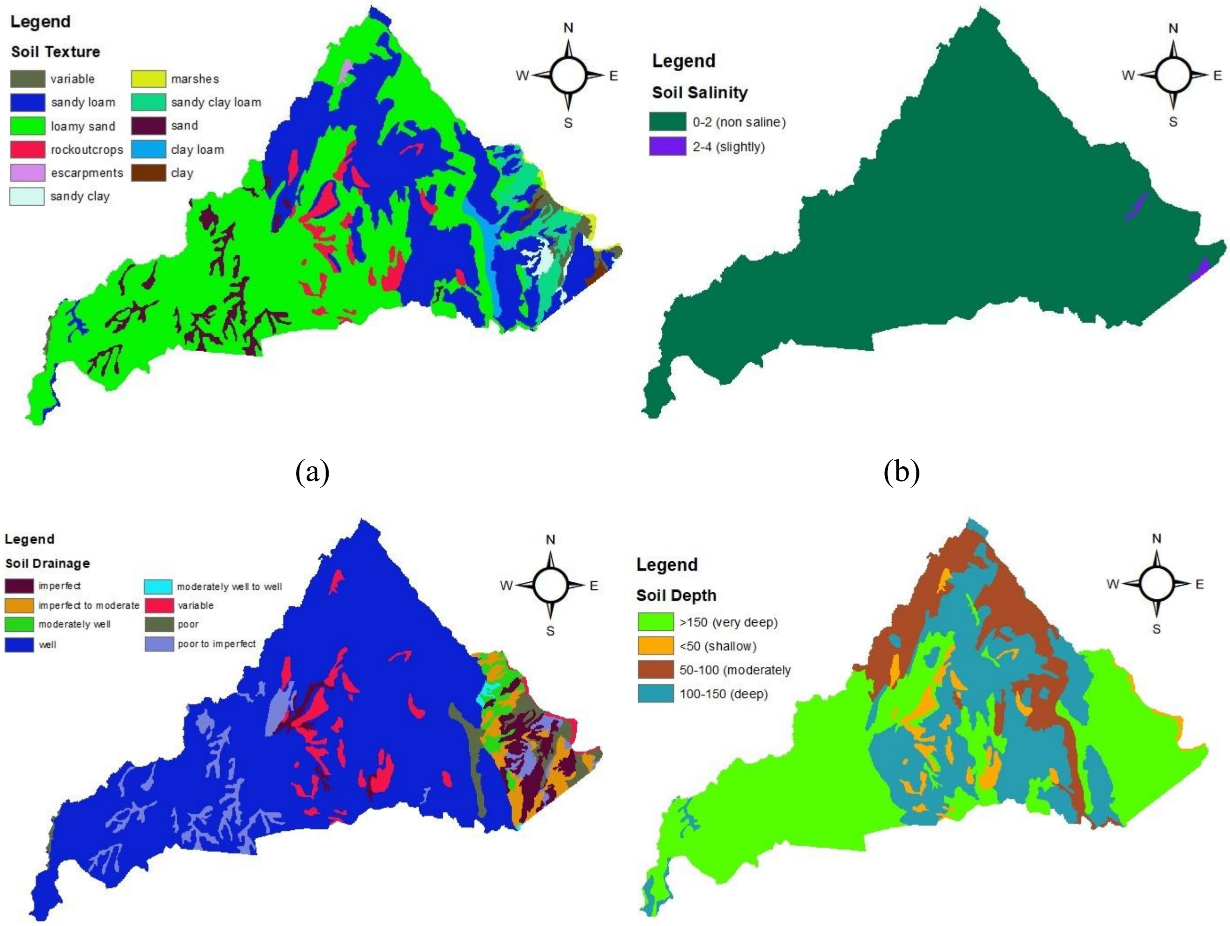
b) Weighting and validation: Informing the relative importance of each criterion in the AHP model to ensure alignment with local priorities and context.

By linking stakeholder insights directly to the GIS-AHP model, the study ensured that both technical and community-driven factors shaped the irrigation site selection framework in Dedza District.

4.3. Identification of Irrigation Suitability Factors

4.3.1. Soil Characteristics

*Figure **4-1***(a–d) shows soil texture, salinity, drainage, and depth across Dedza. Loamy sand (52.6%) and sandy loam (31.2%) dominate, providing favorable infiltration. This was in line with field survey observations. Well-drained soils cover ~76.7% of the area, mitigating waterlogging risks. Deep soils (>100 cm) comprise over 80% of the land, supporting root development, while salinity levels remain within suitable irrigation thresholds.



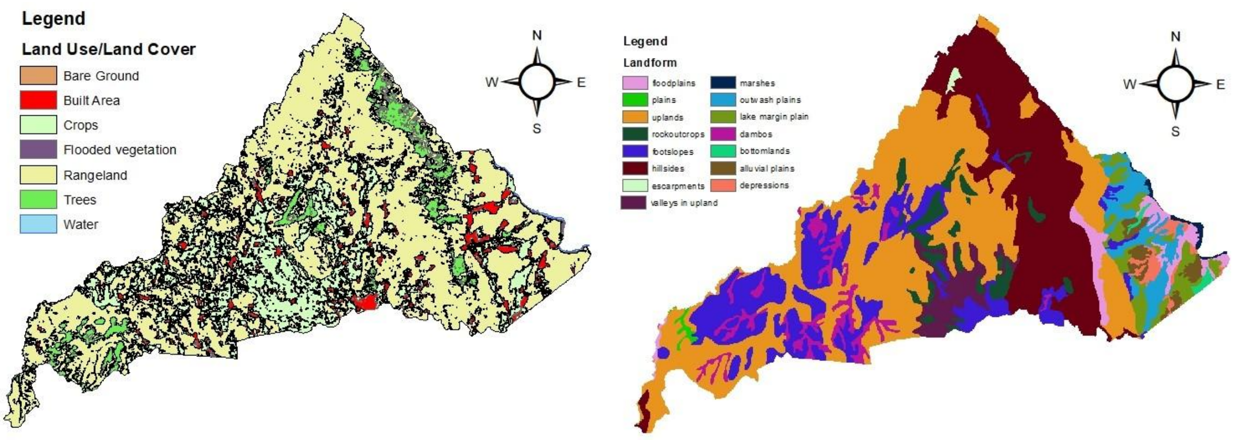
(a) (b)

(c) (d)

Figure 4-1: Soil in Dedza District - Texture, Salinity, Drainage and depth

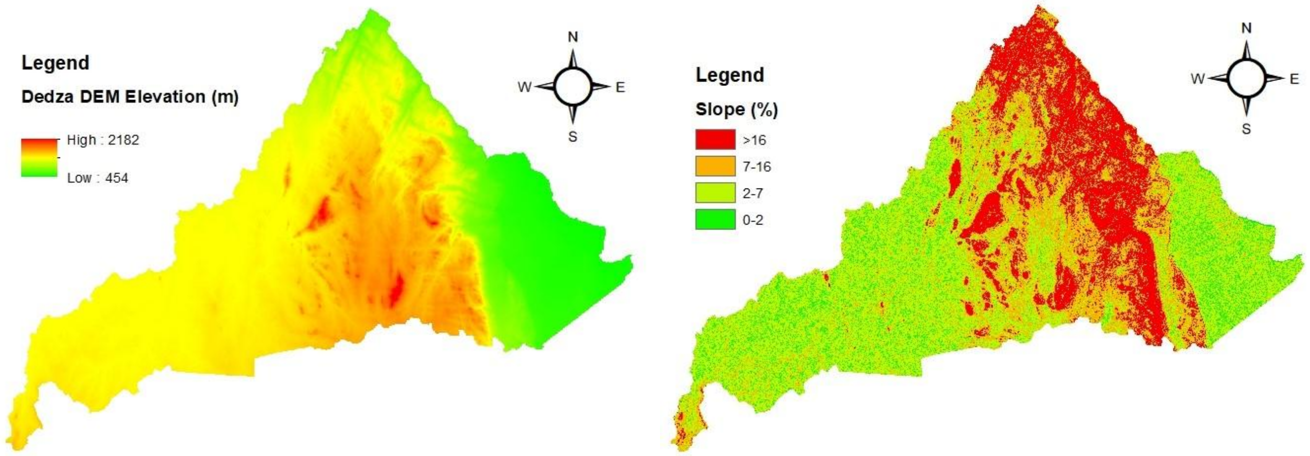
4.3.2. Land Use and Topography

Land cover analysis (*Figure 4-2*a) reveals rangelands (66.3%), croplands (19.1%), and tree-covered areas (8.4%) as dominant types. Built-up zones and forests were excluded during constraint mapping. Figure 4.2b shows landform classification, with uplands (37.3%) and foot slopes (15.1%) being most prevalent. *Figure **4-3***(a–b) shows that only 10.9% of land has slope <2%, ideal for surface irrigation.



(a) (b)

***Figure 4-2:** LULC and Land form in Dedza district*



(a) (b)

Figure 4-3: Slope Percentage and DEM of Dedza

4.3.3. Water Sources and Infrastructure

Hydrological analysis (*Figure 4-4*) shows a dense dendritic river system and proximity to Lake Malawi to the east, providing an additional source of water for irrigation. Zones within 1.5 km of perennial sources were deemed highly suitable. *Figure 4-4* also illustrates road networks—most agricultural areas lie within 5 km, ensuring logistical feasibility.

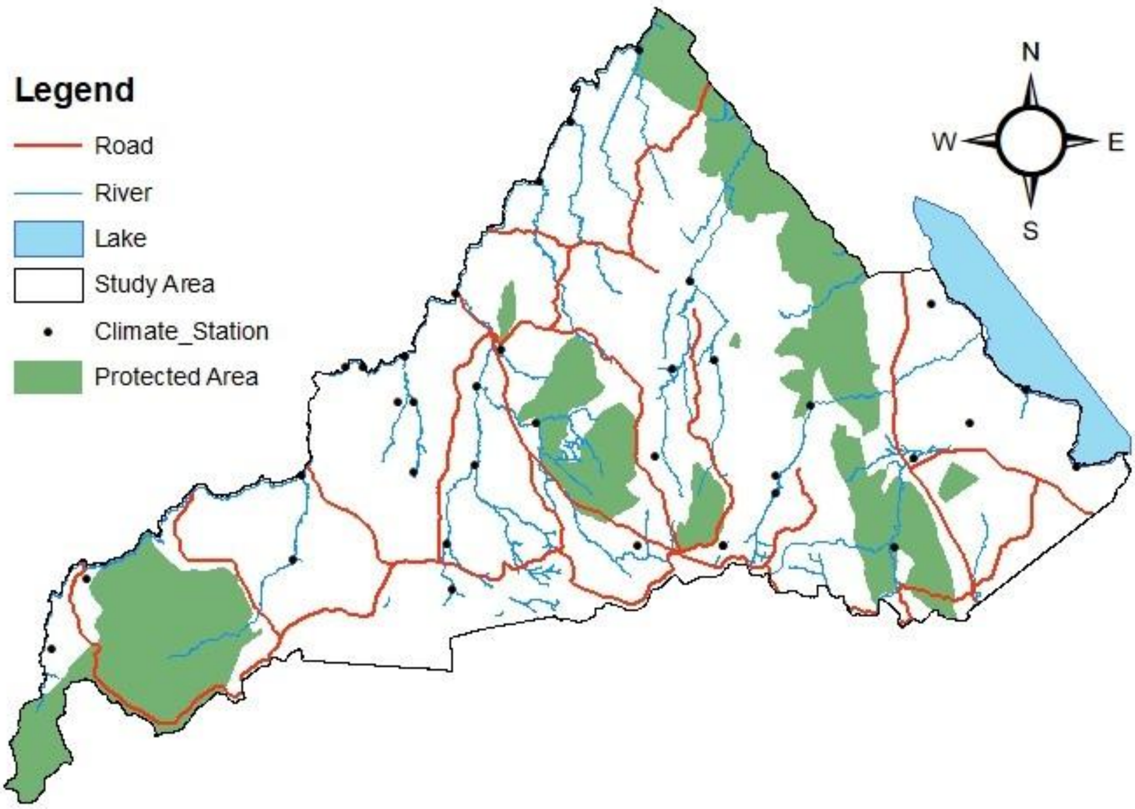


Figure 4-4: Water Sources and Road Network in Dedza

4.3.4. Climate Conditions

Figures 4-5 – 4-8 present spatially interpolated maps of average annual rainfall and temperature across Dedza District from the baseline (2000–2020) through projected future periods (2030s, 2050s, and 2070s) under the SSP585 scenario. These maps highlight climatic variability at both the geographic and temporal scales, a critical factor influencing irrigation planning.

4.3.4.1. Baseline Period (2000–2020):

The rainfall map for this period shows an average spatial variation of 870-980 mm per year, with higher rainfall concentrated in the district's elevated areas, particularly in the highland zones. Temperature varies inversely with altitude, ranging from 18.2°C to 24.4°C, with cooler conditions at higher elevations and warmer conditions in the lowlands. These observations align with Jury & Gwazantini (2002), who reported similar spatial patterns of climate in many areas along the lake. These conditions suggest the presence of agroecological diversity that supports seasonal irrigation, although rainfall variability remains a challenge.

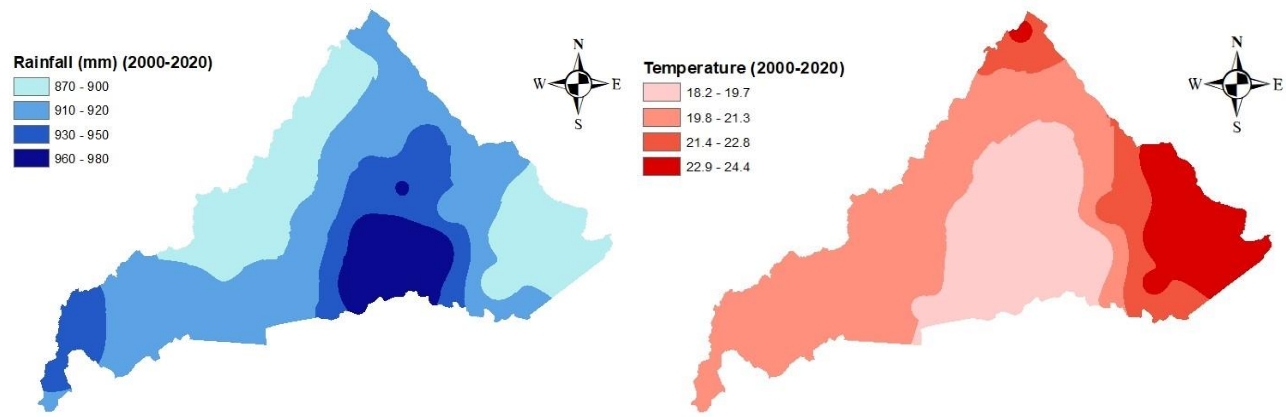


Figure 4-5: *Average annual rainfall and temperature for Baseline Period 2000–2020*

4.3.4.2. 2030s Projection (2021–2040)

The rainfall projection indicates a slight increase in total annual precipitation in some regions, but also a shift in rainfall distribution. Average temperatures rise by about 0.5°C to 1.0°C, which may increase evapotranspiration, reduce effective soil moisture, and amplify the risk of water stress during dry spells. These findings correspond with Coulibaly et al. (2015), who noted increased climate stress in southern Africa, and Kumambala (2010), who emphasized the importance of temperature rise on water demand.

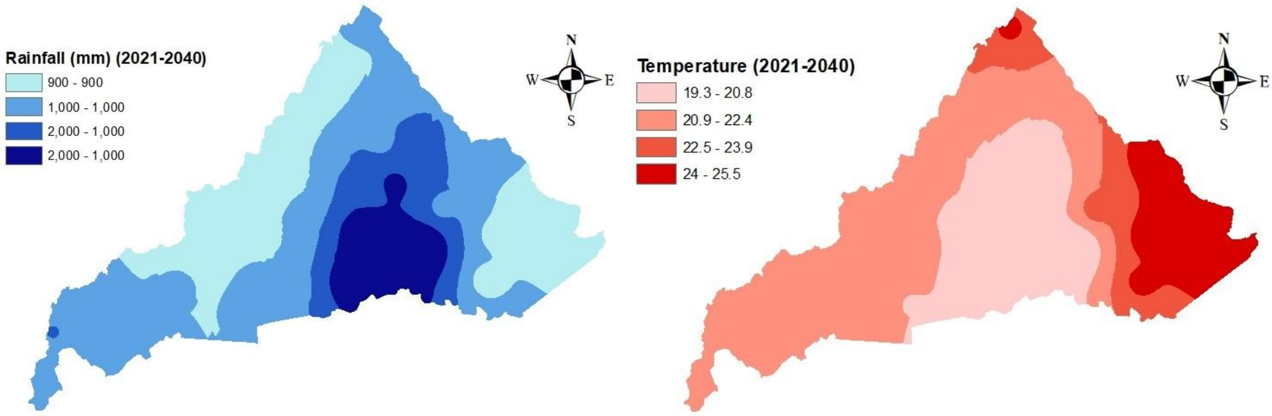


Figure4-6: Average annual rainfall and temperature for Projected Period 2021–2040

4.3.4.3. 2050s Projection (2041–2060)

By this period, the model projects a moderate decline in rainfall across central and southern Dedza, with temperatures increasing by up to 1.5°C relative to baseline, raising concerns about the reliability of rainfed systems. This supports projections by IPCC (2021) and Akpoti et al. (2023), who linked mid-century climate scenarios with increased crop water requirements and hydrological stress, necessitating shifts toward supplemental irrigation.

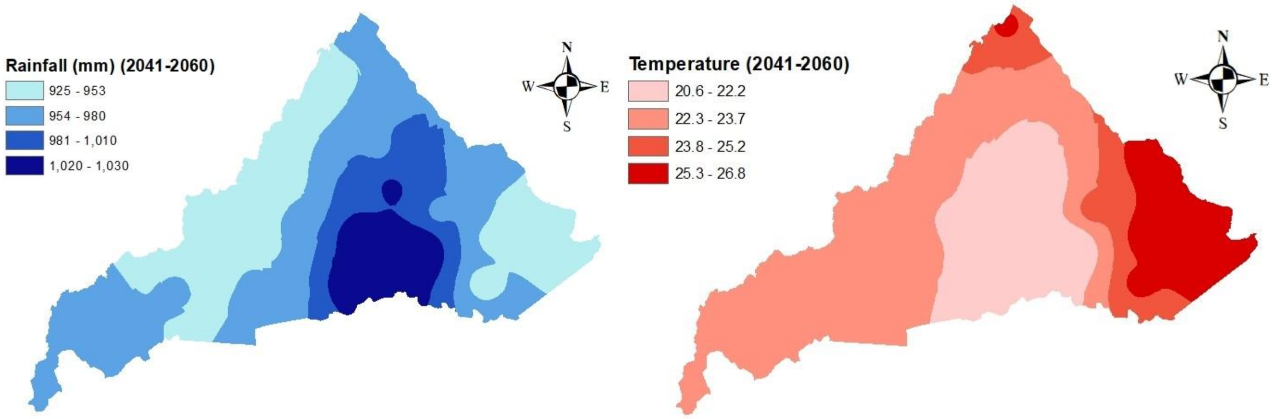


Figure 4-7: Average annual rainfall and temperature for Projected Period 2041–2060

4.3.4.4. 2070s Projection (2061–2080)

This period shows the highest climatic stress. Temperature increases reach up to 2°C–2.5°C above baseline, while rainfall patterns show a downward trend, especially in southern and central Dedza. These changes underline the urgency of integrating climate projections into irrigation planning to ensure water resource sustainability.

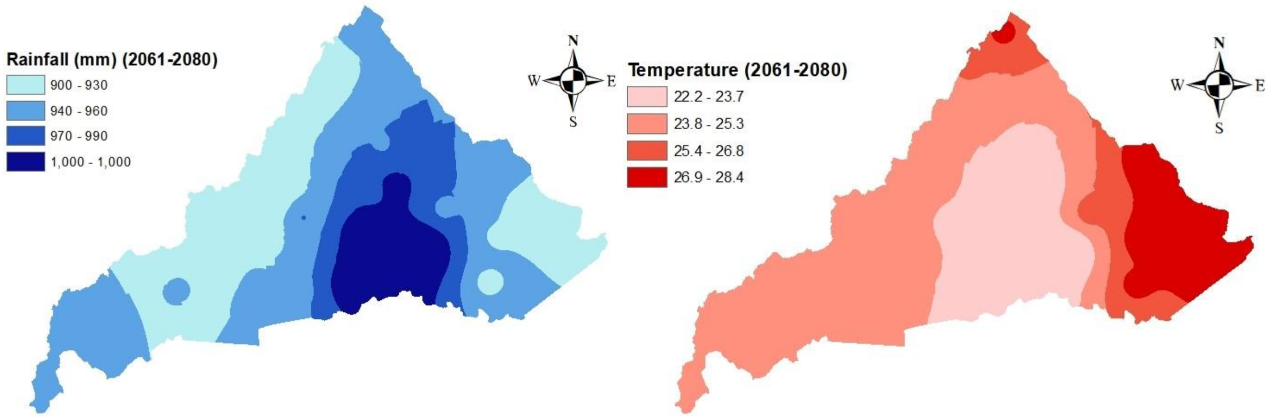


Figure 4-8: Average annual rainfall and temperature for Projected Period 2061–2080

4.4. GIS-based Irrigation Suitability Modelling Using AHP

4.4.1. Standardisation and Reclassification

Biophysical and socio-economic layers were reclassified into four suitability categories: Highly Suitable (4), Moderately Suitable (3), Lowly Suitable (2), and Not Suitable (1), based on FAO (2020) guidelines.

4.4.2. AHP Weighting and Integration

The Analytical Hierarchy Process (AHP) was used to assign relative importance to twelve irrigation suitability factors. As shown in *Table 4-1,* the highest weights were assigned to distance to river (19%), land use/cover (15%), landform (15%), and rainfall deficit (14%), reflecting their dominant influence on irrigation potential. Factors such as slope, drainage, and soil depth received moderate weights, while salinity, flooding risk, and proximity to roads were assigned lower weights, consistent with expert judgment and stakeholder input. The calculated Consistency Ratio (CR) was 0.08, which is within the acceptable threshold (<0.1), confirming that the pairwise comparisons were logically consistent (Saaty, 2008; Worqlul et al., 2017, 2019). These weights were subsequently applied in the GIS-based weighted overlay analysis to develop the final irrigation suitability maps.

Table 4-1: Pairwise Comparison Matrix and AHP-Derived Weights

Factors	Slope	Depth	Drainage	Texture	Salinity	Distance to River	Landuse /Cover	Distance from Road	Landform	Proximity to Lake	Flooding	Rainfall Deficit	Avg	Weighted (%)
Slope	1.00	3.00	3.00	3.00	5.00	0.20	0.33	3.00	0.33	0.33	5.00	0.25	0.07	6.93
Depth	0.33	1.00	0.20	0.33	3.00	0.17	0.20	2.00	0.25	0.25	3.00	0.25	0.03	3.18
Drainage	0.33	5.00	1.00	3.00	5.00	0.20	0.25	3.00	0.25	3.00	3.00	0.25	0.07	7.07
Texture	0.33	3.00	0.33	1.00	4.00	0.20	0.20	4.00	0.20	0.20	3.00	0.33	0.04	4.50
Salinity	0.20	0.33	0.20	0.25	1.00	0.13	0.14	0.50	0.20	0.20	2.00	0.25	0.02	1.88
Distance to River	5.00	6.00	5.00	5.00	8.00	1.00	3.00	7.00	2.00	2.00	6.00	0.33	0.19	18.94
Landuse /Cover	4.00	5.00	4.00	5.00	7.14	0.33	1.00	5.00	2.00	2.00	4.00	2.00	0.15	15.38
Distance from Road	0.33	0.50	0.33	0.25	2.00	0.14	0.20	1.00	0.25	0.20	0.50	0.33	0.02	2.21
Landform	3.00	4.00	4.00	5.00	5.00	0.50	0.50	4.00	1.00	5.00	4.00	3.00	0.15	15.08
Proximity to Lake	3.00	4.00	0.33	5.00	5.00	0.50	0.50	5.00	0.20	1.00	4.00	0.33	0.09	8.53
Flooding	0.20	0.33	0.33	0.33	0.50	0.17	0.25	2.00	0.25	0.25	1.00	0.25	0.02	2.24
Rainfall Deficit	4.00	4.00	4.00	3.00	4.00	3.00	0.50	3.00	0.33	3.00	4.00	1.00	0.14	14.07
CR = 0.08 (8%)														

4.5. Framework Application

4.5.1. Constraint Mapping

To ensure practical applicability, areas unsuitable for irrigation—such as wetlands, forests, and urban zones—were excluded from the final suitability analysis. These were masked out using a constraint map (*Figure 4-9*), developed and integrated into the Weighted Overlay process in ArcGIS.

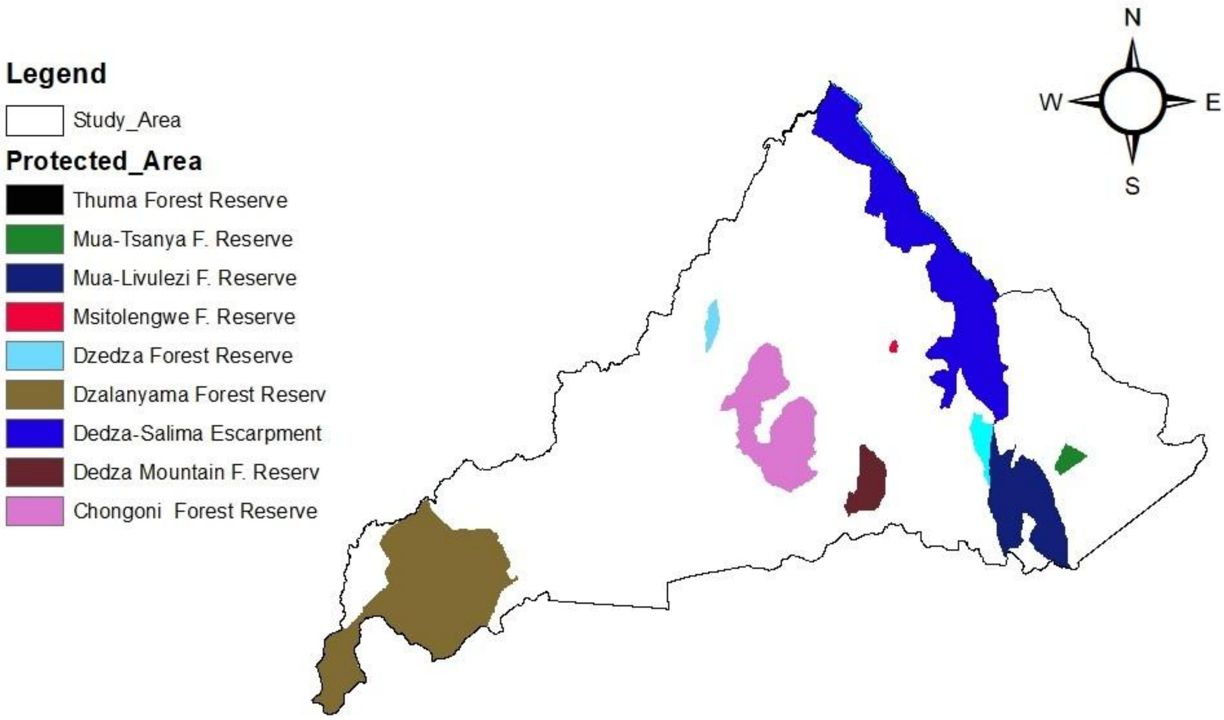


Figure 4-9: Constraint Map - Protected Areas

4.5.2. Weighted Overlay and Suitability Map

Following the standardization, reclassification, and AHP-weighting of all criteria layers, a weighted overlay analysis was conducted using ArcGIS. Each factor was integrated into a composite suitability model, with layers weighted by their relative importance as determined by the AHP. The final output produced a four-class irrigation suitability map.

*Figure **4-10*** illustrates Dedza District's irrigation suitability (2000–2020), categorized into four classes. The majority of the land, 1,848.47 km² (64.6%), was Moderately Suitable, with favourable yet suboptimal conditions such as moderate slopes and medium soil depth. Lowly Suitable areas covered 974.55 km² (34.1%), often limited by factors such as shallow soils or distant water sources. Only 37.25 km² (1.3%) was Highly Suitable, mostly flat, low-lying areas near rivers and roads. A negligible 0.55 km² (0.02%) was Not Suitable, including rocky or protected zones.

4.5.3. Model Validation

To assess the validity of the generated suitability map, known irrigation site shapefiles from the Dedza District Agriculture Office were overlaid onto the final suitability output. As shown in *Figure **4-10***, approximately 97% of the existing irrigation sites fell within areas classified as highly or moderately suitable. This strong alignment between existing scheme locations and model predictions suggests high model reliability and spatial accuracy.

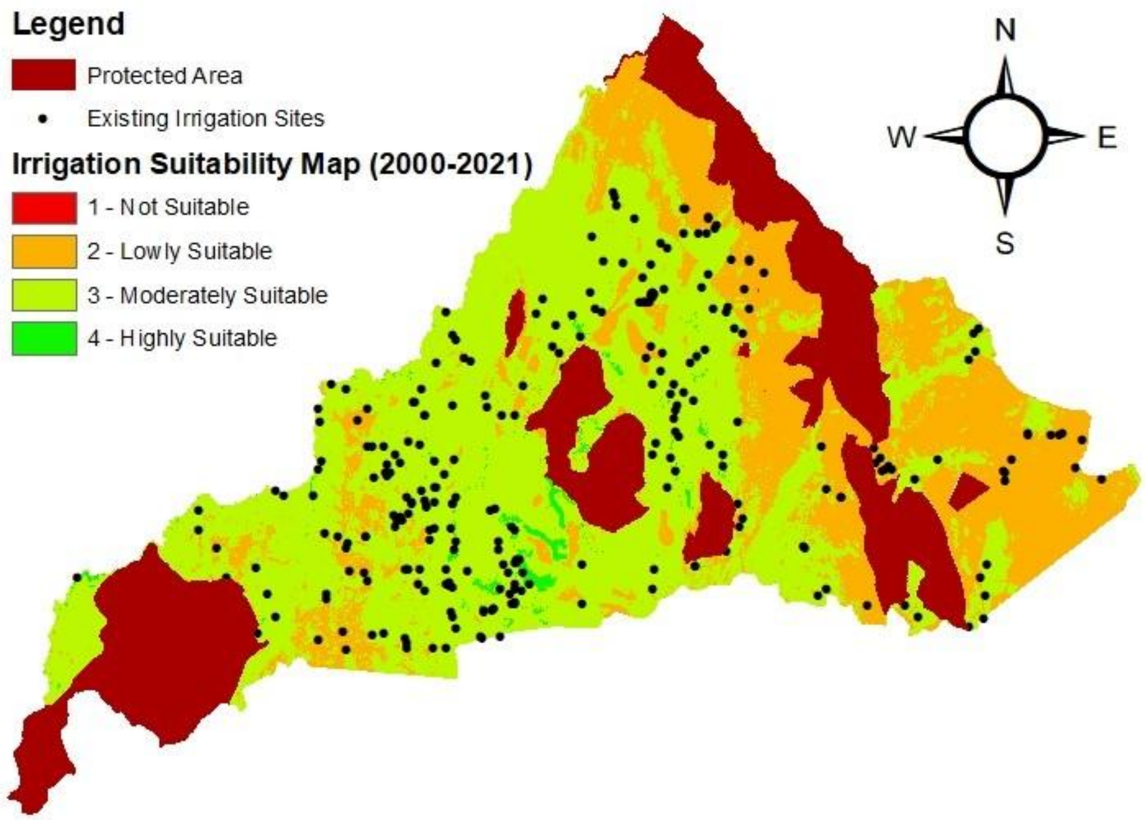


Figure 4-10: Suitability Map (2000–2021) and Validation with Existing Schemes

4.6. Future Climate Scenario Integration

4.6.1. Rainfall Deficit Projections

Rainfall deficit, defined as the difference between annual rainfall and potential evapotranspiration (ETo), serves as a proxy for water availability and irrigation need. *Figure 4 -11 to 13* show rainfall deficit maps for the baseline period and three future climate horizons (2030s, 2050s, and 2070s), based on SSP585 projections using the HadGEM3-GC31-LL model.

4.6.1.1. Baseline Period (2000–2020):

In the baseline period, rainfall generally exceeded or closely matched ETo in much of Dedza's central and highland zones. This is consistent with findings in *section 4.3.4.1*, where annual rainfall ranged between 800–1200 mm and temperatures remained relatively moderate (14–24°C), especially at higher elevations (GoM, 2014). Consequently, water stress was minimal, supporting seasonal irrigation in select areas.

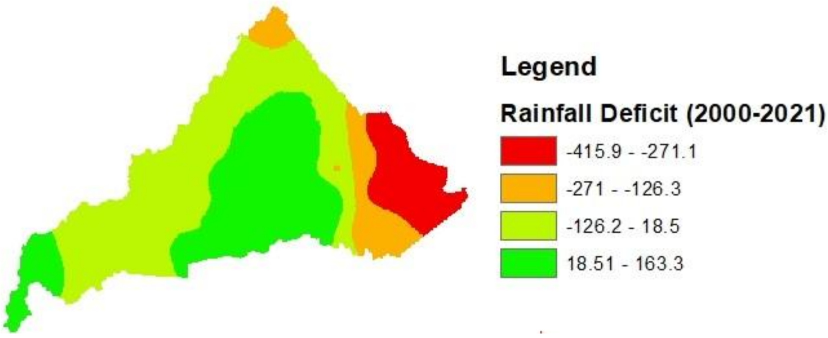


Figure 4-11: Rainfall deficit 2000–2021

4.6.1.2. 2030s Projection (2021–2040)

The rainfall deficit begins to increase modestly in low-lying and eastern parts of the district. While rainfall shows slight increases in some upland areas, the overall rise in temperatures (by ~0.5–1°C) elevates evapotranspiration rates, as noted in *section 4.3.4.2*. These early signs of stress suggest emerging irrigation needs in areas previously reliant on rainfed systems.

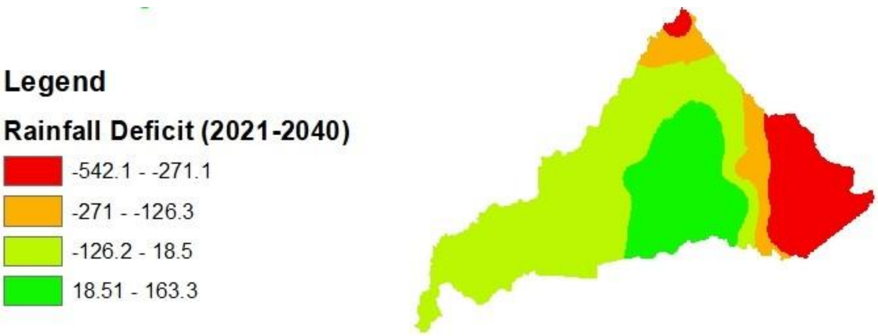


Figure 4-12: Rainfall deficit 2021–2040

4.6.1.3. 2050s Projection (2041–2060)

A significant escalation in rainfall deficit is observed across most of Dedza. This aligns with earlier climate projections, which show a decline in rainfall and a 1.5°C+ temperature increase, contributing to sharp increases in evapotranspiration (Coulibaly et al., 2015; IPCC, 2021). The central plateau and lower slopes now exhibit moderate to severe deficits, signalling increased vulnerability for both surface and groundwater-dependent farming systems.

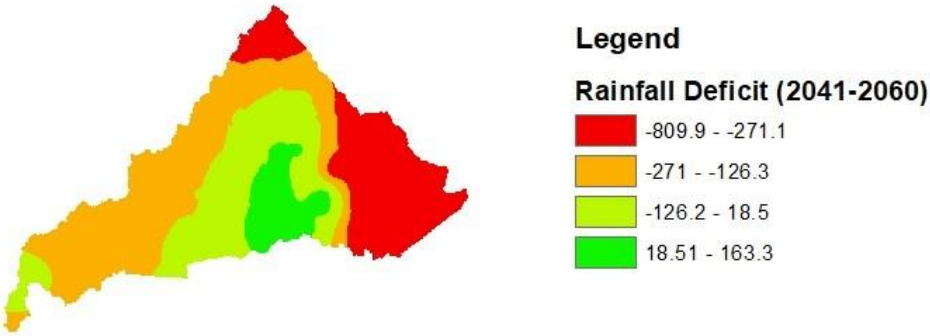


Figure 4-13: Rainfall deficit 2041–2060

4.6.1.4. 2070s Projection (2061–2080)

Rainfall deficit reaches its peak, with much of Dedza—especially the mid and southern zones—facing severe and widespread water stress. As discussed in *section 4.3.4.4*, average annual temperatures are projected to increase by 2–2.5°C, while rainfall declines further, severely limiting natural moisture availability. These trends are consistent with regional findings by Worqlul et al. (2019) and Kumambala (2010), which shows that without adaptive irrigation strategies, farming viability diminishes drastically under SSP585 conditions.

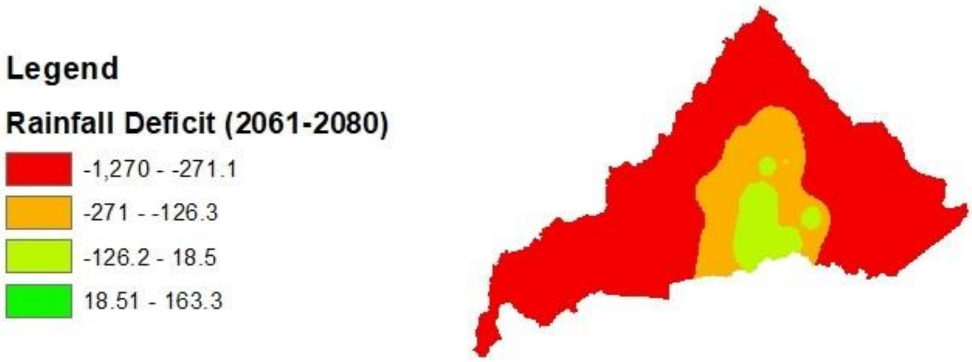
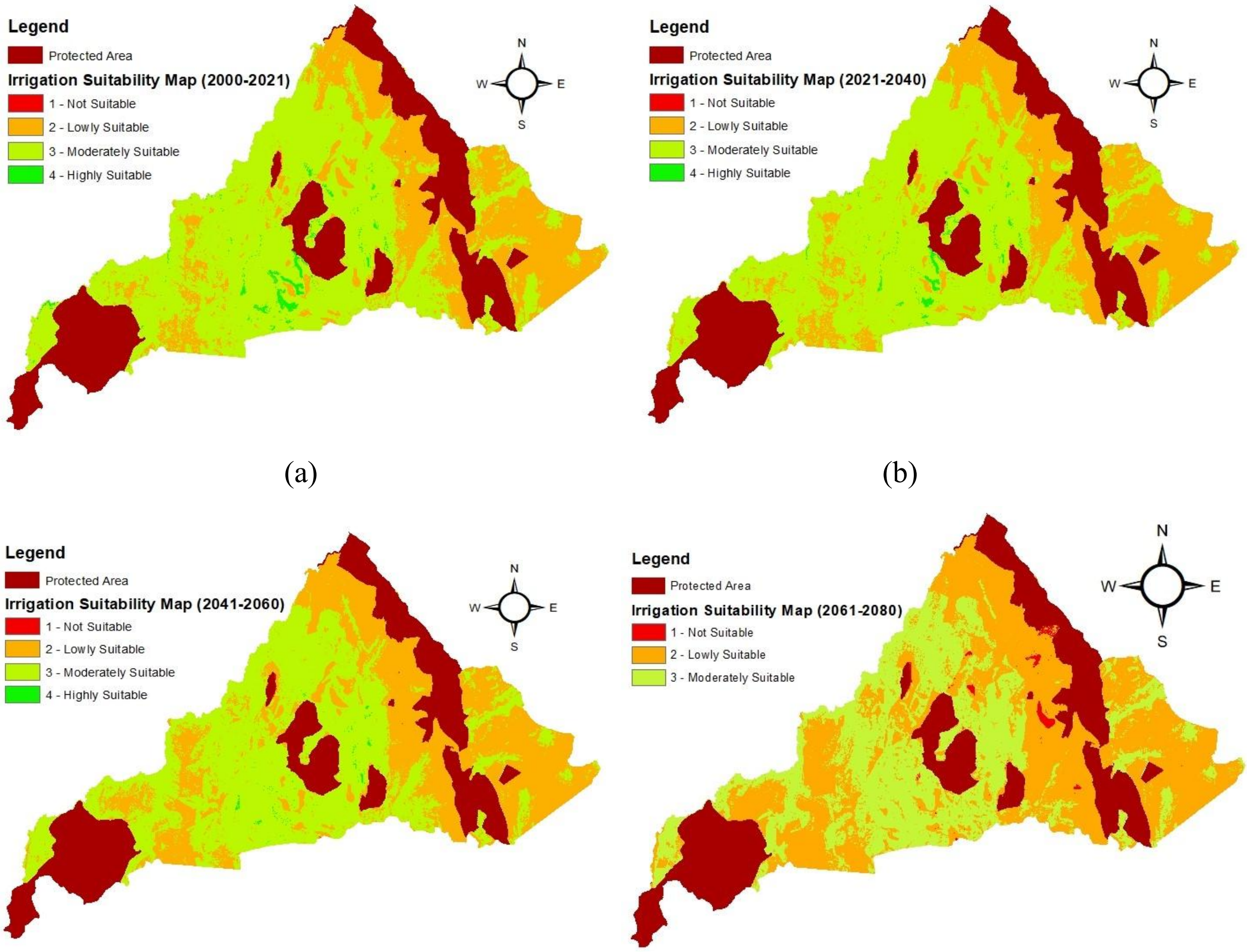


Figure 4-14: Rainfall deficit 2061–2080

4.6.2. Future Suitability Maps

Figure 4-15(a–d) illustrates irrigation suitability across Dedza District under baseline and future period (2030s, 2050s, and 2070s). A consistent decline in suitability is observed over time. Highly Suitable land drops significantly from 37.25 km² (1.3%) in the baseline (2000–2020) to 0 km² by the 2070s, indicating the loss of optimal irrigation zones due to increasing climate stress. Moderately Suitable land also declines—from 1,848.47 km² (64.6%) in the baseline to 1,231.92 km² (43%) in the 2070s. Conversely, Lowly Suitable areas expand markedly from 974.55 km² (34.1%) to 1,607.84 km² (56.2%), while Not Suitable land increases from 0.55 km² to 21.06 km², reflecting worsening agro-ecological conditions. These shifts highlight the growing impact of climate change—particularly rainfall and temperature variations—on irrigation potential, emphasizing the urgency for adaptive planning and climate-resilient infrastructure.



(a) (b)

(c) (d)

Figure 4-15: Irrigation Suitability Maps for (a) Baseline and under SSP585 (b) 2030s, (c) 2050s, (d) 2070s

4.7. Conclusion

This chapter presented spatial and thematic results from the GIS-AHP-MCDA framework applied to Dedza District. Proximity to rivers, land use/cover, landform, and rainfall deficit emerged as dominant factors influencing irrigation suitability. Most of the district was classified as moderately suitable under baseline conditions, with only a small portion rated as highly suitable. However, climate projections under the SSP585 scenario revealed a progressive decline in suitable land, driven by increasing rainfall deficits.

Validation with existing irrigation sites confirmed the model's reliability (97% match), and stakeholder insights reinforced the inclusion of local priorities such as infrastructure access. These results highlight both current opportunities for irrigation expansion and the urgency of adopting climate-resilient planning strategies.

CHAPTER 5: DISCUSSION

5.1. Introduction

This chapter interprets the study's findings in relation to the research objectives, the existing literature, and the broader context of irrigation planning in Malawi. It highlights the novelty of the developed framework, critically examines the implications of integrating qualitative and quantitative methods, and reflects on the approach's strengths and limitations. The discussion also situates the results within regional and global scholarship on climate-resilient irrigation, thereby identifying pathways for improving irrigation planning at both district and national levels.

5.2. Key Influencing Factors of Irrigation Suitability

The results highlight proximity to rivers, landform, land use/cover, and rainfall deficit as the dominant factors influencing irrigation suitability in Dedza District. These variables collectively determine the spatial distribution of areas that are physically and climatically suitable for irrigation development. The prominence of water-related and terrain variables mirrors findings by Worqlul et al. (2019) in Ethiopia, Chikabvumbwa et al. (2021) in Malawi and Akpoti et al. (2023) in Ghana, where water availability and topography emerged as the principal determinants of irrigation potential across diverse agro-ecological zones.

Although road proximity received a relatively low AHP weight (2%) in the quantitative analysis, stakeholder consultations—including farmers, planners, and extension officers—underscored its critical role in determining irrigation scheme viability. Accessibility to roads and markets directly affects the efficiency of input delivery, produce transport, and maintenance services, thereby influencing the sustainability of irrigation systems. This observation aligns with Worqlul et al. (2017) and FAO (2002), who emphasize that infrastructure access is essential for reducing transaction costs and sustaining agricultural investments.

The finding demonstrates how qualitative insights can elevate the practical importance of factors that appear marginal in quantitative models, reinforcing the strength of the mixed-method approach applied in this study. The inclusion of socio-economic variables, such as road access, thus highlights that irrigation suitability mapping in Malawi must extend beyond biophysical assessments to incorporate farmer perspectives, accessibility considerations, and institutional realities, ensuring that model outputs are both technically sound and contextually relevant.

5.3. Model Development and Application

This study developed and applied a GIS-based Multi-Criteria Decision Analysis (MCDA) framework to identify and evaluate the key biophysical, climatic, and socio-economic factors influencing irrigation site suitability in Dedza District. The framework integrates current biophysical conditions, socio-economic accessibility, and future climate projections to guide climate-resilient irrigation site selection.

Unlike previous approaches in Malawi that have relied on coarse-scale datasets and expert-driven judgments (Bwambale et al., 2022; Chikabvumbwa et al., 2021), this study combined literature-based evidence and stakeholder-derived qualitative insights with quantitative spatial analysis in a structured AHP-MCDA environment. This integration enhanced the context specificity, accuracy, and relevance of the resulting suitability maps.

The model represents a novel contribution by explicitly aligning irrigation planning with both present land and water resource conditions and anticipated future climate risks, thereby filling a critical gap in the existing irrigation planning frameworks for Malawi.

5.4. Climate Scenario Analysis

Climate scenario analysis revealed a steep decline in key biophysical and climatic factors influencing irrigation suitability under the SSP5–8.5 high-emission pathway. These shifts resulted in a reduction of highly suitable irrigation areas from 37.25 km^2 in the baseline period (2000–2020) to 0 km^2 by the 2070s. Concurrently, not suitable land increased from 0.55 km^2 to 21.06 km^2, reflecting worsening rainfall deficits and evapotranspiration stress (See **Error! Reference source not found.**).

Similar trends of declining irrigation potential driven by changes in temperature, rainfall variability, and water balance have been observed in East and West Africa (Akpoti et al., 2023; Mabhaudhi et al., 2022). However, this study is among the first to quantify and spatially map these dynamics at a district scale in Malawi, thereby providing localized insights into how climate change reshapes irrigation suitability patterns.

The results underscore the need to integrate climate resilience into irrigation planning and although the model assumes no direct adaptation interventions, its value lies in identifying where adaptive measures such as water harvesting, efficient irrigation technologies, and groundwater integration will be most urgently required to sustain productivity under future climate conditions.

Table 5-1: *Changes in irrigation suitability in Dedza District from 2000 to 2080 by suitability class.*

Period	Not Suitable (km²)	Lowly Suitable (km²)	Moderately Suitable (km²)	Highly Suitable (km²)
Baseline (2000–2020)	0.55	974.55	1848.47	37.25
2030s (2021–2040)	0.57	1042.37	1792.24	25.65
2050s (2041–2060)	1.3	1231.19	1619.93	8.4
2070s (2061–2080)	21.06	1607.84	1231.92	0

5.5. Model Validation and Implications

By validating the framework against existing schemes and achieving 97% alignment, this study demonstrates both methodological robustness and practical relevance. Yet, limitations remain: the exclusion of groundwater may underrepresent potential in upland areas, and reliance on coarse-resolution climate data may mask microclimatic variations. These challenges mirror those noted in other GIS-based irrigation studies Worqlul et al. (2019), underscoring the need for finer-scale datasets and integration of hydrogeological information.

Overall, the framework offers three contributions to scholarship and policy: (1) it operationalizes mixed-methods research in irrigation planning by linking stakeholder knowledge to AHP weighting; (2) it integrates climate projections into site selection, offering a long-term perspective absent in current practice; and (3) it provides a transferable, district-level tool that can inform national policy, aligning with the Malawi 2063 Vision and the National Irrigation Policy (2014). Future applications should extend the model to crop-specific suitability assessments, conduct cost–benefit analyses, and evaluate its scalability across multiple districts.

5.6. Conclusion

In summary, the developed framework advances irrigation planning in Malawi by integrating stakeholder knowledge, climate projections, and spatial analysis into a coherent decision-support tool. It validates the relevance of mixed-methods approaches in addressing complex agricultural challenges, demonstrates strong alignment with existing irrigation infrastructure, and highlights critical vulnerabilities under future climate scenarios. While limitations remain, the study provides a transferable model that bridges the gap between research and practice, offering actionable insights for district and national planners. By embedding this framework into policy and planning processes, Malawi can move toward more climate-resilient and sustainable agricultural systems, in line with the Malawi 2063 Vision and global climate adaptation goals.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Introduction

This study set out to develop a climate-resilient GIS-based framework for irrigation site selection in Dedza District. Guided by the Analytical Hierarchy Process (AHP) within a Multi-Criteria Decision Analysis (MCDA) framework, the research integrated both qualitative and quantitative data to ensure that technical analysis was complemented by stakeholder insights. The conclusions are presented in line with the four specific objectives.

6.2. Factors Affecting Irrigation Site Suitability

The study established that irrigation suitability in Dedza is primarily shaped by proximity to rivers (19%), land use/cover (15%), landform (15%), and rainfall deficit (14%), with soil properties (drainage, depth, texture) also being critical. Stakeholder engagement reinforced the importance of water availability, access to infrastructure, and climate variability. By combining scientific evidence with local knowledge, the study ensured that suitability factors reflected both technical relevance and socio-economic realities. These findings are consistent with other regional studies (Chikabvumbwa et al., 2021; Hussien et al., 2019; Worqlul et al., 2019) while adding a participatory, district-level perspective.

6.3. Developing a GIS-Based MCDA Framework

A GIS-based MCDA framework was successfully designed by integrating twelve spatial criteria, standardised into suitability classes and weighted using AHP. The model showed high reliability (CR = 0.08) and practical validity, with 97% of existing irrigation schemes located in areas classified as suitable. Environmental safeguards were ensured by incorporating constraint layers for forests, wetlands, and protected areas. The participatory design enhances transparency, while the framework's scalability makes it adaptable to other districts. This approach demonstrates the practical value of GIS–AHP integration in supporting structured irrigation planning.

6.4. Application of the Framework in Dedza

When applied to Dedza District, the framework generated spatially explicit suitability maps. Under baseline conditions (2000–2020), the majority of land (64.6%) was classified as moderately suitable, while highly suitable land comprised only 1.3% (37.25 km^2). Low suitability dominated marginal areas with poor soils or steep slopes, and only 0.02% of the land was deemed unsuitable. Validation against existing schemes confirmed strong model accuracy, highlighting both opportunities for irrigation expansion and the constraints that must be considered. These outputs provide concrete planning evidence for district authorities.

6.5. Integrating Future Climate Scenarios

When future climate projections under SSP5-8.5 were integrated, the framework revealed significant reductions in irrigation potential. Highly suitable land declined from 37.25 km² in the baseline to 0 km² by the 2070s, while non-suitable areas expanded from 0.55 km² to 21.06 km². Moderately suitable land also decreased, while low suitability expanded, reflecting worsening water stress. These results underscore the vulnerability of irrigation potential under high-emission scenarios, reinforcing the need for adaptive strategies such as drip irrigation, rainwater harvesting, and catchment management. The findings align with IPCC (2021) and Akpoti et al. (2023), highlighting the importance of embedding climate resilience into irrigation planning.

6.6. Limitations and Areas for Further Study

This study demonstrated the value of a GIS-based MCDA framework for irrigation site selection under climate change. However, several limitations should be acknowledged. First, groundwater availability was not included because of the lack of high-resolution aquifer datasets, which may underrepresent irrigation potential in upland and interior areas. Second, the framework relied on climate projections at relatively coarse resolution (~85 km²), which, while suitable for district-level planning, may mask local microclimatic variations. Third, the Analytic Hierarchy Process (AHP) depends partly on expert judgment, introducing a degree of subjectivity in assigning weights. Finally, the study did not differentiate irrigation suitability by specific crops, limiting crop-level precision in planning.

Future studies should address these gaps by integrating groundwater and hydrogeological data, applying finer-scale climate models, and incorporating economic cost–benefit analysis of irrigation investments. Expanding the framework to include crop-specific water requirements and socio-economic dynamics such as land tenure and market systems would further enhance its applicability. In addition, comparative studies across multiple districts in Malawi would help test the scalability and adaptability of the framework, strengthening its value as a national decision-support tool.

6.7. Recommendations

To strengthen irrigation planning and resilience in Dedza and beyond, the following are recommended:

i. **Mainstream the GIS–MCDA Model into Planning:** Embed the framework into national and district irrigation and land-use planning processes to support data-driven, transparent decision-making in line with Malawi 2063 goals.

ii. **Prioritise Moderately Suitable Zones:** Focus investment in areas that remain viable under future scenarios, while promoting water-efficient technologies (e.g., drip, sprinkler systems) and conservation practices in catchments.

iii. **Strengthen Capacity and Farmer Support:** Train district planners and extension staff in GIS, climate modelling, and participatory planning, and support farmers with drought-tolerant crops, affordable irrigation tools, and water-saving practices.

iv. **Scale and Replicate the Framework:** Apply the model to other districts with similar agroecological conditions to develop regional and national irrigation strategies aligned with climate-smart agriculture.

6.8. Summary

This study developed and applied a climate-resilient GIS-based MCDA framework for irrigation site selection in Dedza District. By aligning geospatial analysis with stakeholder perspectives and integrating future climate scenarios, the study delivered a validated, policy-relevant tool that addresses both immediate and long-term planning needs. The findings demonstrate that while Dedza holds significant irrigation potential, climate change will drastically reduce highly suitable areas by the 2070s, necessitating adaptive investments and forward-looking strategies. Beyond Dedza, the framework offers a scalable approach that can guide sustainable irrigation development across Malawi.

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APPENDICES

Appendix 1: Research Ethics and Regulatory Approval and Permit

MZUZU UNIVERSITY

DIRECTORATE OF RESEARCH

Mzuzu University
Private Bag 201
Luwinga
Mzuzu 2
MALAWI
TEL: 01 320 722
FAX: 01 320 648

MZUZU UNIVERSITY RESEARCH ETHICS COMMITTEE (MZUNIREC)

Ref No: MZUNIREC/DOR/23/53 **06/08/2024.**

Dingani Jomo Mkandawire,,
Mzuzu University,
P/Bag 201,
Luwinga,
Mzuzu 2.

Email: jomomk@gmail.com

Dear Dingani,

RESEARCH ETHICS AND REGULATORY APPROVAL AND PERMIT FOR PROTOCOL REF NO: MZUNIREC/DOR/24/53: CLIMATE-RESILIENT IRRIGATION SITE SELECTION USING AN INTEGRATED GIS

Having satisfied all the relevant ethical and regulatory requirements, I am pleased to inform you that the above referred research protocol has officially been approved. You are now permitted to proceed with its implementation. Should there be any amendments to the approved protocol in the course of implementing it, you shall be required to seek approval of such amendments before implementation of the same.

This approval is valid for one year from the date of issuance of this approval. If the study goes beyond one year, an annual approval for continuation shall be required to be sought from the Mzuzu University Research Ethics Committee (MZUNIREC) in a format that is available at the Secretariat. Once the study is finalised, you are required to furnish the Committee with a final report of the study.

1

The Committee reserves the right to carry out compliance inspection of this approved protocol at any time as may be deemed by it. As such, you are expected to properly maintain all study documents including consent forms.

Wishing you a successful implementation of your study.

Yours Sincerely,

Wanangwa K. Msowoya

MZUNIREC Secretariat
FOR: MZUNIREC CHAIRPERSON

Mzuzu University Research Ethics Committee
Directorate of Research
Mzuzu University
P/Bag 201
Luwinga
Mzuzu 2
Email: mzunirec@mzuni.ac.mw

MZUZU UNIVERSITY
RESEARCH ETHICS COMMITTEE
06 AUG 2024
PRIVATE BAG 201, LUWINGA
MZUZU 2

Appendix 2: Thornthwaite's Formula for Estimating Evapotranspiration (ETo)

Thornthwaite's formula is a widely used empirical method for estimating reference evapotranspiration (ETo), particularly in regions where climatic data is limited. This method relies primarily on temperature and latitude as inputs, providing a simplified yet effective approach to estimate ETo for agricultural and water resource management purposes.

Formula and Variables

Thornthwaite's formula calculates monthly potential evapotranspiration (PET), which is often used as an approximation for ETo. The formula is expressed as:

$$PET = 16\left(\frac{10*T}{I}\right)^{a} \quad \text{(1)}$$

Where:

- PET: Monthly potential evapotranspiration (mm/month)
- *T*: Mean monthly temperature (°C), where T > 0
- *I*: Heat index, calculated as the sum of monthly heat indices (*i*) for a given year
- *a*: An empirical exponent dependent on *I*

Heat Index (*I*)

The heat index *I* is calculated as:

$$I = \sum_{m=1}^{12} i_m \quad \text{(2)}$$

$$i = \left(\frac{T}{5}\right)^{1.514}$$

Where:

- *i*: Monthly heat index
- *m*: Index for each month (1 to 12)

Exponent (a)

The value of a is derived from the heat index (*I*) using the following relationship:

$$a = (6.75\times10^{-7} * I3^{-7}) * (7.71\times10^{-5} * I^{2}) + (1.792\times10^{-2} * I + 0.49239) \quad \text{(3)}$$

Assumptions and Limitations

- Simplicity: Thornthwaite's method requires only temperature data, making it ideal for regions with limited meteorological data.
- Regional Application: The method assumes a direct relationship between temperature and ETo, which may not hold in areas with significant wind, humidity, or radiation variability.
- Seasonality: Adjustment factors for day length improve the accuracy, but the method still lacks precision in arid, humid, or high-altitude regions where additional climatic factors play a critical role.

Applicability in Irrigation Suitability Studies

Thornthwaite's formula is especially useful for preliminary irrigation suitability assessments where detailed meteorological data are unavailable. It provides a baseline ETo estimate, aiding in crop water requirement calculations, irrigation planning, and resource allocation (Thornthwaite, 1948).

By including Thornthwaite's formula in irrigation suitability research, practitioners can balance the trade-offs between data availability and the precision of ETo estimates, enhancing the applicability of results in data-scarce regions.

Appendix 3: Climate Data Summary (Rainfall and Temperature)

Table A-1: Baseline and Projected Average Annual Rainfall and Temperature in Dedza District (mm/°C)

Period	Rainfall (mm)	Temperature (°C)	Rainfall Deficit (mm)
2000–2020	973.5	20.2	-55.3
2021–2040	979.3	21.8	-87.4
2041–2060	983.9	23	-128.6
2061–2080	964.5	24.3	-163.7

Source: *WorldClim v2.1; CRU-TS 4.06; HadGEM3-GC31-LL via CMIP6 SSP585 projections*
Note: *Rainfall deficit calculated as Rainfall – Potential Evapotranspiration (ETo) using Thornthwaite method.*

Appendix 4: Soil Data Summary

Table A-2: Soil Texture Classes and Area Coverage in Dedza District

Texture Class	Suitability Class	Area (km²)	Percentage (%)
Loamy Sand	Highly Suitable	195.7	52.60%
Sandy Loam	Moderately Suitable	116.2	31.20%
Sandy Clay	Lowly Suitable	36.1	9.70%
Rock Outcrops	Not Suitable	25	6.50%

Table A-3: Soil Drainage and Suitability Classification

Drainage Class	Suitability	Area (km²)	Remarks
Well Drained	High	285.7	Ideal for most crops
Moderately Drained	Medium	6.7	Can be improved with drains
Poorly Drained	Low	28.5	Suitable for rice

Source: Africa Soil Information Service (AfSIS); ISRIC-World Soil Information (2021)

Appendix 5: Reclassification Criteria for Suitability Mapping

Table A-4: Reclassification of Rainfall Deficit for Irrigation Suitability

Rainfall Deficit (mm)	Suitability Class
> 163	Highly Suitable (4)
18 – 163	Moderately Suitable (3)
-163 – 18	Lowly Suitable (2)
< -163	Not Suitable (1)

Appendix 6: Climate Sampling Points

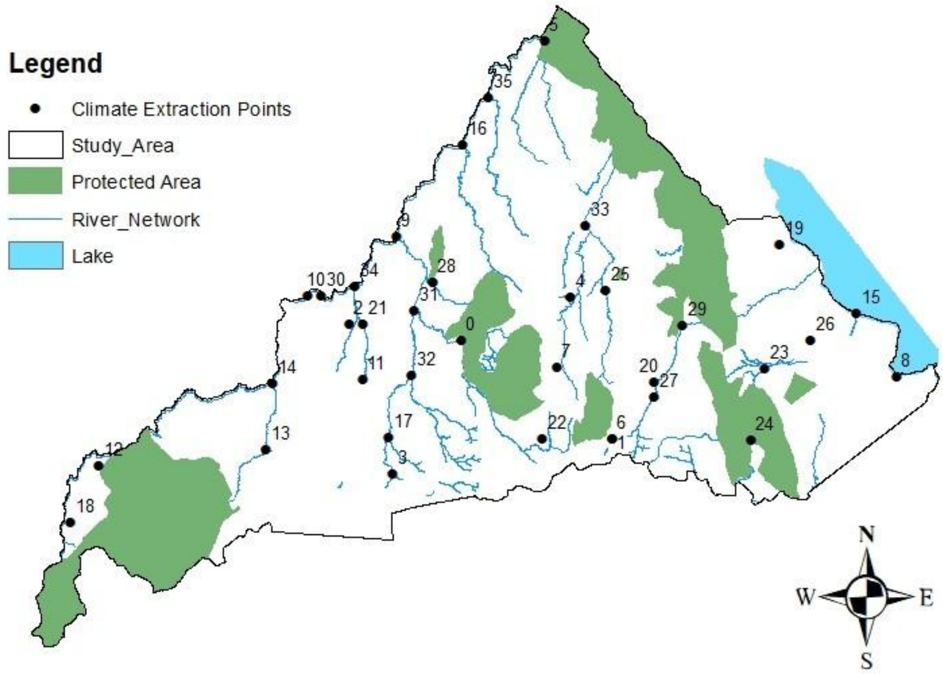

Figure A-1: Climate Data Extraction Points in Dedza District

Table A-5: Coordinates of Selected Climate Points

Point ID	Eastings	Northing	Elevation (m)
CP00	626057.732	8424169.764	978.9
CP01	645565.32	8411295.416	1034.1
CP02	611481.95	8426220.976	928.7
CP03	617219.566	8406812.376	959.6
CP04	640276.407	8429763.882	1001.7
CP05	636857.549	8462969.51	964.8
CP06	645565.32	8411295.416	1034.1
CP07	638426.561	8420555.72	1027.7
CP08	682490.259	8419460.046	926.8
CP09	617631.512	8437642.891	928.2
CP10	606102.704	8429931.011	925.4
CP11	613208.978	8418955.729	943.5
CP12	579055.886	8407909.034	969.9
CP13	600651.329	8409892.705	956.1
CP14	601530.806	8418542.4	944.7
CP15	677229.094	8427561.538	931.5
CP16	626288.046	8449371.049	932.1
CP17	616585.278	8411570.851	955.9
CP18	575440.161	8400546.093	978.2
CP19	667225.423	8436580.595	960.4
CP20	651002.182	8418638.81	1027
CP21	613280.588	8426212.932	928.7

CP22	636578.831	8411346.362	1023.7
CP23	665398.072	8420392.057	945.2
CP24	663540.208	8411183.774	942.1
CP25	644708.32	8430600.597	1011.3
CP26	671290.705	8424076.583	931.5
CP27	650991.044	8416794.657	1027
CP28	622298.607	8431701.596	936.4
CP29	654643.247	8425992.414	972.3
CP30	607901.581	8429923.37	928.7
CP31	619857.525	8427884.833	936.4
CP32	619593.731	8419629.545	948.8
CP33	642127.286	8438971.962	976.2
CP34	612198.371	8431058.314	928.7
CP35	629616.017	8455632.014	928