UNIVERSITY FOR DEVELOPMENT STUDIES

EVALUATION AND OPTIMISATION OF SITING OF SMALL DAMS AND RESERVOIRS IN NORTHERN GHANA

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EVALUATION AND OPTIMISATION OF SITING OF SMALL DAMS AND RESERVOIRS IN NORTHERN GHANA

BY

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A THESIS SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL ENGINEERING, SCHOOL OF ENGINEERING, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY IN IRRIGATION AND DRAINAGE ENGINEERING

FEBRUARY 2026

DECLARATION

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this University or elsewhere. The work of others, which served as sources of information for this study, has been duly acknowledged in the form of references.

Etienne Umukiza		20/04/2026
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DECLARATION BY SUPERVISORS

I hereby declare that the preparation and presentation of the thesis was supervised in accordance with the guidelines on supervision of thesis laid down by the University for Development Studies.

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ABSTRACT

Water shortage is a significant challenge in developing countries, particularly in semi-arid and arid regions, posing obstacles to irrigation and human survival. Northern Ghana experiences a rainy season with occasional floods, water shortages, and dry spells. To address this recurring issue, a study on optimization of small dams and reservoirs was necessary. This study focused on sixteen (16) selected sub-catchments in three (3) northern Ghana regions where small dams and reservoirs were developed for domestic and agricultural purposes. On-site investigation of current status of reservoirs, engineering and structural conditions were conducted. Hydraulic conductivity and soils of embankment were analysed. Upstream simulation of spatio-temporal land use/landcover dynamics impacts on runoff generation was analysed using geographic information system, remote sensing techniques and curve number model. Additionally, the suitability assessment of the constructed small dams and reservoir locations was conducted using an analytic hierarchy process. Scenarios of optimal storage capacity of suitable dam locations were determined using 2D and Civil 3D. The results of the study highlighted the multifaceted challenges associated with small dam failures, emphasizing the need for a holistic approach that integrates engineering solutions and improved design. The comprehensive assessment highlighted variability in hydraulic conductivity ranging from 0.742×10^{-6} to 12.7×10^{-6} cm/s indicating lower and higher permeability and potential seepage, respectively. Spatial-temporal analysis of landuse and landcover from 1995 to 2023 revealed upstream anthropogenic activities, such as the conversion of grassland to agricultural/arable lands and built-up areas, indicating historical landuse and landcover changes and their impact on hydrological mechanisms, and the increase in impervious surfaces resulting in enhanced surface runoff. Findings on suitability assessment of the small dam locations revealed that ten (10) of the dams were located away but less than 100 m from major streamflow networks, posing potential challenges in optimal surface runoff collection. An overall analysis of suitable locations of dams and their optimal storage capacity identified potential relocations for six (6) dams. The proposed new dam locations and their storage capacities were deemed crucial for addressing water scarcity while balancing conflicting needs of various water users. The study findings underscored the significance of research-based decision-making in addressing water shortages and maintaining a balance between agricultural, domestic, and environmental water needs. Regular inspection programmes are recommended to identify and address problems early, preventing complex and costly issues. Assessment of challenges and opportunities in water infrastructure development under changing climatic conditions, and evaluation of socioeconomic impacts and involving communities for sustainability and resilience of small dams were suggested for future research.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHP	Analytic Hierarchy Process
AMC	Antecedent Moisture Condition
ArcGIS	Aeronautic Reconnaissance Coverage Geographic System
AOI	Area of Interest
CN	Curve Number
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
GIDA	Ghana Irrigation Development Authority
GIS	Geographic Information System
GPS	Global Positioning Systems
HSGs	Hydrological Soil Groups
SOLD	International Commission on Large Dams
ICOUR	Irrigation Company of Upper Regions
JICA	Japan International Co-operation Agency
LULCC	Land use and Landcover Change
MCDM	Multicriteria Decision Making
NRCS-CN	Natural Resources Conservation Service Curve Number
SCS-CN	Soil Conservation Services Curve Number
SRTM	Shuttle Radar Topography Mission
TIN	Triangulated Irregular Network
TM	Thematic Mapper
USDA-NRCS	United States Department of Agriculture Natural Resources Conservation Service
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS	World Geodetic System

DEDICATION

I dedicate this work to my beloved family for the prayers, support, and encouragement throughout my studies.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Globally, water resources play a crucial role in sustaining life, supporting agriculture, providing energy, and promoting overall economic development. Water resource development and management have become very important and necessary to conserve water and make it available for humans and animals to use in their immediate environment (Adongo *et al*., 2020). This situation is increasing due to climate change which stands as the primary obstacle to agriculture, and the security of food supply for billions of people, and rural livelihoods as well over the world (Hussain *et al*., 2022). In regions characterized by erratic rainfall patterns and prolonged dry seasons, the construction of small dams is a promising approach to mitigating drought in the drylands (Garg *et al*., 2022). These water infrastructure projects contribute to sustainable development and ensure the prosperity and well-being of the communities they serve.

Although water is the most important resource to improve agricultural production, the low and highly variable rainfall is often inadequate for economic crop production (Ziadat *et al*., 2012). Water storage in small reservoirs, where and when it rains, can be great opportunities to address water scarcity through water storage (Rozycki *et al*., 2006). However, ineffective management and inadequate runoff control during the rainy season frequently result in a high proportion of waste, often becoming destructive. An example is highlighted in a study conducted by Hamze (2020) in Lebanon, which showed that 70 % of surface water goes to the sea, despite the fact that the country is arid and needs water. An effective technical, economical and multidisciplinary solution is necessary to maximize the catchment yield in terms of runoff storage.

Furthermore, it is known that food security and economic prosperity are directly dependent on water availability. Water scarcity severely impairs food security and economic prosperity in many countries today (Alleyne *et al*., 2018). However, in Africa, a third of the African continent's population is living in a water scarcity situation (Khan *et al*., 2017; Mwamila, 2022). Applying new technology, financial investment through research and stakeholder involvement to address this issue could be a way to efficiently and effectively deal with water shortage. In addition, water shortage is the major limiting factor for agricultural development and rangeland improvement (Zaman *et al*., 2011). Correspondingly, water security is considered one of the risks due to climate change and the effects of uncontrolled landuse/landcover changes on hydrological properties (Guzha *et al*., 2018). However, its importance ranges from domestic uses, agriculture, and industry to religious ceremonies, recreation, landscape decoration and even therapy (Berni *et al.*, 2008; Recanatesi *et al.,* 2017).

In general, with climate change and the unreliability of rainfall patterns, farmers are facing a huge challenge of sourcing water for their crops in arid and semi-arid lands (ASALS) and during dry seasons or drought (Yang *et al*., 2019). This long-time challenge has become a setback to food production and food security especially in sub-Saharan Africa, where most farmers rely on rainfall for agriculture. The water scarcity and inadequate methods to sustain agriculture in ASALs as well as in some parts of Africa distributed the socio-economic establishments in the region (Furumai, 2021). The northern regions of Ghana for instance, are characterised by a semi-arid climate, making this part vulnerable to fluctuations in precipitation and water availability. Therefore, controlling rainfall runoff using new techniques such as spatial modelling, and remote sensing for accurate decision-making through the construction of small dams, semi-circular bands, and contours can increase recharge (Milkias *et al*., 2018).

Furthermore, despite the significance of small dams and reservoirs, ASALs are characterized by rainfall shortage and variability, high evapotranspiration and limited water sources to sustain agriculture throughout the year. Rainfall water harvesting through a small dam is one proposed solution to meet the requirements of increasing water demand (Kimani *et al*., 2015; Amoah *et al*., 2019). In Ghana, according to Alleyne *et al.* (2018), there were about 850 small -to large-scale dams from 2011, of which northern Ghana has about 370. However, to ensure their effectiveness and sustainability for agriculture and domestic use is still crucial to undertake thorough evaluations and optimize the design and operation based on catchment characteristics. Since independence, Ghana initiated programmes aimed to improve agricultural productivity, promote rural development and reduce the vulnerability of farmers due to climate change and drought in northern regions of the country. These dams were expected to serve as reservoirs collecting and storing water during the rainy season to further address challenges due to water shortage, particularly during the dry season.

1.2 Problem Statement

Northern Ghana is characterized by arid and semi-arid climate, faces recurrent water shortages for multipurpose use such as domestic and irrigation as well, where farmers struggle to feed their cattle and other livestock, particularly during the dry season. It is estimated that 74 % of communities in northern Ghana are employed in agriculture (Brief, 2016), whereby in rural communities there is very limited economic activity outside the rainy season without irrigation. Hence, farmers rely strongly on rainfall which is available for few months followed by a long dry season. Most of the annual rainfall occurs in August to the end of September and many tributaries drain into the White Volta River, often causing damages due to flood, but drying during the dry season.

Despite the significant potentiality of small dams and reservoirs to provide water for domestic and agricultural use in the region, there are serious challenges in their ability to effectively meet the water demands of local communities. Although the good prospects support dry season gardening and enhance food security, northern Ghana still faces significant water shortage issues whereby many small dams fail to store water for long-term viability in the dry season. In addition, the characterization of upstream dynamics on runoff generation patterns in small catchment is still thoroughly required and eventual unsuitability location, among others, that should be the main drivers of small dam failure to satisfy the expected demand.

1.3 Justification of the Study

The issue of water scarcity is increasingly becoming a significant challenge, especially in arid and semi-arid lands as it is the case in the northern regions of Ghana. Development and adequate implementation of small reservoirs can provide access to water multiple ecosystem services to domestic needs, small scale irrigation, watering livestock and environment. However, many small dams have failed to store water adequately for long-term viability, leading to persistent water scarcity issues. The reasons behind their sub-optimal performance and subsequent failure are multifaceted and require in-depth investigation and analysis. Therefore, there is a critical need to accurately identify factors in the catchments contributing to inflow and assess their optimal storage capacity to support irrigation and multiple water uses through runoff harvesting in selected sub-catchments. This can be addressed by considering hydrological boundaries, landuse dynamics resulting in upstream activities and biophysical factors as they are significant to implement runoff collection structures. Therefore, alternative options like runoff harvesting conditions can play an important role in improving water resources, supporting agricultural activities and contributing to sustainable and resilient rural communities as they require affordable investment (Bekoe *et al.*, 2021).

However, to accurately identify optimal contributing flow areas by considering hydrological boundaries, socioeconomic and biophysical factors are a priority in areas with water scarcity. Moreover, an extension of knowledge, and experiences regarding water resources engineering, availability of feasibility studies, and applying new technologies can contribute to addressing the increasing water shortage exacerbated by current climate change. The integration of remote sensing (RS) and Geographic Information Systems (GIS) with the hydrological model provides ideal tools to delineate the contributing catchment, simulation of surface runoff and peak discharge can provide support to accurately locate the small dams.

Despite the strategic importance of identifying optimal sites for dam construction in these regions, traditional decision-making techniques often prioritize cost and resource constraints, potentially underestimating critical site suitability factors. In addition, the promotion of small dams could effectively reduce the scarcity of freshwater for domestic, agricultural, industrial and service sectors.

It is therefore important to carry out a study about the engineering and structural enhancement of small dams and reservoirs, their catchment characteristics and hydrological processes to maximize water storage yield from sub-catchment, in selected locations where small dams and reservoirs were constructed.

1.4 Objectives of the Study

1.4.1 Main Objective

The main objective of the study was to evaluate selected small dams and reservoirs in northern Ghana regarding their performance and provide optimal site selection for the maximum water capture intended for domestic and agricultural use.

1.4.2 Specific Objectives

The specific objectives of the study were to:

1. Assess the structural functionality and current conditions of the constructed small dams and reservoirs.
2. Evaluate the catchment characteristics of the selected small dams and reservoirs and their effect on runoff generation.
3. Assess the suitability of constructed small dams and reservoirs' sites, to suggest optimal site for improved storage capacity.

1.5 Hypotheses of the Study

To guide the study, the specific objectives were used to formulate null and alternative hypotheses.

1.5.1 Null Hypotheses (Ho)

1) There are significant structural deficiencies in the constructed dams and reservoirs, indicating a potential failure of their functionality.
2) There is no relationship between the evaluated characteristics of upstream features and the generation of runoff into the reservoirs.
3) The proposed locations for dam construction, the constructed small dams and reservoirs, and their storage capacities do not significantly differ from the optimal criteria for suitability and performance.

1.5.2 Alternative Hypothesis (Ha)

1) The structural conditions of the constructed dams meet the specified safety standards and design criteria.
2) The evaluated characteristics have a significant influence on the generation of runoff from the catchment into the study dam.

3) The proposed locations for dam construction, the constructed small dams and reservoirs, and their storage capacities significantly differ from the optimal criteria for suitability and performance.

1.6 Scope and Limitations of the Study

This study focused on the comprehensive evaluation and location suitability to suggest optimal site and optimal storage capacity of specific small dams and reservoirs sites located in northern Ghana, designed primarily for domestic and agricultural purposes. The scope encompasses various key aspects, including examination of the engineering and structural functionalities of the selected small dams and reservoirs, along with in situ assessment of their current conditions. Evaluation of upstream activities, the catchment characteristics of the chosen small dams and reservoirs, with a particular emphasis on understanding their impact on runoff generation, followed by an investigation into the suitable locations for dam construction within the study areas. The scope also extended to tackle an assessment of the suitability of the constructed small dams and reservoirs and proposed alternative locations considering geographical and environmental factors and finally included an analysis of their optimal storage capacity.

While this research aimed to provide a thorough analysis of the selected small dams and reservoirs, the following limitations were recognized:

- The assessment was limited to specific small dams and reservoirs in northern Ghana, with focus on domestic and agricultural use which might result in a narrower perspective.
- Time and resource constraints impacted the depth and breadth of the evaluation on how communities' access to, use by livestock and conflicts that rise over the use of the reservoirs, and the study only considered the extent of physical data collection and analysis.

- The study did not delve into geotechnical analysis for foundation stability, detailed design for implementation and the socio-economic impacts of the small dams and reservoirs, which could be a significant aspect affecting their overall management and effectiveness.

1.7 Structure of the Thesis

This thesis comprised five (5) Chapters. Chapter One (1) is the general overview of the thesis, and the reasons behind it were elucidated. Chapter Two (2) delves into the background and reviews literature pertaining to dams and reservoirs, catchment characteristics that influence runoff generations spanning the global context to the specific scenario in Ghana. Chapter Three (3) outlines the study areas, offering details on the materials and methods employed to achieve the specific objectives mentioned in Chapter One. Chapter Four (4) presents and discusses the results concerning each of the three (3) specific objectives. Chapter Five (5) provides a comprehensive examination of the research findings. It gives also comparisons with previous studies and explores the implications arising from the research outcomes. Finally, the consolidated findings, extracts meaningful conclusions from the study, and provides recommendations for policy implementation and future research. Lastly, a list of references, and appendices used in the thesis are presented.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This Chapter presents a thorough evaluation of the relevant literature, policy, and documents (books, news, etc.) linked to minor dams and reservoirs in accordance with the study's objectives. The Chapter is divided into four (4) main sections:

The first part is drawing on the background of dams' construction, soil engineering assessment, structural designs, and contemporary conditions of the small dams and reservoirs. The second part narrates the evaluation of upstream and catchment characteristics related to rainfall runoff with an accent on their effects on runoff generation. Analysing these catchment features that shed light on the relationship between landuse dynamics, hydrological processes, and runoff generation. The third section is an assessment of criteria and considerations for suitable location of dam construction in the study areas. The fourth part reviews and narrates the evaluation of the suitability and criteria of small dams' construction and reservoirs for optimal storage capacity. The fifth and last part tackles the conceptual framework adapted for this study based on the positive and negative critics drawn from the above review and methodologies.

2.1Study Background

2.1.1 Background

Dams are among the earliest constructions that humans built for common use. A dam is a barrier constructed across a river or stream that allows the water to be held back or impounded, providing water for irrigation and drinking, controlling flooding and generating power (Kim and Kang, 2021). According to Byjani *et al*. (2017), a dam is defined as a structure or a barrier constructed across a valley, river, or stream to conserve, store or control the flow of water. Dams are described by Martínez-Gomariz *et al*. (2023) as a hydraulic system with multiple functions including irrigation, hydropower generation, water provisioning, flood management, recreational activities, fish cultivation, and navigation. The purpose of dam management is to obtain the effectiveness of the dam as highly as possible with appropriate and safe operation.

Dams are different categories vis a vis construction materials, embankment heights, and storage capacity. Dams are typically constructed of earth rock concrete or a combination of materials designed to impound water or create a reservoir. From construction material we distinguish the main areas: earth fill; concrete gravity; concrete arch, rock fill and arch-gravity. Fill dams include all dams made of earth materials (soil and rock) that are compacted together. Since ancient times all the categories of dams listed above have been built. Dam leakage results in failure because they simply can't hold water or because the water seeping through them eats materials away from the inside of the dam causing it to structurally fail.

Currently, most fill dams are also built with zones including a clay centre or core, filter and drainage layers, coarser materials sandwiching the clay core, and rock on the upstream (water) face preventing erosion. These zones can be seen clearly when a cross-section is cut from the dam's upstream to the downstream side. Fill embankments are usually less expensive to construct than concrete dams (Liebe *et al.*, 2015). Soil or rock is present at the site and construction techniques through the complex are also less costly than concrete construction.

2.1.2 History of Dam Construction

In general, the history of dam construction dates back to ancient times when humans built small dams out of stones, earth and wood to control and divert water for irrigation and domestic purposes (Cabral, 2021). The history of the construction of embankment dams is far older than that of concrete dams (Narita and Kunitomo, 2000). It is therefore evident that some earth dams were constructed about 3000 years ago, especially in ancient cultures of eastern countries. Earth embankments have been used to impound and divert water since the earliest times. They are the most common type of dam encountered worldwide and are simple compacted structures that rely on their mass to resist sliding and overturning. In accordance with the guidelines outlined in the manual issued by the International Commission on Large Dams (ICOLD), an organization comprising approximately 63 member nations, structures exceeding a height of fifteen meters (15m) are classified as "high dams." To date, over 14,000 high dams have been officially recorded, with embankment dams constituting more than 70 % of this total. The study by Narita and Kunitomo (2000) distinguished two major features and advantages for the construction of the dam as represented in Table 2.1.

Table 2.1: Comparison Between Earth Dam and Concrete Dam Construction

Earth Dam	Concrete Dam
Rigorous conditions are not required for the earth dam foundation, embankment dams can be constructed even on the alluvial deposit and previous foundations.	a hard and sound rock foundation is necessary for concrete dams.
Construction of embankment dams has an economic advantage: the dam project can be planned in the outskirts of the city area because of the merit mentioned above, and construction materials are principal to be supplied near the dam site.	Concrete dams are expensive and require materials from far away.

Source: Narita and Kunitomo (2000)

Despite the importance gained in dam construction worldwide, driven by the need for water supply, flood control, irrigation, and hydropower especially in developing countries, dam construction has also been controversial due to their negative environmental and social impacts like aquatic ecosystems, sedimentation and displacement of local communities. But these environmental issues can be addressed toward more sustainable design and construction, including the use of environmental impact assessments and community consultation in the planning process.

2.2.3 Types of Earth Dams

Earth dams can be categorised into three (3) primary types. The choice of which type to build is predominantly influenced by the availability of materials in proximity to the construction site

(Martínez-Gomariz *et al*., 2023). Moreover, the embankments are classified into two (2) main categories of construction materials; such as rock-fill dams and earth-fill dams. However, when it comes to a project, the dam type is determined by considering various factors associated with the topography and geology of the dam site, and the quality and quantity of construction materials available. The inclined core is adopted instead of the centre core, for instance, in cases where the dam foundation has a steep inclination along the river, where a blanket zone is provided in the previous foundation to be connected with the impervious core zone, and where different construction processes are available for the placement of core and rockfill materials. In rockfill, the transition can be used to have structural strength, core facing to keep watertight; filter to prevent loss of soil particles, and drain to pass water from upstream to downstream.

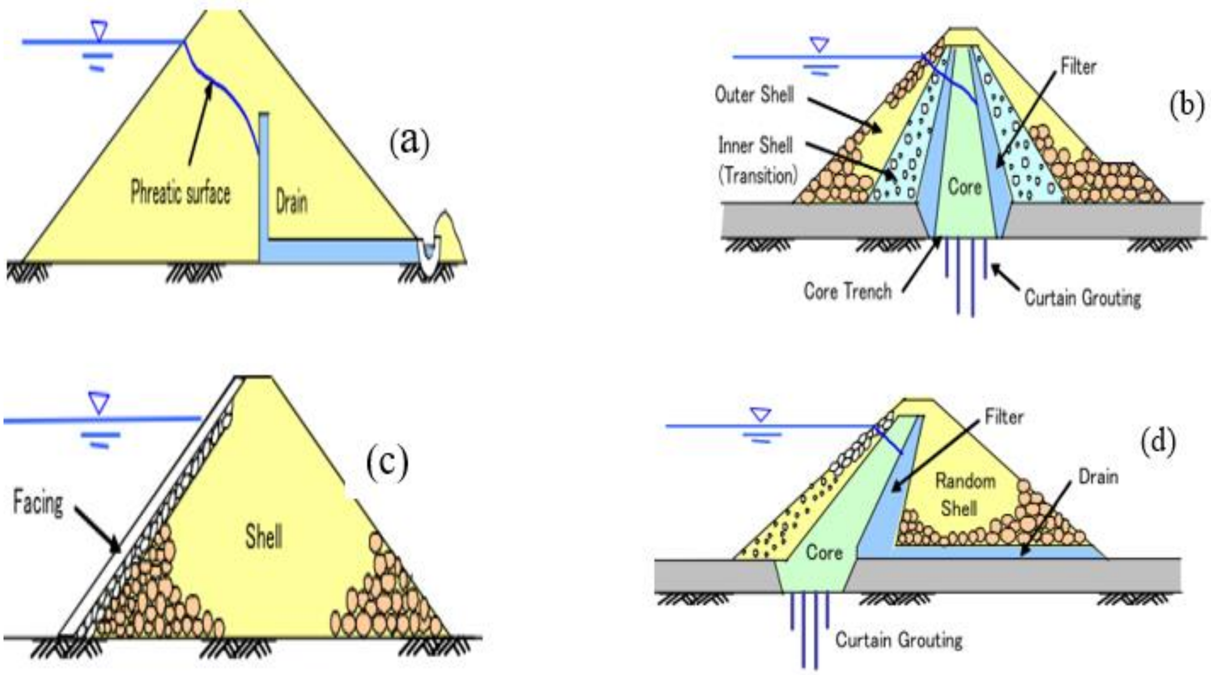


Figure 2.1: (a) Homogeneous Earth Dam; (b) Rockfill Dam with a Centrally Located Core; (c) Rockfill Dam with a Facing; and (d) Rockfill Dam with an Inclined Core

Source: Umukiza *et al*. (2023)

A uniform earth embankment consists of solely one type of substance. The material must possess impermeability in order to function as a proficient water obstruction. Illustrative instances include dams constructed using clayey soil. An embankment dam with zoning features possesses an impermeable central core encompassed by sections of comparatively more permeable materials. The third variation, involving a membrane, is established in locations where impermeable materials are scarce. In such cases, a slender layer of materials like bitumen, concrete, plastic, or other impermeable substances is employed as a sealing layer. The structure of the embankment mainly comprises permeable materials. When selecting suitable locations for water storage structures such as dams; serval criteria should be considered to ensure optimal functionality and efficiency. The construction of dam components involves several conceptual stages that are crucial for the successful implementation of dam projects (Henrique and Canno, 2022). These stages ensure that the design, construction, and operation of the dam are carried out effectively and efficiently. A brief overview of the conceptual stages involved in dam component construction is presented in Figure 2.2.

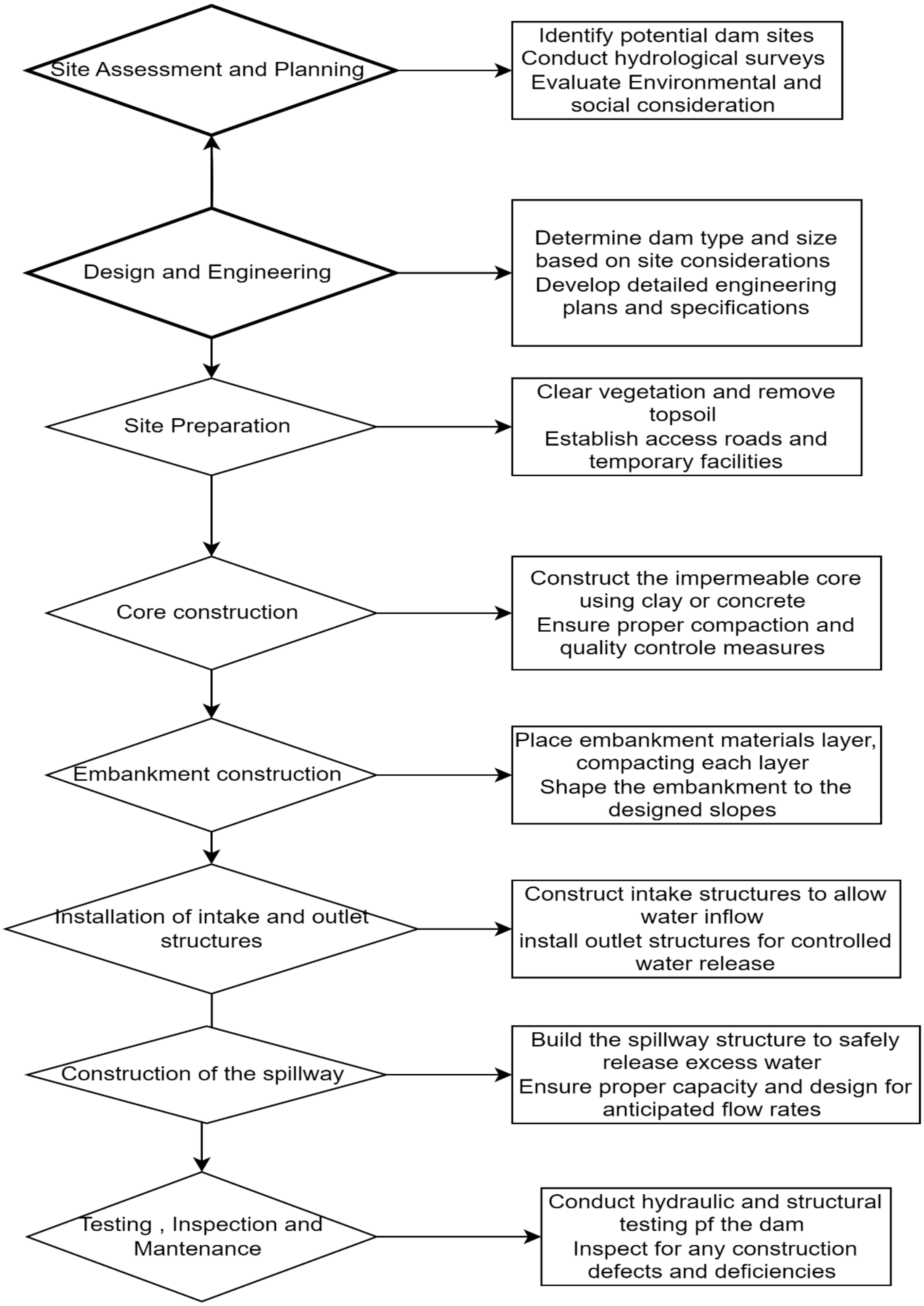


Figure 2.2: Conceptual Stages for Dam's Components Construction

Source: Umukiza *et al*. (2023)

These conceptual stages provide a structured framework for the construction of dam components ensuring that all aspects from feasibility assessment to design, construction and operation are carefully planned and executed. Each stage contributes to the successful completion and functionality of a dam, fulfilling its intended purpose.

2.1.4 Failures and Damages of Embankment Dams

The preponderance of catastrophic earthen dam failures is triggered by reservoir water overflowing due to flooding or a loss of freeboard. According to Athani *et al*. (2015), even though embankment dams should not be built to withstand the erosive effect of water flowing over the crest, case studies show that insufficient estimation of the amount of flooding has often led to the decisive defeat of embankment dams.

Overtopping has frequently caused embankments to fail due to spillway capacity, or inadequate water volume prediction of the volume of water. Failures of this nature, however, cannot be a definitive flow of embankment dams because the problem may be easily solved by compiling correct hydrology data already available and refining the compilation of correct hydrology data that is already available and the refinement of the design methodology (Singh and Roy, 2009). First of all, damages from embankment dam failures induced by heavy water are classified into three (3) types such as seepage failure, sliding, and overflow.

High pore-water pressure, earthquake impacts, hydraulic erosion, and other variables are all important contributors to embankment failures. Hydraulic erosion is the primary cause of more than 50 % of embankment failures, with the remaining few percent caused by other factors. Table 2.2 and Figure 2.3 present examples of several typical failure causes and damage patterns for embankment dams and their foundations.

Table 2.2: Failure Causes of Embankment Dams

Parameter	• **Failure Causes**
During Construction	• Pore water pressure built-up during construction • Reduction of shear strength due to thixotropic property
After Construction	• Hydraulic fracturing / Internal erosion / Piping • Excess hydrostatic pressure due to rapid drawdown • Reduction in shear strength / Weathering, swelling of compacted soil • Settlement and cracking • Earthquake forces
Damage of Embankment	• Sliding (by pore-water pressure, earthquake • Deformation (settlement and lateral deflection • Leakage • Hydraulic fracture (quicksand and piping
Damage of Foundation	• Bearing capacity • Settlement • Leakage • Hydraulic fracture • Liquefaction

Source: Umukiza *et al.* (2023)

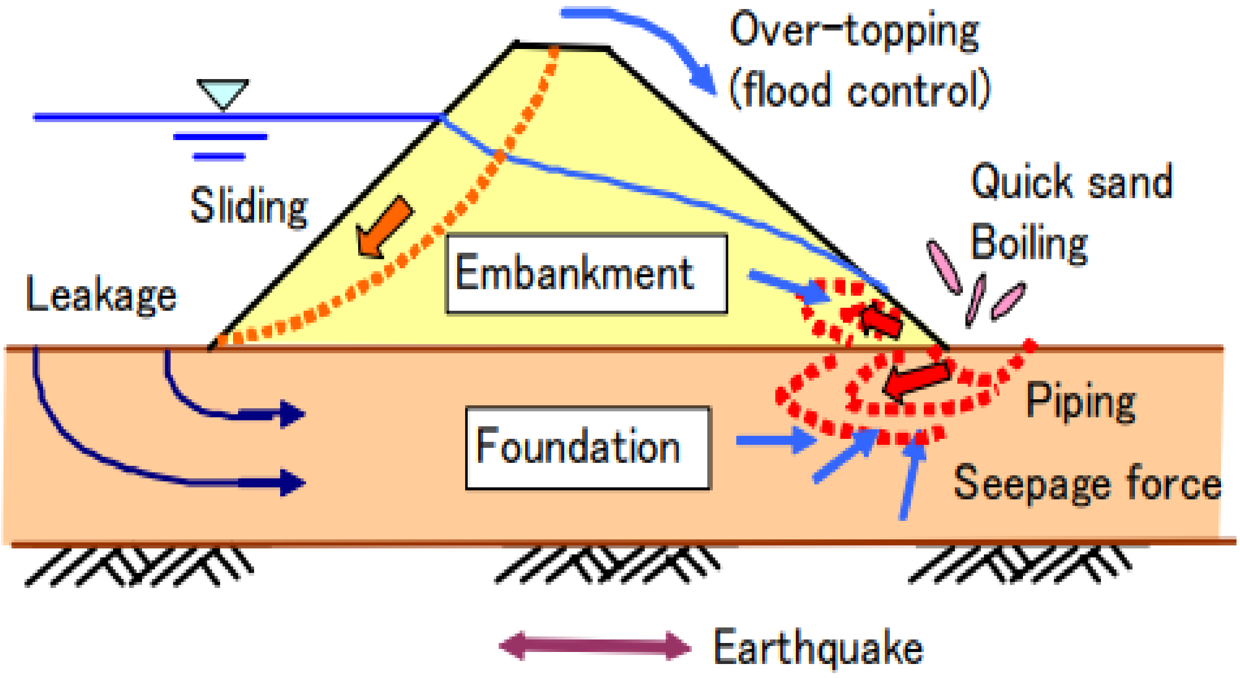


Figure 2.3: Illustration of Dam Failure Causes

Source: Umukiza *et al.* (2023)

The representation of features leading to embankment dam failures has been described as follow:

i. Overtopping occurs when the water level in the reservoir exceeds the height of the dam crest resulting in water flowing over the top of the dam;

ii. Seepage and piping: Seepage refers to the flow of water through the embankment or foundation while piping is a more severe form of seepage, occurs when the seepage water erodes and channels through the dam, creating internal passages that can read to the collapse of the dam;

iii. Foundation failure: the foundation plays a crucial role in its stability. If the foundation is weak or prone to settlement, it can cause differential movement in the dam, leading to cracks, deformations and potential failure;

iv. Construction and design deficiencies: Poor construction practices and design flows can result in failures and damage to embankment dams. Inadequate compaction, improper placement of materials, insufficient or poorly designed drainage systems or errors in structural analysis can compromise the overall integrity of the dam;

v. Natural disasters: Embankment dams are susceptible to damage from natural disasters such as earthquakes, floods, and landslides;

vi. Lack of Maintenance: Over time, embankment dams may experience deterioration due to ageing and lack of proper maintenance.

2.1.5 Seepage Failure and Hydraulic Fracture

Seepage failure and hydraulic fracture are two (2) different types of geological phenomena related to the movement of fluids in the earth’s crust. Seepage failure occurs when water or other fluids infiltrate and weaken the soil or rock mass leading to instability and failure while hydraulic fracture occurs when fluid pressure is used to create cracks in rock formations (García-Gutiérrez *et al*., 2018). When water flows passing through the soil in an embankment and foundation, seepage forces act on soil particles due to their viscosity. If seepage forces acting in the soil are large enough as compared to the resisting forces based on the effective earth pressure, erosion by quicksand takes place by washing soil particles away from the surface, and piping successively develops as erosion gradually progresses. While seepage failure and hydraulic fracture are different phenomena, they can both have significant impacts on the stability of soil and rock formations. Hydraulic fracture can trigger seepage failure in some cases by creating pathways for water to flow through the rock which can lead to instability and landslides.

2.1.6 Benefits of Small Dams and Reservoirs

Inadequate soil and water management could result in drought and flooding during the dry season and as well as erosion and flooding during the rainy season (Faizal *et al.*, 2021). The improper management of soil and water may result in drought and flooding during the dry season, as well as erosion and flooding during the rainy season. There is wide recognition that small dams have contributed to improving the quality of life in rural communities. The primary functions of a dam include retaining and controlling water. Through these functions, several purposes can be observed including water supply, storage for municipal uses, irrigation, livestock, aquaculture, hydropower, and flood control. For instance, according to Amoatey (2023), dams were a promising approach in northern Ghana to secure a water supply for irrigation to increase agricultural productivity, because the use of groundwater was very low (https://newsghana.com.gh/gimpa-to-undertake-research-on-one-village-one-dam). The multi-purpose nature of dams makes them ideal for community-scale water supplies for irrigation, livestock watering, and domestic water supplies. Therefore, many researchers including Taylor (1935); Chaleeraktrakoon & Chinsomboon (2015); Marques *et al*. (2018); Vienna (2020); Faizal *et al*. (2021); Hanazaki *et al*. (2022); Merchán-sanmartín *et al*. (2022); Karakatsanis *et* *al*. (2023); and Umukiza *et al*. (2023) highlighted that dams and reservoirs are of vital importance for different purposes such as :

i. Irrigation: Small earth dams are particularly useful for providing water for irrigation in dry areas, and from streams which have low or no flows during the dry season.

ii. Hydroelectric power generation: small earth dams can be used for hydropower generation. This is particularly possible in dams having a steady flow and built across a gorge where there is a relatively good head drop. Many countries have rivers with adequate water flow that can be dammed for power generation purposes.

iii. Land reclamation: Dams are used for land reclamation and to prevent the inundation of water in an area that would otherwise be submerged. This facilitates the reclamation of such areas for other use. Normally, dykes or levees are used for diverting the water.

iv. Flood prevention: Dams are sometimes constructed to impound excess flows during the rainy season and prevent flooding of downstream areas or infrastructure. They help to stabilize river flow, especially of ephemeral streams.

Water diversion: small dams can be used to divert water for irrigation, power generation, or other uses. Sometimes, they are used to divert water to another drainage or reservoir to increase flow there and improve water use in that particular area. Dams are classified in many types based on construction materials. Dam can be concrete, rock feel, masonry or earth (Zakaria and Luleå., 2012). Earth dams may also take various forms, like gravity dams which are huge structures designed to use their dead weight to resist the horizontal force of the water. An arch dam is built with its context front facing the upstream side of the horizontal of the valley or reservoir and derives its strength essentially from its shape. Figure 2.4 shows a view of an earth dam.

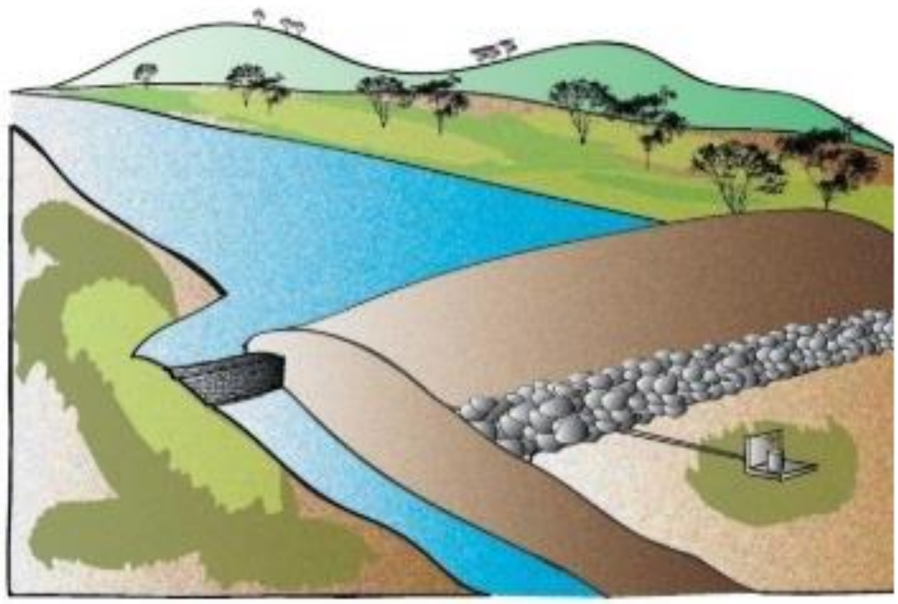


Figure 2.4: Illustration of Dam Operation

Source: Narita and Kunitomo (2000)

2.1.7 Classification of Type of Dam

In general, dams may be classified into several different categories, depending upon the purpose of the classification (Faizal *et al.*, 2021). According to Venot and Krishnan (2011), defining what 'makes' a small reservoir is indeed not agreed upon, as the criteria (type of infrastructure, size, modes of management, planning approaches) and thresholds (volume, height, irrigated area) can vary widely depending on the vantage point considered and the problems or actors at stake. However, the World Commission on Reservoirs (WCR) defines a small reservoir as a structure that has a height of less than fifteen meters (15 m) and a storage capacity ranging from fifty thousand to one million cubic meters (50,000 to 1×10^6 m^3)". Meanwhile, Annor *et al.* (2007) also argued that, though small reservoirs can be defined in terms of surface area coverage (water storage systems greater than 1 ha but less than 100 ha), the volume of water stored in most reservoirs varies with time mostly as a function of siltation, seepage, evaporation and availability of rainfall.

Most of the cases, dams are classified according to their use, their hydraulic design, or the materials in which they are constructed.

Table 2.3: Classification of Dams and Reservoir Based on Height and Storage Capacity

Author(s)/Organization	Classification	Maximum Height of Dam Wall (m)	Gross Storage Capacity of Reservoir (10^6 m^3)
Basson (2007)	Small	2.5 – 5	< 1
	Medium	5 – 10	1 – 3
	Large	10 – 15+	> 3
Kolala (2015)	Small	< 8	< 1
	Medium	8 – 15	1 – 3
	Large	15^+	3^+
Mishra (2017)	Small	7.5 – 12	0.5 – 10
	Medium	12 – 30	10 – 60
	Large	> 30	> 60
USA (Senzanje and Chimbari, 2002; Sawunyama, 2005)	Small	≤ 6	0.123
	Medium	6 – 12	0.123 – 5
	Large	≥ 12	≥ 5
Zimbabwe (Senzanje and Chimbari, 2002; Sawunyama, 2005)	Small	< 8	< 1
	Medium	8 – 15	1 – 3
	Large	≥ 15	≥ 3
Kabell (1986)	Small	< 8	< 1
	Medium	8 – 15	1 – 3
	Large	15 – 30	3 – 20
	Major	> 30	> 20

The classification in Table 2.3 is commonly used though there are variations in the classifications depending on the institutions and purposes of the reservoirs. Common types of dams based on their purposes as given by Neachell (2014) and Vienna (2020) include:

i. Storage dams: These dams are built to store water for later use, such as irrigation, drinking water hydropower.

ii. Diversion dams: These are dams constructed to deviate water from one location to another, usually to supply water for irrigation or municipal use.

iii. Detention dams: These are dams designed to temporarily hold back water during heavy rainfall or snowmelt, to prevent downstream flooding.

iv. Coffer dams: These are temporary dams built to isolate a construction site or repair an existing dam.

v. Embankment dams: These are dams constructed from compacted earth or rock fill material. They are typically used for flood control and water storage

vi. Concrete dams: These are dams made of reinforcement concrete and are often used for hydroelectric power generation and water storage.

vii. Gravity dams: These are dams relying on their weight and the force of gravity to resist the water pressure. They are often made of concrete and used for hydroelectric generation.

viii. Buttresses: These dams are made of concrete and slab supported by a series of buttresses or columns. They are used for hydroelectric power generation or water storage.

ix. Roller compacted concrete (RCC): These are dams made of concrete that are placed and compacted using rulers. They are often used for water storage for flood control.

Dams can also be classified based on their construction material and structural design. The classes are reported in Table 2.4 as follows:

Table 2.4: Comparison between Earth Dam and Concrete Dam

Criteria	**Details of Classes**
Classification according to use	Dams may be classified according to their broad function. They can be used for storage, diversion or detention
Classification based on hydraulic design	Dams may also be classified as overflow or non-overflow dams. Overflow dams are designed to carry the discharge over their crest. In this type of dam, concrete is the most used material. Non-overflow dams are those designed not to be overtopped. This type extends materials to include earth fill and rockfill dams
Classification based on material	The most common classification used for the discussion of design procedures is based on the materials used to build the structure

Source: Lavaa *et al*. (2023)

2.1.8 Small Earth Dam

A small earth dam is a structure made of compacted soil, rocks and other materials that are designed to impound water (Narita and Kunitomo, 2000). Small earth dam is used for small-scale water management projects. Although it is said small earth dams; they must be designed to effectively respond to the need for irrigation, livestock watering, or recreational purposes. Furthermore, it can be noted that the construction of any dam can have significant environmental impacts including habitat destruction and alteration of natural waterways. Earth embankments have been used since the earliest times to impound and divert water (Goff *et al*., 2020). According to Umukiza *et al*. (2023),the construction of a small earth dam typically involves key steps such as:

i. Site selection: The site selection must be carefully done based on factors such as topography, soil type and amount of water to be impounded;
ii. Design: the design of the dam must take into account factors such as the height of the dam, the size of the reservoir and the potential location zone;
iii. Accessibility and excavation: The site where the dam will be constructed must be accessible for construction machines for excavation and levelling;
iv. Foundation preparation: The foundation must be prepared by removing any organic matter and compacting the soil;
v. Embankment construction: The embankment of the dam is constructed by layering compacted soil and other materials such as gravel and rock;
vi. Spillway construction: The spillway allows excess water to flow out of the reservoir in a controlled manner preventing the dam from overtopping and potentially failing. The spillway is therefore a very important safety feature that ensures the proper functioning of dams and protects the surrounding area from eventual flooding and damage.

Whereas gravity dams are the most common type of dam found worldwide, they resist sliding and overturning (Ali *et al.*, 2012).

2.1.9 Advantages and Disadvantages of Small Earth Dam

While small earth dams offer several advantages, they also come with certain disadvantages. Table 2.5 presents the advantages and disadvantages of small earth dams as given by Faizal *et al.* (2021).

Table 2.5: Advantages and Disadvantages of Small Earth Dam

Small Earth Dam	
Advantages	**Disadvantages**
• Local natural materials are used. • Design procedures are straightforward. • Comparatively small plants and equipment are required • Foundation requirements are less stringent than for other types of Dams. The broad base of the earth dam spreads the load on the foundation. • Earth fill dams resist settlement and movement better than rigid structures and can be more suitable for areas where earth movements are common.	• An embankment is easily damaged or destroyed by water flowing on, over or against it. Thus, spillway and adequate upstream protection are essential for any dam. • Designing and constructing adequate spillways is usually the most technically difficult part of any dam building work. • Any site with a poor-quality spillway should not be used. • If not adequately compacted during construction, the dam will offer weak structural integrity, offering possible pathways for preferential seepage. • Earth dams require continual maintenance to prevent erosion, tree growth, subsidence, animal and insect damage and seepage.

Source: Faizal *et al.* (2021)

2.1.10 Assessment of Engineering Aspects of Small Earthen Dams

For thousands of years, earthen dams have been constructed primarily for the purposes of storing water and managing flooding. For a variety of reasons, mostly social and environmental ones, including the operation and preservation of existing structures, new dam construction has been made possible. Because of this, geotechnical engineering is increasingly involved in managing the safety of dams, therefore understanding the principles of analysis and design employed in their construction is crucial (Senzanje, 2006; WEBs, 2012).

The most important factors that affect the choice of the type of dam are topography, regional geology, availability of construction materials, seismicity of the region, hydrology of the river basin, environment and geotechnical conditions of the reservoir, and curtain site.

2.1.11 Safety Assessment of Dams

To assess a dam's security, it is advisable to carry out inspections annually, every five years, and if an unusual incident occurs. The annual inspections should seek to comprehend the dam's behaviour and short-term functioning, in accordance with (Fowler and Missionary, 1995; Okyereh *et al*., 2019) recommendations. During inspections every five years, a complete assessment of the dam's condition must be made, and potential corrective actions must be identified.

The safety assessment of a dam is a critical system that entails evaluating the structural integrity, functionality, and usual protection of the dam (Okyereh *et al*., 2019). It is crucial to ensure that the dam can resist diverse stresses and capability risks, including floods, earthquakes, and normal put on and tear, to prevent catastrophic screw-ups that might bring about loss of existence and belongings harm. Safety checks ought to be performed periodically, with frequency decided by way of the dam's length, purpose, and related dangers. The outcomes of these assessments guide choice-making regarding preservation, maintenance, and potential upgrades to ensure the continuing safe operation of the dam. Some of the key parameters to consider in the assessment are described in Table 2.6.

Table 2.6: Important Steps and Considerations for the Safety Assessment of a Dam

Key Parameters	Process
Inspection and tracking	Dams ought to go through ordinary visual inspections by using trained professionals to identify signs and symptoms of harm, erosion, seepage, or some other issues *(*Zedan *et al.*, 2022).
Hydrological and Hydraulic analysis	Checking the dam's capacity to deal with various influx situations, which includes excessive flood activities, to ensure that it could thoroughly manage and manipulate water levels. Examine the spillway capability and assess its effectiveness in managing extra water (Liu *et al*., 2023).
Geotechnical assessment	Conduct geotechnical investigations to evaluate the steadiness of the dam's foundation and embankment materials. Determine soil and rock residences, slope stability, and seepage characteristics (Whitman, 1984).
Seepage analysis	Perform seepage analysis to decide if water is infiltrating via or below the dam. Cope with any seepage issues to prevent erosion and capability dam failure (Athani *et al*., 2015; Hasani *et al*., 2013).
Geologic and Geophysical research	Geological survey has undertaken a comprehensive suite of geological investigations aimed at understanding the interaction between geologic structure, seepage patterns, reservoirs and grand water levels. Behaviour research to assess the geological and geophysical situations around the dam, which may have an effect on its stability and safety (Bedrosian *et al*., 2012).

Public protection is paramount in dam safety evaluation and control, and any diagnosed dangers should be addressed directly to save injuries and protect downstream communities and the surroundings (Ghanbari, 2017).

2.1.12 Similarities and Difference Between Dam and Reservoir

Reservoir and dam are two related concepts in civil engineering and water resource management (Lin and Rutten, 2016). A dam is a structure built across a river, stream, or watercourse to create a reservoir by impounding water (Henrique and Canno, 2022). While a reservoir is an artificial or man-made body of water created by impounding or damming a river, stream, or other water source (Owusu *et al*., 2022). Reservoirs serve several important single and multipurpose. Single purpose reservoirs are constructed to store water during the period of high flow for use during periods of drought when the demand is more due to depletion of natural water storage. A multipurpose reservoir is a manmade lake which is managed for multiple purposes like water supply, flood control, soil erosion, environmental management, hydroelectric power generation, navigation, recreation and irrigation (Kim and Kang, 2021).

The importance of the reservoir dams can therefore be detailed in following areas:
Water Storage: Reservoirs are primarily designed to store water for various purposes, including drinking water supply, irrigation, industrial use, and hydropower generation. They help regulate the flow of water, ensuring a steady supply during periods of drought or seasonal variation (Lin and Rutten, 2016).

Dams are designed to hold back a large volume of water, which forms the reservoir behind them. They control the flow of water downstream, allowing for regulated release. Reservoirs can help mitigate the impact of floods by temporarily storing excess water during heavy rainfall or snowmelt events (Benson, 2016). This prevents downstream flooding and protects communities and infrastructure. Many reservoirs are used for recreational activities such as boating, fishing, swimming, and camping, making them valuable for tourism and leisure. Reservoirs often support diverse ecosystems and provide habitats for aquatic plants and animals (Wisser *et al*., 2010). They can be designed to balance human water needs with ecological conservation. Some reservoirs are integral components of hydroelectric power generation systems. Water released from the reservoir flows through turbines, producing electricity.

However, it is important to note that while dams and reservoirs provide numerous benefits, they also come with environmental, social, and safety considerations. Large dams can impact ecosystems, displace communities, and require careful engineering and maintenance to ensure their structural integrity (Kim and Kang, 2021). Moreover, construction and operation of dams must consider the potential downstream and upstream impacts on the environment and society.

Overall, reservoirs and dams are integral components of water resource management and play a crucial role in providing water for various purposes while also addressing flood or draught control and energy needs (Kim and Kang, 2021). However, design and management of dams require a careful balance between costs and benefits at one hand and human and environmental considerations on the other (Brown *et al*., 2009).

2.1.13 Small Dam and Reservoir Development in Ghana

Small dams in northern Ghana are vital for water resource management and agriculture. Small dam's development has been part of Ghana's rural economy since 1960 (Namara *et al*., 2011). The period of 1950s to mid-1960s saw the construction of approximately 240 earth dams and dug-outs in northern Ghana with the prime objective (Acheampong *et al.*, 2014a). Majority of the dams are under management of Ghana Irrigation Development Authority (GIDA) and Water Users' Associations (WUAs) while the lower part is managed by the Irrigation Company of Upper East Region (ICOUR).

Promoting agricultural water management, particularly the management of multi-purpose small reservoirs (SRs) in the drier savanna regions of northern Ghana, is seen as vital to enhancing agricultural production, food security, and smallholder farm households' standard of living (Acheampong *et al*., 2018). However, there is no empirical data on how effective these modest water infrastructures are at providing a range of advantages, design records and how they affect the livelihood of smallholder farmers. Northern Ghana is susceptible to droughts and water shortages due to its semi-arid climate and seasonal rainfall patterns. Small reservoirs and dams are essential for reducing these problems and promoting local sustainable growth.

In an area prone to water scarcity and climate variability, efforts to build tiny dams and reservoirs in northern Ghana are a part of a larger plan to boost agricultural output and foster sustainable development (Acheampong *et al.*, 2018).

2.2 Geophysical Characteristics and Soil Analysis for Dam Construction

Geophysical characteristics and soil analysis are essential components for site investigation for construction projects. Geophysical surveys such as seismic surveys, resistivity measurements and ground penetrating radar, provide valuable information about subsurface conditions without the need for extensive excavation (Dalan and Bevan, 2002). In the evaluation of small dams and reservoirs, a critical aspect that demands thorough examination is the classification of the underlying soil types and their hydraulic conductivity properties (Ghanbarian and Yokeley, 2021). Understanding soil classes is crucial as it directly influences the stability and integrity of the dam structure. According to Baiamonte *et al*. (2017), different soil types have varying compaction, cohesion, and permeability levels, which can impact the dam's ability to hold water effectively. Moreover, assessing hydraulic conductivity is vital to determine how quickly water can pass through the soil (García-Gutiérrez *et al.*, 2018), which is essential in preventing seepage and potential dam failure (Juliá *et al.*, 2021). A comprehensive understanding of these soil-related factors is indispensable for successfully designing, constructing, and maintaining hydraulic structures such as: small dams and reservoirs, to ensure their long-term functionality and safety.

2.2.2 Geotechnical Engineering and Hydraulic Conductivity for Dam Construction

2.2.2.1 Geotechnical Engineering

Geotechnical engineering is essential for small dam projects to ensure the overall safety, stability, and functionality of the structure (Roy and Bhalla, 2019). It involves a comprehensive understanding of the geological and geotechnical conditions at the site, allowing engineers to make informed decisions throughout the planning, design, and construction phases of the project. Geotechnical analysis involves the study of soil and its properties to assess its suitability for construction project (Widomski *et al*., 2015). Geotechnical engineering is crucial in the field of civil engineering and construction of various civil engineering projects, such as buildings, roads, bridges, dams, and more (Steiakakis *et al*., 2012).

The use of the information obtained from soil particle analysis and hydraulic conductivity testing to make informed decisions about construction methods and foundation designs, which are essential for ensuring the stability and safety of structures and preventing issues like soil erosion, foundation settlement, and seepage (Ocheli *et al*., 2021). Soil particle analysis and hydraulic conductivity are essential aspects of geotechnical engineering.

2.2.2.2. Soil Analysis

Soil is composed of various mineral and organic particles, and the distribution of these particles determines the soil's characteristics (Ghanbarian and Yokeley, 2021). Soil particle analysis involves identifying and quantifying the size and distribution of these particles (Roy and Bhalla, 2019). However, the rate of distribution of soils in landscape fluctuations varies from location to location. Grain size distribution involves classifying soil particles into different size fractions, such as clay, silt, sand, and gravel. The distribution of these fractions is often presented in a soil texture triangle or a particle size distribution curve (Roy and Bhalla, 2019). Soils are classified based on their particle size distribution, mineral composition, and plasticity. Common soil classification systems include the Unified Soil Classification System (USCS) and the AASHTO classification system (Rozhko, 2007). There are also other tests such as Atterberg Limits; Hydraulic Conductivity. Atterberg Limits are tests that determine the water content at which soil changes from a solid to a plastic or liquid state. The key Atterberg limits include the liquid limit, plastic limit, and shrinkage limit.

2.2.2.3. Hydraulic Conductivity

Hydraulic conductivity is a measure or a property of porous media that describes the ability of a material to transmit fluids, typically water (Widomski *et al.*, 2015; Ghanbarian and Yokeley, 2021). It is a fundamental parameter in hydrogeology and soil mechanics, playing a crucial role in various environmental and engineering applications. Hydraulic conductivity is denoted by the symbol "K" and is expressed in terms of velocity or flow rate per unit gradient of hydraulic head (Chapuis and Aubertin, 2003; Steiakakis *et al*., 2012).

Hydraulic conductivity depends on the soil's porosity, particle size distribution, and compaction. It is a critical parameter in geotechnical engineering, as it affects drainage, seepage, and foundation design. The hydraulic conductivity as the main parameter for modelling the water flow through the soil and determination of seepage losses is conducted through the saturated hydraulic conductivity of a soil (Steiakakis *et al*., 2012). According to Kirkham (2005), there are different methods for measuring hydraulic conductivity namely:

i. Constant Head Permeability Test: This test involves applying a constant head of water to a soil specimen and measuring the rate of flow through it. Darcy's law is commonly used to calculate hydraulic conductivity.

ii. Falling Head Permeability Test: In this test, water level within a permeable soil specimen falls over time, and the rate of water level change is used to calculate hydraulic conductivity.

iii. Laboratory and Field Test: Various laboratory and field tests are used to estimate hydraulic conductivity. These include the use of boreholes, slug tests, and infiltration tests.

Moreover, according to Chapuis and Aubertin (2003), hydraulic conductivity can be calculated using empirical relationship, capillary models, statistical models and hydraulic radius theories.

2.3 Characterization of Catchment Factors Influencing Runoff

2.3.1 Effects of Landuse and Landcover Change on Runoff

Landuse and landcover (LULC) is important for planning and management activities of any watershed. However, there still have confusion between land use and land cover though there are differences. According to Yang *et al*. (2019), there is a difference between land use and land cover whereby for land cover, it is understood to mean the physical environment. Landcover refers to the physical and biophysical attributes of the Earth's surface, encompassing elements like soil, water, vegetation, and various other land-related features. This includes both natural aspects and human-made components like settlements and road networks. Also, each type of land cover influences hydrological conductivities, and peak discharge (Mireille *et al*., 2019; Umukiza *et al*., 2021).

Furthermore, the study conducted by Ogban *et al.* (2015) in Akwa Ibom State, South-Eastern Nigeria found that oil palm plantation increases infiltration more than fallow and continuously cultivated farmland. Therefore, all activities taking place on land describe land use. Such activities include growing food, cutting trees, or building cities. On the other hand, the land cover represents the physical characteristics of the land surface, including grain crops, trees, or concrete (Brown *et al*., 2014). Due to the growth of society and the economy, various human activities have profoundly influenced the hydrological cycle and water resources management (Umukiza *et al*., 2021).

The phenomenon of LULC change is a significant indicator of such impacts. LULC changes have important impacts on hydrological processes, the economy, and the ecology of watersheds (Umukiza *et al*., 2022). Broadly stated, the effects of LULC changes on soil physical properties are known, especially when considering the conversion of forests to pastures or croplands. Although the impacts of LULC changes on watershed hydrology are known, variability in local factors and their influence on the hydrograph make it difficult to draw generalisations (Yosef and Asmamaw, 2015).

LULC classes represent different categories or types of landcover and the human activities associated with them. The specific classes may vary depending on the classification system used (Han *et al*., 2009; Olokeogun *et al*., 2014; Apollonio *et al*., 2016; Habete and Ferreira, 2016; Owar Othow *et al*., 2017; Recanatesi and Petroselli, 2020), but some common categories include:

i. Forest: Areas covered by trees and dense vegetation.
ii. Grassland: Open areas dominated by grasses and non-woody vegetation.
iii. Cropland: Landused for cultivating crops and agricultural activities.
iv. Urban: Developed areas with buildings, infrastructure, and human settlements.
v. Water Bodies: Includes lakes, rivers, reservoirs, and other water features.
vi. Wetlands: Areas with marshes, swamps, or other waterlogged conditions.
vii. Bare Land: Unvegetated and non-built-up areas, like deserts or barren lands.
viii. Mixed Land: Areas with a combination of various landuses and covers.
ix. Rangeland: Open areas used for grazing livestock and natural vegetation.
x. Agricultural Land: A broader category encompassing croplands, orchards, vineyards, etc.
xi. Open Space: Unoccupied or undeveloped areas within urban environments.
xii. Built-up Area: Regions with extensive infrastructure and human settlements.

These are some examples, and different classification schemes might have more or fewer classes depending on the level of detail required for specific applications. The classification of land use and land cover is crucial for various environmental, ecological, and urban planning studies (Guzha *et al*., 2018; Bhatti *et al*., 2019).

Catchment and Basin: A Catchment is a portion of the earth's surface that collects runoff and concentrates it at its furthest downstream point, referred to as the catchment outlet. The terms watershed and basin are commonly used to refer to catchments (www.about civil.org). Generally, the watershed is used to describe a small catchment (stream watershed), whereas a basin is reserved for large catchments (river basins).

2.3.2 Factors Influencing Runoff

The importance of hydrology consists in assessment, estimation, development, utilisation and management of water resources of any region. The accurate estimation of runoff is not only a useful task in physiography but also important for proper watershed management (Gajbhiye and Ashish, 2014). There are different factors affecting runoff from different categories such as:

i. Meteorological Factors:

   Type of precipitation (rain, snow, sleet, etc.); Rainfall intensity; Rainfall amount; Rainfall duration; Distribution of rainfall over the drainage basin; Direction of storm movement; Precipitation that occurred earlier and resulting soil moisture. Other meteorological and climatic conditions affect evapotranspiration, such as temperature, wind, relative humidity, and season

ii. Catchment Physical Characteristics Affecting Runoff:

   The physical characteristics that affect runoff include; land use, vegetation, soil type, drainage area, basin shape, elevation, topography, especially the slope of the land, drainage network patterns, ponds, lakes, reservoirs, sinks, etc. These characteristics are also found in the study by Cabral, (2021), some criteria are summarised in Table 2.7.

Table 2.7: Summary of Characteristics and Rationale Influencing Location of Dams

Characteristics	Rationale
Elevation	Elevation influences the location of dams/reservoirs since it affects water accumulation and movement. Lower elevations are preferable to higher elevations
Slope	Higher slopes have a higher risk of landslides and put more pressure on the foundation of the infrastructure. The higher the slope in the construction site the lower the potential for storing water and sediment, meaning that lower slopes have more storage volumes.
Lineaments	The higher the slope in the construction site the lower the potential for storing water and sediment, meaning that lower slopes have more storage volumes. Areas near lineaments are potential weakness zones for installing infrastructure
Distance to villages	The closer dams/reservoirs are to populations the lower will be the costs of water transportation
Landuse /landcover	Areas proposed for constructing dams/reservoirs should be in or close to agricultural land to reduce the distances of farmers searching for water and the cost of transferring water from the reservoir to agricultural land. In addition, the primary objective of the dam/reservoir proposed for the study area is to assist crop field irrigation
Soil type	The type of soil is influenced by its texture, structure and depth which determine soil infiltration rates and the amount of runoff.
Stream density	Provides the necessary runoff water for dam/reservoir function, since different drainage network levels indicate different amounts of runoff water when the streams are upper stream tributaries and main downstream streams. Areas with high drainage density are ranked higher in suitability compared to areas of low drainage

Source: Bhatti *et al.* (2023).

Furthermore, human activities can affect runoff. The intensification, density, location and patterns of urbanised areas may subsequently affect rainfall-runoff relations (Ohana-Levi *et al*., 2018). As more people inhabit the earth and as more development of urbanisation occurs, more of the natural landscape is replaced by impervious surfaces, such as roads, houses, parking lots, and buildings (Ohana-Levi *et al*., 2018; Umukiza *et al*., 2022). These activities reduce the infiltration of water into the ground and accelerate runoff to ditches and streams. In addition to increasing imperviousness, removal of vegetation and soil, grading the land surface, and constructing drainage networks increase runoff volumes and shorten runoff time into streams from rainfall (Ohana *et al*., 2013; Dawod and Mirza, 2014).

However, drought and flood are drastically and interchangeably affecting some regions due to mismanagement of runoff (Ngigi *et al*., 2005). Therefore, rain water harvesting through dam construction, especially for supplemental irrigation of the Kitchen Garden, and sometimes for domestic and livestock is a very important capital (Mati & Bock, 2006). Currently, there is software used to determine, and observe accurately the variability of runoff through spatial changes in land use and land cover changes, such as Geographic Information System (GIS) and Remote Sensing (RS) (Santillan *et al*., 2011). Advancing technology has encouraged much research into the best ways to optimise water catchment and distribution in Ghana, but little documented evidence exists on the application of GIS and RS in selecting suitable locations for water harvesting.

2.3.3 Application of Geographic Information System and Remote Sensing in Detection of Landuse and Landcover

Geographic Information System (GIS) and Remote Sensing (RS) are powerful tools used in the detection and analysis of LULC changes (Hundecha and Bárdossy, 2004; Mustafa *et al*., 2012). Geographic information system (GIS) is a tool for gathering, storing, and analysing geographical and non-spatial data (Mutiso, 2019). One of the primary applications of GIS and RS is change detection by comparing images taken at different times, analysts can detect and quantify changes in land use and land cover. This is crucial in monitoring urban expansion, deforestation, agricultural changes, natural disasters, and environmental changes over time.

RS involves the collection of information about an object without direct physical contact. This is often done through satellites or aircraft equipped with sensors where these sensors capture data in the form of images that are then analysed to understand land cover and land use patterns (Aher *et al.*, 2017). Different types of sensors, such as optical, thermal, and radar, capture various information about the Earth's surface. Once the data is obtained through remote sensing, it undergoes various processes such as preprocessing, image enhancement, and classification. Preprocessing involves cleaning and enhancing the image to remove noise or distortions (Wijesinghe, 2022). Image enhancement techniques improve the visual quality of the images, making features more distinguishable (Aher *et al*., 2017). Classification techniques group pixels in an image into different land cover or land use classes, allowing for the identification of areas (Wijesinghe, 2022) like forests, water bodies, urban areas, agricultural land, etc.

GIS software is used to integrate, manage, and visualise the spatial data derived from remote sensing. It allows for the creation of detailed maps and the overlay of different layers of information, enabling a comprehensive understanding of the land. GIS enables the creation of thematic maps that display specific land cover and land use types, providing insights into the spatial distribution and changes over time (Wijesinghe, 2022).

Information derived from GIS and remote sensing analyses assists in making informed decisions for land management, urban planning, resource allocation, conservation efforts, disaster management, and policy-making. GIS and remote sensing aid in efficient resource management by identifying suitable areas for water resources, agriculture, forestry, urban development, and conservation, contributing to sustainable land use practices. Recently, GIS and remote sensing (RS) were used in the Study conducted by Hassan *et al*. (2021) and Umukiza *et al*. (2021) in Narok town, Kenya, for potential recharge zone and landuse/landcover (LULC) respectively. Change detection analysis is defined as the estimation of the distinct data framework and thematic change information that can lead to more tangible underlying process involved in upbringing of land use land cover changes (Mustafa *et al*., 2012).

Integration of Remote Sensing and GIS plays a crucial role in mapping, monitoring, and analysing LULC, making it an indispensable tool for land management, environmental conservation, and sustainable development planning (Olokeogun *et al*., 2014). From the aforementioned information, the combined strengths of remote sensing in data acquisition and GIS in data integration and analysis, professionals can gain valuable insights into LULC changes, which are crucial for effective environmental management and planning.

2.3.4 Determination of Hydrological Parameters Affecting Runoff

In this part, watershed characteristics will be defined as travel time, lag, and time of concentration. These watershed characteristics influence the shape and peak of the runoff hydrograph.

2.3.4.1 Time of Concentration

The time of concentration (Tc) is an important metric in determining peak runoff 'Q' (Grimaldi & Petroselli, 2014). When the catchment and drainage basin sizes have been calculated, the next step in determining discharge is to calculate the time of concentration (Descroix *et al*., 2009). Each watershed has a distinct time of concentration based on its size, shape, slope, and ground cover. Time of concentration is a measure of the time required for runoff to flow from the higher end of the watershed to the lower end, or the site of analysis. Despite the large use of the time of concentration, according to Grimaldi *et al*. (2012), a unique working definition is currently not available. Nevertheless, several numbers of "computational" and "theoretical" definitions are methodologically proposed and practically adopted in the literature.

Therefore, when both rainfall and runoff observations are available, six (6) computational definitions for the time of concentration were reported by Grimaldi *et al*. (2012), as follows:

(i) Time from the end of rainfall excess to the inflection point on the total storm hydrograph;

(ii) Time from the centre of mass of rainfall excess to the centre of mass of direct runoff;

(iii) Time from the maximum rainfall intensity to the time of the peak discharge;

(iv) Time from the centre of mass of rainfall excess to the time of the peak of direct runoff;

(v) Time from the centre of mass of rainfall excess to the time of the peak of total runoff; and

(vi) The time from the start of the total runoff to the time of the peak discharge of the total runoff.

The above definitions are considered to be computational. According to Piscopia *et al*. (2015), the theoretical six (6) computational definitions are the most employed, including: The time of concentration (Tc) is the time it takes for runoff to flow from the watershed's hydraulically most remote point to the outlet. The hydraulically most distant location is the one with the longest trip time to the watershed outflow, not necessarily the point with the greatest flow distance to the exit (Grimaldi *et al*., 2012). The period of concentration can be calculated using a variety of approaches and is often exclusively used to surface runoff. In hydrograph analysis, the period of concentration is the time between the end of excess rainfall and the point on the descending limb of the dimensionless unit hydrograph.

The time of concentration is generally calculated by using empirical formulas at the basin scale. Giandotti's formula (Giandotti 1934) is extensively used in Italy. While the Kirpich (Kirpich 1940) and NRCS (National Research Conservation Service; Mockus 1961 unpublished report, Folmar *et al.* 2007) formulas are widely adopted in the USA (Grimaldi *et al.*, 2012). However, the various formulas to determine the time of concentration can be used in the model to check the influence of time of concentration on the peak discharge.

2.3.4.2 Lag Time

Lag time is the delay between the times of runoff from a rainfall event over a watershed that begins until runoff reaches its maximum peak. It is calculated according to the following formula:

$$L = \frac{\sum(a_x\, T_{tx}\, Q_X)}{\sum(a_x\, Q_X)}$$ Eqn 2.1

Where:

L - Lag (h),

Axe - Increment of watershed area (m^2),

Qx - Runoff in inches from area axe,

Tc - Travel time from the centroid of the axe to the point of reference (h),

A - Total area of the watershed above the point of reference (m^2), and

Qa - Total runoff (m^3/s).

The NRCS (formerly known as SCS) lag formula from 1973 is commonly used in hydrology to estimate the time it takes for runoff to travel from a point within a watershed to the outlet or designated location downstream (Grimaldi *et al.*, 2012). This formula is often referred to as the SCS (Soil Conservation Service) or NRCS (Natural Resources Conservation Service) lag formula. The formula to calculate travel time (Tc) (Barati, 2011) using the NRCS 1973 lag formula (Equation 2.2):

$$Tc = 2.27\times 10^{-4} L^{0.8} \left(\frac{1000}{CN} - 9\right) S^{-0.5}$$ Eqn 2.2

Where:

L – Watershed length (m),

S – Watershed slope (%),

Tc – Concentration time (hour), and

CN - Curve number.

Here, watershed length can be estimated from relationship (NRCS 1998) whereby:

$$L = 1{,}740A^{0.6} \quad \text{Eqn 2.3}$$

Where:

A - Upstream drainage area (km^2).

The NRCS 1973 lag formula provides a simplified estimate of travel time and is suitable for preliminary hydrological assessments. Actual conditions in the watershed may introduce variability, so it's essential to consider other factors and use more complex hydrological models for detailed studies. Additionally, local guidelines and standards may have variations or updates to the NRCS 1973 formula, so it's advisable to check with your local water resources or engineering authorities for any specific recommendations or modifications applicable to your region.

2.3.4.2 Relationship Between Lag and Time of Concentration

Various researchers such as Mockus (1957) and Simas (1996) found that for average natural watershed conditions and approximately uniform distribution of runoff:

$$L = 0.6T_c \quad \text{Eqn 2.4}$$

Where:

L - lag (hr), and

Tc - Time of concentration (hr).

According to the same literature, when runoff is not uniformly distributed, the watershed can be subdivided into areas with a nearly uniform flow to apply Equation 2.3 to each of the subareas.

2.3.4.4 Curve Number

The curve number CN is a dimensionless parameter indicating the runoff response characteristics of the drainage basin (Mishra and Singh, 2006; Grimaldi *et al*., 2013; Ara and Zakwan, 2018). It utilises geological information to assign a unique Curve Number (CN) coefficient value for each area depending on soil use type. According to the original formulation, the CN value ranges theoretically between 0-100 (Ara and Zakwan, 2018). Where zero (0) means that all precipitation infiltrates and does not lead to the formation of surface runoff, while 100 means that infiltration is occurring, due to extreme soil impermeabilization, and all the precipitation is transformed into runoff. That parameter serves to be used to estimate the surface runoff depth and the peak discharge (Al-Ghamdi, *et al.*, 2012). The Soil Conservation Service (SCS) method was also used in many engineering design and runoff control projects (Xianzhao and Jiazhu, 2008; Al-Jabari *et al.*, 2009; Adebayo *et al.*, 2009; Elaji, 2010; Masoud, 2011). From the same literature, the basic formulas of the SCS-CN approach are presented in equations 2.5 to 2.10 (Sitterson *et al.*, 2018; Ara and Zakawan 2018).

$$\frac{P_e}{P-I_a} = \frac{F}{S} \qquad \text{Eqn 2.5}$$

Water balance Equation can be written as:

$$F = P - I_a - P_e \qquad \text{Eqn 2.6}$$

By combining Equations 2.5 and 2.6 yields

$$P_e = \frac{(P-I_a)^2}{P-I_a+S} \qquad \text{Eqn 2.7}$$

To eliminate the estimation of two variables I_a and S the Equation 2.8 relationship was found by Soil Conservation Service (1972):

$$I_a = 0.2s \qquad \text{Eqn 2.8}$$

Combining Equations 2. 7 and 2.8:

$$P_e = \frac{(P-0.2S)^2}{(P+0.8S)} \quad \text{for } P > 0.2s \qquad \text{Eqn 2.9}$$

$$S = \frac{1000}{CN} - 10 \qquad \text{Eqn 2.10}$$

Where:

P_e - Runoff (mm),

P - Rainfall (mm),

S - Potential maximum retention (mm),

F- actual retention (mm)

I_a - Initial abstraction (mm), and

CN - Runoff Curve Number value.

Where the look up table containing values of CN is presented in several hydraulic works in literature (Al-Ghamdi *et al.*, 2012).

In brief, the CN method can be described as a lumped (in space and in time) approach that defines the total surface runoff of a rainfall event. Its popularity is rooted in its convenience, its simplicity, and its authoritative origin, and consequently, it is applied in a large number of research papers.

2.3.4.5 Hydrologic Soil Groups

Hydrologic soil groups (HSGS) are a fundamental component of the USDA CN method for runoff estimation (Hengl *et al.*, 2017; Data, 2020). The data relating to HSGs are made available in a spatial resolution suitable for regional to global scale modelling applications. For instance, the Soil Conservation Service (SCS) classified more than 4000 soils into four hydrologic soil groups (HSGs) (Kowalik and Walega, 2015). Hydrologic Soil Groups, are a system of categorization used in the fields of soil science and hydrology to classify soils according to their hydrological characteristics. HSGs are useful in determining how various soils interact with water, including how quickly water infiltrates, how much runoff is produced, and how suitable they are for various land uses. Each of the four (4) categories in the HSG system A, B, C, and D represents distinct soil characteristics related to water infiltration and runoff where classes A, B, C and D correspond to soil with low, moderately low, moderately low, moderately high and high runoff potential respectively (Ross *et al*., 2018).

Group A: soils have minimal potential for runoff and high rates of infiltration. They often consist of gravels, coarse-textured soils, or well-structured sandy soils. These soils are good for applications where rapid infiltration is sought, including groundwater recharge zones or stormwater management, because water tends to permeate them quickly.

Group B: The infiltration rates and runoff possibilities of these soils are both moderately high. They consist of soils having a fair number of fine-textured constituents, such as silt and loam. They do permit some infiltration, but under some circumstances, they can also cause runoff. These soils are frequently found in agricultural areas and, depending on regional conditions, may be appropriate for a range of land uses.

Group C: Soils in this group have increased runoff potential and relatively lower infiltration rates. They frequently have high concentrations of fine-textured substances, such as clay or silt, which prevent water infiltration. This group is less appropriate for applications needing rapid infiltration because it is more prone to runoff and can contribute to surface water flows.

Group D: Soils in this group have very low infiltration rates and high runoff potential. They are typically saturated or nearly saturated, with minimal ability to absorb additional water. These soils are often associated with wetlands, swamps, and poorly drained areas, where water remains near the surface.

Moreover, HSGs were described with wide samples according to the United States Department of Agriculture -Natural Resources Conservation Services (USDA-NRCS).

The description of each hydrologic soil group vis a vis to runoff is reported in Table 2.8 as follows:

Table 2.8: Classification Scheme Used to Develop Hydrologic Soil Group According to SCS

HSGs	Soil Texture class	Description Rate	Runoff Potential
A	Sand	More than 90 % sand and less than 10 % sand	Low runoff Potential
B	Sandy loamy sand	50-90 % sand and 10-20 % clay	Moderately low runoff potential
C	Clay loam, silt clay loam, Sand clay loam, loam, silt	Less than 50 % sand and 20 - 40 % clay	Moderately low runoff potential
D	Clay, Silty clay, sandy clay	Less than 40 % sand and more than 40 % clay	High runoff potential unless drained

Source: USDA-NRCS (1985)

Hydrologic Soil Groups are essential for various applications, including landuse planning, stormwater management, flood risk assessment, and the design of drainage systems (El-Hames, 2012; Bisantino *et al*., 2015). According to Ara and Zakwan (2018), categorising soils into these groups, hydrologists and land planners can make informed decisions about how to manage water resources, prevent erosion, and reduce the risk of flooding in specific areas. Additionally, they help determine suitable construction practices and land development standards to minimise environmental impacts related to soil and water interactions.

However, regardless of texture, wet soils have high runoff potential due to the potential presence of a groundwater table within 60 cm of the surface. In addition to CN, Antecedent Moisture Condition (AMC) is preceding moisture present in the soil before the storm event and obtained based on five days of antecedent rainfall before the rainfall event under consideration during a particular dormant or growing season. The AMC is classified into three (3) classes known as I, II, III corresponding to dry season, moderate season and very wet season.

2.3.5 Effects of Modification of Catchment Physical Characteristics on Runoff

Modifying catchment physical characteristics can have significant effects on runoff patterns and hydrology. Catchment physical characteristics refer to the natural features of a watershed, such as its topography, land use, soil type, vegetation cover, and geology (Siriwardena *et al.*, 2006). Altering these characteristics can be intentional, as in land development projects, or unintentional, as in the case of environmental changes due to climate variability or natural disasters (Menzel and Bürger, 2002). Runoff patterns and hydrology can significantly be impacted by changing the physical characteristics of a catchment, such as changing land use, vegetation cover, soil conditions, and surface infrastructure (Han *et al*., 2009; Apollonio *et al*., 2016; Mwangi *et al*., 2017; Recanatesi and Petroselli, 2020). These alterations may affect local water supplies, water quality, and the likelihood of flooding by increasing or decreasing the volume and velocity of runoff. Altering catchment characteristics such as replacing natural vegetation with impervious surfaces (e.g., buildings, roads, parking lots) can increase runoff volume (Siriwardena *et al*., 2006).

Impervious surfaces prevent infiltration, leading to greater surface runoff during rainfall events. The modification of physical characteristics in the catchment known as landuse or landcover change or urbanisation among others results in the waterproofing of soils, and as consequences increase runoff, the peak flows, and the flow volumes accordingly. Changes in the catchment's topography, such as the construction of roads or the removal of vegetation, can lead to accelerated runoff. Water flows more quickly over impermeable surfaces, increasing the risk of erosion and flash flooding. Historically, the study conducted by Desbordes *et al*. (1975) stated that the relative complexity of physical processes translating the transformation of rainfall into runoff flow, at the outlet of a small urban catchment area equipped with a drainage network, and above all the difficulties of evaluating the hydraulic parameters involved in this transformation, have led researchers to model conceptual in nature, derived from systems analysis. Sustainable land management and water resource planning should aim to balance human needs with the preservation and protection of natural ecosystems to minimise adverse effects on runoff and hydrology. Additionally, modelling and monitoring tools can help assess and mitigate the impacts of such modifications on catchment hydrology.

2.3.6 Estimation of Runoff Depth and Volume in Catchments of Reservoirs

A catchment is the area covering all the land that contributes runoff to a common point such as the reservoir of a dam. Estimating runoff depth and volume in catchments of reservoirs is a crucial step in reservoir management and water resource planning (Roba and Kassa, 2020). This estimation involves assessing how much water will flow into the reservoir from the surrounding catchment area. Gathering necessary data about the catchment area, including: Precipitation data (historical rainfall records); Hydrological data (streamflow records, groundwater levels); Geographic information (topography, land use, soil types) and Climate data (temperature, evaporation rates) are the most important to estimate rainfall runoff.

Furthermore, Runoff Models (RM) can be used for rainfall runoff simulation. Once the model is calibrated and validated it can be used to estimate runoff depth and volume for various scenarios. This may involve inputting different rainfall scenarios or land use changes to predict runoff under different conditions. In addition, Simplified Empirical Models (SEM) can use historical rainfall-runoff relationships, such as the Rational Method, or Curve Number (CN) method to estimate runoff depth based on rainfall intensity and catchment characteristics.

CN approach was developed by Soil Conservation Service (SCS) in the 1950s and was subsequently updated by the National Resources Conservation Service (NRCS). Currently, this approach is widely used in rainfall-runoff models (e.g. HEC-HMS, EPA-SWMM, SWAT, GLEAMS). Moreover, by assuming only one parameter (CN) that is well classified concerning soil properties and antecedent moisture conditions, researchers can easily estimate infiltration and surface runoff to accurately design water storage, as it gives idea of the inflows to the reservoirs (Mutiso, 2019).

2.4 Assessment of Dams and Reservoirs for Suitable Rainfall Runoff Harvesting

2.4.1 Selection of Suitable Dam Location

The selection of a suitable dam location is a crucial and complex process that involves careful consideration of various geological, hydrological, environmental, and engineering factors (Dorfeshan *et al*., 2014). The choice of a dam site can be based on a number of qualitative and quantitative factors, including geology, soil type, and altitude. Moreover, the selection of suitable dam location involves multidisciplinary studies such as engineers, geologists, hydrologists, environmental experts, and social scientists (Jeon *et al*., 2009; Bekoe *et al*., 2021; Kim and Kang, 2021). Table 2.9 summarises the key consideration for choosing suitable dam location.

Table 2.9: Key Factors to Consider when Choosing a Suitable Dam Location

Factor	Description
Hydrological and Hydraulic Factors	Assessment of the river's flow characteristics, including its peak flows and low-flow conditions is required. This information is essential for determining the dam's capacity and spillway design. Conduct hydrological studies to analyze rainfall patterns, runoff, and flood frequencies in the catchment area.
Topographical and Geographic Factors	Analyze the topographical features of the site, including slope, elevation, and drainage patterns. The topography will influence dam design and reservoir capacity.
Environmental and Ecological Factors	Assess the potential impact of the dam on local ecosystems, including aquatic habitats, wildlife, and vegetation. Implement mitigation measures to minimise ecological disruption. Consider the water quality of the river and its tributaries, as well as any potential changes due to dam construction. Implement measures to maintain or improve water quality.
Social and Cultural Factors	Evaluate the impact on local communities and assess the need for resettlement or compensation for affected residents. Identify and protect any cultural or historical sites in the dam's vicinity.
Economic and Financial Considerations	Conduct a thorough cost-benefit analysis to determine the economic feasibility of the dam project. Identifying potential funding sources, such as government grants, loans, or private investors can help to decide on the type of dam and its location.
Public Engagement	This is engaging local communities, stakeholders, and experts to gather input, address concerns, and build support for the project.

Source: Kim and Kang (2021)

The selection of suitable sites for dam construction should adhere to best practices and guidelines for dam construction and safety. Ultimately, the goal is to choose a location that minimizes environmental and social impacts while meeting the project's technical and economic objectives. A key water management approach for resolving floods and droughts is the construction of dams in suitable locations. The study conducted in Great Zab, Iraq, by Noori *et al*. (2019), determined suitable dam site selection locations for water management using remote sensing, geographic information systems (GIS), and multi-criteria decision-making methodologies. Additionally, the proposed site suitability approach was assessed by contrast with the established analytic hierarchy process (AHP). AHP has been employed in a wide variety of applications in different fields, including site suitability (Noori *et al.*, 2019; Shao *et al.*, 2020).

Typically, the optimal location for a dam is where the maximum amount of water can be stored using the most compact and cost-effective embankment. Additional factors in the selection process encompass a stable foundation, the presence of construction resources, and the positioning of the dam concerning the region intended to receive the water supply. Search for locations where the valley constricts. In the upstream direction from this narrower segment, the valley ought to broaden gradually, ensuring a substantial storage capability (Staudinger *et al.*, 2017). The valley where towering mountains on either side drop rather sharply into the valley is typically the most ideal location for the dam. The storage space should be as big and lengthy as feasible, and the wall should ideally be constructed where the valley narrows.

Frequently, prime spots are situated slightly downstream from the point where two rivers converged, as illustrated in the Figure 2.5:

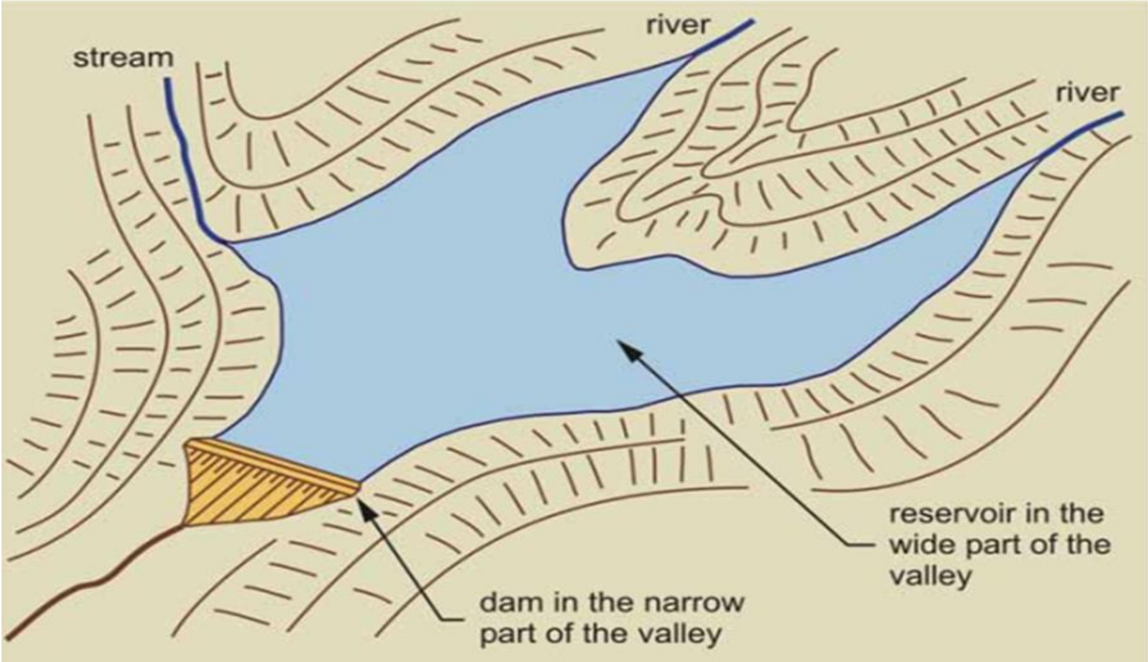


Figure 2.5: Suitable Area for Dam Location Based on Streams Confluences

Source: Cabral *et al*. (2021)

According to Adham *et al.* (2016) and Doulabian *et al*. (2021), rainwater harvesting (RWH) can be considered as one of the cost-effective and environmentally-friendly water conservation methods, especially in ASALs. Nevertheless, due to the inherent uncertainty of input data and subjectivity involved in the selection of influential parameters, the identification of RWH potential areas is a challenging procedure (Doulabian *et al.*, 2021). In some cases, however, runoff is collected from catchments as large as 200 ha. The runoff is conveyed through overland, rill, gully or channel flow and either diverted onto cultivated fields (where water is stored in the soil) or into specifically designed storage facilities. RWH is usually classified into two types: harvesting for agriculture (irrigation) needs and harvesting for domestic and other needs (N Ka Patel *et al.*, 2020). The identification of the potential locations for conventional RWH techniques, and pond and pan techniques are the most proper options, covering high-potential areas of RWH more effectively than other techniques (Doulabian *et al*., 2021). To make water harvesting facilities for irrigation systems efficient and sustainably, several hurdles need to be overcome. An elevation against the intended irrigation area; Vegetation cover and proximity to farms topography vs land. A balancing act between fair access to water, sustainable water and land use, agricultural development and poverty reduction through higher generation of food and cash crops needs to be accomplished (Mutiso, 2019).

2.4.2 Assessment of Surface Runoff for Rainwater Harvesting

Assessing dams and reservoirs for suitable runoff harvesting involves evaluating their capacity to capture and store rainwater effectively. This assessment is essential for ensuring the success of rainwater harvesting projects. Surface runoff harvesting is a technique used to collect and store rainwater that flows off the surface of the land during rainfall events. It involves capturing and directing rainwater runoff into storage systems. The storage of rainwater on the surface is a traditional technique and structures used are small dams such as check dams, ponds, tanks etc (Winnaar *et al*., 2007).

Research on rainwater harvesting in the Coastal Savannah regions of Ghana recommended that the government intensifies its programmes and activities, including awareness campaigns and training of artisans at the local level to create renewed interest in the activity (Andoh *et al*., 2018). It was also recommended that the available water resources, especially the major rivers be harnessed for irrigation. The research again recommended that the manufacturing industry in Ghana takes up the challenge to produce RWH components for sale to the public.

The process of surface runoff rainwater harvesting starts with the identification and collection of runoff areas that contribute to the flow of rainwater. Check dams are constructed to impound the surface water in them and excess water is allowed to flow over the dam (Singh, 2016; Roba and Kassa, 2020). There is also another way of collecting surface runoff rainwater harvesting which can be done by storage reservoir to store the great amount of rainwater from the precipitation, but on the other side it is also very expensive or we can say most expensive amongst all of the methods or ways which can be utilized. It requires a careful design which should be strong enough to sustain such an amount of loads and it should also be watertight and free from contamination. Surface runoff rainwater harvesting is therefore a practical and sustainable approach to capturing and utilizing rainwater. By collecting runoff water and storing it for future use, this method contributes to water conservation, reduces strain on water resources and enhances overall water management.

2.4.3 Criteria for Selecting Suitable Locations for Water Storage Structure

The selection of a site is a very essential exercise in the construction of a reservoir or dam. For the economy, the length of the dam should be as small as possible and should store the maximum volume of water. Best location of water storage structures, where the valley allows for building a straight embankment dam, the foundation should be watertight from seepage (Azam and Li, 2010; Hempen, 2015) and where construction will be simple and a stable structure can be guaranteed. The study conducted by Omolabi and Fagbohun (2019) in the Sokoto-Rima Basin, Nigeria, took into account eight (8) factors such as: landuse landcover, soil, geology, slope, drainage density, lineament density, distance to drainage and precipitation.

However, the classification of factors must be assigned based on the preference values and knowledge of the study area. Moreover, the integration of weighted overlay analysis using factors weights computed from analytical hierarchy processes are required. The storage structure must fill with runoff or store enough water to fill the structure between runoff occurrences. The reservoir must have enough depth and volume to last through prolonged droughts. A topographical survey is typically conducted to evaluate gradient, storage structure breadth and height, calculate reservoir volume, estimate quantities, produce relevant licensing documents, and offer construction specifics (Dorfeshan *et al*., 2014). The site should be located in a valley with a high depth-to-surface area ratio to minimise evaporation losses. Where steep slopes border, the valley is a straightforward approach to identify such a site. For example, to increase capacity, a dam can be built directly below the confluence of two streams. To eliminate cracks, loose soil, or other flaws that could cause seepage or failure, thorough site studies are required, particularly for the structure's foundation. The foundation must be solid impermeable rock with no soil pockets or fracture lines, and rock surfaces should not be broken or split to reduce leakage losses.

2.4.4 Physical Factors Contributing to Dam Location

Various physical factors involved in selection of dam location to ensure safety, stability, and efficiency of the dam. However, these factors can vary depending on the specific project and its environmental context. Based on common physical factors, different researchers (Acheampong *et al*., 2014; Dorfeshan *et al*., 2014; Chezgi, 2019; Omolabi and Fagbohun, 2019; Index, 2021) elaborate several factors such as:

a. Topography: Having identified the boundaries and altitude variations in order to acquire precise data about the topographical conditions and determining the region's slope layer, the Digital Elevation Model (DEM) layer of the region. A suitable topography should provide a natural basin for water storage and minimise the amount of excavation and construction required.

b. Waterways: In locating dams, the stream tributaries collecting the maximum runoff are key parameters to have a direct correlation with the waterway category.

c. Fault boundary: The choice of suitable sites for the construction of dams is influenced by faults as well. If there is a fault boundary, structural instability develops in the dam's base and abutment, which causes water to leak from the reservoir.

d. Distance from consumption site: Prior to dam construction, it is crucial to ascertain the distance between the dam and the point of consumption site.

Depending on the goal of the dam's construction, the water stored in the reservoir may be utilized for drinking, irrigating gardens and farmlands, and providing water to cattle. Moreover, convenient access to the dam construction site can significantly raise the cost of the project. Therefore, although it is relatively less important than distance from consuming sites, this parameter should be considered as one of the economic variables contributing to any dam construction project.

2.4.5 GIS Analysis and Generation of Suitability Maps

The GIS database is a helping tool for identifying potential sites for RWH. It was developed using both vector and raster databases such as ArcGIS. Literature indicated that GIS is a suitable model developed using Model Builder in ArcGIS to implement all processes for identifying sites suitable for RWH (Figure 2.6). Areas suitable for dams can be identified by reclassifying layers of biophysical criteria and combining them using the raster calculator tool in the spatial analyst module of ArcGIS. Each criterion can be clipped to the study area, reclassified to numeric values, and assigned suitability rankings for dams based on the following chart according to (Ali *et al*., 2012).

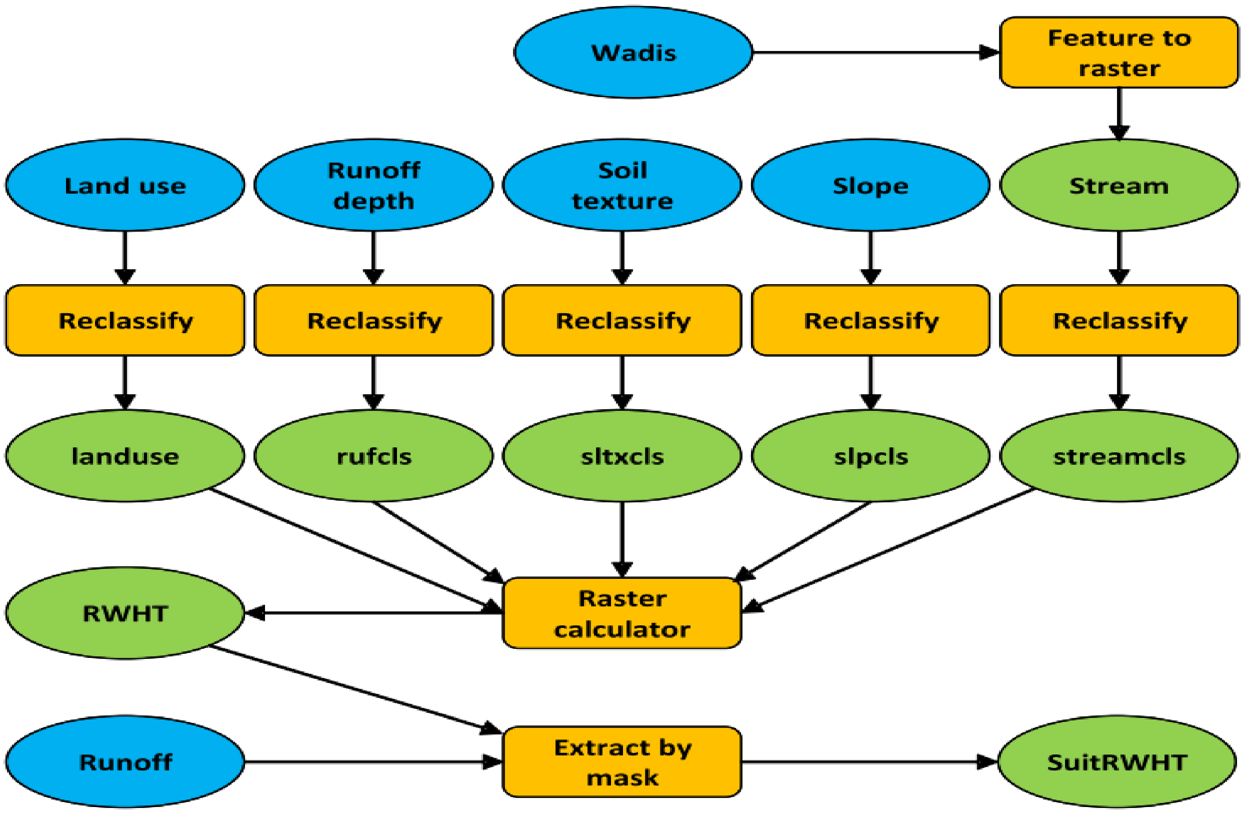


Figure 2.6: Flow Chart for the Identification of Potential RWH Sites

Source: Ali *et al*. (2017)

2.4.6 Dam Site Selection Using Analytical Hierarchy Process

A set of quantitative and qualitative criteria influence optimal location for rainwater harvesting sites (Rejani *et al*., 2017). However, it is still one of the problems associated with water resources management, especially site suitability analysis for dam construction is very crucial (Shao *et al*., 2020). In water resources management, spotting feasible sites and dam construction have high fiscal cost (Shao *et al*., 2020). Therefore, Analytical Hierarchy Process (AHP) with combination of GIS is known as the method of multicriteria decision making on selecting dam sites (Dai, 2016).

The main steps involved in AHP are comprehending problem identification; selecting criteria and making hierarchy, pairwise comparison of chosen criteria and weighting each criteria (Minatour and Khazaei, 2013). According to Minatour and Khazaei (2013), AHP procedure can be divided into three (3) parts namely; identifying the hierarchy of objectives, criteria and alternatives. Moreover, dam construction inducts high costs. Therefore, it should be constructed in a high potential site to compensate for the costs (City, 2011). Since various studies must be conducted in order to locate optimal dam site, multi criteria decision making (MCDM) can be applied to solve problems related to different quantitative and qualitative criteria (Al-Ruzouq *et al*., 2019). Furthermore, MCDM is categorised into two main groups such as multi objective decision making (MODM) and multi attribute decision making (MADM) (Minatour and Khazaei, 2013). While MODM techniques are used to design and optimize problems, the MADM methods are used for selecting the best alternative amongst various alternatives and obtaining a ranking for the alternatives.

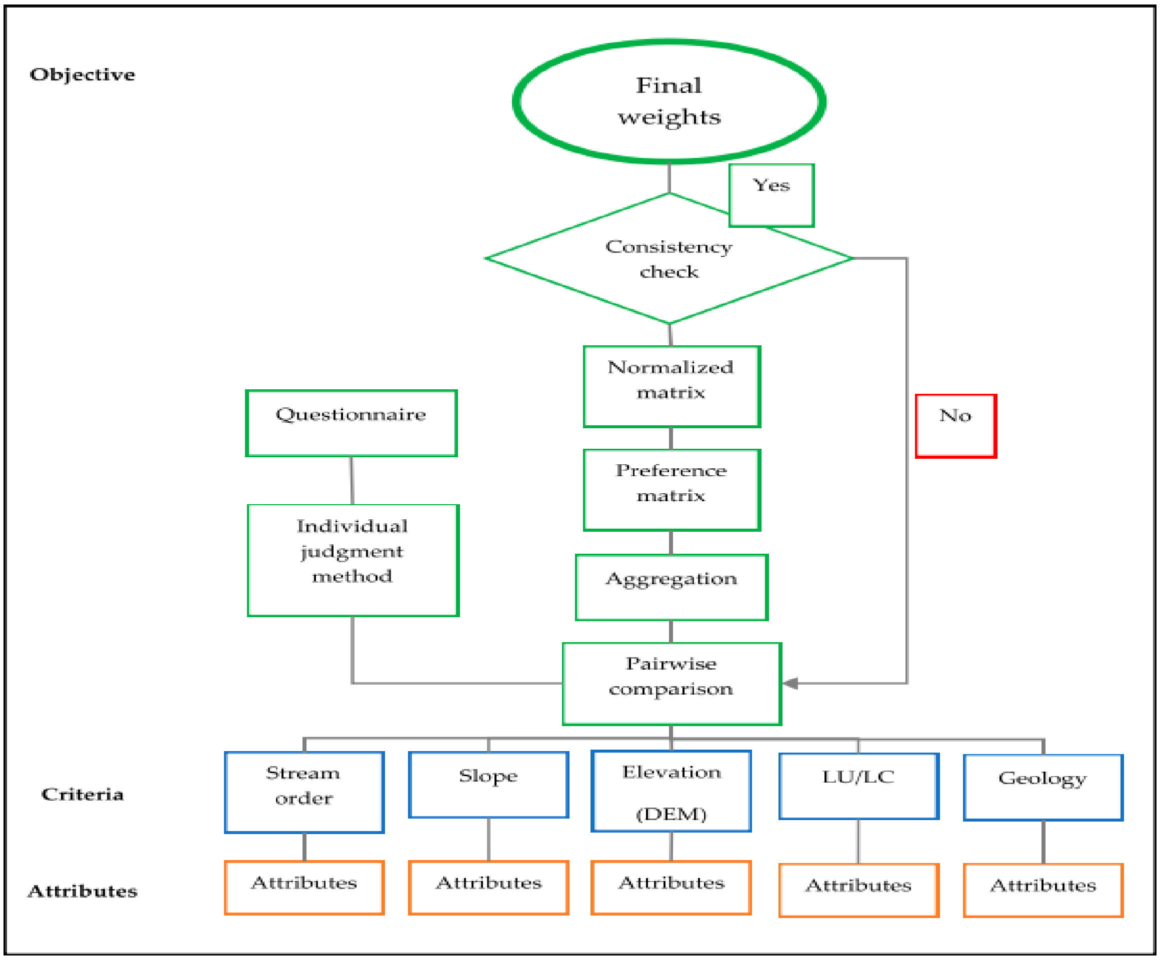


Figure 2.7: Analytic Hierarchy Process (AHP) as Weighting Method

Source: Shao *et al*. (2020)

Table 2.10: Saaty's Comparison Scale

Intensity of Importance	Numeric Value
Equal importance	1
Equal to moderate importance	2
Moderate importance	3
Moderate to strong importance	4
Strong importance	5
Strong to very strong importance	6
Very strong importance	7
Very strong to extremely strong importance	8
Extreme importance	9

Source: Shao *et al.* (2020)

Finally, AHP methods have been used as a weighting method with GIS based- based MCDM for dam site suitability analysis (Minatour *et al.*, 2015). Nevertheless, the pairwise comparison of each criterion with the other is the most crucial step. The judgement of the appropriate values of each criterion can be made based on knowledge of user and experts' consultation.

2.5 Water Harvesting Capacity for Multi-usage

2.5.1 Water Storage and Purpose

Stored water can serve various purposes. It plays a crucial role in ensuring stable and reliable water supply, especially in regions where water scarcity or variability in water availability is a concern (Kimani *et al*., 2015). The construction of water storage facilities can efficiently regulate the spatial temporal distribution of water resources (Turner *et al*., 2021). However, there is still a lack of widespread data on catchment water release and adequate structures to optimally store water for further use. Proper management of storage is crucial to balance the competing needs of various users and ensure sustainable water use. It involves considerations such as reservoir operation, water quality maintenance and environmental impacts assessments. Integrated water resource management is a holistic approach that takes into account the entire water cycle including storage to meet the needs of both humans and the environment.

2.5.2 Runoff Harvesting Technologies

Interest in water harvesting is growing in Africa, as more people are beginning to realize that surface runoff is a resource as important as rain, and it can be used for sustainable crop production and/or livestock watering (de Winnaar *et al*., 2007). Consequently, there has been a major development in a diverse range of technologies in water harvesting and conservation. This has been attributed, in part, to the transition from the imposed top-down rural development approaches to the more progressive adoption of community-based participatory approaches (Lundgren, 1993). These have probably favored the development of a diversified set of runoff farming techniques. Today, one can see these techniques being used in various farming systems in the region. RWH systems are also applicable over a wide range of conditions in areas where average annual rainfall is insufficient to meet the crop water requirement, with seasonal rainfall being as low as 100 to 350 mm (Critchley and Siegert 1991; SIWI 2000; Oweis *et al*. 2001).

Innovations by progressive farmers seem common in the field of runoff farming (Mburu 2000; Kibwana 2001). Farmers observe the flow of surface water through their watersheds, and based on experimentation on a trial-and-error basis, sophisticated runoff farming systems are developed (SIWI, 2001). This can, for example, be the tapping of sheet flow from roads, diversion of sheet flow from rocky areas adjacent to the farmland, or diversion of surface runoff from footpaths. Runoff farming systems play an important role in small-scale farming practices, which is explained by the fact that: (i) the techniques are easy to design, (ii) runoff volume is reasonably limited (sheet and rill runoff), which means that the farmer can control the inflow of water with little effort, and (iii) relatively simple methods and a significant volume of water can be added to crops during rainfall periods.

From the literature review it has been seen rainwater harvesting has been practiced over many decades for multipurpose, and this practice has contributed largely to sustainable development.

However, the best technology to optimize the reliability of rainwater harvesting is still a task to work on to fill the gap and deficit of water demand. It has also been seen as a novel way for developing countries to construct and maintain long-term water availability. In addition, it has not been considered in need of development among non-conventional resources. Nevertheless, rainwater harvesting (RWH) can be incorporated with existing appropriate technologies, considering that it has a low operational cost and is capable of performing with low technology and in a decentralized manner (Mwamila, 2016).

2.5.3 Reservoir Design Based on Water Demands

Designing a reservoir can be based on available sources or water demands (Venot *et al*., 2011; Acheampong *et al*., 2014b). This activity involves several considerations to ensure that it meets the needs of the area it serves. Therefore, the assessment of forecast future water use is critical throughout the design procedure of the dam's construction to meet the needs of its users in the future (Doost *et al*., 2024). These requirements may include household, pastoral, industrial and irrigation requirements. However, hydrological study is most important to determine available water sources including rainfall, rivers, streams, and groundwater (Dorfeshan *et al*., 2014). Therefore, the hydrological study helps in understanding the water inflow to the reservoir and the potential for filling it. Furthermore, suitable locations of the reservoir involve considering factors like proximity to water sources, minimizing environmental impact, accessibility and topography. The selection of the type of reservoir can therefore be based on the available space, local conditions (Mugo and Odera, 2019). The reservoir could be an embankment dam, concrete dam or natural lake expansion. Finally, the design should consider safety measures to prevent flooding, erosion and other potential risks. Hence, to effectively, sustainably, and safely design a reservoir involves a multidisciplinary team of engineers, environmental experts, and stakeholders to ensure successful reservoir design.

2.5.4 Runoff Estimation in Catchment of Reservoir

A catchment is defined as the area covering all the land that contributes runoff to a common point such as the reservoir of a dam (Mwangi *et al*., 2017; Ohana-Levi *et al.*, 2018). Each catchment has unique characteristics such as shape, slope, size, drainage, vegetation, geology, climate, soil type, geomorphology and land use classes. Moreover, the occurrence, quantity and rate of runoff are dependent on the characteristics of a particular rainfall event, namely, the duration, intensity and distribution of rainfall (Antwi-Agyei *et al*., 2015). For any catchment flow volume and peak flow directly depend on characteristics of the catchment and the infiltration capacity of the catchment (Larbi *et al*., 2020; Umukiza *et al*., 2021). To accurately estimate rainfall runoff is essential in water resources, dam construction as it provides an idea of the inflows to the reservoirs (Hu *et al.*, 2020). The flow from the catchment depends mainly on couple of parameters namely:

i. The catchment area: Its area, slope, Topography soil types and;
ii. The weather in the region: The annual quantity and frequency, intensity and duration of storm

As a general rule, it can be observed that, a larger catchment area, at a specific dam location, corresponds to a higher volume of run-off

With a fixed catchment area and rainfall quantity, increased rainfall intensity results in a greater run-off volume.

In the case of perennial rivers, estimating run-off can be accomplished by measuring the flow at various points throughout the year. For seasonal rivers, empirical equations are often needed. Seeking guidance from a Hydrologist within the respective regional or national service is recommended.

2.5.5 Estimation of Reservoir Storage Capacity

In order to determine the reservoir's storage capacity, it is essential to possess knowledge regarding the topographical characteristics of the basin in which the reservoir is located. However, the initial bottom morphology of the reservoir is affected to changes caused by erosion processes that occur in the watershed (Fuska *et al*., 2017). Bathymetric survey is one of on-site method often used in determining water surface area and water depth, where the bathymetry inventory is determined by echo sounders (Grin, 2014). Furthermore, the surveyed data taken by bathymetric need to be translated into a workable platform such as 3D- model. The model can be used to obtain area and volumes series at different depths for each reservoir from full supply to comply empty (Grin, 2014). Getting high quality data related to different depths is very necessary for creating an accurate digital elevation model (DEM) of the bed of the reservoir. Therefore, reservoir bed mapping is the challenge to deal with the most effective reservoir management. Nevertheless, there is a simplified approach for providing a rough estimate of the storage capacity involves the computation of both the surface area and the elevation corresponding to the spillway crest level that can be estimated using Equation 2.11:

$$V = \frac{1}{2.67} \times H \times S \qquad \text{Eqn 2.11}$$

Where:

H- Water level at the crest of the spillway (m),

S- Surface area of the reservoir, (m^2) and

V- Volume (m^3).

Understand a reservoir operation with regards of various factor such as inflow, outflow volumes and water levels are most important to monitor and manage the water resource (Yin *et al*., 2015). Therefore, studies in reservoir operations of various optimization techniques are currently important research topics. Nevertheless, in the latest years optimization techniques have been developed due to the development of computer technology, to monitor reservoirs storge capacity.

2.6. Conceptual Framework of the Study

To achieve the set objectives, this study followed the structure shown in Figure 2.8.

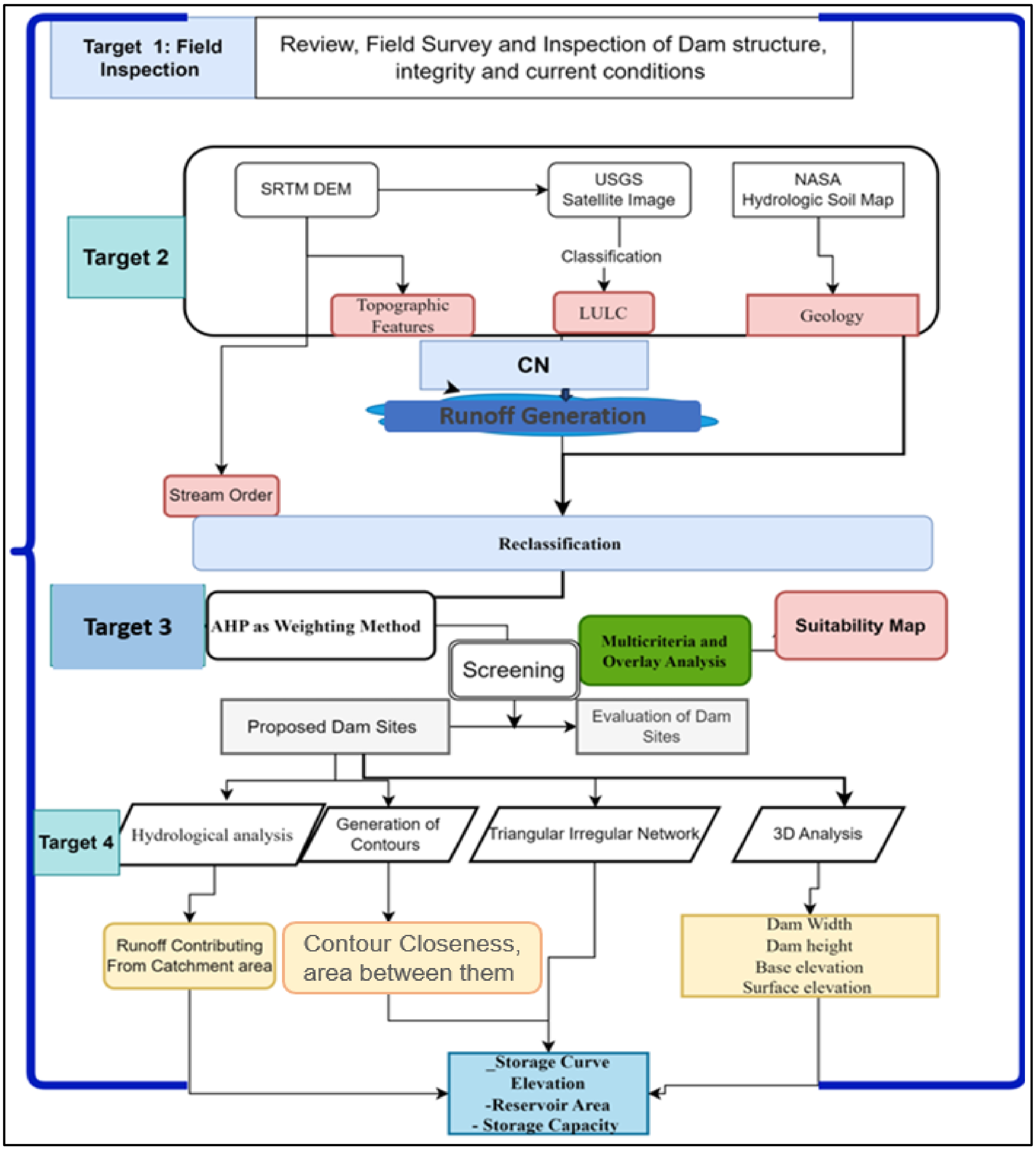


Figure 2.8: Flow Chart of the Study

Source**:** Umukiza *et al*. (2023)

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was conducted in four (4) regions of northern Ghana i.e. Northern, Upper East, Upper West and Savannah Regions. Ghana is a West African country bordered to the north by Burkina Faso, to the west by Côte d'Ivoire, and to the East by Togo. The southern border of the country is the Gulf of Guinea and the Atlantic Ocean. It is geographically positioned between latitudes $4^{o}30'$ N and 11^{o} N and longitudes 1^{o} E and 3^{o} 30' W. The United Nations Population Division (Toure *et al.*, 2020) estimated that the country has a population of 31.73 million people in 2020. The Northern Region is one of the driest regions in Ghana due to its proximity to the Sahara Desert and the Sahel region.

Despite the region facing the water shortage issues, northern Ghana is known for its agricultural pursuits, with farming serving as a primary occupation and a key economic activity Agriculture contributes to 54 % of Ghana's GDP, and accounts for over 40 % of export earnings, while at the same time providing over 90 % of the food needs of the country (Owusu and Asante, 2020). The principal feature of rainfall in Ghana is its seasonal character and its variability from year to year. In the northern region of Ghana, the climate is dry and hot while in the South is more humid. Generally monthly rainfall totals rise slowly from March with a check in June or July until a maximum is reached in August or September with mean annual rainfall of approximately 956 mm. The average daily temperature is 34 °C, while the annual average temperature is 31.5 °C, except during the wet months of July, August, and September. The life expectancy in Ghana is 59 years and 60 years for men and women respectively (Mba, 2010).

Vegetation in northern Ghana is predominantly savannah grassland, with scattered trees and shrubs (Ampim *et al*., 2021; Manzoor *et al*., 2022).

Table 3.1: Description and Specific Details of the Study Areas

Number	Catchment Names	Latitude (Degree)	Longitude (Degree)	Year of Construction	Districts	Regions
1	Gbalahi	9.426522	-0.761370	2019	Tamale Metropolitan	Northern
2	Guno	9.599071	-0.748359	2021	Nanton	Northern
3	Sambu	9.421129	-0.105968	2019	Mion	Northern
4	Sandu	9.643587	-0.730433	2020	Nanton	Northern
5	Nyeko 1	9.79261	-0.65729	1980	Karaga	Northern
	Nyeko 2	9.7035313	-0.643086	2021	Karaga	Northern
6	Denugu	10.761581	-0.135997	2020	Garu	Upper East
7	Saboro	10.917569	-1.093346	2019	Kasena-Nankana Municipal	Upper East
8	Gia Kwosongo Busona	10.915739	-1.14238	1979	Kasena Nankana Municipal	Upper East
9	Gia Bagania Chafia	10.91510	-1.141402	1990	Kasena Nankana Municipal	Upper East
10	Gia Bagania 2 (1V1D)	10.914675	-1.130696	2019	Kasena Nankana Municipal	Upper East
11	Duongo1	10.326808	-2.544880	1980	Nadowli-Kaleo	Upper West
12	Kperisi Dam	10.907583	-2.44581	2021	Wa Municipal	Upper West
13	Siiru /Balawa	10.021704	-2.553314	1988	Wa Municipal	Upper West
14	Dinaso Boo	10.063607	-2.444080	2021	Wa Municipal	Upper West
15	Busa Dampu	10.215136	-2.369804	1990	Wa East	Upper West
16	Kwisini	9.127211	-0.493400	2020	North East Gonja	Savannah

Source : Umukiza *et al*.(2024)

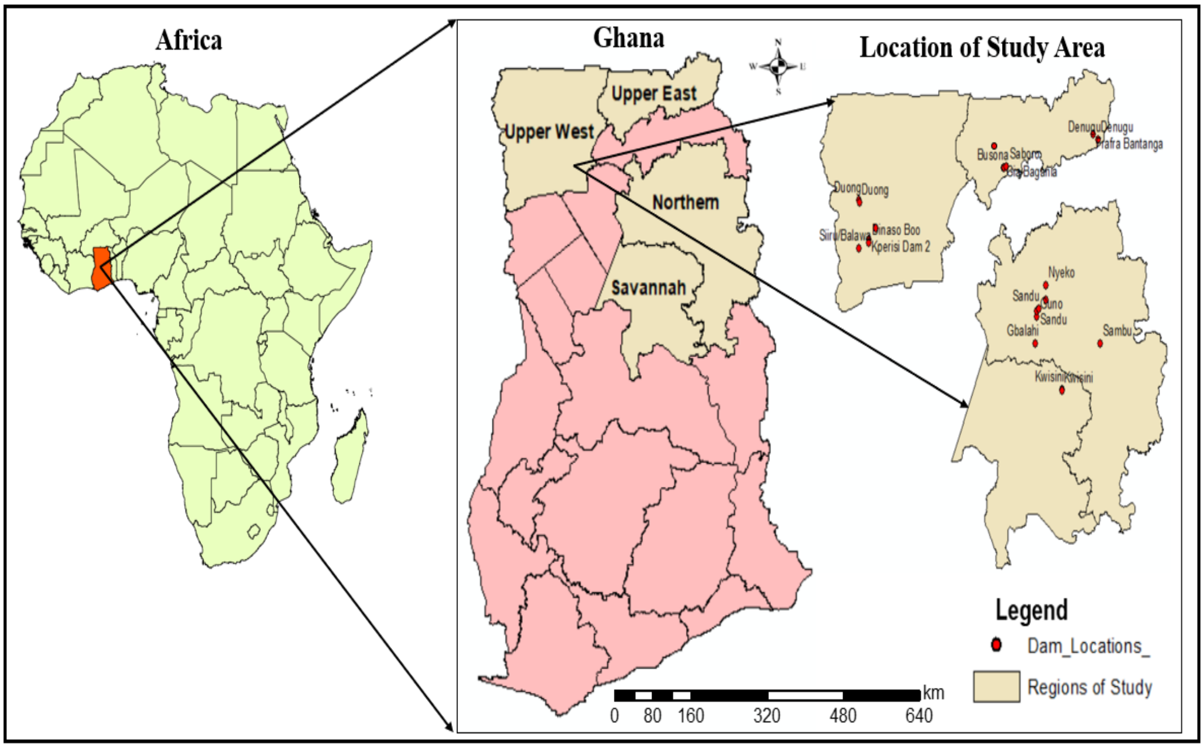


Figure 3.1: Map of Ghana Showing the Study Regions and Dams

Source : Umukiza *et al*. (2024)

3.2 Materials for Field Data Collection

3.2.1 Field Data Collection Materials

The field inspection of structural conditions was conducted following engineering and safety protocols. The materials used for data collection at the field level are presented in Table 3.2.

Table 3.2: Field Data Collection Materials

<table>
<tr><th>S/No.</th><th colspan="2">Field Data Collection Materials and Equipment</th></tr>
<tr><td>1.</td><td>Global Positioning System (Garmin Map64S)</td><td rowspan="9"></td></tr>
<tr><td>2.</td><td>Hondex Digital Depth Meter (PS-7)</td></tr>
<tr><td>3.</td><td>Measuring Tapes (30 m metallic tape and 100 m fibre tape)</td></tr>
<tr><td>4.</td><td>Camera</td></tr>
<tr><td>5.</td><td>Safety boots and water coat</td></tr>
<tr><td>6.</td><td>Notebook, Pen and Marker for recording observations and measurements</td></tr>
<tr><td>7.</td><td>Soil Probe</td></tr>
<tr><td>8.</td><td>Bucket Containers for sample storage</td></tr>
<tr><td>9.</td><td>Soil sampler</td></tr>
</table>

3.3 Data Sources and Methods

Data was obtained from primary and secondary sources. The methods used for the data collection were reconnaissance and detailed surveys, desk study, interviews, field survey, transect walk, remote sensing and GIS.

3.3.1 Site Reconnaissance, Detailed Surveys and Visual Inspection

A reconnaissance survey was carried out on constructed small dams and reservoirs in selected districts in northern Ghana. However, the main focus was in the northern region (5 dams), Upper East region (5 dams), Upper West region (5 dams) and Savannah region (1 dam). After the reconnaissance survey sixteen (16) dams were purposely selected for the study and a detailed survey was carried out. Site visits to the dams and reservoirs were conducted for a comprehensive visual inspection of their physical condition, looking for signs of distress, erosion, seepage, settlement, cracks, or any structural issues in the dam and its surroundings, examination of spillways, outlet works, embankments, and other critical components. During this survey, the existing state and the general physical attributes of the dams' embankments, spillways and reservoirs were recorded.

The catchments study was spatial-temporally delineated and analyzed in terms of landuse and landcover, and detailed visual observations were made through transect walks along selected routes for the identification and discernment of parameters such as upstream characteristics, soil types/classes, land use, landcover types and farming practices. Ground truthing was conducted for verification of classified satellite images. Hotspot areas were given special attention to document the real factors influencing such changes. Garmin Map64S GPS with an accuracy of ± 3 m was used to take coordinates for geo-referencing the satellite images as well as for accuracy verification of the classified satellite images.

3.3.2 Desk Study

To establish an understanding of the situation that is antecedent to the current state of the dams and the threat to productive water for sustaining irrigation and livelihoods in the study areas, a desk study which entailed reviewing published information and records was done.

3.4 Assessment of Engineering Status of Small Dams and Reservoirs

The assessment of selected small dams constructed was conducted with field investigation aimed to assess the safety of the existing small dams, focusing on all critical engineering services of the dam that include, upstream and downstream embankment and assessment of cracking due to differential movements, erosion, spillway crest and channel, and soil analysis.

In addition to *in-situ* assessment of current conditions of the small dams and reservoirs, historical and general information related to design and construction of small earth dams' information from literature study were carried out to acquire a better understanding of the engineering, structural designs, their failure or malfunctioning, safety regulation amongst others.

Site assessment was conducted to gather comprehensive physical conditions. Measurements and observation of key aspects of the dam were evaluated with checks listed across the standards. The maintenance and management practices in place were also inspected. Soil samples were collected and tested in the laboratory to understand the soil properties and stability used for embankment especially the hydraulic conductivity, soil texture and bulk density.

3.4.1 Field Inspection and Laboratory Analysis

Soil samples were collected from embankments at depth of 20 cm of the study dams to determine their suitability for dam engineering purposes. The samples were analysed for engineering characteristics and composition of different-size particles used for embankment construction. Although that wider variety of soil can be used for construction of zoned embankments, more careful supervision is required since soil will always settle even the best consolidated walls (Juliá *et al*., 2021). Hence, this information was crucial for soil classification and engineering design and the analysis focused on three (3) key soil properties; hydraulic conductivity (Ksat), bulk density (BD) and soil particles distribution.

3.4.2 Hydraulic Conductivity

Hydraulic conductivity refers to the ability of a porous material, such as soil or rock to transmit water through it (King & Franzmeier, 1981), it was critical to determine how quickly water can flow through the embankment materials. Therefore, undisturbed soil samples were taken from each dam's embankment for laboratory analysis. Falling head method was used to measure the hydraulic conductivity (K) of saturated soil in the laboratory. Darcy's equation to a saturated column of a uniform cross-sectional area was used and the hydraulic conductivity was calculated using Equation (3.1):

$$K = \frac{2.303.A.L}{t.log\ 10\ (\frac{h1}{h2})} \qquad \text{Eqn 3.1}$$

Where:

K - Hydraulic conductivity (m/s),

A - Cross-sectional area of the piezometer (m^2),

L - Length of the flow path (m),

t - Time for water level to fall (s),

h1 - Initial water level (m), and

h2 - Final water level (m).

Figure 3.2. summarises an extensive field survey and laboratory analysis that were carried out at each dam location, the activities inferred the laboratory as presented.

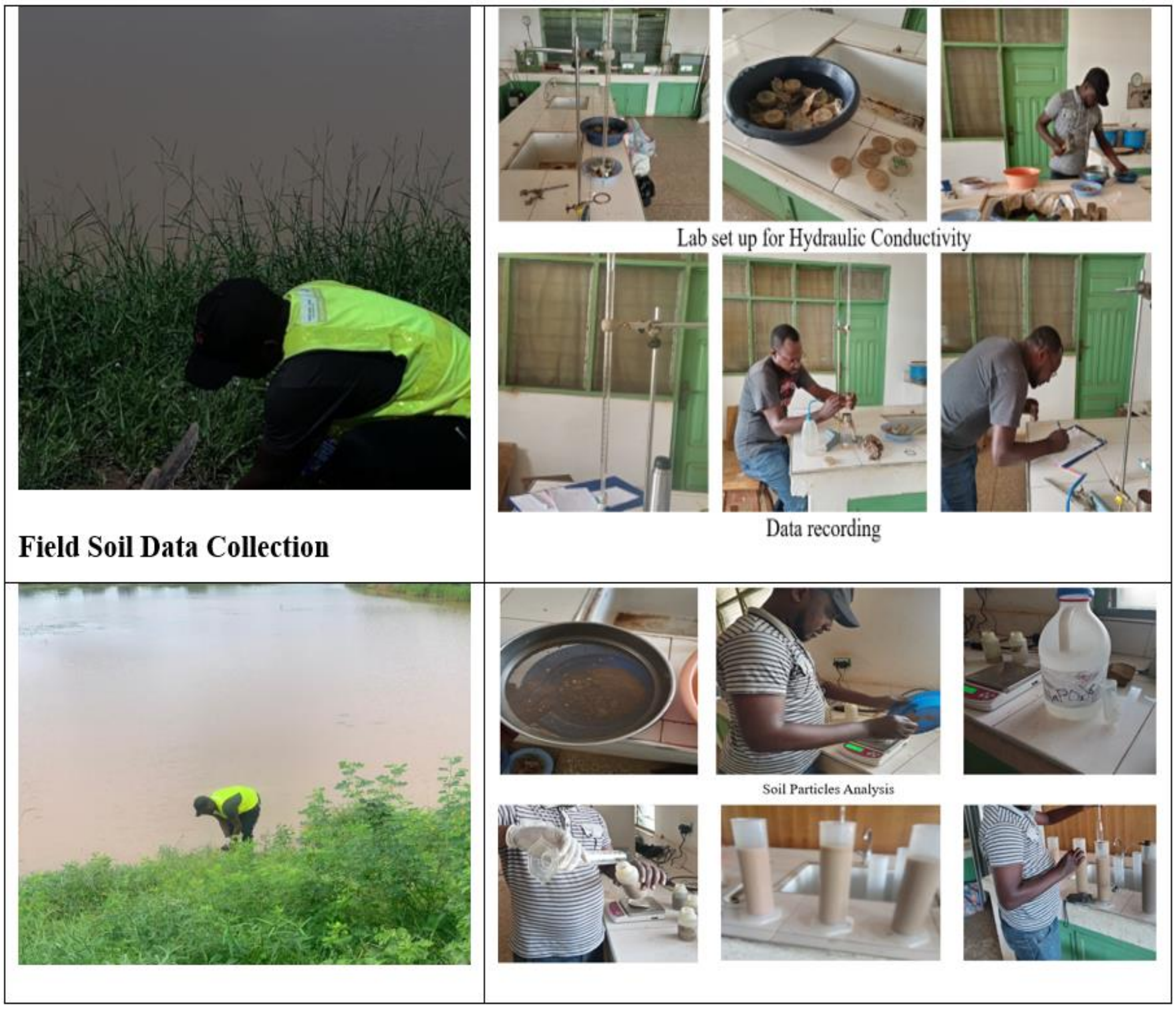


Figure 3.2: Soil Data Collection and Analysis

Source: Author's construction (2023)

Disturbed soil samples were collected at the dam's embankment for laboratory analysis. The hydrometer analysis was used to determine the relative proportions of different grain sizes by measuring the rate at which soil particles settle in a fluid, providing a detailed understanding of the soil's texture and composition. As the particle sizes were smaller than 75 micrometers (µm), they were analyzed using the hydrometer method as described by American Society for Testing and Materials (ASTM) codes D7928-17, which outlines the standard test methods for particle-size distribution (gradation) of soils using the hydrometer analysis (Carlos *et al*., 2021; Pardoyo *et al*., 2023). This method is typically used for fine-grained soils, such as silts and clays, where the particles are too small to be accurately measured using sieving methods.

3.5 Evaluation of Catchment Characteristics and their Effect on Runoff Generation

3.5.1 Data Collection Procedure

Field assessment through review was conducted for data collection during the reconnaissance survey of the study areas. The catchment delineation was carried out to define the catchment area for each dam and reservoir. LULC changes as important factors influencing runoff were assessed. This was done using Geographic Information System (GIS), aerial photographs and remote sensing tools. Surface reflectance images (level 2) Landsat 5 and 8 at the resolution of 30 m were used for LULC classification. For purposes of determining LULC change using supervised classification, four (4) sets of Landsat ETM images from 1995, 2005, 2015 and 2023 were obtained from the United States Geological Survey (USGS) official website (https://earthexplorer.usgs.gov/). The USGS had previously finished some normal preprocessing (such as geometric and radiometric correction) on the downloaded Landsat pictures, which can be taken into consideration for the type of analysis carried out (Guzha *et al*., 2018).

To avoid confusion that may arise in distinguishing some vegetation-based landuse classes (e.g. Crops vs grassland), the downloaded images were taken during the peak dry season period (January- March) in combination with Google Earth used to identify and detect LULC changes.

3.5.2 Data Processing and Analysis

3.5.2.1 Determination of Landuse and Landcover Changes

Landuse and landcover (LULC) dynamics were analysed with a scale interval of 10 years between 1995, 2005, 2015 and 2023 years. To detect LULC change, Landsat satellite images from the year 1995 to 2023 were used. The datasets were prepared through Landsat 5 and 8 at a resolution of 30 m obtained from the United States Geological Survey (USGS) and processed in Environmental Resource Data Analysis System (ERDAS) imagine version 2015 using supervised classification.

Layer stacking where separate image bands of Landsat images acquired were combined into a single multispectral image file through the layer stacking procedure. Mosaicking was done as it was important and necessary since it enables the assembly of two (2) or more raster datasets and combines them into a single, seamless raster dataset. The Raster mosaic dataset was created from multiple raster datasets. This was performed for the entire northern regions and after which the clipping and sub-setting of the Area of Interest (AOI) for the respective sub-catchment was done. These datasets were put together using the Raster Mosaic Tool in ArcGIS 10.7 geo-referencing, sub-setting and training of the images according to the Area of Interest (AOI).

Clipping and sub-setting images were performed through a subset of the raster dataset. It removes data outside the AOI, thus reducing the file size and enhancing the processing time for many operations. The area of each catchment was used in the clipping and sub-setting of the images. ArcGIS10.8 was used for converting classified images from raster (tiff) to Polygon

(.shp) for determining the area of each cover type. Landuse maps of each catchment for 1995, 2025, 2015 and 2023 years were developed and used to perform landuse dynamics analysis. The processed raster images were imported into ArcMap and converted into shapefiles for perfection.

An overall followed methodological framework is presented as a flow chart in Figure 3.2.

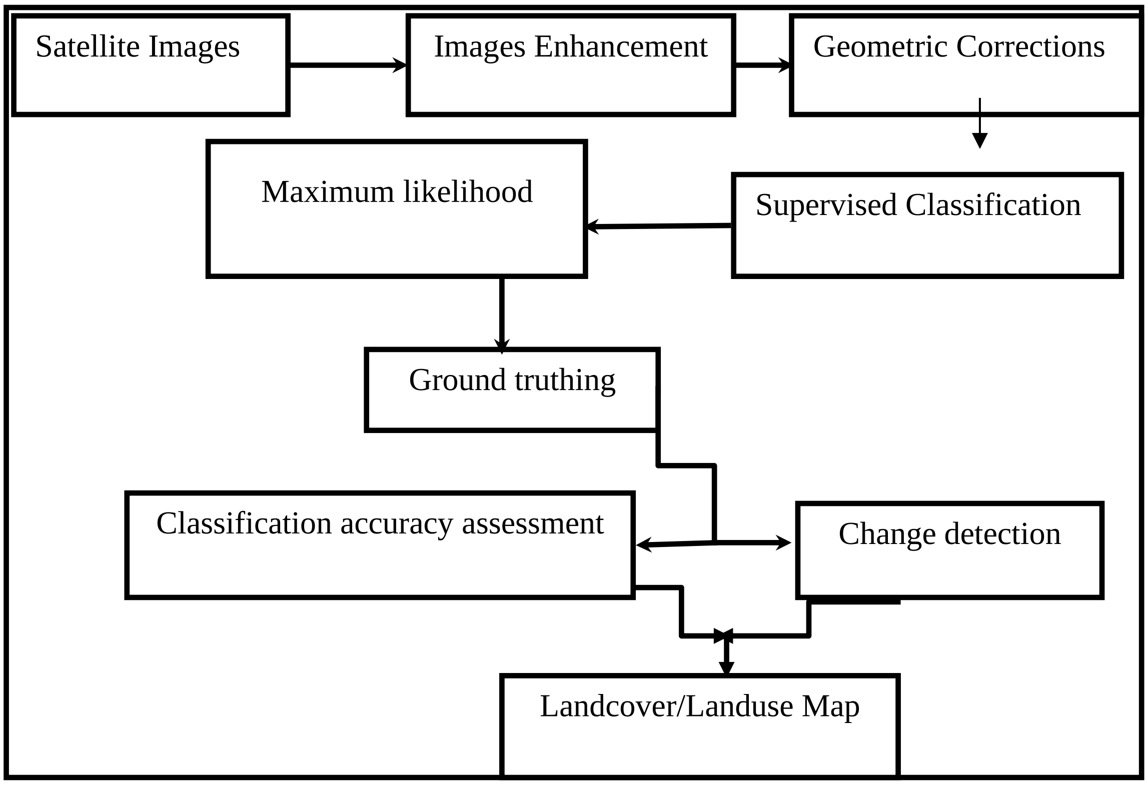


Figure 3.3: Flowchart for Determining the Land use and Landcover Change in the Catchments of the Dams

Source: Umukiza *et.al* (2024)

3.5.2.2 Acquired Satellite Images

The downloaded Landsat images had already some standard pre-processing (e.g. geometric, radiometric correction) done by USGS which can be considered for the type of analysis performed (Guzha et al., 2018; Ohana-Levi et al., 2018). World Reference System (WRS), Path 194 or 195, and Row 052 or 053, was applied to select the area of interest. An interval of ten (10) years was selected as it struck a balance between effectively monitoring land change dynamics and keeping the data and analysis workload manageable. To avoid confusion that may arise in distinguishing some vegetation-based landuse classes (e.g. crops versus grassland), the downloaded images were taken during the peak dry season period in the region (January- March) at most 5 % cloud cover.

Table 3.3: Details of Acquired Satellite Images

Satellite	Sensor id	Path/Row	Acquisition Date	Spatial Resolution (m)
Landsat 5	***TM	194/195/052/053	29 January 1995	30,30
Landsat 7	**ETM+	194/195/052/053	06 February 2005	30,30
Landsat 8	*OLI/TIRS	194/195/052/053	30 January 2015	30,30
Landsat 8	*OLI/TIRS	194/195/052/053	23 March 2023	30,30

*Note: **ETM+ (Enhanced Thematic Mapper Plus; ***TM (Thematic Mapper); *OLI/TIRS (Operational Land Imager/ Thermal Infrared Sensor*

Source: Author’s Construct (2024)

ERDAS IMAGINE and Google Earth were extensively used as they are widely used tools in the field of remote sensing that offer powerful capabilities for image classification, understanding landcover and monitoring changes. Figure 3.4 illustrates the used combination of Google Earth and ERDAS Imagine classification.

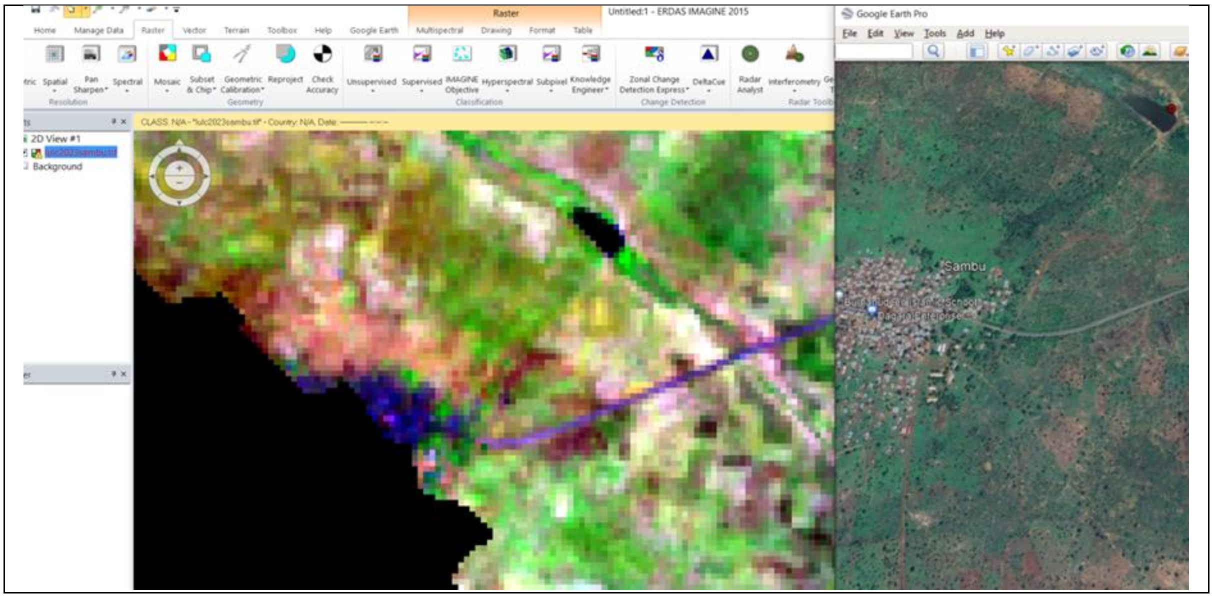


Figure 3.4: Illustration on ERDAS Imagine and Google Earth for Supervised Classification

Source: Author’s Construct (2024)

3.5.2.3 Image Classification

Image classification was a valuable application of machine learning and remote sensing to detect LULC changes. The principal purpose of image classification was to spontaneously identify and classify different landcover types and monitor changes over time. The classification legend was made based on the spectral attributes of the multi-spectral dataset acquired. A combination of both unsupervised and supervised classification was used for classifying the two images for each catchment. An unsupervised classification was first done using the classification algorithm, Iterative-Self-Organizing Data-Analysis Technique (ISODATA) with a maximum iteration of six (6). This was used as guidance for the collection of training sample points on the field. The points were then overlaid on the images and used as guidance to define polygons to extract the signatures for the various LULC types. Supervised Maximum likelihood classification (MLC) was used for the supervised classification. MLC has been widely used to obtain LUC information from multidimensional raster images through the process of image interpretation and classification (Fufa *et al*., 2023). All pixels in an image are into LULC classes based on the classification in Table 3.4.

Table 3.4: Landuse and Landcover Classes of Catchments

Serial Number	Landuse/Landcover Class	Description
1	Agricultural Lands	Crop fields
2	Waterbody	Reservoirs, lakes, ponds and rivers
3	Built-up Area/Bare land/Rocky ground	Residential areas, Roads, school commercial areas, recreational grounds, farmsteads, schools, lorry parks, roads, rocks and bare lands
4	Grassland	Thick forest lands, groves, rangelands, thick plantations
5	Open trees/ Open space	Shrublands, grasslands and fallow lands; scattered trees / empty spaces

Source: Author's construction (2023)

3.5.2.4 Accuracy Assessment

Accuracy assessment indicates the degree to which the corresponding categorized image accurately reflects the ground truth (Fufa *et al*., 2023). Accuracy assessment was conducted to evaluate the reliability of the classification results from the satellite images. The assessment aimed to determine the quality of the information obtained from the field and classified images. Performing an accuracy assessment is essential for each classification individual, as it ensures the usefulness of the classification data in change detection analysis (Mati *et al*., 2006; Yang *et al*., 2019). An error/confusion matrix is the most commonly employed and reliable technique to assess the accuracy of classified images from remotely sensed photography (Foody, 2020).

The overall accuracy was driven by dividing the total number of correctly classified classes (pixels) by the number of referenced pixels. When dividing the number of correctly classified pixels used for that class (column) then the user accuracy was computed. If the number of correctly classified pixels in every class is divided by the total number of pixels that were classified in that class (row total) then producer accuracy is calculated (Owa *et al.*, 2017). Therefore, the user's accuracy shows the percentage of the correctly classified pixels per landcover class while the producer's accuracy provides the percentage of correctly classified pixels per reference class (Yang *et al*., 2019).

The kappa coefficient or statistics can be applied as a measure of how well the remotely sensed classification agrees with reference data. In an investigation led by the Food and Agriculture Organization of the United Nations (FAO, 2016) concerning map accuracy assessment and area estimation, a trio of critical metrics emerged. These metrics encompass the overall accuracy, denoting the proportion of correctly categorized areas reflecting the likelihood that an arbitrarily chosen point on the map is accurately categorized (Equation 3.7). The user's accuracy, a second measure, signifies the proportion of an area classified as class *i* that also corresponds to class *i* in the reference dataset (Equation 3.8). This metric extends the probability that a designated region of class *i* on the map corresponds to the same class in reality. Finally, the producer's accuracy, the third metric, signifies the proportion of area characterized as reference class *j*, which also aligns with class *j* on the map (Equation identified as the same class on the map (FAO, 2016).

$$A = \sum_{j=1}^{q} p^{jj}$$ Eqn 3.7

$$Ui = \frac{Pii}{pi}$$ Eqn 3.8

$$Pj = \frac{Pjj}{pj}$$ Eqn 3.9

Where:

A - overall accuracy,

U*i* - user's accuracy,

p*j* - producer's accuracy,

p*ii* - number of classes *i* classified on the map and also on the ground,

p*jj* - number of class *j* on the ground and also classified as the same class on the map, and

p*i* - classified total of class *i* on the map and p*j* is the total number of class *j* on the ground.

Accuracy assessment was very important to determine how accurate the referenced data agreed with classified images of the remotely sensed data (Owar *et al*., 2017; Guzha *et al*., 2018).

3.5.2.5 Change Detection Analysis

The classification comparison of the LULC statistics method was used for the change detection analysis. This method was adapted because the study sought to determine quantitative changes in the areas of the various LULC categories. Using the post-classification procedure, the area statistics for each of the LULC classes was carried out from the classification of each year using ERDAS IMAGINE 2015 software and processed in ArcGIS 10.7. Change rates were computed with the help of Excel.

3.5.2.6 Digital Elevation Model and Hydrologic Soil Group

The Digital Elevation Model (DEM) for each of the respective catchments was gathered from Shuttle Radar Topography Mission (SRTM) of the United States Geological Survey's Earth Explorer (USGS) site (http://earth explorer.usgs.gov/) with 30 by 30 meters (30 m x 30 m) resolution. All data were projected to the Universal Traverse Mercator (UTM) zone 30 N projection. The DEM was processed and clipped for each catchment for delineation of the whole watersheds and sub-basins in ArcMap 10.7.

The hydrologic soil data as a fundamental component of the USD curve-number method for estimation of rainfall-runoff was gathered from NASA website global hydrologic soil group (HYSOGs250m) (https://daac.ornl.gov/SOILS/guides/Global_Hydrologic_Soil_Group.html) for Curve Number based runoff modelling. The data characteristics are global with spatial coverage. These data are modelled to represent contemporary soil runoff potential (Ross *et al*., 2018). The data information was one data file of global HSGs at 250 m resolution in GeoTIFF format. The Ghana Hydrologic soil map was therefore extracted by mask with the help of Arc GIS as done in Hengl *et al*. (2017). Thereafter, the hydrological soil group of the research zone was produced from the Ghana soil map with the help of GIS and the hydrological soil group classification look-up table (Mishra and Singh, 2006). Soil hydrologic maps are presented in in appendices 7. The hydrologic soil group was decided in group C (predominantly sandy loam) from the Curve Number (CN) classification. After subtracting each catchment area in terms of hydrologic soil group, the proportions in percentage (Appendix 7) indicate the distribution rate of each catchment area, and group classification C was found to be representative of each catchment.

3.5.2.7 Determination of Curve Number (CN) and Surface Runoff

The effects of LULC changes on surface runoff are well known when considering the conversion of forests or grassland to cropland or built up (Hundecha and Bárdossy, 2004; Descroix *et al.*, 2009; Mustafa *et al.*, 2012). Although, the impact of LULC on watershed hydrology are known, the spatial distribution of LULC characteristics can affect the runoff (Pechlivanidis *et al.*, 2011; Kalantari *et al.*, 2014).

In this study direct runoff was determined using Curve Number (CN) methods. As the intention of the process was to be applicable in ungauged watersheds without observed available data, the model parameter (CN) was linked to soil and vegetation characteristics and can be approximated using looked-up tables (Garen and Moore, 2005; Knightes, 2017). The determination of CN in this context involved the integration of spatial LULC data, soil type information, and an assumption of AMC (Antecedent Moisture Condition) categorized as II (indicating moderate wetness of the soil prior to precipitation). The detailed process encompassed the initial assignment of CN values to distinct LULC types based on authoritative lookup tables. Average CN values have been determined on each catchment-wide scale for combined land areas and types.

The values of the CN were assigned for each type of LULC considering the official lookup tables. Hence the values of CN were calculated based on tables provided in the NEH-4 (Zeng *et al*., 2017; Yang *et al*., 2019) for various situations considering the proportion of different uses in the study area. Finally, the average CN was calculated for composite areas using Equation 3.10 (Gajbhiye and Ashish, 2014):

$$CN = \frac{\sum CN_i A_i}{\sum A_i} \qquad \text{Eqn 3.10}$$

Where:

Ai - sub-areas (km^2),

CNi - Curve Number of each identified land use (unitless), and

A - Total area (km^2).

Runoff coefficient which depends on landuse and slopes was established in the same fashion as the soil conservation service (SCS) Curve Number method for estimating runoff flow for different landuse conditions where the average was calculated for composite areas according to the formula reported in Equation 3.11 as follows:

$$C = \frac{\sum C_i A_i}{\sum A_i} \quad \text{Eqn 3.11}$$

Where:

Ci - coefficient applicable to the area.

Ai - Composite area (km^2).

The surface runoff depth for the entire catchments were respectfully computed using Equation 2.5. The time of concentration (Tc) which depends on watershed length, slope, and surface, was computed using methods among the several existing methods (USDA-NRCS, 2010; Grimaldi *et al*., 2012).

3.5.2.8 Estimation and Calculation of Runoff Generation from Dam Catchments

Rainfall data for each of the catchments under study was collected from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) (Gelaro *et al.*, 2017) product of NASA POWER. It incorporates observational data from various sources to create a comprehensive and accurate representation of the earth's climate over a specific period. The re-analysis was performed to determine maximum yearly data from 1990 to 2021. Since the catchments of our study are ungauged and no meteorological weather is available, MERRA-2 data was used and acquired using coordinates of each catchment to perform precipitation and temperature analysis. MERRA-2 was re-analysed in the study conducted by Rodrigues and Braga (2021), to estimate daily weather variables in hot summer Mediterranean climate, the study found good agreement between MERRA-2 data and observed data for all parameters except wind speed. Also, comparisons between daily values from MERRA-2 and meteorological stations using several statistical tools are in acceptable agreement (Marzouk, 2021). The study conducted by Ngurah *et al.* (2022), on the island of Bali using observed rainfall from several locations and MERRA-2 rainfall data found high correlation values. In places where rainfall data are not available as it is a case of the study catchments; rainfall from MERRA-2 was used as a credible source. MERRA-2 is reliable source for global meteorological data (precipitation, maximum and minimum temperature, humidity and solar radiation) when compared with observed data (Bandira *et al.*, 2022).

The historical rainfall data helped to analyze how different factors interplay and influence runoff generation in the study areas. The runoff generation for each dam catchment was calculated to determine the catchment's discharge, which represents the portion of rainfall that becomes runoff using CN methods. The runoff coefficient was determined by considering factors like landuse, soil types, and antecedent moisture conditions.

3.6 Assessment of Suitable Location for Dam Construction

3.6.1 Data Collection and Processing for Dam Siting

Suitable site selection for dam construction is one of the critical assignments in water resource engineering and management (Abdulla and Thomas, 2016). In this study, identification of potential sites was analyzed, based on hydrological streamflow networks, ranked using a combination of a watershed modelling system, Geographic Information Systems (GIS) and remote sensing techniques to determine potential drainage networks. The geographical position of current dams/reservoirs was acquired directly from the sites. Each catchment was delineated with the support of an assembly of Arch Hydro and hydrology tool watershed modelling approach in a GIS environment using SRTM DEM (Khan *et al*., 2014). The stream order was defined and extracted for each catchment concerning the closeness of maximal flow accumulation while the elevations and slope from DEM were organized into four (4) classes. To identify the most pertinent factors for the suitable location of dams and reservoirs, an investigation of the literature was conducted. Each criterion was classified based on existing literature and experts' opinion judgments (Singh *et al*., 2014; Raj *et al*., 2021).

The Analytic Hierarchy Process (AHP) method was therefore used as a weighting method for GIS-based MCDM to determine the site suitable for small dams/reservoirs (Ahmed, 2011; Yasser *et al*., 2012; Estoque, 2012; Dai, 2016). The systematic steps on identification and selection of criteria for siting small dams/reservoirs, data acquisition and pre-processing; pairwise comparison matrix; and overlay analysis were undertaken. Correspondingly, after acquiring and pre-processing all data, they were all converted into raster format and rescaled in the same spatial resolution of 30 m using the World Geodetic System 84 (WGS84), Universe Transverse Mercator (UTM) zone 30 N coordinate system. Finally, from the proposed sites for small dams/reservoirs, the suitability assessment was performed as well as their optimal storage capacity.

3.6.2 Process Adopted for Dam Selection

The process of selecting a dam site was influenced by various factors, necessitating the application of multicriteria decision-making techniques to address this complexity. Following the initial screening utilizing stream density to identify potential dam sites, based on stream order and Euclidean distance (distance from streams. As the second step, the application of the AHP method across six (6) catchments of the small reservoirs found highly far located from the mainstream, revealed distinct suitable locations in different levels as: highly suitable, moderately suitable, less suitable, and least suitable. The usefulness of this method was recognized as a potent and adaptable tool for resolving issues involving multiple criteria, to assess and identify an optimal location for constructing a small earth dam within diverse catchments (Estoque, 2012; Yasser *et al*., 2012; Chezgi, 2019).

3.6.3 Reclassification and Analytical Hierarchy Process (AHP) Analysis

Reclassification was implemented using the reclassification tool in ArcGIS. Raster layers were reclassified into four classes, except for geological, which is divided into two potential categories based on profession in geology, water resource management and civil engineering judgment. In addition, an extensive review of existing literature was consulted (Ahmed and Corresponding, 2011; City, 2011; Yasser *et al*., 2012; Estoque, 2012; Minatour and Khazaei, 2013; Minatour *et al*., 2015; Dai, 2016; Staudinger *et al*., 2017; Kim and Kang, 2020). Therefore, a pair-wise comparison matrix (AHP) in alignment with experts' judgment was used to evaluate criteria weights. From many identified and analysed criteria affecting dam site suitability by earlier researchers (Karakuş and Yıldız, 2023, Engineering *et al*., 2024), slope ,landuse/landcover, and soil type were identified as the most significant factors. During the analysis of potential dam sites, the parameters summarized in Table 3.5 were considered.

Table 3.5: Reclassified Layers and their Preference Value of Suitability

Criteria	Classes	Preference Value	Suitability
Stream order	1st order	0	Restricted
	2nd order	1	Not suitable
	3rd order	3	Modestly Suitable
	4th order	5	Highly Suitable
Slope	>25	0	Restricted
	20-25	1	Not suitable
	13-20	3	Modestly Suitable
	<6	5	highly suitable
Land Cover	Built-Up		Restricted
	Agriculture	0	Not suitable
	Forest	1	less
	water Bady	5	highly suitable
	Barren Land	3	Moderately suitable
Elevation	---	---	---
Stream density	---	---	---

Note (---): preference depends on specific catchment

Source: Haq and Mundher (2024)

The implementation of AHP involved the application of the MCDM preference matrix and determining the parameter's weight (Choice, 2005; Saaty, 2008) for site suitability analysis. The pairwise comparison was applied to all criteria (Table 3.6).

Table 3.6: Pairwise Scale of Relative Importance

Intensity of Relative Importance	Definition	Description
1	Equal Importance	Two criteria contribute equally to the objective.
3	Moderate Importance	Experience and judgment slightly favour one criterion over another.
5	Strong Importance	Experience and judgment strongly favour one criterion over another.
7	Very Strong	A criterion is favoured very strongly over another.
9	Extreme Importance	The evidence favouring one criterion over another is the highest possible order of affirmation.

Source: Luís and Cabral (2021).

After that pairwise comparison matrix was done, the normalized weighted matrix was calculated according to a relative level of importance (Luís and Cabral, 2021). Furthermore, a consistency ratio (CR) was computed from the normalized vector values to ensure the reliability and consistency of judgements, Equation 3.12 (Kim and Kang, 2020).

$$CR = \frac{CI}{RI} \qquad \text{Eqn 3.12}$$

Where:

CR - Consistency ratio,

CI - Consistency index and RI represents the standard value as presented in Table 3.7.

Table 3.7: Consistency Indices for Randomly Generated Matrix (RI) Values

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

Source: Chezgi, (2019)

Consistency index resulting from sample-produced joint matrixes. If the CR < 0.10, it means that the pairwise matrix has an acceptable consistency (Staaty, 1987). Otherwise, it has inadequate consistency, and the comparison process must be repeated. Therefore, CI was given by Equation 3.13:

$$CI = \frac{\lambda - n}{n - 1} \quad \text{Eqn 3.13}$$

Where:

λmax - the number of factors being compared to the matrix and λ is the highest eigenvalue of the pairwise comparison matrix.

According to Saaty (1987), the maximum eigenvalue of the comparison matrix can be calculated using the following method:

- Multiplying each value in the column (in the matrix table which is not normalized) by criteria weight;
- Computing the weighted sum value by adding the values in the rows;
- Calculating the ratio of each weighted sum value to the respective criteria weight, and
- Averaging the ratio of weighted sum value to the criteria weight.

After performing the weights and reclassification of all criteria, the weighted overlay analysis was performed in ArcGIS Spatial Analyst using a weighted overlay technique, producing suitability maps with a spatial resolution of 30 m x 30 m.

3.6.4 Overlay Analysis

An Analytical Hierarchy Process (AHP) was employed, using a weighted overlay technique in ArcGIS, and all criteria layers were aggregated to find suitability maps. With their computed weights, all raster layers with a spatial resolution of 30 m x 30 m were then inputted. Choosing the criteria to be applied in the process of identifying the best places for the dam site and creating the database are crucial decisions (Al-Ruzouq *et al*., 2019; Zewdie and Tesfa, 2023).

In this study four steps make up the general approach applied to this study: (i) data collection; (ii) data conversion into GIS data format; (iii) identification of appropriate locations for dam site selection using the GIS-based AHP method; and (iv) accuracy analysis. Figure 3.4 illustrates the flowchart of the procedure used in the investigation.

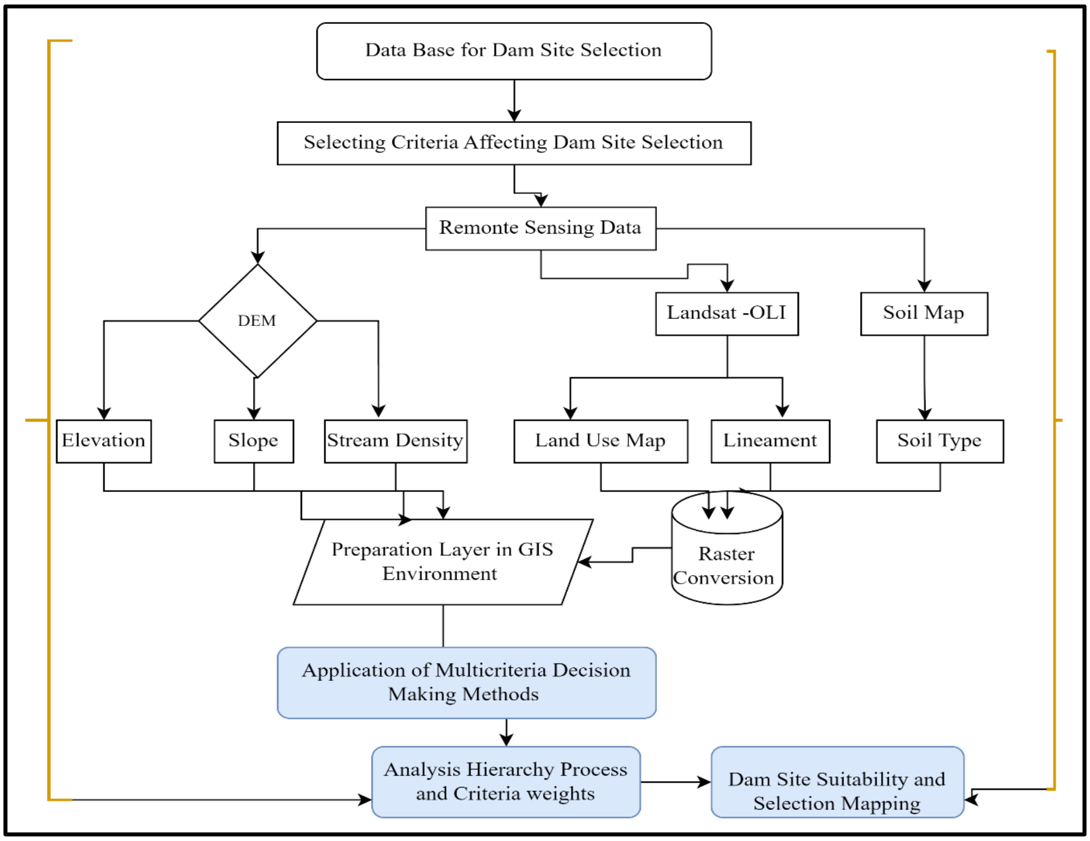


Figure 3.5: Flowchart of the Procedure used in Dam Site Selection

Source: Author's Construct (2024)

3.6.5 Evaluation of Current and Proposed Dam Sites Storage Capacities

Further analysis was conducted for six catchments named Dinaso Boo, Denegu; Busona; Sambu; Duago and Kepersii. After the potential dam site locations were investigated, six proposed new dam locations underwent evaluation of optimal storage capacity including a thorough analysis to ascertain the viability and appropriateness of possible dam construction sites. This procedure took into account several variables, such as 3D surface analysis, 2D surface area topographical features, dam height, catchment area, water flow patterns, hydrological, and maximum volume were used to guarantee the dam's long-term sustainability and structural integrity. Triangular Irregular Network (TIN) was determined from topographical maps in GIS environment. To discern elevational differences and, consequently, delineate the reservoir's boundaries, created contour lines on these maps were exported in Civil 3D. Contours were generated with interval of 2.5 m from the DEM. Civil 3D software, the Spatial analyst tool, was added as an extension to the arc toolbox and the 3D analyst tool was used to determine the storage capacities and represent the elevation, storage capacity, and elevation submerged under different areas respectively.

The stream networks in the catchment were analysed and this included information about the catchment characteristics, like rainfall and hydrological patterns.

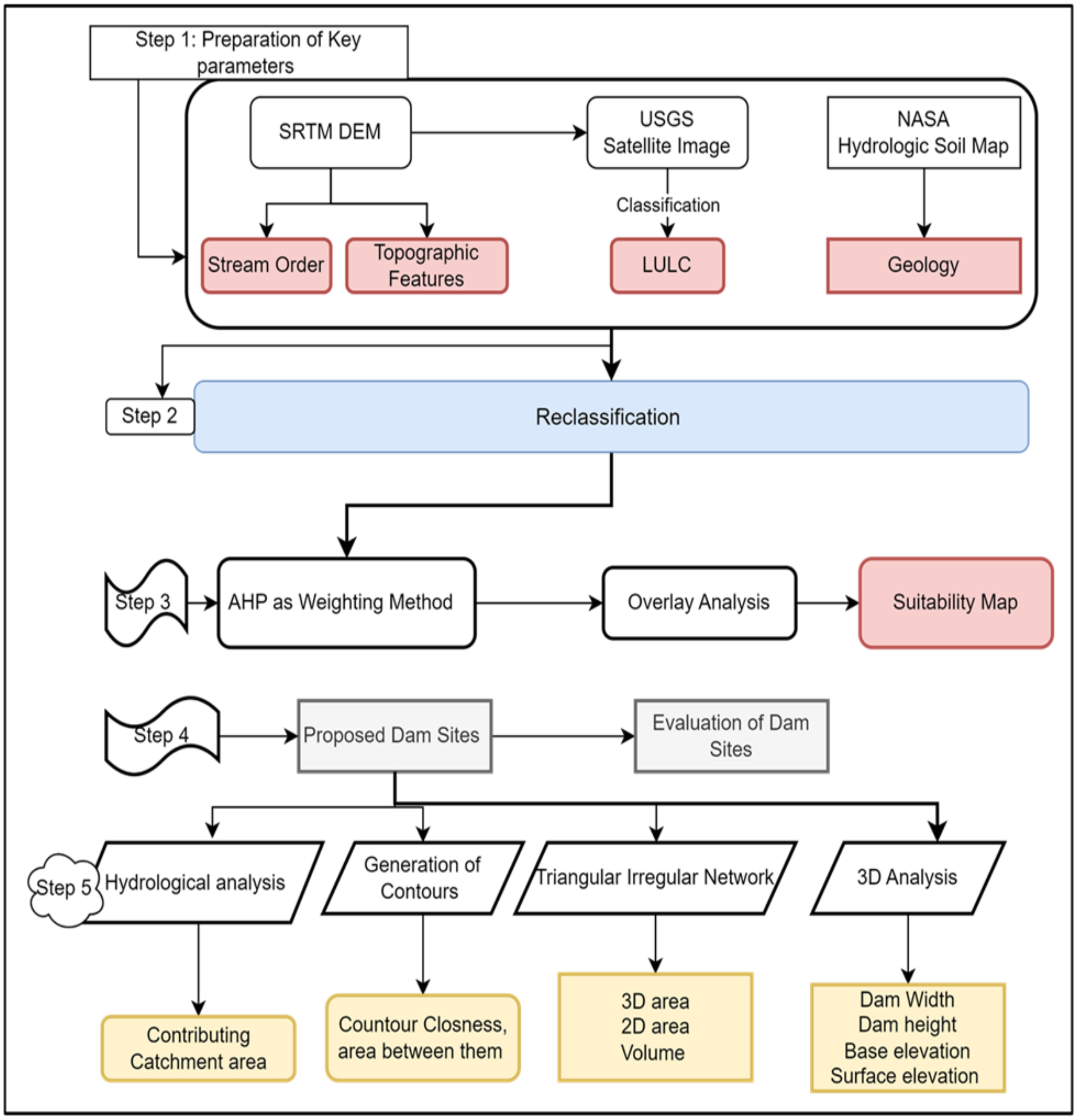


Figure 3.6: Overall Methodological Framework

Source: Author's Construct (2024)

By systematically applying this methodology, comprehensive elevation-area-capacity curves were constructed to reflect the reservoir's storage dynamics under different storage stages. Mathematically, the incremental volume between any contour elevations and live capacity of reservoir can be calculated using Equations 3.14, 3.15, and 3.16.

$$\Delta V_i = \Delta \text{h} \left(A_I + A_{i+1} + \sqrt{AA_{I+1}} \right) {}^{1}\!/_{3}$$ Eqn 3.14

$$V_I = \sum_{k=1}^{i} \Delta V_k$$ Eqn 3.15

$$Y_a = \sum_{i=1}^{N-1} \Delta V_i$$ Eqn 3.16

Where:

ΔVi - Volume between contour elevations i and i+1

Δh - Contour interval,

Ai - Area at contour elevation I,

Ai+1 - Area at contour elevation 1+i,

Ya - Live capacity of reservoir, and

N - Number of contour elevations.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Assessment of the Engineering and Structural Conditions of the Reservoirs/Dams

Figure 4.1 presents the saturated hydraulic conductivity (Ksat) values from dam embankments of inspected sites.

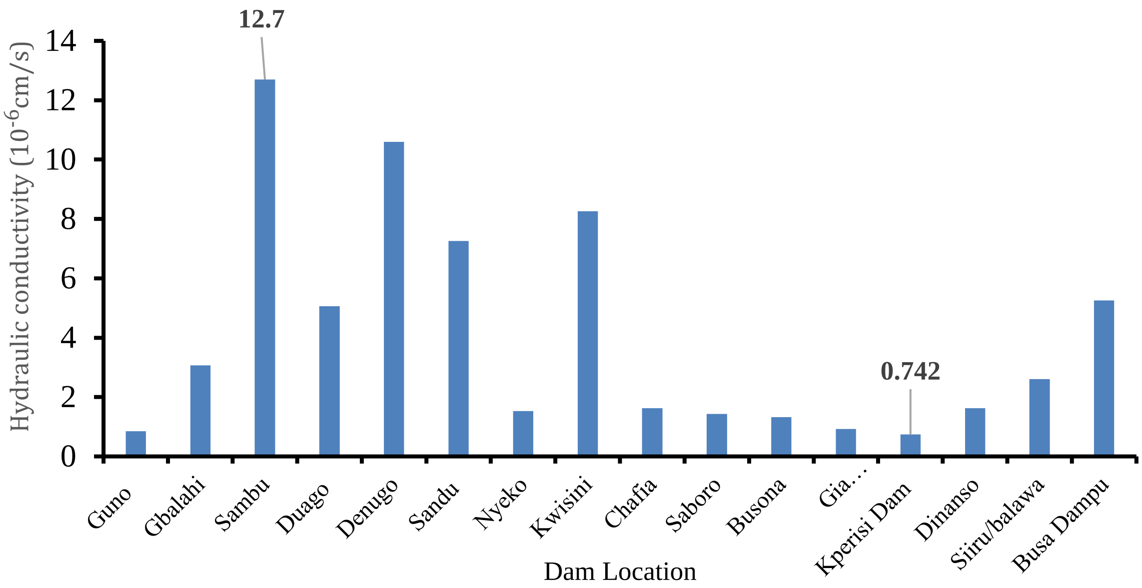


Figure 4.1: Hydraulic Conductivity (Ksat)

Source: Umukiza *et al.* (2024)

The lowest and highest hydraulic conductivity of all the study dam embankments ranged from 0.742×10^{-6} to 12.7×10^{-6} cm/s for Kperisi and Sambu which are located in the Upper West and Northern region respectively. Conversely, Nyeko dam's Ksat was found to be 1.53×10^{-6} cm/s. For Kperisii dam, the Ksat was found to be 0.742×10^{-6} cm/s, indicating lower hydraulic conductivity. Bulk density (BD) values ranged from 1.52 to 1.69 g/cm³, consistent with reported densities of compacted earth dam materials. Overall, the observed variations in Ksat and BD can be explained by materials used that could be from the vicinity of the dam which are often different in nature of soil (heterogeneous) properties.

In the context of earth dam, high Ksat indicates that these areas have higher permeability, potentially increasing the risk of seepage which may lead to catastrophic failures of dam (Calamak and Kentel, 2014). The bulk density values fall within the soil properties range reported for Guinea Savanna soils of Northern Ghana, indicating that the embankment materials and compaction conditions are representative of typical regional earthen structures (Yeboah *et al*., 2022). Furthermore, seepage studies on earthen dams in the Northern Region, such as the Bontanga Dam, highlight the importance of hydraulic conductivity and soil properties in controlling seepage discharge and dam safety (Sibale *et al.*, 2025). Therefore, seepage should not be significant enough to erode material from inside the dam body.

Moreover, due to the scarcity of materials with homogeneous properties in sites near the dam, earthen dams show high variability of hydraulic properties (Galindo *et al*., 2020). Also, different compaction levels, and overall load-bearing capacity considered for construction of dam embankments can lead to variation of geotechnical characteristics (Calamak and Kentel, 2014). Nevertheless, due to uncontrolled seepage and inadequate material and filter zonation can lead to dam failures, and consequently have devastating impact upon humankind and the environmental health (Utepov *et al*., 2022).

4.1.1 Structural Conditions of Constructed Dams and Reservoirs

Given the important expectations and investments being made on dams, it was important to assess and ascertain the safety of the small dams and their reservoirs. Safety inspections were carried out on all critical sections of the structural, and non-structural defects, and engineering characteristics. The assessment of reservoir condition, upstream, downstream embankment and spillway revealed good, fair and lack of maintenance, poor to very poor conditions. Detailed findings from the studied dams and reservoir across the Northern, Upper West, Upper East, and Savannah regions are presented in Tables 4.1, 4.2, 4.3 and 4.4 for each inspected dam respectively.

The reservoirs in good conditions had high structure integrity and were free of vegetation, algae, and debris indicative of regular maintenance, whereas the presence of vegetation, algae, and debris revealed poor maintenance leading to reduced storage and reduced overall safety and functionality of the reservoir (Tomás *et al*., 2013).

Table 4.1: Characteristics and Status of Inspected Dams and Reservoirs in Northern Region

Name of Dam	Spillway and Up/Downstream Embankment Construction Material	Reservoir Conditions	Conclusions on Structural and Reservoir Observations
Gbalahi	The observed materials on topsoil were made of loam-sand, underlain by lateritic gravel grading to hardpan. There was no rip-rap, but upstream embankment was stable and the downstream slope was protected with grasses. Spillway was eroded but properly located.	The reservoir was in good condition; no presence of grasses, algae, debris, etc. The reservoir perimeter did not show any signs of seepage or leakage.	There was no significant operation or maintenance issues noted. Generally, few construction techniques were employed.
Guno	Materials used for embankment construction are made of compacted soil from the current reservoir. Upstream and downstream embankment were not protected. Spillway: degraded and eroded, partially obstructed by shrubs; some cracks visible; location seems suboptimal causing inefficient water discharge.	The reservoir was not well-maintained, had degraded and eroded spillway with presence shrub growth.	Cattle grazing on the embankment and overall conditions of the dam were characterized by lack of embankment protection, erosion of earthfill material, poor operational control, and insufficient maintenance practices, which collectively reflect a low level of engineering and dam safety compliance.
Sambu	Materials used in construction are compacted, homogeneous silty-sand, upstream embankment covered deposition and poor protection of downstream slope. Spillway is narrow, partially blocked by sediment and vegetation; minor cracks on side walls; slope erosion visible	The reservoir areas were full of vegetation, algae, indicating shallow water depth, hence low water stored.	The dam exhibits inadequate maintenance and lack of erosion protection on both upstream and downstream embankment slopes, resulting in overall poor condition.
Sandu	Construction materials were homogeneous clay-sand, with grass on upstream embankment and poor protection of downstream slope. Spillway was found eroded channel possibly undersized for peak flows.	The reservoir was full of vegetation and algae, indicating shallow water depth and low water storage.	The reservoir and dam embarkment upstream and downstream suffered from a lack of maintenance. Overall dam condition classified as poor, reflecting inadequate embankment protection, erosion, and deficient operation and maintenance practices.
Nyeko	Embankments are made of earth and rockfill with riprap on its upstream side whilst downstream side is protected by grass. Spillway was well-located, structurally sound, no cracks or erosion.	Overall condition of the reservoir was good. The stilling basin is sound.	Spillway was well located and had adequate capacity. Dam was safe, operated safely, and was maintained in a safe condition. The overall condition was good.

Source: Umukiza *et al.* (2024)

The inspection on selected dams and reservoir was carried out also in Upper West region on five (5) dams. Structural integrity, reservoir conditions, and overall maintenance status are presented in Table 4.2.

Table 4.2: Characteristics and Status of Inspected Dams and Reservoirs from Upper West Region

Name of Dam	Spillway and Up/Downstream Embankment Construction Material	Reservoir Conditions	Conclusions on Structural and Reservoir Observations
Dinaso Boo	Earth fill embankment, upstream was not protected by rip-rap. The spillway was poorly constructed in lined stones, low causing significant water loss; risk of erosion and inefficient discharge.	Overall dams' condition is good and there was vegetation explaining potential loading of sedimentation and reservoir is good.	Presence of vegetation can probably lead to seepage. Spillway is very wide (15m) and low, with large volume of water loss.
Busa Dampu	Embankment is made with well consolidated homogenous soil, upstream protected with rip-rap. Good maintenance, spillway concrete; earth and rock fill, structurally sound	The reservoir was well maintained. Easy accessibility with practicable roads.	The overall condition of the dam/ reservoir was satisfactory, no outstanding sign of distress, erosion, seepage and cracks.
Siiru Balawa	Concrete used for spillway rip-rap upper side of the embankment, and downstream protected by grass.	No presence of vegetation in the reservoir and storage reservoir seems safe.	No signs of distress, erosion seepage or any other structural issues were noticed.
epersii	Embankment constructed with earth and rock fill, upstream with rip-rap and spillway with concrete.	Presence of siltation. Excessive vegetation in reservoir.	Maintenance is required. Buffer zone between catchment and reservoir is necessary.
uago	Embankment was protected rip rap upstream. Downstream slope protected by grass. However, the dam wall has been breached.	The reservoir exhibited significant growth of grasses and algae; lack of maintenance, the reservoir was reduced because of embankment failure and inadequate sediment removal.	Based on the on-site inspection, there is need to repair the damaged section of the dam. Silt removal, and regular maintenance are necessary to ensure sustainable water storage.

Source: Umukiza *et al.* (2024)

Furthermore, the evaluation followed to selected dams and reservoirs in Upper East Region and the findings from site inspections are presented in Table 4.3.

Table 4.3: Characteristics and status of Inspected Dams and Reservoirs from Upper East Region

Name of Dam	Spillway and Up/Downstream Embankment Construction Material	Reservoir Conditions	Conclusions on Structural and Reservoir Observations
Chafia	Downstream slope protection is ensured by vegetative cover and upstream slope with a riprap	Overall reservoir was in good condition; however, buffer zone is required to separate cropland and reservoirs' upstream.	No sign of spillway chute or dam wall overtopping observed and maintenance improvement is encouraged to maintain good conditions and performance

Gia Bagania 2	Downstream and upstream sides of embankments were protected with grass and riprap respectively. Spillway is made of concrete but height was at the level of reservoir and sand bags were used to increase its height.	Reservoir is in poor condition, characterized by limited effective storage capacity and buffer is necessary to separate the catchment from the reservoir.	Lack of maintenance as spillway is eroded to a lower level.
Gia Kwosongo Busona	Material erosion was observed and absence of a rip-rap on the upstream side.	Upstream was eroded, presence of trees on downstream embankment and no buffer zone observed.	There is lack of protection of the dam wall and the structures as well as erosion on the upstream side.
Saboro	Upstream slope has riprap and downstream has vegetative cover and presence of trees promotes water seepage.	Overall observations and findings indicate good reservoir condition.	No signs of spillway chute weir overtopping but spillway drain was found with deficiencies in design and maintenance evidenced by vegetation encroachment and lack of proper flow conveyance control.
Denugu	Riprap was used on upstream and downstream slope protected with grasses.	Fair reservoir conditions but spillway at its lower level had potential of causing water loss from the reservoir.	Reservoir was fairly in good condition

Source: Umukiza *et al.* (2024)

Table 4.4: Characteristics and status of Inspected Dams and Reservoirs from Savannah Region

Dam Location	Spillway and Up/Downstream Embankment Construction Material	Reservoir Conditions	Conclusions on Structural and Reservoir Observations
Kwisini	Downstream slope was not protected and erosion was noticeable at the upstream. Spillway presents potential risk of uncontrolled overflow.	Lack of maintenance suggesting fair condition for buffer zone.	Poor dam condition was observed, as evidenced by extensive embankment erosion, absence of slope protection, uncontrolled vegetation growth, unrestricted livestock access, and lack of routine maintenance. These deficiencies collectively indicate a reduced level of structural integrity and non-compliance with standard earth embankment dam safety and maintenance requirements.

Source: Umukiza *et al.* (2024)

The presence of riprap upstream and vegetative cover downstream of the dam embankment, and concrete spillways at sites like Saboro, Busona, and Siiru/Balawa contributed to relatively good condition and structural integrity of these reservoirs.

Generally, the results presented in Tables 4.1, 4.2, 4.3 and 4.4 highlight the importance of maintenance in each of the inspected dams. These findings are supported by previous studies conducted by Talukdar *et al.*(2019); Chen *et al.* (2019) and Adamo *et al.* (2020a) which stated that despite the good construction measures, lack of maintenance of dam resulted in its failure. For instance, the study by Adamo *et al*. (2020), explored key factors in embankment dam safety, including protection methods, reservoir management practices, and the impact of poor construction techniques and maintenance issues. The study concluded that, despite considerable research and innovation, dam failures still occur, pointing to gaps in users' knowledge and involvement in necessary maintenance and safety measures. As the demand for water increases to support industrial and agricultural growth, the construction and heightening of dams is expected to rise. It is therefore crucial to emphasize stringent safety precautions and meticulous maintenance to ensure the structural integrity of these projects, addressing the gaps identified to mitigate risks and prevent future failures (Chen *et al*., 2019). Presence of vegetation and algae can significantly impact dam performance and reservoir conditions, particularly in scenarios involving shallow water and poor design (Ricci *et al*., 2019; Stave *et al*., 2005). Vegetation and siltation affect both the structural integrity of the dam and the ecological balance within the reservoir, aligning with the issues as observed by Li *et al*. (2019).

Poor spillway maintenance and uncontrolled vegetation contribute to sediment accumulation, reduced reservoir capacity (Adamo *et al*., 2020b). These conditions exacerbate maintenance challenges and elevate the risk of dam failure. Reservoirs with good structural design and maintenance practices, including well-protected embankments and effective spillways, tend to maintain better water quality and storage capacity (Rubinato *et al*., 2020). Conversely, poorly maintained dams show signs of degradation, such as shallow water depths and structural erosion. Therefore, the selection of construction materials, proper compaction, combined with adequate protective measures like riprap and grass cover, frequent maintenance is essential for preventing erosion and ensuring structural integrity.

4.2 Assessment and Impact of Catchment Characteristics on Runoff Generation

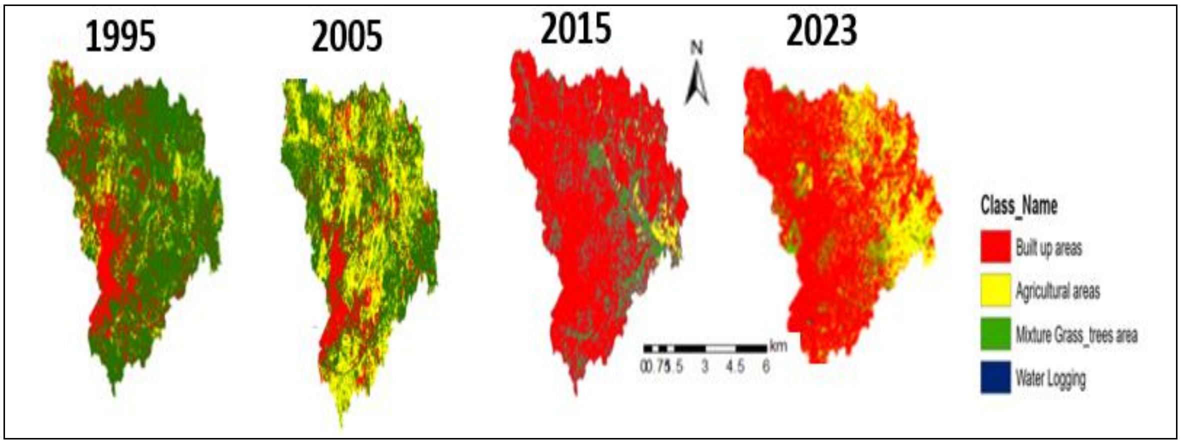
4.2.1 Accuracy Assessment

The accuracy of landuse and landcover (LULC) classification for categorised images from 1995, 2005, 2015 and 2023 was systematically evaluated for each class using confusion matrix analysis. Rwanga and Ndambuki (2017) reported that, accuracy assessment was evaluated by constructing confusion matrix which compared the classified maps with reference to classified maps. User accuracy, producer accuracy, and overall accuracy were used for the evaluation in this study. The assessment results for all classified LULC maps revealed an overall classification accuracy exceeding 80 % (Appendix 4). This means that the classified satellite images have shown acceptable agreement with ground truth data. Mohamed (2021) reported that the overall accuracy beyond 80 % is recommended as excellent accuracy.

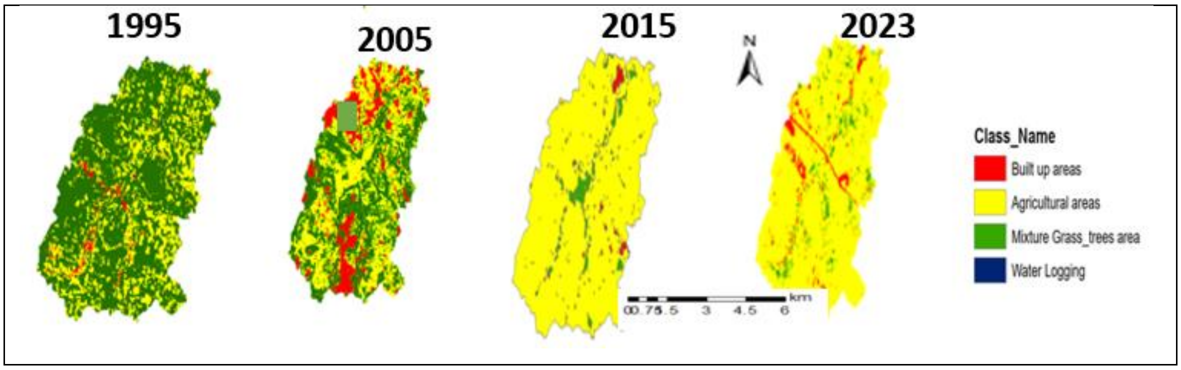
4.2.2 Analysis of LULC Dynamics from Study Areas in Northern Region

Analysis of LULC dynamics in the study areas of the Northern region was conducted and four (4) major LULC classes namely; agricultural lands, water bodies, built-up, and grasslands (open savannah) were identified in the study catchments. Distribution and composition of different LULC classifications highlighted diverse trends in LULC across the studied catchments as shown in Figure 4.2. The analysis of different LULC types categorized each studied catchment into different LULC classes and the corresponding coverage area (km^2) for each year is presented in Table 4.5.

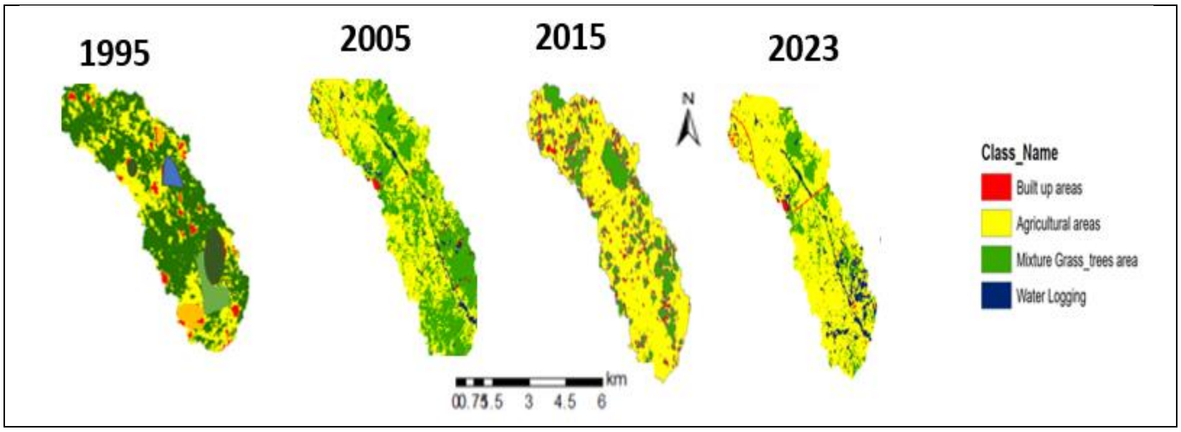
Gbalahi



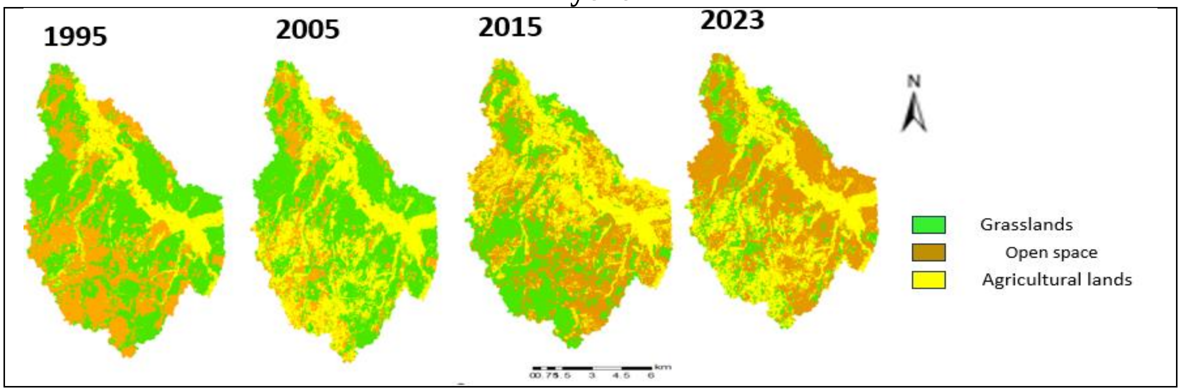
Guno



Sambu



Nyeko



Sandu

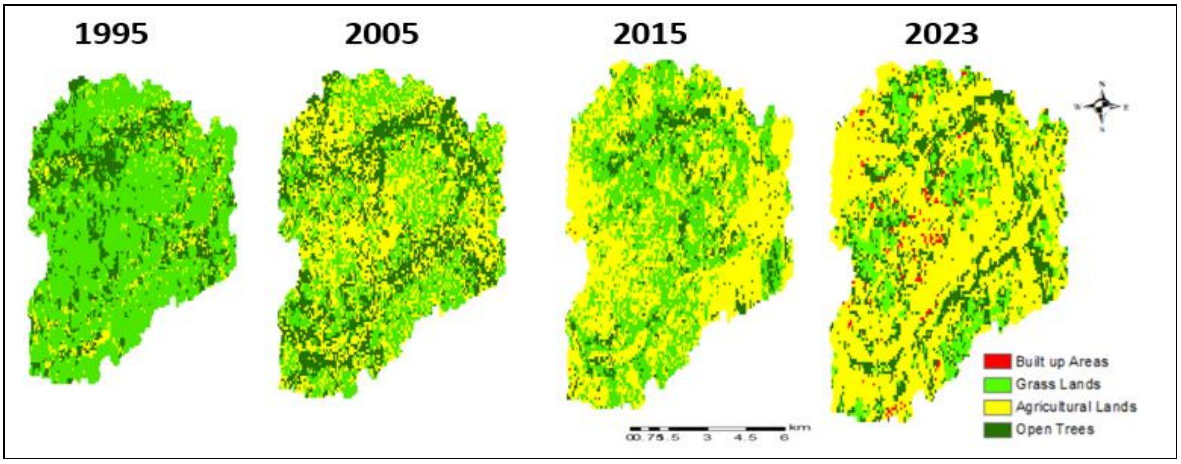


Figure 4.2: LULC of the Study Areas in Northern Region

Source:Umukiza *et al.* (2024)

Table 4.5: LULC Classes and Dynamics in Analysed Catchments in Northern Region

Sub-Catchment	LULC Classes	Area (km^2)				% Change
		1995	2005	2015	2023	1995-2023
Guno	Built-up area	1.6	2	2.1	2.3	+2.3
	Grasslands	18.5	5.1	3.1	1.46	-92.11
	Agricultural lands	9	22.1	24.1	25.64	184.89
	Waterbody	0.4	0.3	0	0.3	-25
Total Area		**29.5**	**29.5**	**29.5**	**29.5**	
Gbalahi	Built-up area	21	36.86	68.72	80	+280.95
	Grasslands	79.8	24	21	19	-76.19
	Agricultural lands	9	48.9	20	10.5	+16.67
	Waterbody	0.2	0.24	0.28	0.5	-150
Total Area		**110**	**110**	**110**	**110**	
Sambu	Built-up areas	2.72	3.5	3.96	4.5	+65.44
	Grasslands	22.1	18	7.3	5.5	+75.11
	Agricultural lands	13.6	17	27.24	28.5	+109.56
	Waterbody	0.08	0	0	0	-100
Total Area		**38.5**	**38.5**	**38.5**	**38.5**	
Sandu	Agricultural lands	2.92	4.05	5.65	6.43	+21.20
	Built-up area	0.49	0.50	0.54	0.54	+10.2
	Grassland	6.07	4.01	3.43	1.55	-74.46
	Open trees	1.09	2.00	0.93	2.04	+87.16
Total Area		**10.56**	**10.56**	**10.56**	**10.56**	
Nyeko	Agricultural lands	21.35	26.47	40.52	44.07	+106.42
	Grasslands	57.39	54.74	37.10	19.32	-66.34
	Open space	41.91	39.45	43.03	57.26	36.63

Total Area	**120.65**	**120.65**	**120.65**	**120.65**	

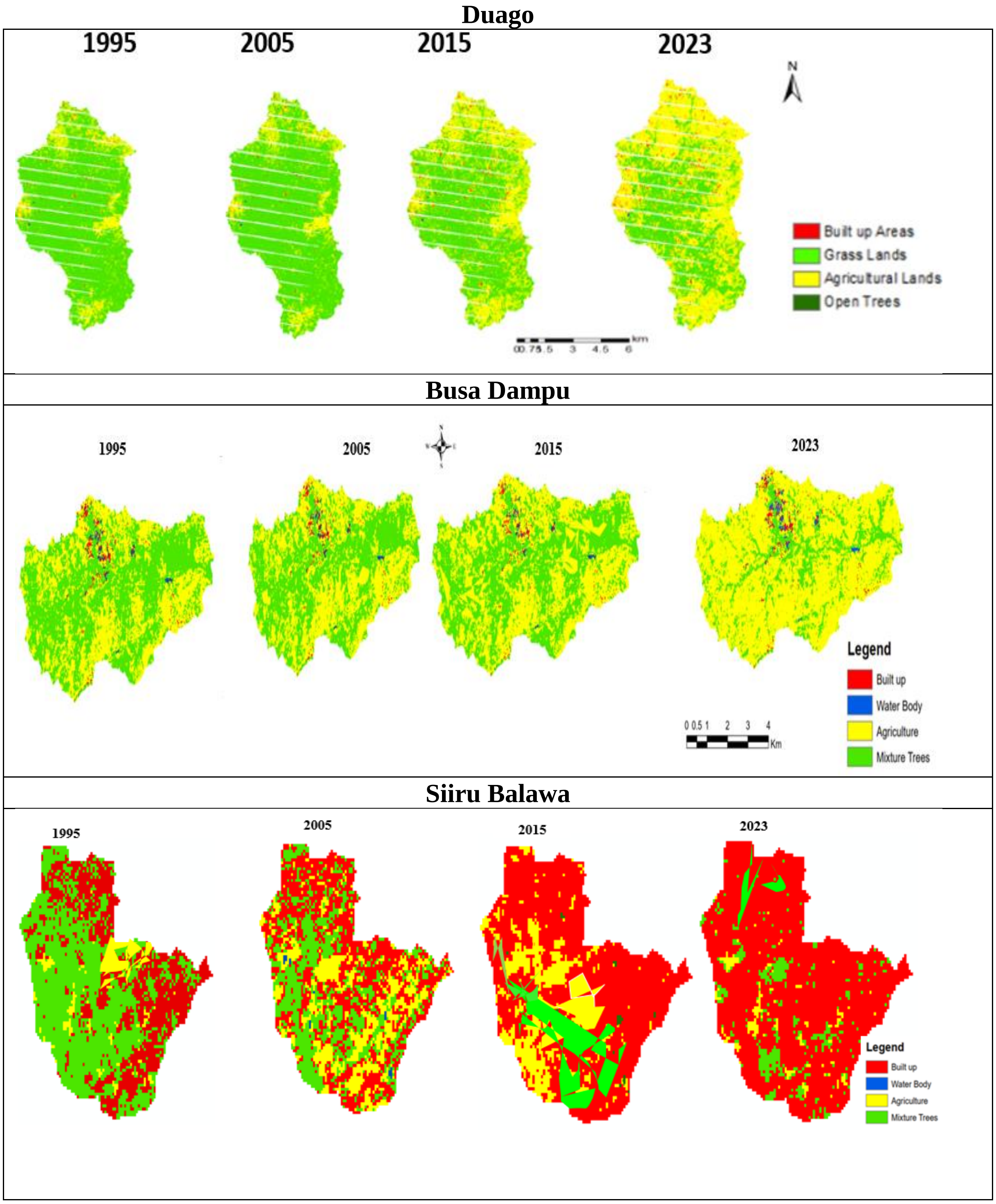
Note: +Sign shows increase and – sign shows decrease

The LULC analysis presented in Table 4.4 indicates changes across the study catchments and demonstrating that each catchment has experienced unique trends over the period. Grasslands and mixed trees/forests decreased while agricultural lands and built-up areas increased.

In the Guno sub-catchment, an increase in built-up area of 43.75 % from 1.6 to 2.3 km² between in 1995 and 2023 was observed. Grasslands experienced a drastic reduction, decreasing from 18.5 to 1.46 km² while agricultural lands increased substantially (184.89 %) from 9 to 25.64 km², reflecting agricultural expansion. The 1995-2023 LULC analysis for Gbalahi Sub-catchment showed a noticeable change in built-up from 21 to 80 km², substantial increase of 280.95 % showing urban sprawl. While grasslands were characterised by significant decline of 76.19 % from 79.8 to 19 km². Spatio-temporal changes from 1995-2023 for Sambu sub-catchment indicated an increase of 109.56 % in agricultural land from 13.6 to 28.5 km², suggesting a shift towards agriculture followed by built-up areas that registered an increase of 65.44 % while grasslands showed a significant decline of 75 %. From 1995 to 2023, the changes showed 106.42 % increase in agricultural lands for Nyeko sub-catchment whilst grasslands declined sharply with a decrease of 66.34 %. For Sandu sub-catchment, agricultural lands increased from 2.92 km² to 6.43 km² and built-up showed an increase of 10.2 % from 0.49 to 0.54 km² while grassland decreased significantly with a rate of -74.46 %. The results obtained are in agreement with recent literature findings which revealed that LULC pattern has drastically changed in which the built-up and agricultural area increase year after year as long as human beings continue to exist, urbanization continues (Guzha et *al*., 2018; Shaina and Prince, 2018; Dionizio and Costa, 2019).

4.2.3 Analysis of LULC Dynamics from Study Areas in Upper West Region

The LULC dynamics of different classes were detected and analysed from Landsat 5 (ETM), Landsat 7 (ETM+) and Landsat 8 (OLI) imageries focused on four (4) periods from 1995, 2005, 2015 and 2023 for each study period, as shown in Figure 4.3 and the analysis and detection of different LULC classes prevalent in each catchment are presented in Table 4.6.



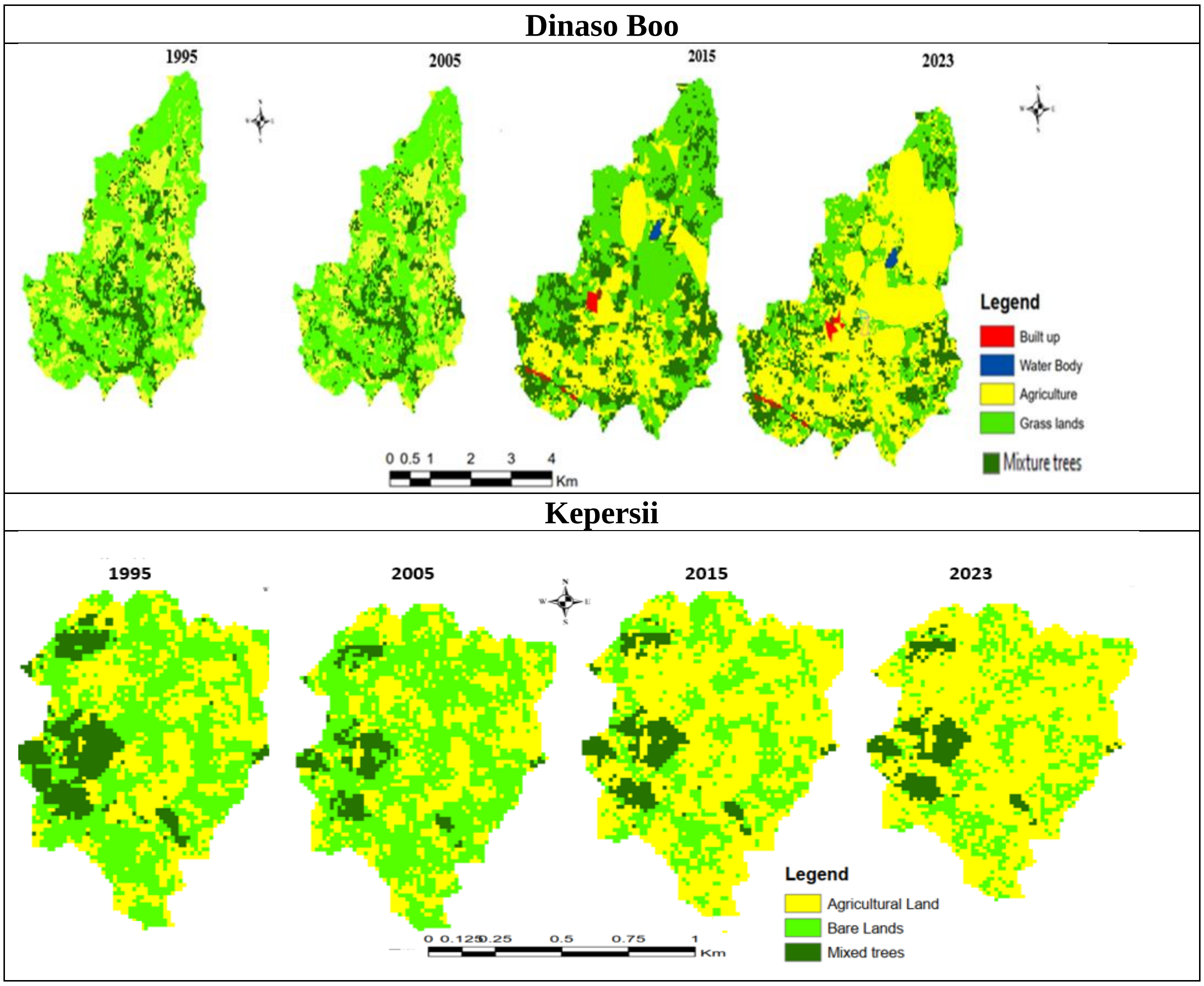


Figure 4.3: LULC of the Study Areas in Upper West Region

Source: Umukiza *et al.* (2024**)**

Table 4.6 : LULC Classes and Dynamics in Analysed Catchment from Upper West Region

Sub-Catchment	**LULC Classes**	**Area (km^2)**				**% Change**
		1995	**2005**	**2015**	**2023**	**1995-2023**
Dinaso Boo	Mixed tree/ forest	1.41	2.00	0.50	0.001	-100
	Agricultural land	2.49	3.40	6.19	7.92	+218.07
	Grasslands	4.81	3.20	1.90	0.65	-86.49
	Water Body	0.001	0.10	0.11	0.13	-
Total		**8.70**	**8.70**	**8.70**	**8.70**	
Busa Dampu	Agricultural land	15.10	17.56	22.16	29.73	+96.89
	Built-up area	1.22	1.42	2.82	2.49	+104.1
	Grasslands	22.00	19.13	13.15	5.86	+73.36
	Water Body	0.08	0.28	0.27	0.33	+312.5
Total Area		**38.40**	**38.40**	**38.40**	**38.40**	
Siiru Balawa	Agricultural land	0.10	0.50	0.80	0.86	+760
	Built-up area	1.64	2.15	2.57	2.81	

						+71.34
	Grassland	2.64	1.81	1.07	0.79	-70.08
	Mixed forest	0.1	0	0.02	0.12	+20
	Waterbody	0.08	0	0	0	-100
Total Area		**4.46**	**4.46**	**4.46**	**4.46**	
Kepersii	Agricultural lands	1.16	2.18	2.300	2.45	+111.21
	Bare lands	2.05	0.96	0.828	0.70	-65.85
	Open forest	0.22	0.29	0.304	0.29	+31.82
Total Area		**3.43**	**3.43**	**3.43**	**3.43**	
Duago	Agricultural lands	28.22	35.87	39.53	58.21	106.27
	Built up Area	3.27	3.64	4.29	4.32	+31.19
	Grasslands	74.34	66.49	62.18	43.46	-41.54
	Water Body	0.20	0.04	0.04	0.05	-75
Total Area		**106.04**	**106.04**	**106.04**	**106.04**	

Note: +sign show increase and – sign shows decrease

Source: Umukiza *et al.* (2024)

From the analysis, it was generally found that agricultural land and built-up areas were showed an increase trend, whereas grasslands and mixed forest were reducing. For instance, over the time of analysis (1995-2023), agricultural land expanded from 2.49 to 7.92 km² indicating a 218 % increase, while grasslands decreased by 86.49 % from 4.81 to 0.65 km² at Dinaso Boo sub-catchment. Built-up areas also increased from 1.22 to 2.49 km² a rate of 104.1 %, while grasslands decreased significantly from 22 to 5.86 km². For Busa Dampu sub-catchment, changes in agricultural lands from 15.1 to 29.73 km² was observed with an increase of 96.89 %. At Siiru Balawa sub-catchment, agricultural lands increased from 0.1 km² to 0.86 km², built-up area increased from 1.64 to 2.81 km² while a decrease of 70.08 % occurred in grasslands over the same period. At Duago sub-catchment, agricultural lands changed from 28.22 to 58.21 km² with an increase of 106.27 % and built-up area expanded from 3.27 to 4.32 km² while grasslands decreased significantly (41 %) from 74.34 to 43.46 km².

Across all catchments, there was an increase in agricultural lands and built-up areas. These trends can be attributed to growing demand for agricultural land driven by population growth and food security concerns, as well as urban sprawl (Yonaba *et al*., 2021). This pattern mirrors global trends, where agricultural expansion is a leading cause of habitat loss (Larbi *et al*., 2019).

The findings align with the study by Fufa *et al*. (2023), which reported significant changes in landuse within Vea catchment, Ghana. Specifically, they found that cropland expanded from 10.9 to 51.98%, while grassland and mixed vegetation areas decreased from 54.8 to 18.14 % and 31.7 to 22.73%, respectively between 1998 and 2022.

4.2.4 Analysis of LULC Dynamics from Study area in Upper East Region

The analysis of LULC dynamics from study area in Upper East region as shown in Figure 4.4 and the analysis of LULC changes is presented in Table 4.7. Results shows that for Denugo sub-catchment covering total are of 67.81km^2, has seen a remarkable shift towards agricultural expansion and built-up at the expense of natural grasslands between 1995 and 2023. For instance, agricultural lands increased dramatically (+340.74 %) from 11.61 to 51.17 km^2, while a sharp decline from 50.68 to 11.16 km^2, a reduction of 77.98 % in grasslands was noticed. Gradual increase in built up areas from 4.97 to 6.48 km^2 registered a change rate of +30 %. However, Busona, Gia Bagania, Saboro Sub-catchments, were fund having total areas of 0.76, 0.54 and 0.84 km^2 respectively. Such small catchments limited the generalizability to draw significant changes about landcover and landuse trends. Therefore, due to their very small total areas (less than one square kilometer), they were excluded from LULC analysis.

Denugu

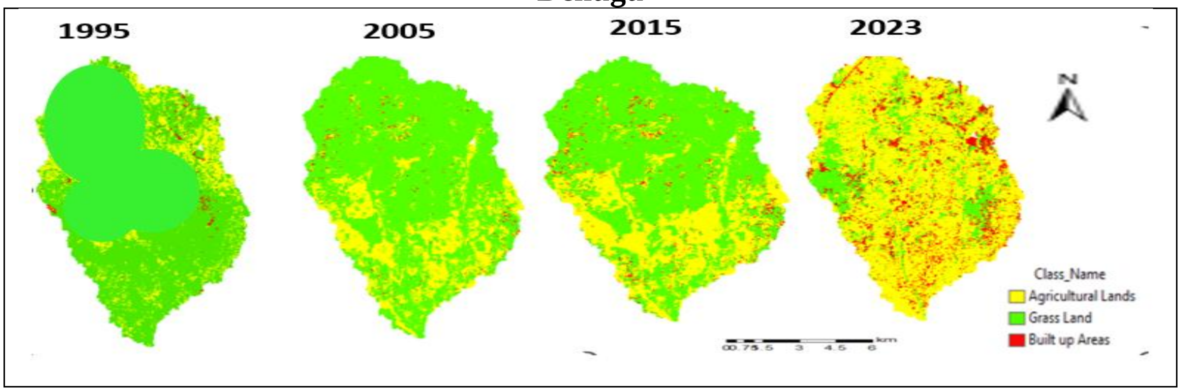


Figure 4.4: LULC of the Study areas in Upper East Region

Source: Umukiza *et al.* (2024)

Table 4.7: LULC Classes and Dynamics of Analyzed Catchment from Upper East Region

Sub-Catchment	LULC Classes	Area (km^2)				% Changes
		1995	2005	2015	2023	1995-2023
Denugo	Agricultural lands	11.61	14.66	22.29	51.17	+340.74
	Built up Areas	4.97	5.52	5.34	6.48	+30.38
	Grasslands	50.68	47.64	40.18	11.16	-77.98
	Water Bady	0.54	00	00	00	-100
Total Area		**67.81**	**67.81**	**67.81**	**68.81**	

Note: +sign show increase and – sign shows decrease

The substantial growth in agricultural areas may be indicative of changing land use practices, potentially driven by population growth, economic factors, or agricultural policies (Othow *et al*., 2017; Mohamed, 2021; Umukiza *et al*., 2021 and Umukiza *et al*.2022).

4.2.5 Analysis of LULC Dynamics from Study area in Savannah Region

LULC classes and their dynamics over the years 1995, 2005, 2015 and 2023 for the Kwisini sub-catchment are shown in Figure 4.5 and the analysis of different transitions LULC classes is presented in Table 4.8.

Kwisini

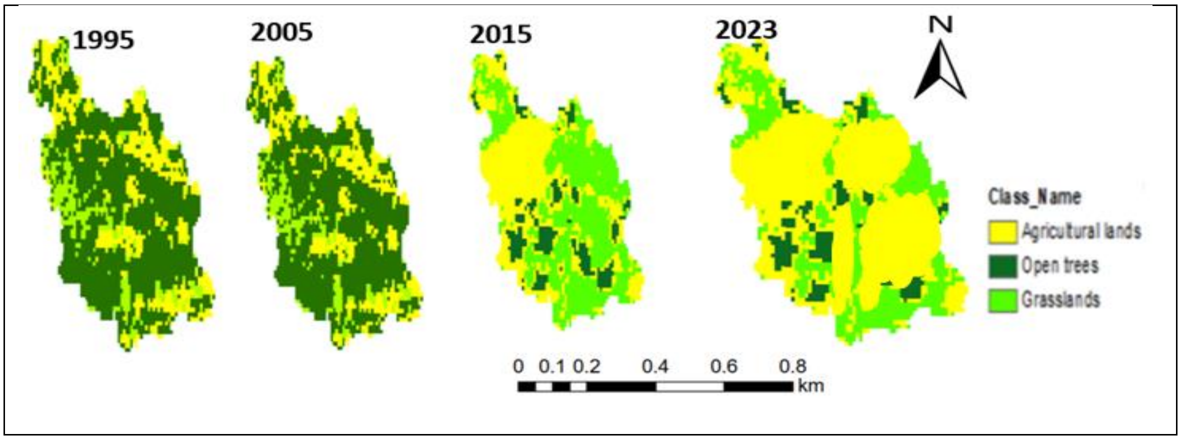


Figure 4.5: LULC of the Study areas in Savannah Region

Source: Umukiza *et al.* (2024)

Table 4.8: LULC Classes and Dynamics in Analysed Catchment from Savannah Region

Sub-catchment	LULC Classes	Area (km²)				% Change
		1995	2005	2015	2023	1995-2023
Kwisini	Agricultural lands	0.27	0.69	1.15	1.61	+496.3
	Grasslands	1.74	1.36	1.16	0.67	-61.49
	Open forest/ trees	0.58	0.54	0.29	0.31	-46.55
Total Area		**2.59**	**2.59**	**2.59**	**2.59**	

Note: +sign show increase and – sign shows decrease

Significant change rates were noticeable, with an increase of 496.3 % in agricultural lands detected between the periods of 1995 and 2023. However, the area covered by grasslands has decreased significantly, with a reduction of over 61 % whilst the area of mixed trees/open forest declined by 46.55 % over the same period.

The observed trends of LULC dynamics between 1995 and 2023 for Kwisini sub-catchment highlights significant transformation of land, possibly due to increased human activities. Importantly, the results reflect significant increase in agricultural lands indicating a shift towards more intensive agricultural practices. However, both grasslands and open forest /trees have seen substantial decline, suggesting a reduction in natural vegetation cover, potentially due to anthropogenic activities and climate change (Yonaba *et al*., 2021a; Yonaba, *et al*., 2021b).

4.2.5. Overall Analysis of LULC Dynamics in Studied Catchments

The overall detection rates of LULC changes in the study catchments in northern Ghana, are shown in Figure 4.6. The results show a significant increase in agricultural lands and a corresponding decrease in grasslands and forest/open space over the study period (1995-2023). Across all catchments, the study results indicated a high level of conversion of agricultural/arable lands that emerged as the dominant land use category, followed by built-up areas displaying remarkable expansion while grassland and open forest/vegetation decreased from over the period. For instance, in Northern region, Guno registered a significant increase in agricultural lands by 184.89 %, while grasslands decreased by 92 %. Similarly, Gbalahi sub-catchment experienced an increase of 280.95 % in built- up areas and a reduction of 76.19 % in grasslands. In Upper West region, significant LULC changes were observed as in Busa Dampu, an increase of 96.89 % in agricultural lands and an increase of 104.1 % in built up areas was recorded. This attribution is in line with recent findings which revealed that LULC pattern has drastically changed, in which built-up area increases year after year due to population growth (Guzha *et al*., 2018; Shaina and Prince , 2018; Dionizio and Costa, 2019). Denugo sub-catchment in Upper East region experienced the most significant changes with agricultural lands increasing by 340.74 % while grasslands declined by 77 %. The observed expansion in agricultural lands can probably be attributed to increase in food demands leading commercial production of food crops and adoption of mechanized agriculture in the region. From the perspective of hydrological engineering, drastic reductions in natural cover, declining forests, and increases in built-up areas have significant engineering and hydrological implications that can lead to altered hydrological cycles, reduced groundwater recharge, and increased surface runoff. Therefore, anthropogenic activities leading to the conversion of natural landcover, such as urbanization and intensification of agricultural activities, can enhance the extent of impervious surfaces (Guzha *et al*., 2018; Shaina and Prince, 2018; Dionizio and Costa, 2019). However, since the increase in impervious surfaces affects the infiltration rates, and increases surface runoff, the engineering response finds its way, such as the necessity to construct small dam alongside land management practices as well. Figure 4.6 shows overall LULC rates from the period of 1995 to 2023.

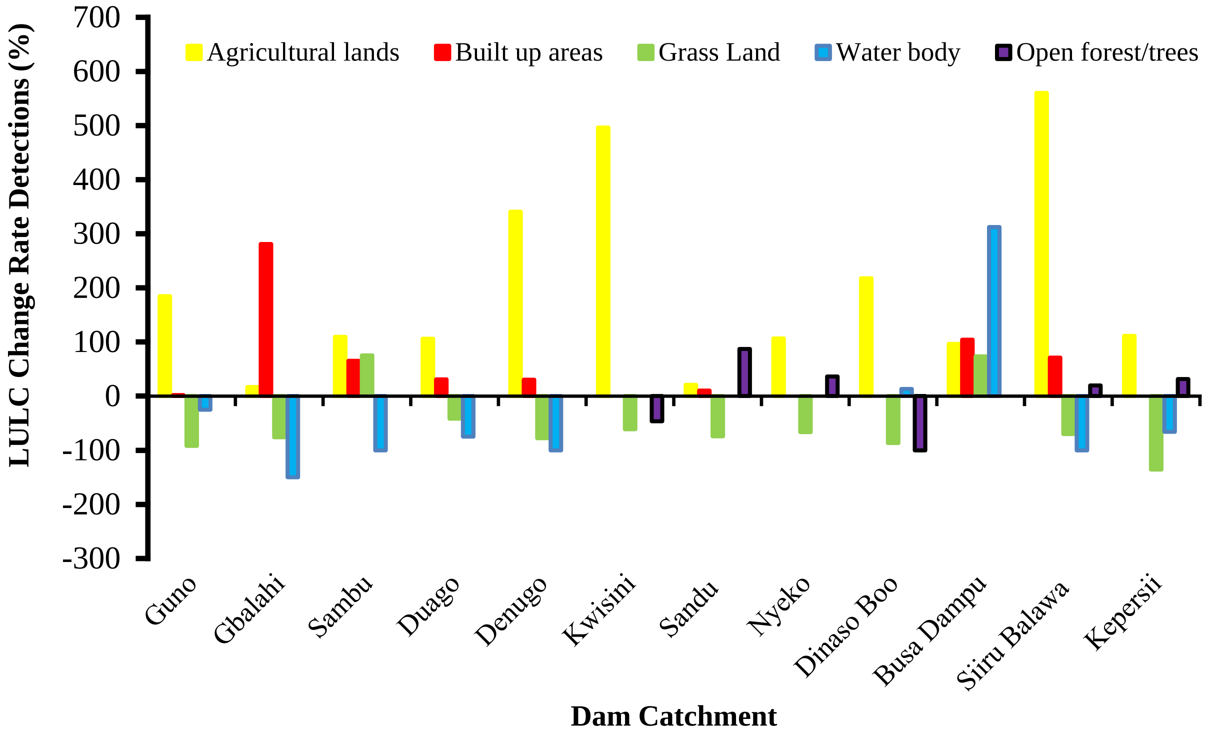


Figure 4.6: LULC Dynamics between 1995-2023

Source: Umukiza *et al.* (2024)

4.2.6 Digital Elevation Model of the Study Catchments

As Digital Elevation Models (DEMs) play crucial role in the context of water resource management, it was therefore important to analyse essential information, enabling the potential placement of check dams such as topography and slopes. This study analyzed different catchments using DEM Maps (Appendix 8) obtained from the Shuttle Radar Topography Mission (SRTM) satellite data, ensuring a spatial resolution of 30 m for each of the respective catchments. The catchment areas were identified by delineating the boundaries of watersheds, with the range of elevation varying substantially from one area to another. The minimum, average and maximum elevations were recorded for each catchment areas (Figure 4.7), providing insights into topographical diversity of the study area.

In terms of water resource management, these variations in elevations, have implications for the distribution of runoff, influencing the potential placement of check dams in considered study areas. For instance, areas with steeper gradients have more runoff, whereas flat areas facilitate more recharge (Hassan *et al*., 2021). This suggests that different catchments areas might experience varying levels of overall hydrological behaviour. However, despite the fact that the area receives an equal amount of precipitation, the spatial patterns appear of runoff to be controlled significantly by landcover and slope.

DEMs are critical for delineating watersheds and analyzing catchment characteristics, which are essential for small dam site selection and design. They provide detailed topographic data, enabling accurate hydrological modeling to predict water flow and potential flood zones (Mallick *et al*., 2021). In context of small dam construction, DEMs are instrumental in assessing topography and identifying optimal dam locations by analyzing factors such as elevation, slope, and drainage patterns. This helps planners in determining the most effective sites for water storage, ensuring structural stability and maximizing reservoir capacity (Dávila-Hernández *et al*., 2022).

Figure 4.7 shows data about the maximum, average, and minimum ground elevation of the study areas.

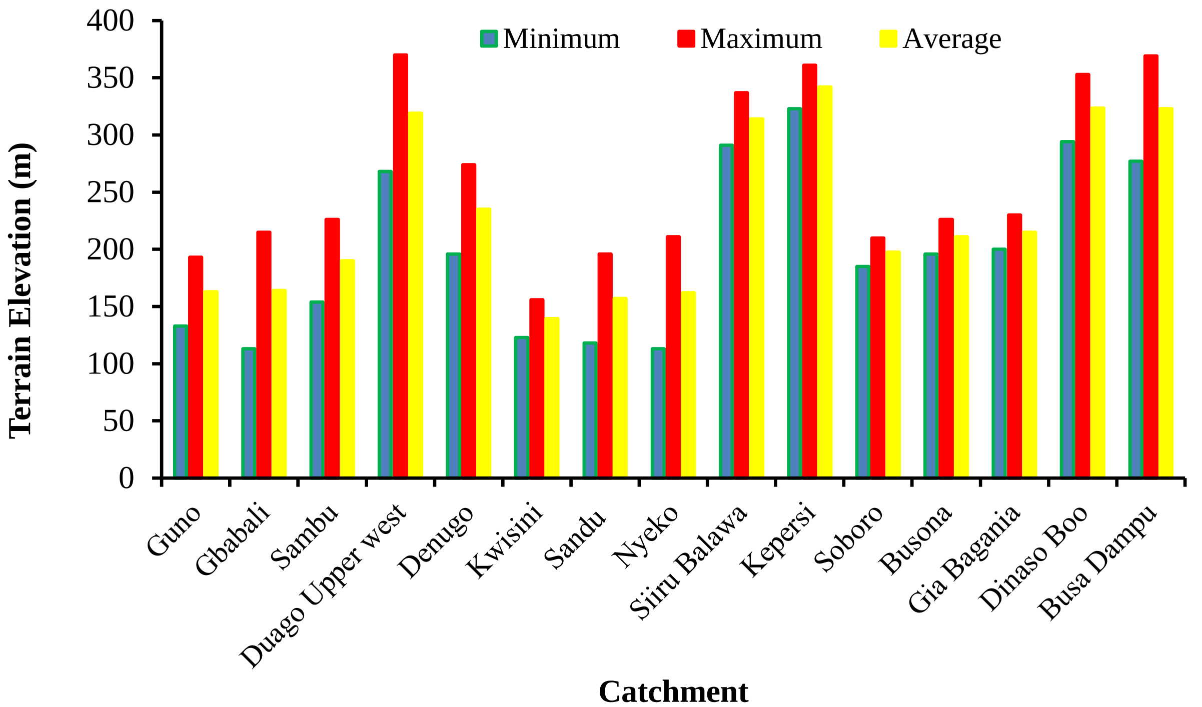


Figure 4.7: Maximum, Minimum, and Average Terrain Elevation from Digital Elevation Model

Source: Umukiza *et al.* (2024)

4.2.7 Runoff Characterization and Curve Number

Focusing on the effects of LULC changes to determine the Curve Number (CN) as an important parameter related to the generation of runoff, average CN values were determined from the analyzed LULC and are presented in Figure 4.8.

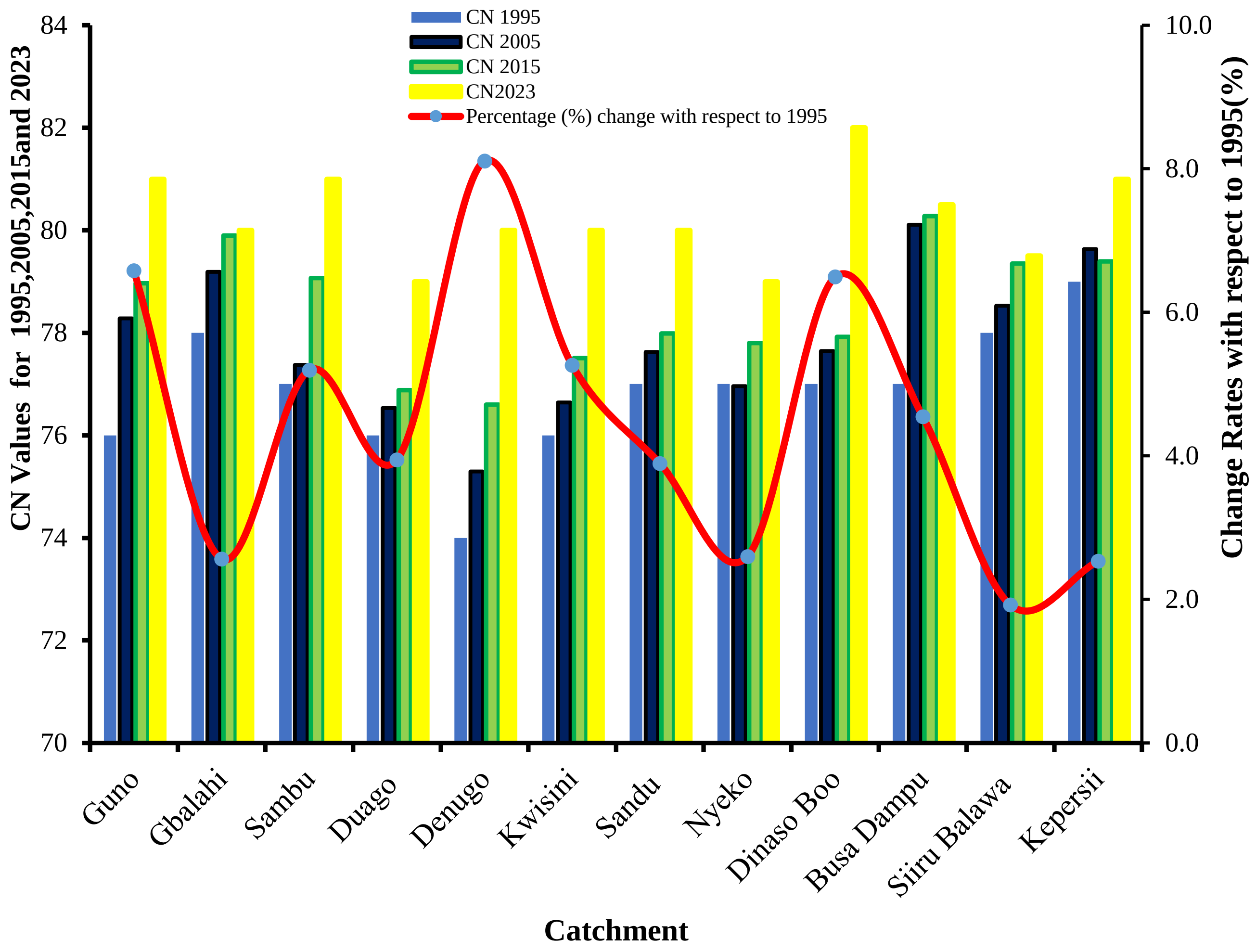


Figure 4.8: Curve Number Characteristics of the Study Catchments

Source: Umukiza *et al.* (2024)

By comparing the CN values of 1995 and 2023 for each catchment, an increasing trend was observed. This increase relates to the changes in each catchment's ability to manage rainfall runoff over the period. Comparing the data from 1995 and 2023, Figure 4.9 provides an understanding on how landuse changes have influenced CN trends over this period.

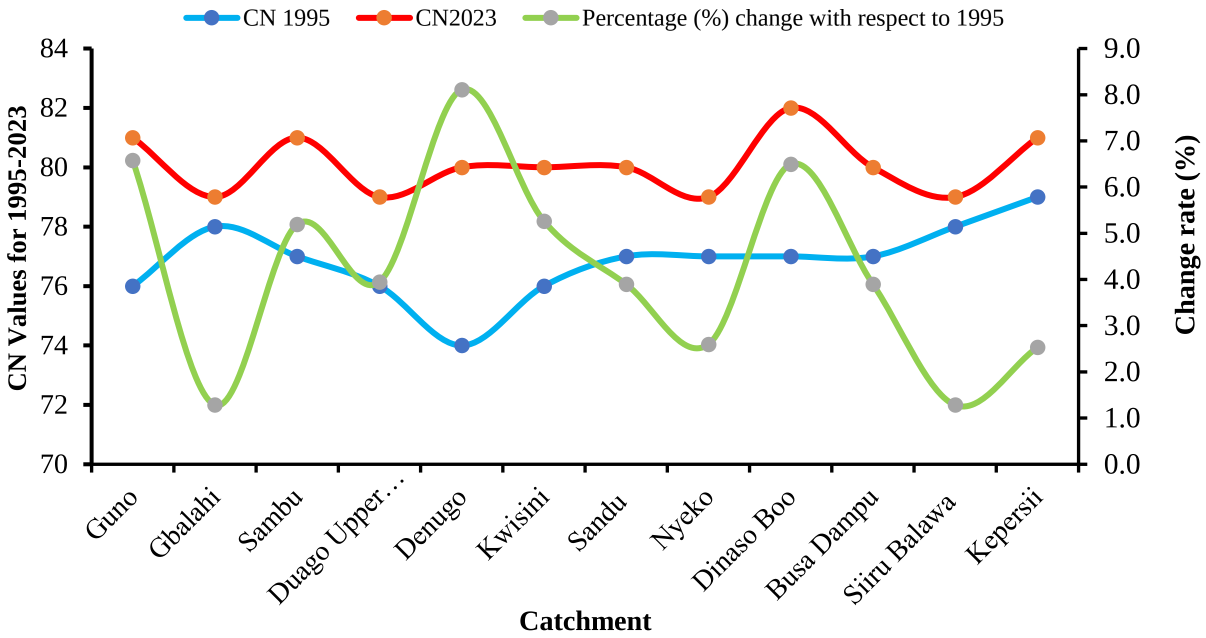


Figure 4.9: CN Values of Catchment Areas with Respect to 1995 Conditions

Source: ***Umukiza et al. (2024)***

The results reported in Figure 4.8 and 4.9 showed that the CN for the investigated areas was increasing and noted as 13.88, 3.88, and 9.85 % with respect to the 1995 condition for Guno, Gbalahi, and Sambu catchments, respectively. These findings contribute to our understanding of how LULC changes over time influence hydrological characteristics of various catchments in northern Ghana, thus having significant implications on water resource management and sustainable development in the catchment areas. This is in agreement with previous studies (Stewart *et al.*, 2012; Grimaldi *et al.*, 2013; Kowalik and Walega, 2015; Zeng *et al.*, 2017; Vojtek and Vojteková, 2019; Hu *et al.*, 2020) from which it was worth noting that runoff in the given watershed is dependent on LULC, hydrologic soil group and rainfall occurrence. The CN values offer essential insights into the hydrological characteristics of each catchment (Gajbhiye *et al.*, 2014; Wróbel and Boczoń, 2020). A study by Vojtek and Vojteková (2019) analyzed the change in surface runoff based on LULC between 1949 to 2017 in Radisa basin, Western Slovakia concluded that the surface runoff was affected by deforestation. By comparing the CN values of the years 1995 and 2023, the changes in each catchments' ability to manage surface runoff can be observed over the period (Umukiza *et al*., 2024). It is worth noting that runoff in a given watershed is dependent on landuse and landcover (Kowalik and Walega, 2015). The increase in CN values suggests that potential runoff generation has increased in the catchments (Kang and Yoo, 2020). This shows how LULC dynamics impacted the CN parameters within the 1995 - 2023 period and, hence, influenced runoff generation. The increase of CN could be attributed to various factors such as LULC, urbanisation due to population growth, intensification of mechnisation agriculture leading to soil compaction, and alteration in natural vegetation (Yonaba *et al*., 2021a). Therefore, it can be stated that land management practices play a crucial role in influencing runoff dynamics, which are pivotal for effective water resource management. Effective land management practices are essential to consider for controlling runoff. LULC changes such as deforestation, urbanisation and agricultural expansion can significantly alter the natural hydrological cycle by increasing or decreasing runoff volumes, time of concentration and intensity of water flow (Umukiza *et al*., 2021; Shaibu and Issaka, 2024). These changes often result in an increase in impervious surface, which enhances surface runoff (Mwangi *et al*., 2017; Owar *et al*., 2017).

Due to its direct and indirect effects on infiltration, evaporation and sediment dynamics, LULC has a significant influence on hydrological and geomorphological pathways (Odiji *et al*., 2021; Nkonge *et al*., 2023). Vojtek and Vojteková (2019), stated that in small basins of Golestan province, Iran, subjected to great deforestation and increase in urbanization, resulted in an increase of 5 % in CN strongly enhanced the surface runoff.

Furthermore, the distribution of runoff follows the same trend of precipitation, as the correlation trend was remarkable (Figure 4.10).

The annual maximum rainfall of the respective catchments supported to the analyses of how different factors interplay and influence runoff generation in the study areas.

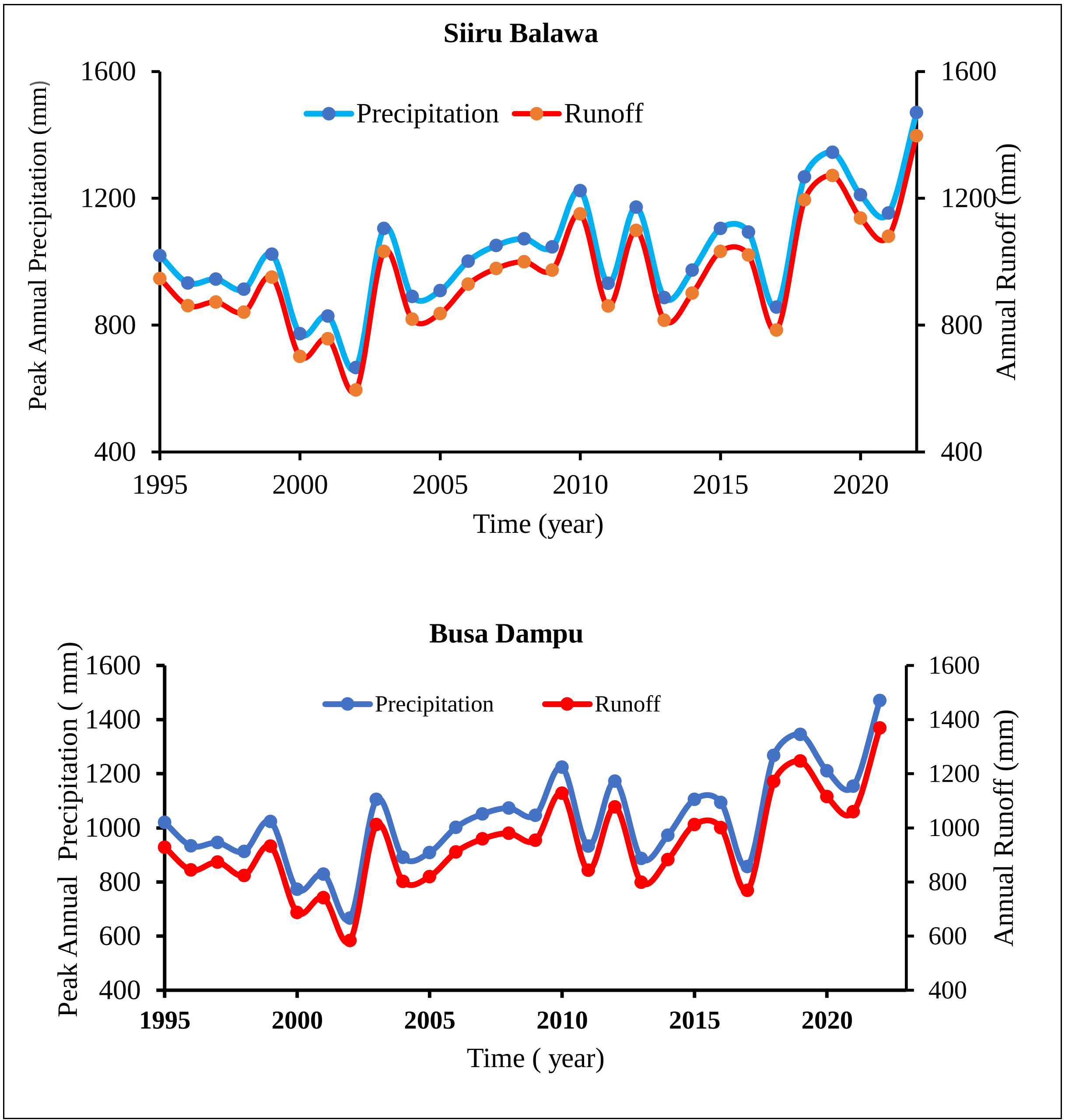


Figure 4.10a: Generated Annual Runoff Trends from Different Catchments

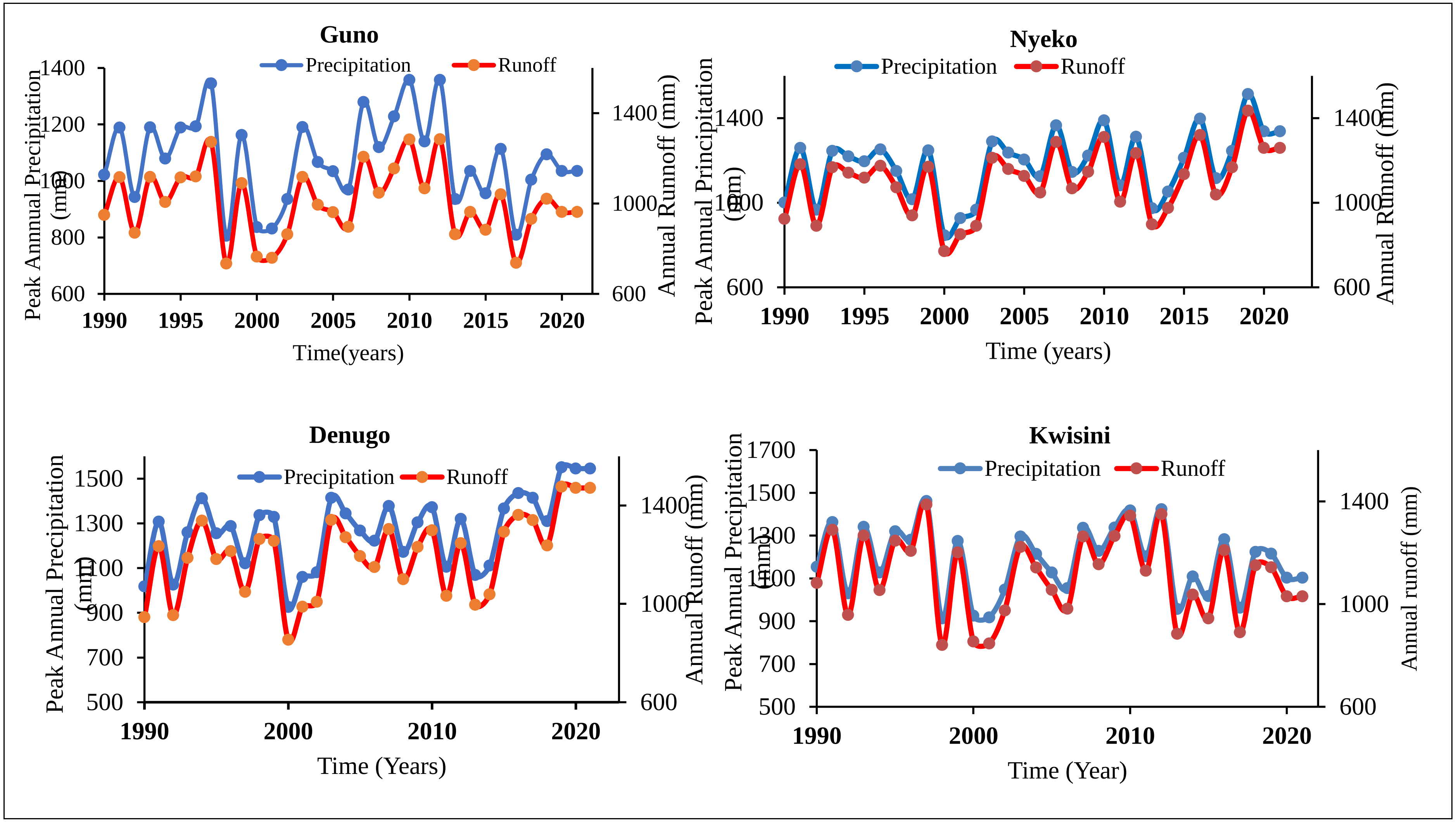


Figure 4.10b: Generated Annual Runoff Trends from Different Catchments

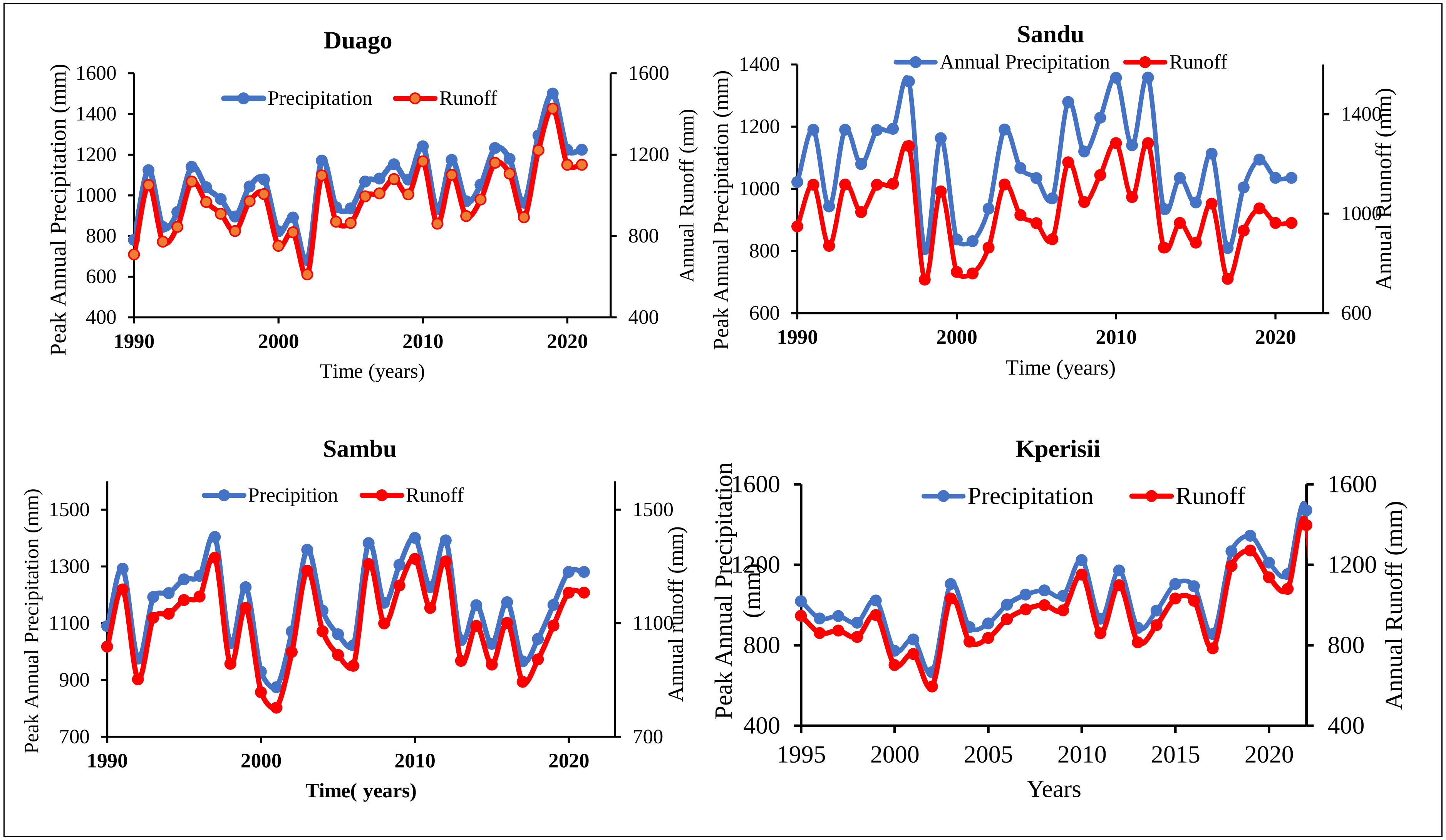


Figure 4.10c: Generated Annual Runoff Trends from Different Catchments

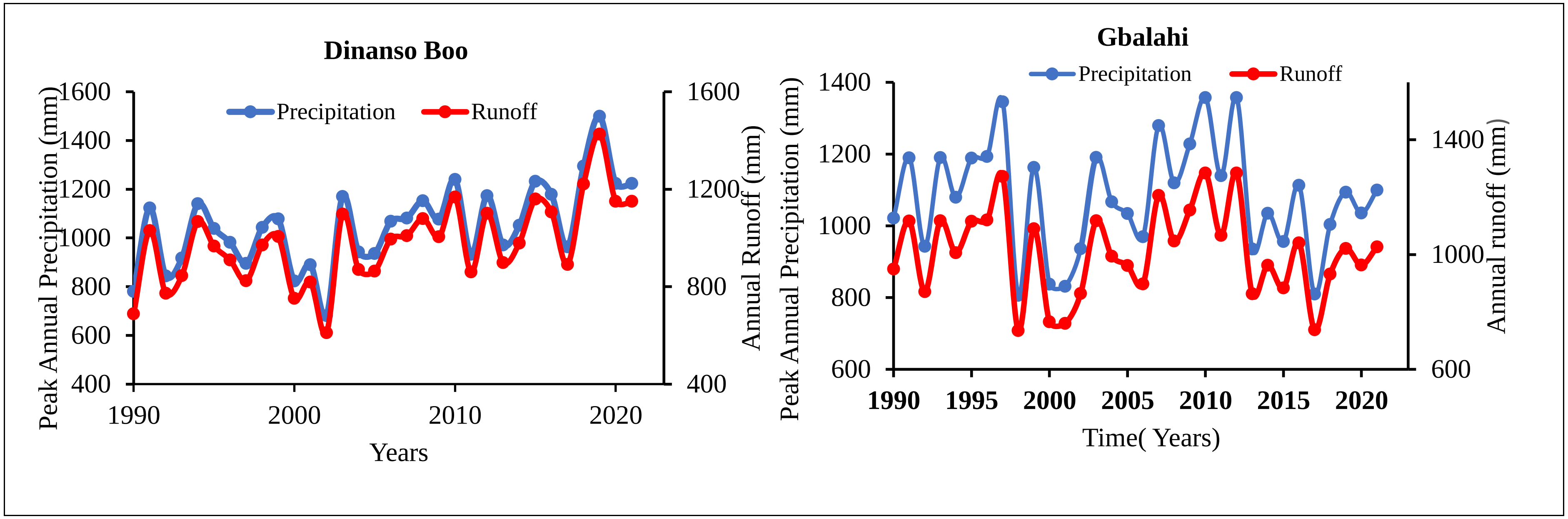


Figure 4.10d: Generated Annual Runoff Trends from Different Catchments

Generally, an understanding the catchment nature relating to the landuse trajectory is very important key for water resources management. Archana *et al.* (2015), defined urbanization as the process of landuse alteration highlighting its significant role in transforming landscapes and reallocating land functions. This transformation often results in increased impervious surface areas, leading to the increase in surface runoff. The study conducted by Namulunda (2010) in the Sosiani River basin in Kenya, examined the correlation between LULC changes and river peak discharge. Their findings revealed a direct association between an increase in farmlands and urban areas and a corresponding rise in peak discharge, while a reduction in forest areas was also linked to the same increase in peak discharge.

Figure 4.11 presents the minimum, maximum and average total annual runoffs of the study catchments.

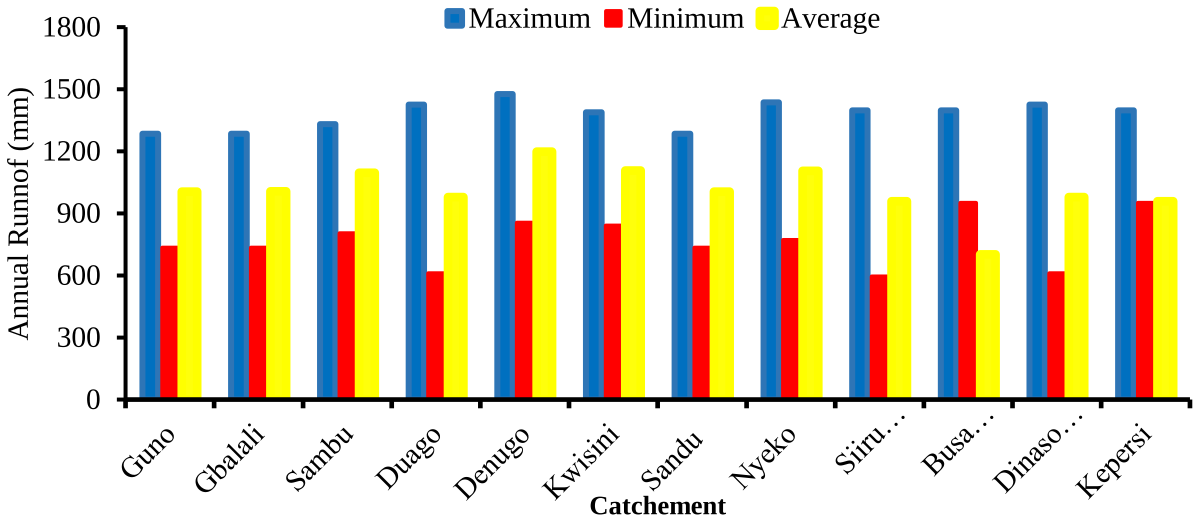


Figure 4.11: Estimated Annual Surface Runoff of Study Catchments

Significant variability in annual surface runoff was observed across the study areas, reflecting differences in topography, soil type, vegetation cover, and rainfall patterns. Total annual runoff across the catchments ranged from 701.52 mm (50% of annual rainfall) in Busa Dampu to 1197.88 mm (72% of annual rainfall) in Denugo, with corresponding total annual rainfall ranging approximately from 900 mm to 1500 mm. The lowest average runoff occurred at Busa Dampu, while Denugo recorded the highest, demonstrating spatial heterogeneity in hydrological responses.

Analysis of minimum annual runoff revealed relatively high base flows, ranging from 585 mm (65% of annual rainfall) in Siiru Balawa to 1080 mm (72% of annual rainfall) in Busa Dampu, corresponding to total rainfall within the 900–1500 mm range. These observations indicate that even catchments with lower average runoff maintain a significant proportion of rainfall as base flow, likely due to good soil moisture retention, localized rainfall distribution, and infiltration capacity.

These runoff levels are indicative of extreme hydrological events, possibly driven by heavy precipitation events or seasonal variations that cause significant peaks in surface runoff. The higher maximum surface runoff values are critical for understanding flood risks and the capacity of catchment areas to handle large volumes of water, which is essential for water resource management and infrastructure planning.

These findings are in agreement with previous research. For instance, Yonaba *et al*. (2021) reported that the conversion of natural vegetation into cultivated areas led to a significant increase in the runoff potential under dynamic LULC inputs, illustrating the Sahelian paradox. This paradox refers to increased runoff despite declining rainfall trends, largely driven by land use change. According to the study by Gbohoui *et al.* (2021), in understanding the hydrological behaviour of watersheds in the West Africa Sahel (WAS), the findings underscored the impact of climate and environmental shifts on surface runoff within the Sahelian context. Climate and LULC have a great influence on hydrological processes (Planète *et al*., 2023), and awareness of their occurrence and respective impacts is of great importance concerning land use planning (Obahoundje and Diedhiou, 2022). However, the study by Yonaba *et al.* (2021) assessed variability and attribution of changes in surface runoff in the Sahelian watershed, noted that LULC changes exert a more dominant influence on runoff than climate variability alone, underscoring the need to prioritize land use planning in hydrological assessments.

4.3 Identification of Potential Zones for Dam Sites Location

4.3.1 Suitability Assessment of Existing Dams Location and Stream Networks

The first stage of suitability assessment drove an understanding of the appropriateness of dam's placement concerning the natural hydrological features of landscape. This stage of the study focused on evaluating the alignment of current dam locations with the available stream networks within each catchment.

The outcomes of the analysis across the studied catchments in Northern Regions of Ghana, where current dam locations were analyzed versus stream networks within the catchment are presented for Northern Region, Upper East, and Upper West, in Figures 4.12, 4.13, 4.14 and 4.15 respectively.

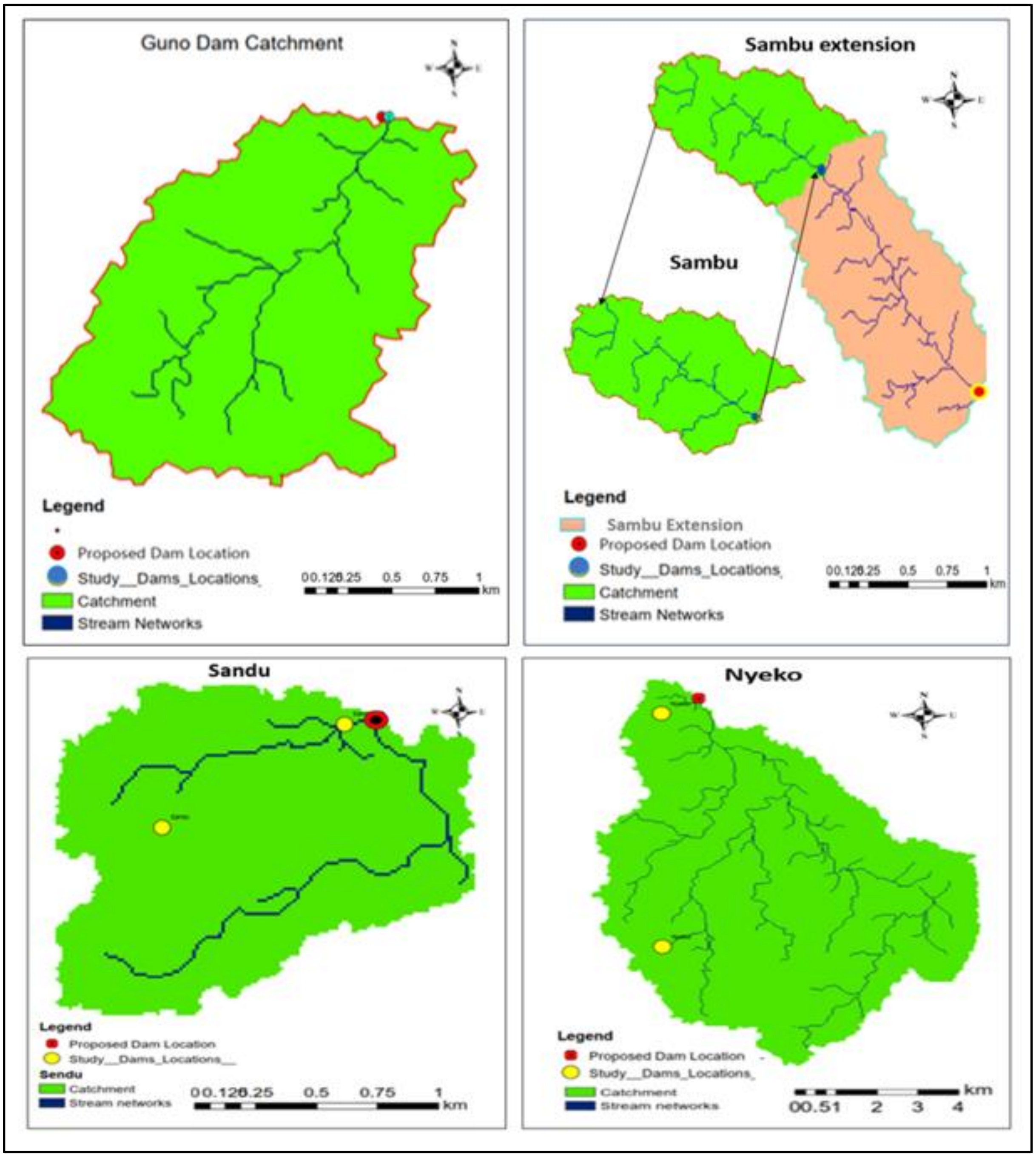


Figure 4.12: Suitability Maps Based on Stream Networks of selected Dam Catchments in Northen Region

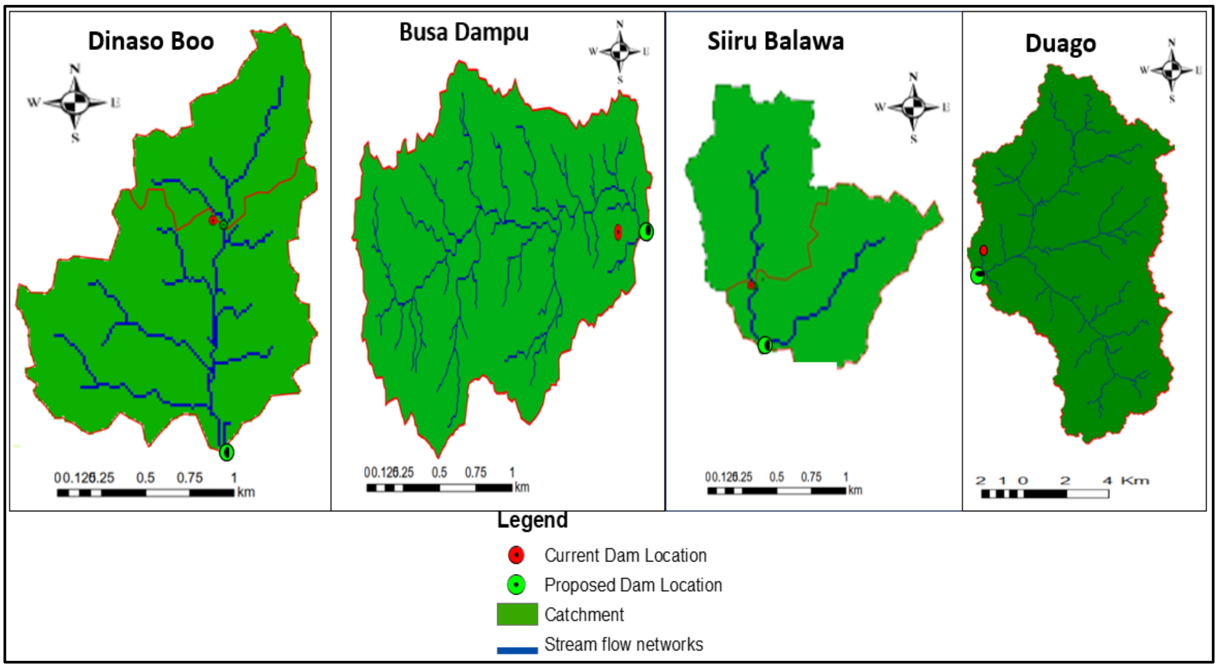


Figure 4.13: Suitability Maps Based on Stream Networks on Selected Dam Catchments in Upper West Region

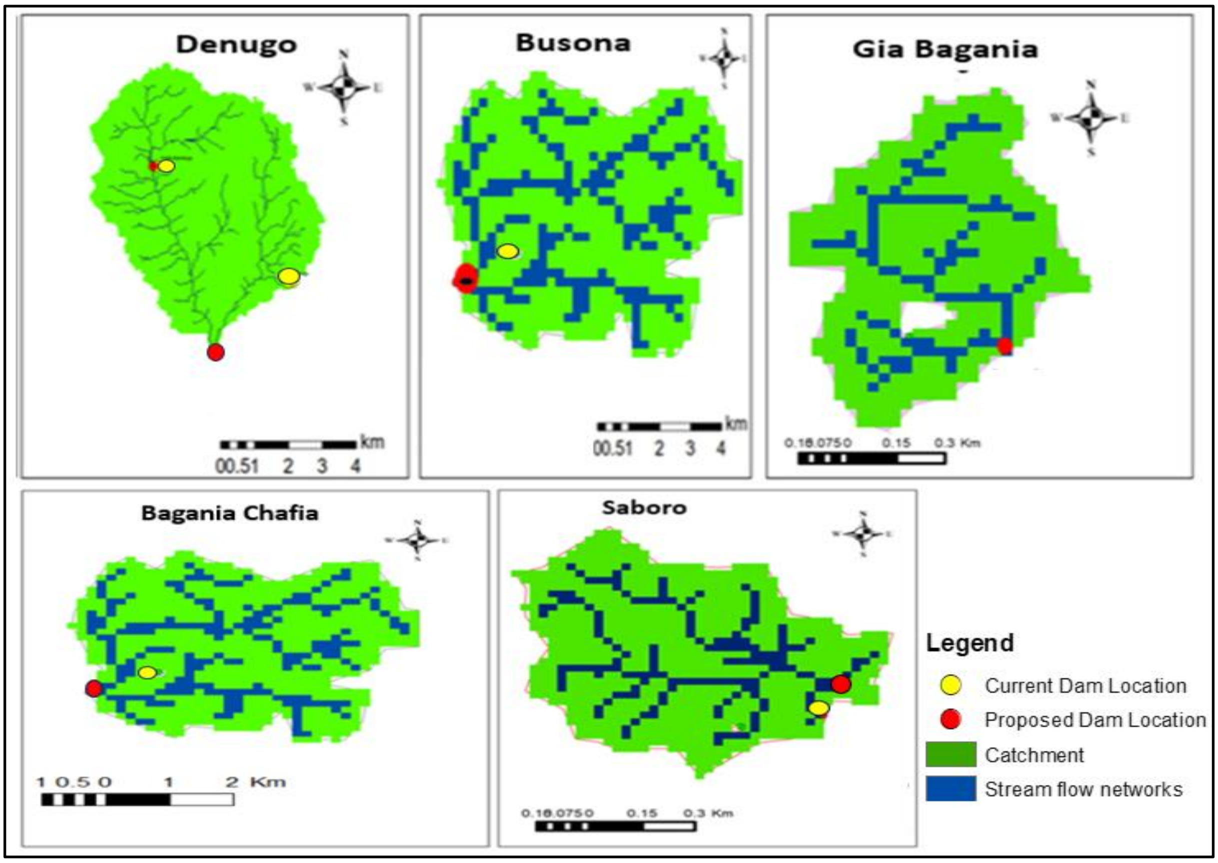


Figure 4.14: Suitability Maps Based on Stream Networks on Selected Dam Catchments in Upper East Region

In general, outcome of the analysis showed that among the 16 analyzed catchments (Figures 4.12, 4.13, 4.14), ten (10) were in reasonable distance (less than 100 m) to major stream networks and, consequently, judged relatively well located. However, for six (6) of them (Kepersii, Sambu, Duago, Denugo, Dinaso and Busona) a potential suitable relocation was proposed to maximize the catchment runoff yield.

In the pursuit of sustainable water resource management, it is indeed imperative to ensure that dams are strategically located to optimize their functionality and minimize environmental impact. After analysing each catchment, the results from the first part of this study show the assessed suitable sites based on stream network prevail in the respective catchments with the existing dam locations. Results reported in Figures 4.12, 4.13 and 4.14 highlight disparities in dam placement across the studied catchments. Some dams exhibit a considerable distance (more than 100 m) away from available stream network, indicating potential challenges in harnessing the full hydrological potential of the catchment. However, other dams were found to be strategically positioned at reasonable distances from tributaries, suggesting a more judicious selection in their locations. The usefulness of stream network in selecting optimal dam location was confirmed by Singh *et al.* (2014), who discussed the use of geospatial techniques and hydrological modeling to evaluate the suitability of dam sites within a river basin, emphasizing the importance of stream network analysis in determining the most effective and sustainable locations for dam construction.

4.3.2 Assessment of Potential Zones for Suitable Dam Siting

Identification of potential sites for improvement of water storage, was analyzed within the dams catchments namely Dinaso Boo, Denegu, Busona, Sambu, Duago and Kepersi. Analytic Hierarchy Process (AHP) method was employed for site suitability assessment through overlay analysis, facilitating the identification of suitable dam location, by considering the surrounding area and overlaying of layers such as slope, elevation, LULC, drainage density and geology was undertaken. The use of an integrated GIS and AHP approach for dam site selection, focusing on how various criteria like landuse, slope, geology among others influence significantely the suitability of Dam site (Haq and Mundher, 2024). The pairwise weighs each element against each other (Table 4.9), where each level is related to reality from the ground morphology, knowledge from literature and experts' opinions (Dortaj *et al*., 2020).

Table 4.9: Preference and Pairwise Matrices with Intensity Judgements

Criteria	Stream	DEM	LULC	Geology	Slope
Stream	1	3	2	3	4
DEM	1/3	1	2	3	5
LULC	½	½	1	2	3
Geology	1/3	1/3	½	1	2
Slope	¼	1/5	1/3	½	1
Sum	2.416	5.033	5.833	9.5	15

Source: Umukiza *et al*,(2024).

The normalized matrix was established, by dividing each entity's parameters by the sum of all from their respective column. According to our study, stream networks were given the highest importance while DEM and Geology were attributed equal value to moderate values. While the slope was attributed lower values based on its insignificance from the ground nature (flat areas). Thus, the weight used in overlay for each criterion was calculated from an average of each raw multiplied by 100 and results are presented in Table 4.10:

Table 4.10: Normalized Matrix

Criteria	Stream	DEM	LULC	Geology	Slope	Weight
Stream	0.413	0.596	0.342	0.316	0.267	39
DEM	0.138	0.199	0.342	0.316	0.333	27
LULC	0.206	0.099	0.171	0.210	0.2	18
Geology	0.138	0.066	0.086	0.105	0.133	10
Slope	0.113	0.093	0.056	0.052	0.067	6

Source: Umukiza *et al*, (2024).

With λmax was equal to 5.18, the resulting consistency ratio (CR) was acceptable (0.04) (Ahmed and Corresponding, 2011; Yasser *et al.*, 2012; Minatour and Khazaei, 2013). Moreover, CR was less than 0.1. the judgments were considered consistent (City, 2011; Yasser *et al*., 2012; Kim and Kang, 2020). CR exceeding 10 % is not reliable. Otherwise, the iteration starts again unless the result is less than 0.1(Rahmati *et al*., 2019).

The overlay analysis was operated by agreeing with all criteria layers to perform suitability maps based on superimposition activities in ArcGIS. In combination with other parameters, higher to less suitable areas of the six further analysed catchments are displayed in Figure 4.15.

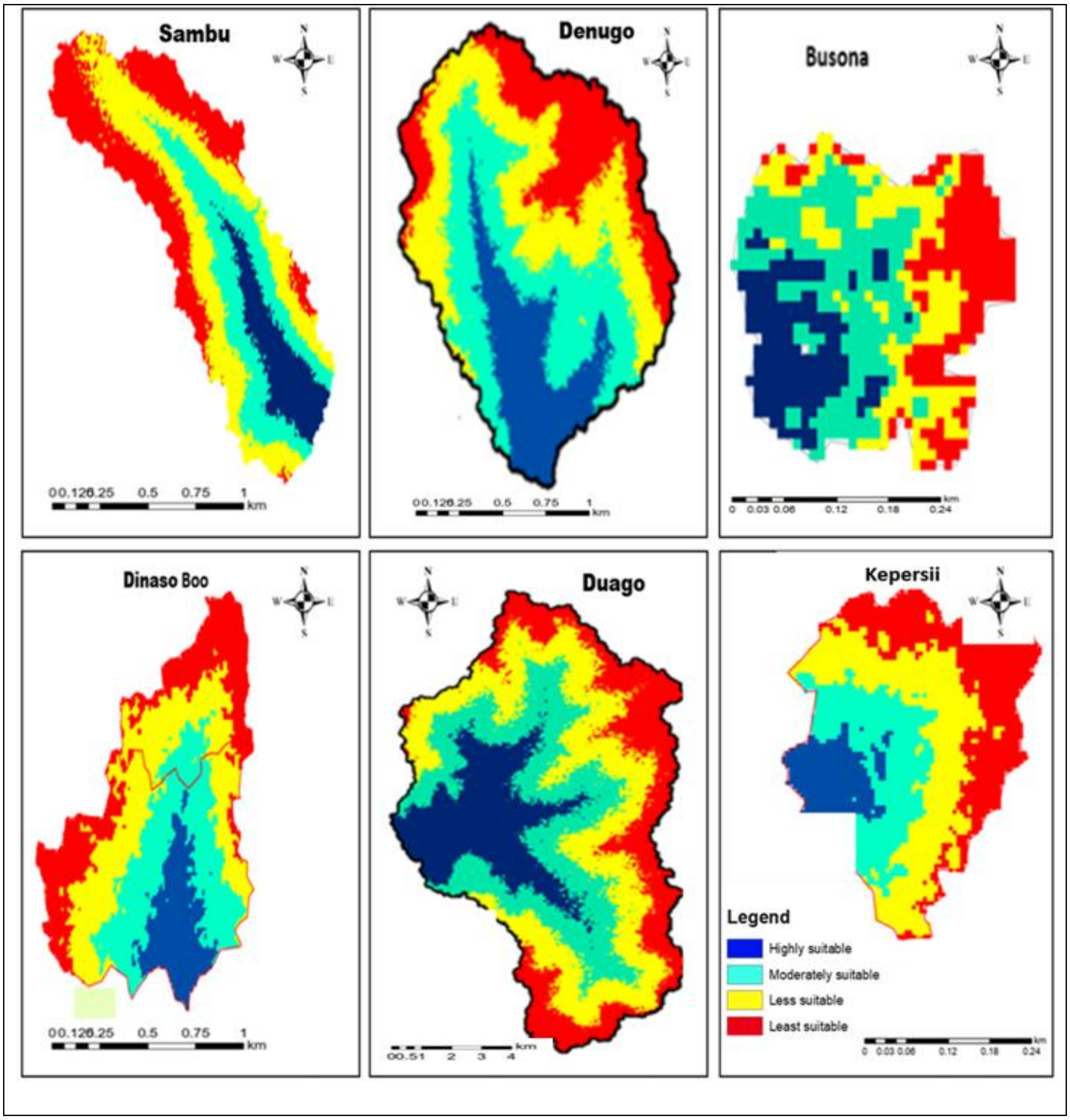


Figure 4.15: Suitability Levels for Dam Sites in the Catchment

Source: Umukiza *et al.*, (2024).

The proposed highly suitable zones can positively satisfy the potential yield of water considering the shape of the valley to construct a dam. Regarding dam planning, construction, and optimization, this visual analysis serves as fundamental step for detailed examination of each catchment's unique characteristics, facilitating informed decision- making and tailored engineering solutions.

The application of the AHP method across the investigated catchments found that six (6) small reservoirs are located far from the mainstream, and revealed distinct suitability levels as highly suitable, moderately suitable, less suitability and least suitable. The usefulness of this method was recognized as a potent and adaptable tool for resolving issues involving multiple criteria, allowing for the assessment and identification of optimal location for constructing a small earth dam within diverse catchments (Estoque, 2012; Yasser *et al*., 2012; Chezgi, 2019). Moreover, the study by Karakuş and Yıldız (2023) employed GIS-based multicriteria evaluation, considering factors like land use, slope, soil type, and proximity to water bodies. AHP method was applied to evaluate dam sites based on environmental and socioeconomic criteria (Al-Ruzouq *et al*., 2019; Karakuş & Yıldız, 2023; Zewdie & Tesfa, 2023). The integration of diverse criteria in the current study aligns with this approach but is distinguished by the detailed use of AHP for specific hydrological factors, adding novelty by incorporating detailed elevation-area-storage curves, which offer a more dynamic analysis of storage capacities.

4.3.3 Evaluation of Storage Capacities of Existing Dams

The results of current reservoirs storage capacities of each dam/reservoir area are presented in 4.16 whilst the topographical maps and details of current dams' location are presented in Appendix 6.

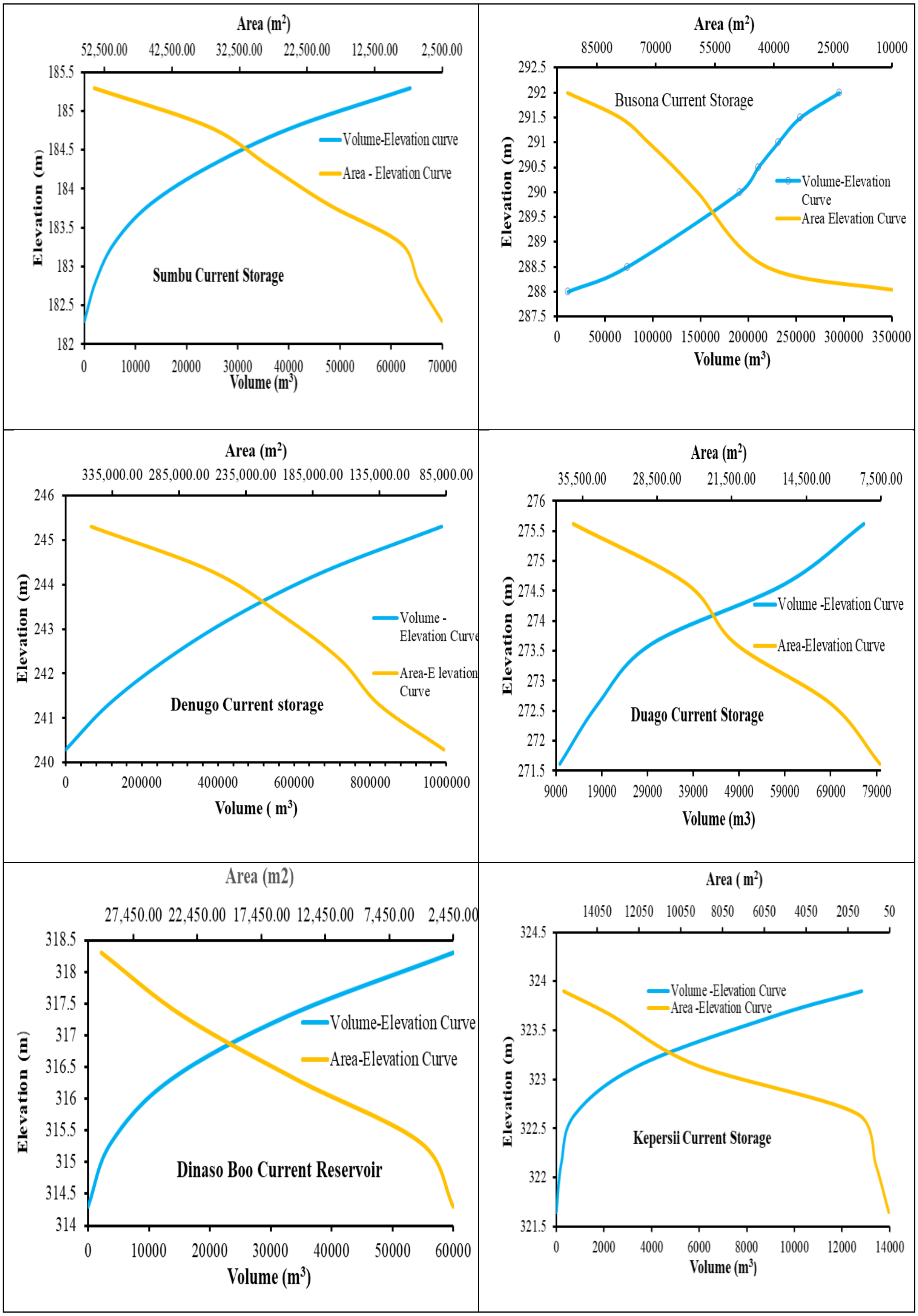


Figure 4.16: Dam Storage Capacity of the Existing Reservoirs

Source: Umukiza *et al*., (2024).

Kepersii catchment which covered an area of 3.43 km², has the smallest reservoir storage capacity among the studied sites, with a maximum of 12,827.96 m³ at an elevation of 323.9 m. Sambu catchment, which spans 38.5 km², has a mid-range reservoir capacity, reaching 63,766.16 m³ at 185.3 m. Duago catchment, covering 106.04 km², records a maximum storage capacity of 76,312.12 m³ at 275.62 m. Notably, Denugo catchment, with an area of 67.81 km², has the highest reservoir capacity at 986,655.24 m³ at an elevation of 245.3 m. These findings highlight the variability in reservoir storage capacity, which is influenced by both catchment area and elevation. The differences in storage capacities among the catchments where larger and higher-elevation catchments tend to offer greater storage potential, are reported in the study by Wisser *et al*. (2013), that discussed how catchment size and elevation are critical in determining the potential storage capacity of reservoirs, particularly in the context of irrigation demand and water resource management. Moreover, Yan *et al*. (2023), explored how extreme climate conditions and geographic configurations to control the performance of flood, reservoir storage capacities, pointed out how factors like catchment area, elevation, and sedimentation can impact the overall capacity of reservoirs.

4.3.4 Assessment of Optimal Storage Capacities in Evaluated Suitable Dam Sites

Two (2) options of optimal storage were identified. Option 1 highlights the maximum storage capacity, while option 2 presents the alternative potential storage based on ground morphology and catchment characteristics. Figure 4.17 delineates various storage stages in volume and corresponding area, to the different elevations. From the identified suitable dam locations, the storage capacity of each reservoir was estimated. The results for option 1 and 2 across various elevations, detail the corresponding reservoir areas and volumes as represented in Figure 4.18. The results showed possible options for increasing storage capacity to attenuate the water shortage and reverse the effects of climate change.

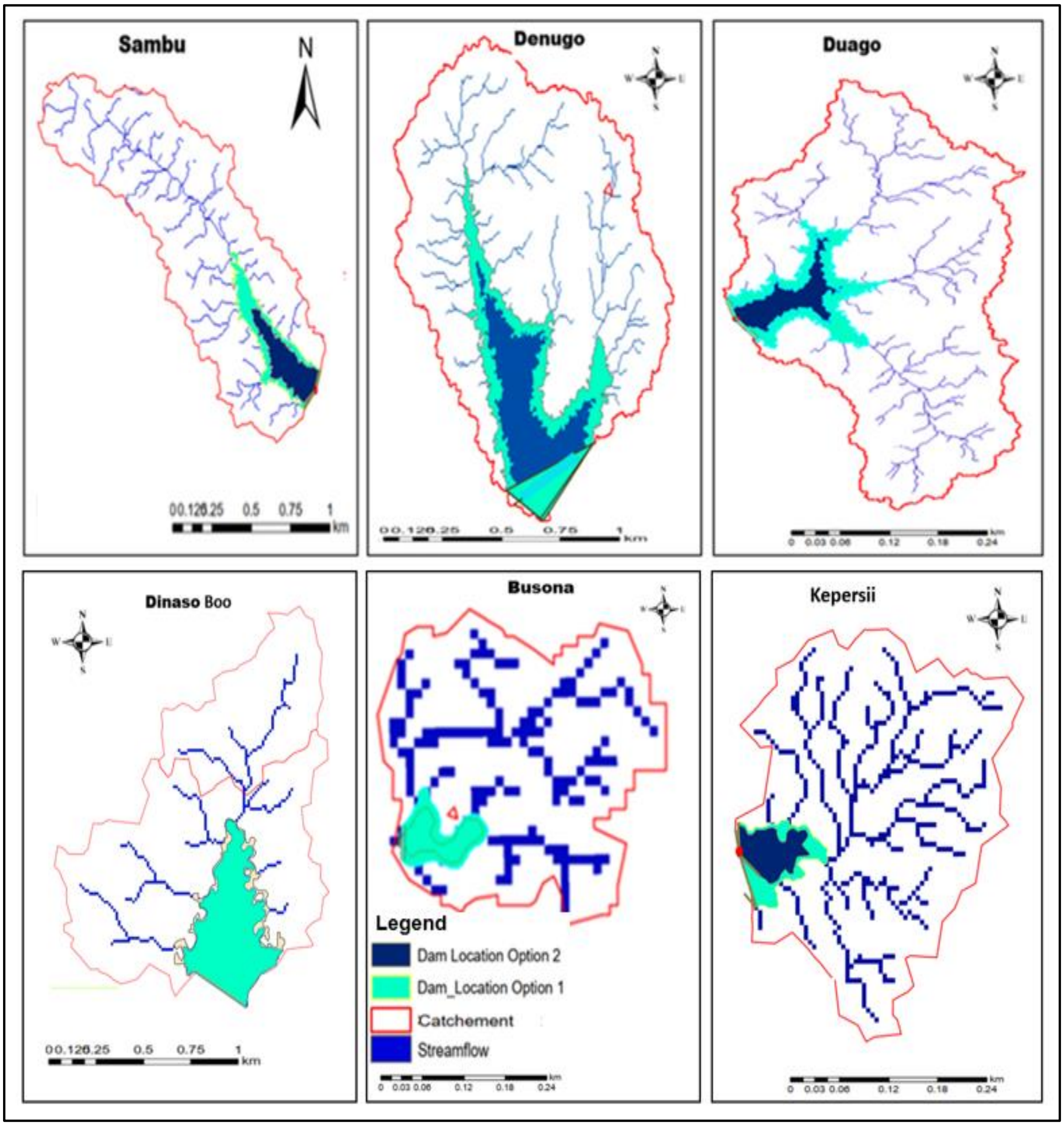
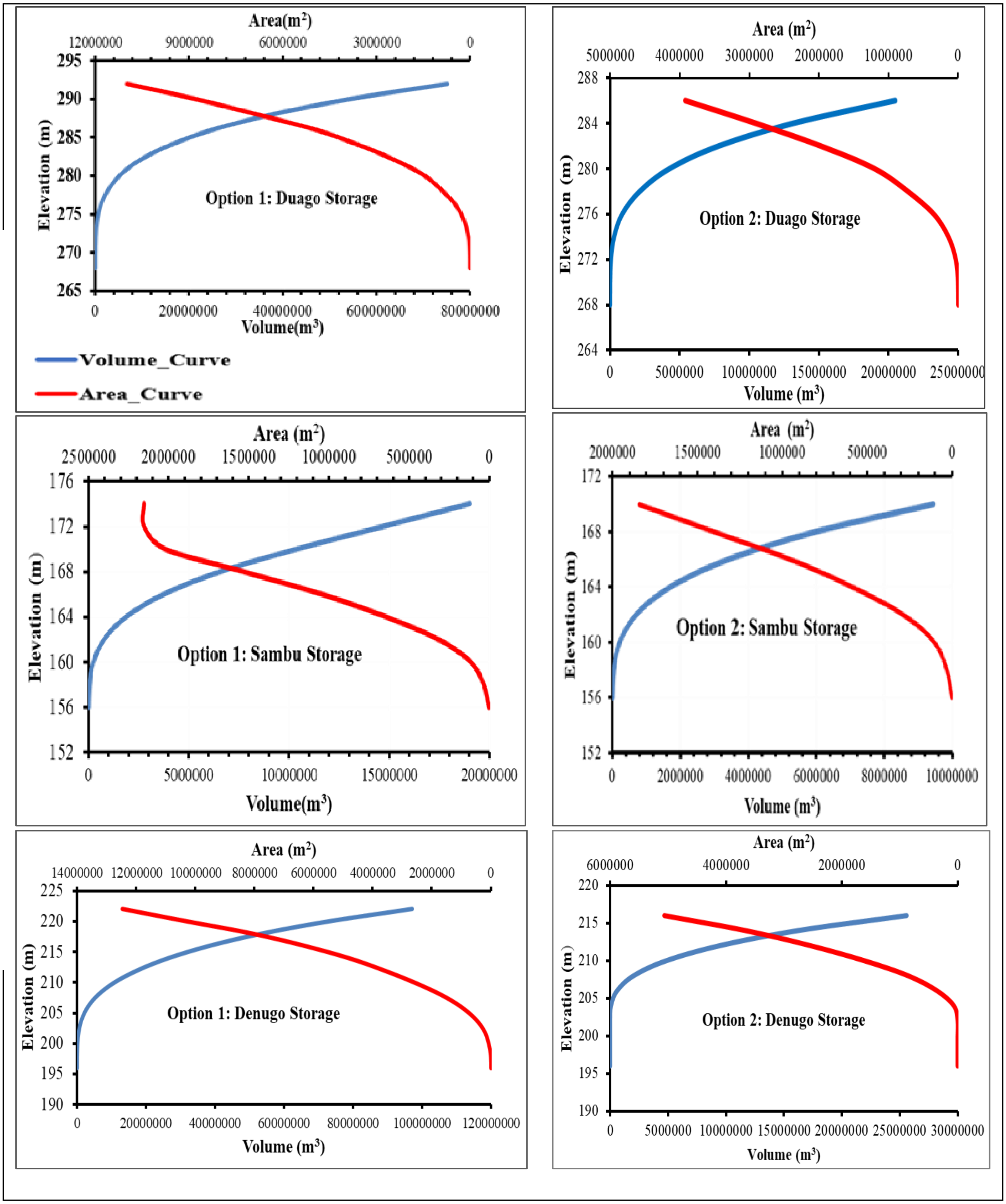


Figure 4.17: Proposed Dam Location and Options of Storage Stage

Source: Umukiza *et al., (2024).*


Area(m²)
Elevation (m)
Volume(m³)
Option 1: Duago Storage
Volume_Curve
Area_Curve
Option 2: Duago Storage
Option 1: Sambu Storage
Option 2: Sambu Storage
Option 1: Denugo Storage
Option 2: Denugo Storage

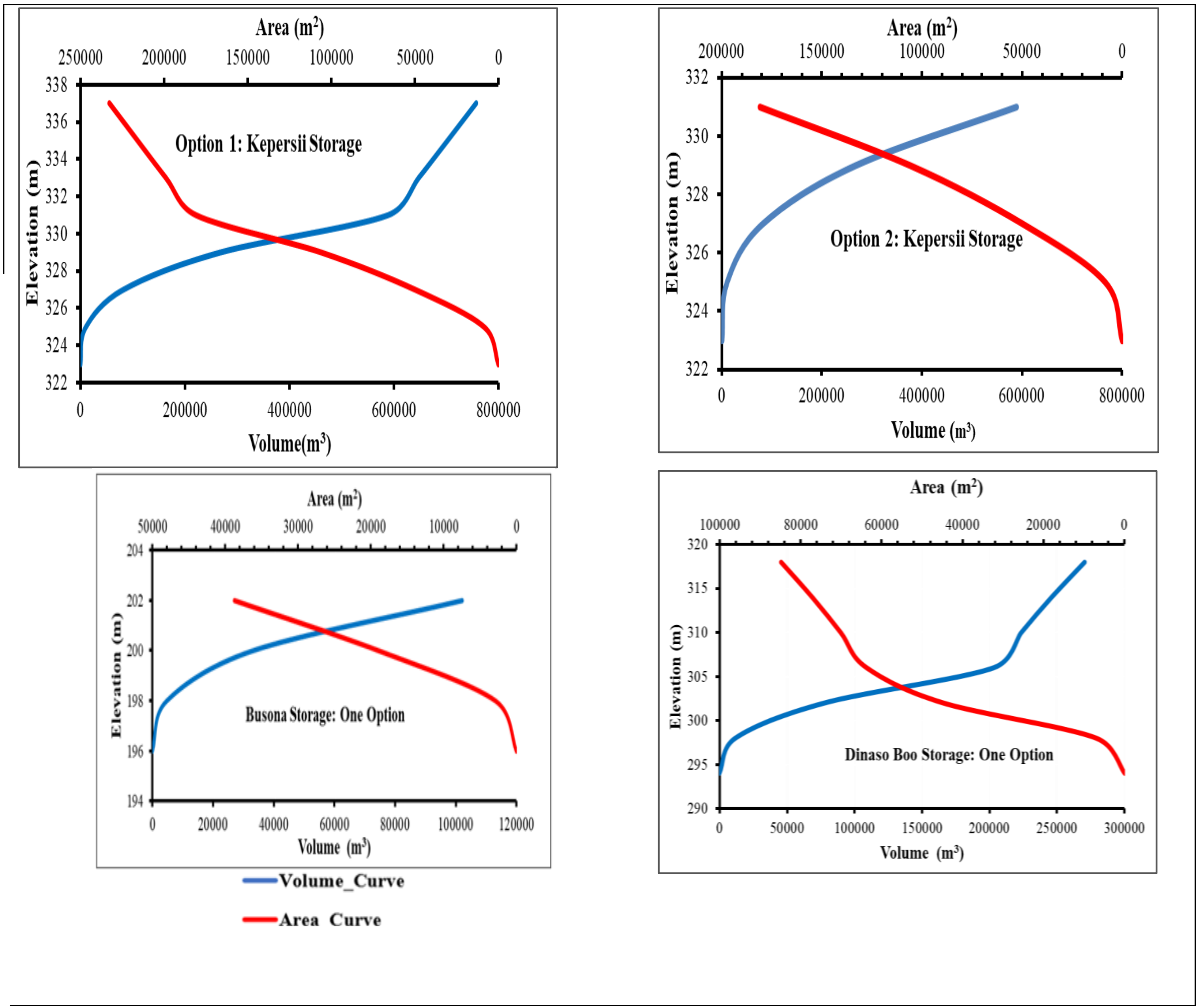


Figure 4.18b: Elevation-Storage Curve and Elevation-Area Curve of the Reservoirs

Umukiza *et al., (2024).*

The data provide valuable insights into the optimal storage capacity under each option, showcasing the dynamic changes in area and volume as the elevation varies. After a general analysis of the respective proposed relocation of the small dam/reservoir, optimal elevation area - storage curves displayed different storage capacities and corresponding areas and elevations for each. The estimated storage capacities of different dam options were compared. It was found that the storage capacity of Option 1 for the Duago Dam is 20 % greater than that of Option 2 and Option 1 offers a 40 % increase in storage capacity compared to the dam's current capacity.

Option 1 for Sambu Dam shows an increase of 80 % in storage capacity over the suggested capacity in Option 2 and a 40 % increase over the reservoir's present capacity. Option 2 for Denugo Dam shows a 50 % increase over the current storage and a 25 % increase over Option 1 in terms of area and volume. Option 1 for Kepersii dam proposes a 60 % increase in storage capacity over the current storage in the watershed and 30 % increase in volume over Option 2. The comparison between these options allows for a nuanced understanding of the potential storage variations based on ground morphology and elevation changes. Understanding these relationships is crucial for informed decision-making in stored water usage and planning.

The combination of both curves offered a comprehensive understanding of precise estimation and management of the reservoir's storage capacity. The storage curves not only facilitate better understanding but also serve as a vital reference for reservoir management, flood control in case of occurrence, and water resource planning (Fuska *et al*., 2017). Therefore, good capture of runoff in accordance with purposes and needs , sufficient storage of the reservoirs contribute greatly to water supply assurance as reported by Yin *et al.* (2015) and Fuska *et al*. (2017).
The comparison between these options allows for a nuanced understanding of the potential storage variations based on ground morphology and elevation changes. With climate uncertainty and the vulnerability of water resources, the developed options of reservoir operations can allow decision-makers to address both water supply-demand and the implication of the effects of climate change, which is in agreement with the study by Liebe *et al*. (2005). Therefore, the presented options for storage capacity hold significant implications for decision-makers involved in dam site selection and reservoir planning.

Moreover, these findings emphasize the understanding of the estimation of area-storage capacities using Triangular Irregular Network (TIN) model in the archMap at appreciable costs (Fuska *et al*., 2017) compared to existing techniques that require labor-intensive, time-consuming and have cost implications (Liebe *et al.*, 2005; Fuska *et al*., 2017). The study by Sawunyama *et al*. (2006), conducted in the estimation of the small reservoir storage capacities, emphasized the significance and linear correlation from data collected from the field and using GIS and remote sensing. The presentation of storage options empowers them to make informed choices that balance environmental, economic, and social considerations contributing to the overall success and sustainability of the dam project.

CHAPTER FIVE

SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Findings

This study investigated the structural conditions, LULC dynamics, runoff generation, and the suitability of small dams and reservoirs across sixteen (16) selected sub-catchments in northern Ghana. Key findings from the research are summarized as follows:

5.1.1 Engineering and Structural Conditions of the Dams/Reservoirs

The results showed significant variability in hydraulic conductivity (Ksat) values across the assessed dam embankments. This variability indicates differences in soil permeability, with higher Ksat values observed in dams like Sambu, potentially leading to faster infiltration and increased seepage. Dam embankments with lower hydraulic conductivity, such as Busona and Kepersii, reflected more compacted soils, while geotechnical characteristics and materials used during construction also played a role.

In addition, onsite inspection of the dams and reservoirs highlighted significant issues related to structural integrity, maintenance practices, and reservoir conditions. In the Northern Region, dams like Gbalahi and Nyeko exhibit fair structural conditions with relatively effective materials and protection, whereas dams such as Guno and Sandu suffer from, lack of maintenance, and vegetation overgrowth, indicating an overall poor condition. Most of the investigated dams in the Upper West Region, were relatively well maintained where earth and rockfill with riprap upstream and vegetative cover downstream slopes were found to offer robust protection against embankment erosion. However, Kepersii showed poor structural conditions and presence of vegetation growth in the reservoir. The Upper East Region showcases a mix of well – maintained reservoirs such as Chafia and Saboro dams. However, Gia Bagania and Gia Kwosongo Busona were poorly maintained, where erosion on embankments and lack of buffer zones are prominent issues. In Savannah region, Kwisini dam shows significant signs of poor conditions and insufficient protection and maintenance. The observed presence of trees and shrubs, particularly on dam embankments can lead to root penetration and potential breaches. Reservoirs in good conditions had structure integrity and were free of vegetation, algae, and debris indicative of regular maintenance, whereas their presence revealed poor maintenance, which led to reduced storage and reduced overall safety and functionality of the reservoir.

5.1.2 Landuse and Landcover Dynamics and Runoff Patterns in the Dam Catchments

Results from the overall analysis of LULC dynamics in the dam catchments from 1995 to 2023 revealed significant shifts in landscape patterns. Agricultural lands emerged as the dominant landuse, with built-up areas showing remarkable expansion across the period while grasslands witnessed significant declines. In sub-catchments such as Guno, Gbalahi, and Denugo, agricultural expansion was particularly pronounced. Meanwhile, sub-catchments like Guno, Sambu, Denugo, Kwisini, Sandu, Nyeko, Dinaso Boo, and Siiru Balawa experienced substantial declines in grassland cover. These changes highlight the ongoing pressures of urbanization and agricultural expansion, which have significant implications for water resource management. Understanding these LULC dynamics is critical for assessing surface runoff, water availability and ensuring sustainable water management.

The study also examined runoff generation using Curve Number (CN) method, which reflected the evolving hydrological characteristics of the catchments. Increases in CN values by 13.88%, 3.88%, and 9.85% for the Guno, Gbalahi, and Sambu catchments, respectively, indicate reduced land capacity to manage runoff due to landuse changes. These trends, influenced by interannual variability in precipitation, changes in LULC, and hydrological soil group C (low infiltration), suggest a heightened potential of runoff under extreme rainfall conditions.

5.1.3 Suitability Assessment and Optimization of Dam siting of Small Dams and Reservoirs

In general, outcome of the analysis showed that among the 16 analysed catchments, 10 of the dam walls were within reasonable distance (less than 100 m) to major stream networks and, consequently, judged relatively well located. However, for 6 of them (Kepersii, Sambu, Duago, Denugo, Dinaso and Busona) a potential suitable relocation was proposed to maximize the catchment runoff yield. Comparison of various dam location options showed significant differences in storage capacity based on ground morphology and elevation. For instance, Option 1 for the Duago dam showed a 20 % increase in storage capacity compared to Option 2 and a 40 % increase over the current capacity. Similarly, Option 1 for the Sambu dam showed an 80 % increase in storage capacity compared to Option 2. These variations in storage capacity were linked to changes in location and catchment area, providing valuable insights into optimal storage strategies for each dam. Such understanding is crucial for improving water resource management, flood control, and water supply assurance, especially under the influence of climate change.

5.2 Conclusions

The following conclusions are drawn based on the specific objectives and findings of the study:

5.2.1 Structural Conditions of the Reservoirs/Dams

The assessment of selected dams and reservoirs across the Northern, Upper West, Upper East, and Savannah regions revealed marked variability in structural condition, hydraulic performance, and maintenance practices. Measured hydraulic conductivity (Ksat) values of embankment materials ranged from 0.742×10^{-6} to 12.7×10^{-6} cm/s, confirming that higher compaction levels are associated with reduced permeability and improved embankment performance.

Onsite inspections demonstrated a strong relationship between maintenance practices and dam condition. Well-maintained dams, such as Nyeko and Saboro, exhibited stable embankments, protected spillways, and reservoirs largely free from excessive vegetation. In contrast, poorly maintained dams, including Guno and Sambu, showed significant degradation manifested through embankment erosion, vegetation overgrowth, reduced storage capacity, and impaired water conveyance. These deficiencies adversely affect operational efficiency and long-term structural integrity.

Given the critical role of small dams in supporting agricultural, domestic, and industrial water supply, the findings highlight the urgent need for routine maintenance, systematic monitoring, and timely rehabilitation to ensure dam safety, functionality, and sustainability. Persistent dry-season water shortages were linked primarily to inadequate maintenance and substandard engineering practices rather than the mere number of constructed dams.

5.2.2 LULC Dynamics and their Impact on Runoff Patterns in Dam Catchments

Analysis of LULC changes between 1995 and 2023 revealed substantial transformation across all investigated sub-catchments. Agricultural and built-up areas expanded significantly, while grasslands declined sharply, driven largely by socio-economic pressures and population growth. Notable increases in built-up areas were observed in Guno (43.75%) and Gbalahi (280.95%), accompanied by significant grassland losses.

Application of the Curve Number (CN) method indicated corresponding increases in CN values of 13.88%, 3.88%, and 9.85% for the Guno, Gbalahi, and Sambu sub-catchments, respectively. These changes reflect increased runoff potential resulting from reduced vegetation cover and expanding impervious surfaces. Variations in surface runoff were further influenced by local factors such as soil type, topography, and climatic conditions.

Overall, the results emphasize the importance of integrating land use planning and catchment management into water resource and dam management strategies to mitigate increased runoff and sedimentation risks.

5.2.3 Suitability Assessment and Optimization of Small Dams and Reservoirs

The process Multicriteria decision analysis (MCA) using GIS, remote sensing, and the Analytical Hierarchy Process (AHP) demonstrated that six (6) reservoirs (Kepersii, Sambu, Duago, Denugo, Dinaso, and Busona) were found to be located away from mainstream flow paths, indicating limited consideration of key hydrological and geomorphological factors during site selection.

Highly suitable zones identified through the AHP analysis were characterized by favorable valley geometry, high stream density, and adequate contributing catchment area. Elevation–area–storage curve analysis further enhanced understanding of reservoir capacity dynamics and provided valuable input for water storage optimization, flood management, and long-term planning.

The study confirms that GIS- and remote-sensing-based approaches offer cost-effective, efficient, and reliable tools for dam siting and reservoir management. Future dam development should prioritize hydrological suitability, environmental sustainability, and long-term performance alongside economic considerations.

5.3 Recommendations

The findings of this study encourage interdisciplinary collaboration between engineers, environmental scientists, social scientists, and policymakers.

5.3.1 Recommendations for Policy

Based on the findings of this research, the following are recommended for policy:

1. The study suggests a need for enhanced planning and decision-making processes in small dam development. This should include steps to ensure safe operation, proper maintenance, and adequate surveillance of dams.
2. Consideration of catchment characteristics, suitable locations, and ongoing maintenance should be integral components of future water infrastructure projects.
3. Allocation of resources for development of robust infrastructure and research-based solutions for efficient and effective water storage.
4. It can also be recommended to implement regular inspection programs for the safe operation and maintenance of small dams. Early detection and resolution of issues are crucial to preventing complex and costly problems.

5.3.2 Recommendations for Further Research

Future studies are necessary to contribute to the ongoing improvement of small dam development practices and facilitate the sustainable management of water resources. The following recommendations are formulated for future research:

1. Evaluation of climate change impacts on small dams and reservoir failures in diverse geographic regions. This will contribute to a more comprehensive understanding of the challenges and opportunities associated with water infrastructure development under ongoing climate change.
2. Investigation on the feasibility and implications of developing small dams and reservoirs for multiple purposes beyond domestic and agricultural use. This could include assessment their potential for energy generation, flood control, and recreational activities.
3. Assessment of community perceptions regarding the construction of dams /reservoirs in proposed locations. Understanding these perceptions is crucial for ensuring that these projects are embraced as community assets.

4. Assessment of socioeconomic impacts of small dams/reservoirs and community engagement to monitor the performance and structural integrity of these infrastructures over time. This will provide valuable insights into their sustainability and resilience under various environmental conditions.

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APPENDICES

Appendix 1: Scientific Communication

1.Published Articles

GEOCARTO INTERNATIONAL
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Characterization of landuse and landcover dynamics and their impact on runoff generation patterns in dam catchments of Northern Ghana

Etienne Umukiza[a,b], Felix K. Abagale[a,b] and Thomas Apusiga Adongo[a,c]

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Suitability Assessment and Optimization of Small Dams and Reservoirs in Northern Ghana

Etienne Umukiza; Felix K. Abagale; Thomas Apusiga Adongo; Andrea Petroselli

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JIPE
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A Review on Significance and Failure Causes of Small-Scale Irrigation Dams in Arid and Semi-arid Lands

Etienne Umukiza[1,2,*], Felix K. Abagale[1,2], Thomas Apusiga Adongo[1,3]

DOI: https://doi.org/10.22225/jipe.2.2.2023.1-9

2.Scientific Communications

IRAD 2024

4th IRAD 2024 International Conference .
21&22 February 2024

Annual International Congress on Civil Engineering
February 13-14, 2025
Oxford, United Kingdom / Online

Dear Etienne Umukiza,

We're delighted to inform you that your name has been officially added to our website as a member of the Scientific Committee.
Your contribution and expertise are invaluable, and we are proud to highlight your role in shaping the quality and success of this event.

Appendix 2: On-Site Assessment

Mainly systematic field inspection was required to assess the dam and reservoirs' current structural and engineering conditions and functionality. Key assessed areas:

Survey Date: ………………….

Location: ………………………………...

1: General Information

- Name of Dam / Reservoir: ………………………………………
- Construction Date: ………………………………………………
- Project Purpose: …………………………………………………
- Design Capacity (if available): ……………………………………….
- Period of construction…………………

2. Geographical Information

- Latitude: ……………………………………………….
- Longitude: …………………………………………….

3. Ownership and Maintenance

- Owner/Authority: …………………………………………………
- Responsible Department/Agency: …………………………………….
- Purpose of the Dam: ……………………………………
- Number Community users …………………………………..

Part 2: Engineering and Structural Assessment

1. Design and Specifications

- Are there any from the original design?

If yes, specify and

Can it be accessible to review initial design plans and specifications?

2. Materials Used

-Check materials used for embankment, spillway construction.

Concrete	
Earth and Rock Fill	
Steel	
Masonry	
Composite Materials	
Asphalt	
Rip-Rap	

Part 3: Current Conditions

1. Physical Inspection

- Overall condition of the dam/reservoir:

- Look for signs of distress, erosion, seepage, settlement, cracks, or any structural issues in the dam and its surroundings.

- Check for vegetation growth within the reservoir area.

  - Record the conditions of each component through Photographs and detailed notes

  - Identify any outstanding dam safety issues

-Taking soil sample to assess the hydraulic conductivity, Bulk density and soil particles.

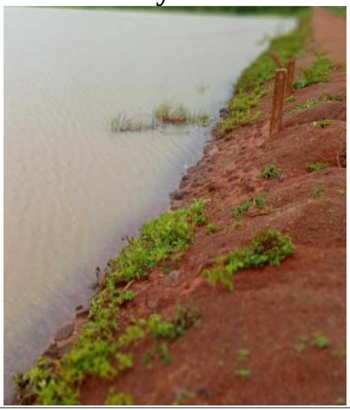
2. Structure Conditions of embankment (upstream and downstream), Spillway and Outlet

- Inspect the spillway design: Width; height and length)

- Evaluate the condition of the hydraulic structures,

- Eventual Livestock damage.

Apendix 2: Characteristics and Current conditions of Inspected Dams in Northern Ghana

Dam Location		
Gbalahi 	**Guno** 	**Sambu** 
Sandu 		**Nyeko** 
Gia 	**Denugo** 	**Chafia** 

Gia (1V1D)	Busona	
		

Appendix 3: Characteristics of hydraulic conductivity and Soil particles

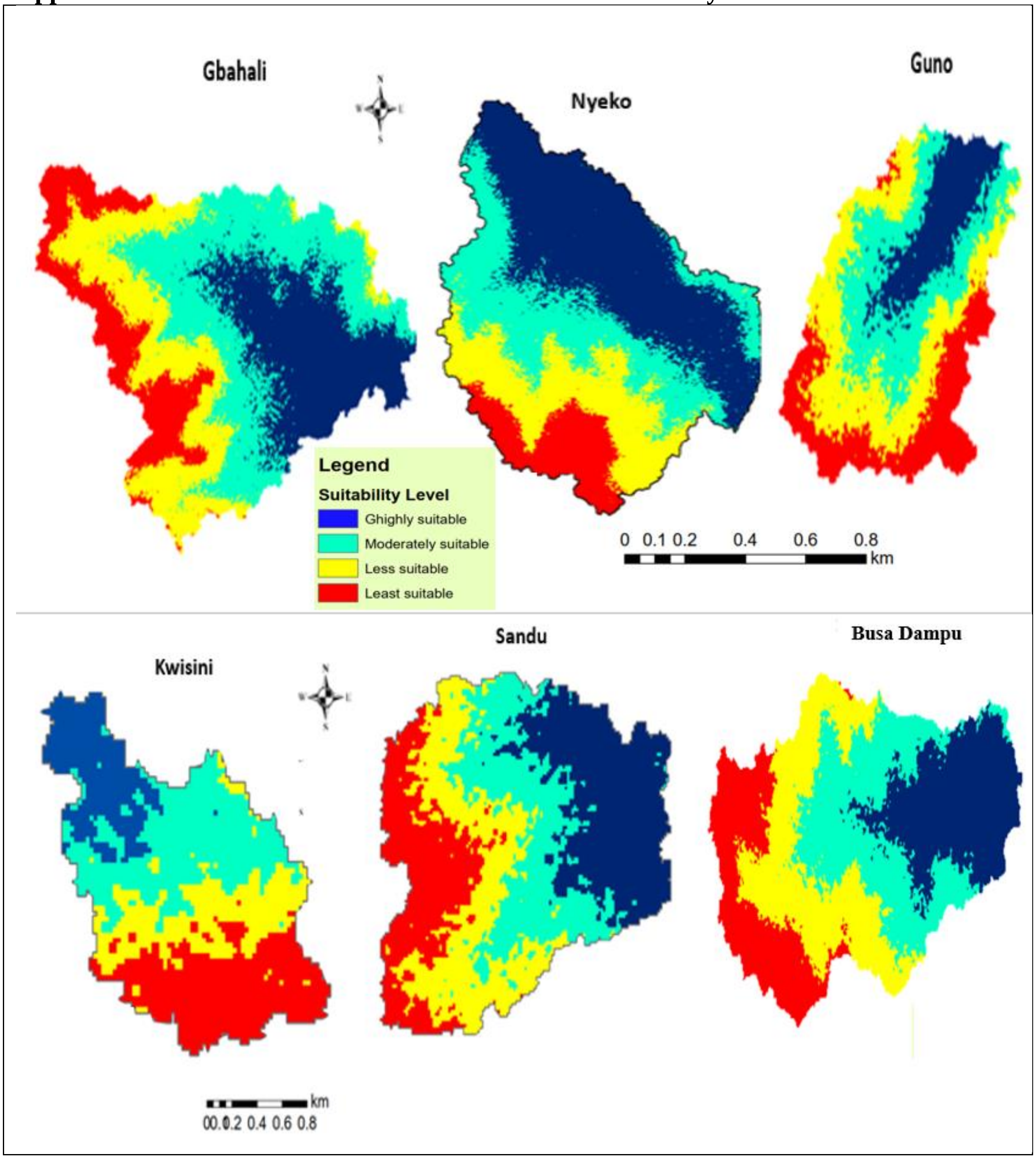
Dam Location	Ksat (10^{-6}cm/h)	Soil Particles		
		Sand (%)	Clay (%)	Silt (%)
Guno	0.853	53.92	30.24	15.84
Gbalahi	3.07	65.92	20.24	13.84
Sambu	12.7	69.96	14.24	15.8
Duago	5.06	68.93	15.1	15.97
Denugo	10.6	67.06	15.54	17.4
Sandu - Sandu	7.26	69.01	14.26	16.73
Nyeko-Nyeko	1.53	68.04	12	19.96
Kwisini	8.26	60	25.45	14.55
Chafio	1.626	66.71	13.1	20.19
Saboro	1.426	67.02	13.05	19.93
Busona	1.326	69.01	11.8	19.19
Busona 2	0.92	68.71	13.67	17.62
Kperisi	0.742	67.08	13.65	19.27
Dinanso	1.62	60.07	14.61	25.32
Siiru/balawa	2.6	70.23	13.24	16.53
Busa Dampu	5.26	62.47	15.8	21.73

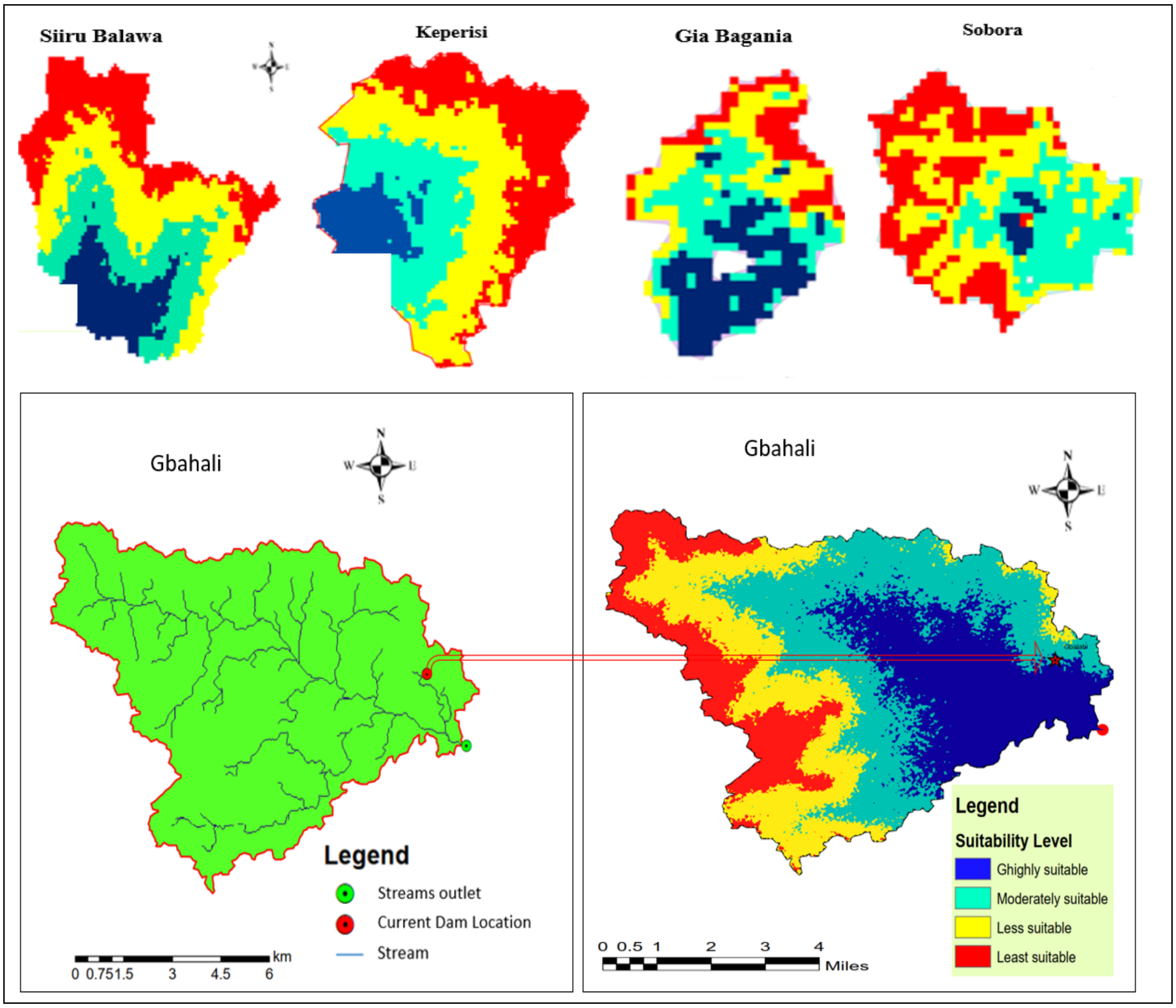
Appendix 4: Accuracy Assessment of Classified Images

Subcathcment	LULC Classes	1995 PA (%)	1995 UA %	2005 PA (%)	2005 UA (%)	2015 PA (%)	2015 UA %	2023 PA (%)	2023 UA %
Guno	Built up	80.6	81.3	82.2	82.9	83.9	81.6	85.5	86.3
	Grasslands	81.8	90	83.4	91.8	85.1	93.6	86.8	94.5
	Agricultural Lands	87.7	88.4	89.5	90.2	91.2	92.0	90.1	93.8
	Waterbody	81.4	84.7	83.0	86.4	84.7	88.1	86.4	89.9
Gbalahi	Built up	82. 3	81.3	78	82.1	80	82.9	79.8	83.8
	Grasslands	80.5	82.7	81.3	83.5	82.1	84.4	82.9	85.2
	Agricultural Land	85.3	84.7	86.2	85.5	87.0	86.4	87.9	87.3
	Waterbody	84.3	82. 1	85.1	79	86.0	85.4	86.9	83.4
Sambu	Built up	100	100	99.9	99.9	99.8	99.8	99.7	99.7
	Grasslands	86.7	84.6	86.6	84.5	86.5	84.4	86.4	84.3
	Agricultural Land	90	87.5	89.9	87.4	89.8	87.3	89.7	87.2
	Waterbody	91.1	92.5	91.0	92.4	90.9	92.3	90.8	92.2
Duago	Agricultural Lands	84.3	79.5	84.6	79.7	84.8	80.0	85.1	80.2
	Built up Area	87.2	80.2	87.5	80.4	87.7	80.7	88.0	80.9
	Grass lands	83.1	81.5	83.3	81.7	83.6	82.0	83.9	82.2
	Water Body	70	79.4	70.21	76.3	70.42	73	70.61	79
Denugo	Agricultural Lands	79.3	81.3	79.6	81.6	80.0	82.0	80.3	82.4
	Built up Areas	80.1	82.5	80.4	82.9	80.8	83.2	81.1	83.6
	Grasslands	81	76.4	81.3	76.7	81.7	77.1	82.0	77.4
	Water Bady	78	80	78.3	80.3	78.7	80.7	79.0	81.0
Kwisini	Agricultural lands	78.8	77.7	77.2	76.1	75.7	74.6	74.2	73.1
	Grasslands	80.2	81.8	78.6	80.2	77.0	78.6	75.5	77.0
	Open trees	81.3	92	79.7	90.2	78.1	88.3	76.5	86.6
	Agricultural lands	83	84	83.4	84.4	83.8	84.8	84.3	85.3
	Built up Area	75.7	80.4	76.1	80.8	76.5	81.2	76.8	81.6

Sandu	Grass land	87.9	79	88.3	79.4	88.8	79.8	89.2	80.2
	Open trees	79.4	81	79.8	81.4	80.2	81.8	80.6	82.2
	Agricultura l lands	78	80	78.4	80.4	78.7	80.8	79.1	81.1
Nyeko	Grasslands	81	79.8	81.4	79.4	81.8	79.7	78.1	81.1
	Open Lands	83	81.2	83.4	81.6	83.8	82.0	84.2	82.4

Appendix 5: Flow Accumulation and Dam Location Suitability Levels

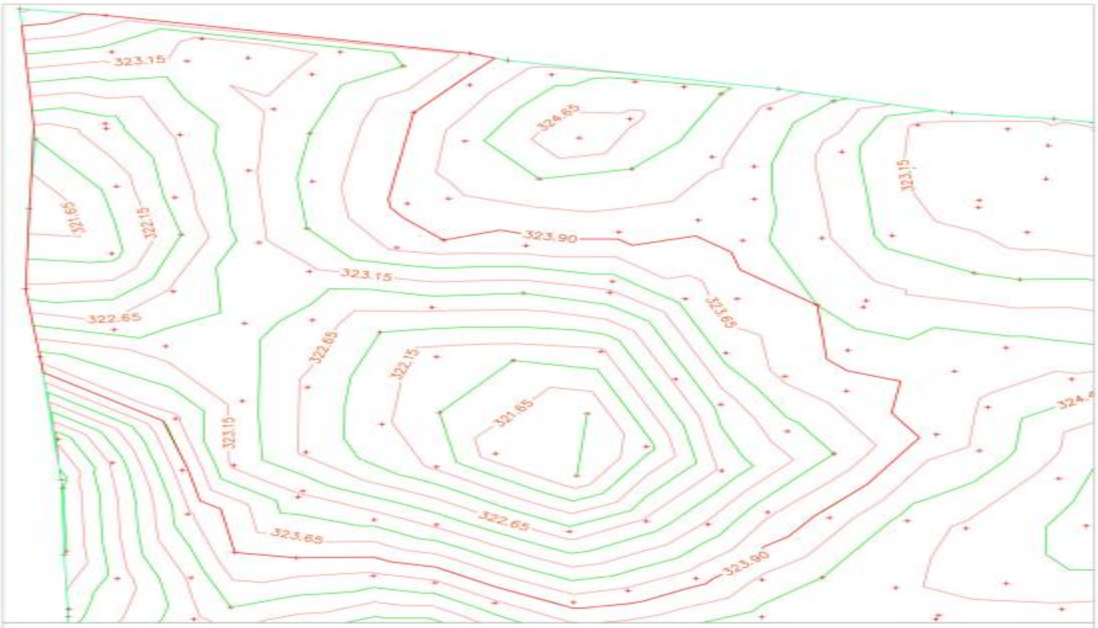




Siiru Balawa
Keperisi
Gia Bagania
Sobora
Gbahali
Legend
Streams outlet
Current Dam Location
Stream
km
0 0.751.5 3 4.5 6
Gbahali
Legend
Suitability Level
Ghighly suitable
Moderately suitable
Less suitable
Least suitable
0 0.5 1 2 3 4
Miles

Appendix 6 a: Topographical Maps of Dams and Reservoirs

TOPOGRAPHICAL MAP OF KEPERSII RESERVOIR



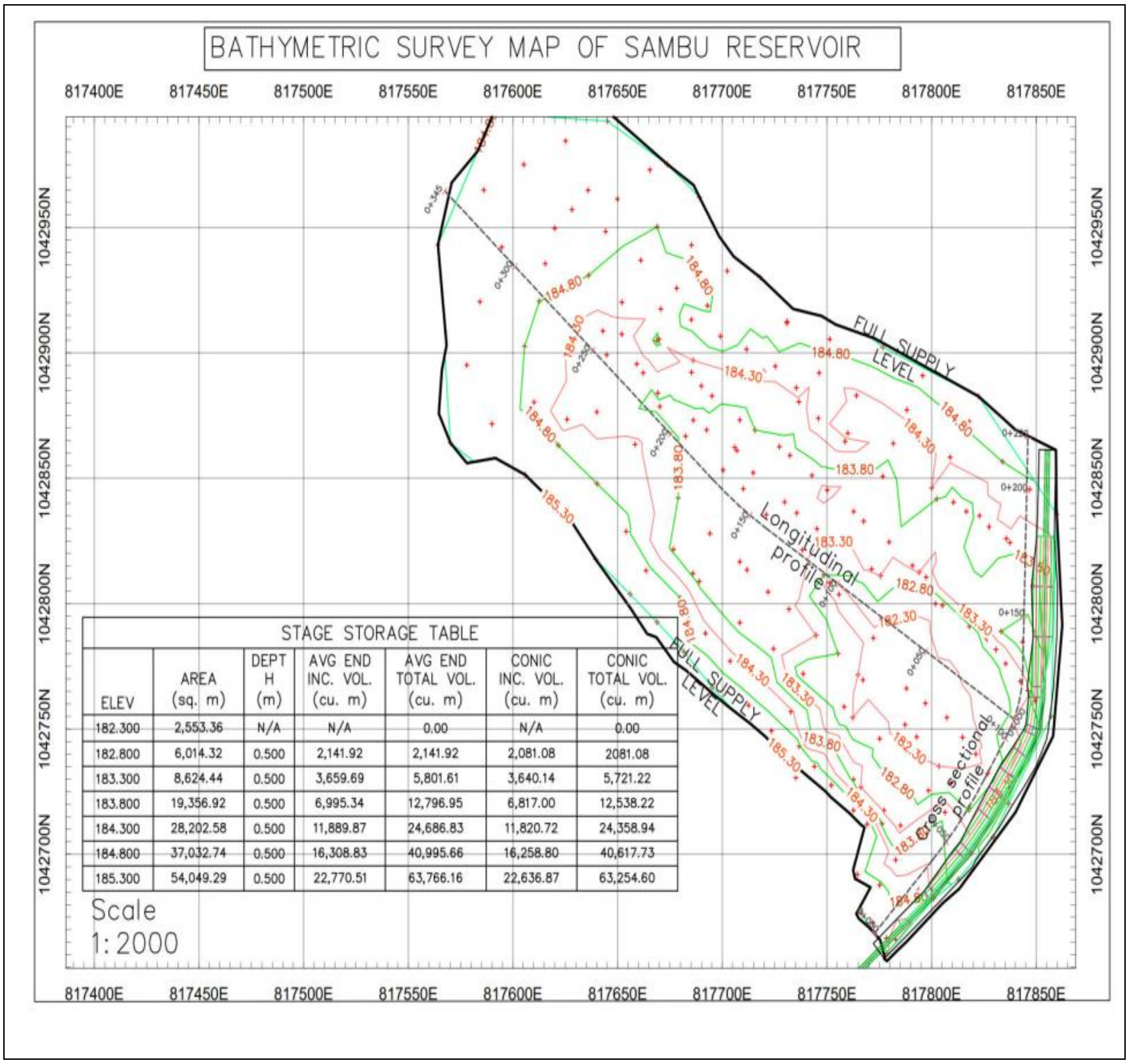
STAGE STORAGE TABLE						
ELEV	AREA (sq. m)	DEPTH (m)	AVG END INC. VOL. (cu. m)	AVG END TOTAL VOL. (cu. m)	CONIC INC. VOL. (cu. m)	CONIC TOTAL VOL. (cu. m)
321.650	98.12	N/A	N/A	0.00	N/A	0.00
322.150	740.62	0.500	209.68	209.68	184.72	184.72
322.650	1,591.52	0.500	583.03	792.72	569.64	754.35
323.150	9,349.69	0.500	2735.30	3528.02	2466.45	3220.80
323.650	13,345.33	0.500	5673.76	9201.78	5644.21	8865.02
323.900	15,664.16	0.250	3626.19	12827.96	3622.32	12487.34

Scale
1:1000

TOPOGRAPHICAL MAP OF DENUGO RESERVOIR

STAGE STORAGE TABLE						
ELEV	AREA (sq. m)	DEPTH (m)	AVG END INC. VOL. (cu. m)	AVG END TOTAL VOL. (cu. m)	CONIC INC. VOL. (cu. m)	CONIC TOTAL VOL. (cu. m)
240.300	86,819.86	N/A	N/A	0.00	N/A	0.00
241.300	135,124.45	1.000	110972.15	110972.15	110085.43	110085.43
242.300	163,963.14	1.000	149543.80	260515.95	149311.53	259396.96
243.300	207,597.97	1.000	185780.56	446296.50	185352.05	444749.01
244.300	260,945.20	1.000	234271.58	680568.09	233763.77	678512.77
245.300	351,229.10	1.000	306087.15	986655.24	304971.45	983484.23

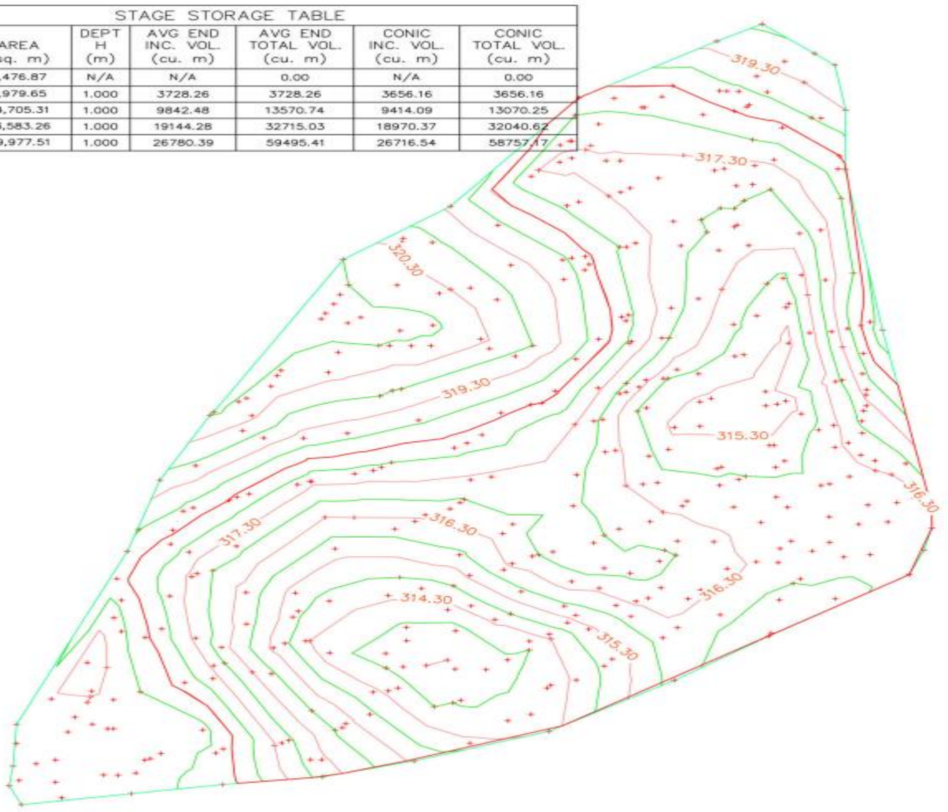
Scale
1: 5000



STAGE STORAGE TABLE						
ELEV	AREA (sq. m)	DEPT H (m)	AVG END INC. VOL. (cu. m)	AVG END TOTAL VOL. (cu. m)	CONIC INC. VOL. (cu. m)	CONIC TOTAL VOL. (cu. m)
182.300	2,553.36	N/A	N/A	0.00	N/A	0.00
182.800	6,014.32	0.500	2,141.92	2,141.92	2,081.08	2081.08
183.300	8,624.44	0.500	3,659.69	5,801.61	3,640.14	5,721.22
183.800	19,356.92	0.500	6,995.34	12,796.95	6,817.00	12,538.22
184.300	28,202.58	0.500	11,889.87	24,686.83	11,820.72	24,358.94
184.800	37,032.74	0.500	16,308.83	40,995.66	16,258.80	40,617.73
185.300	54,049.29	0.500	22,770.51	63,766.16	22,636.87	63,254.60

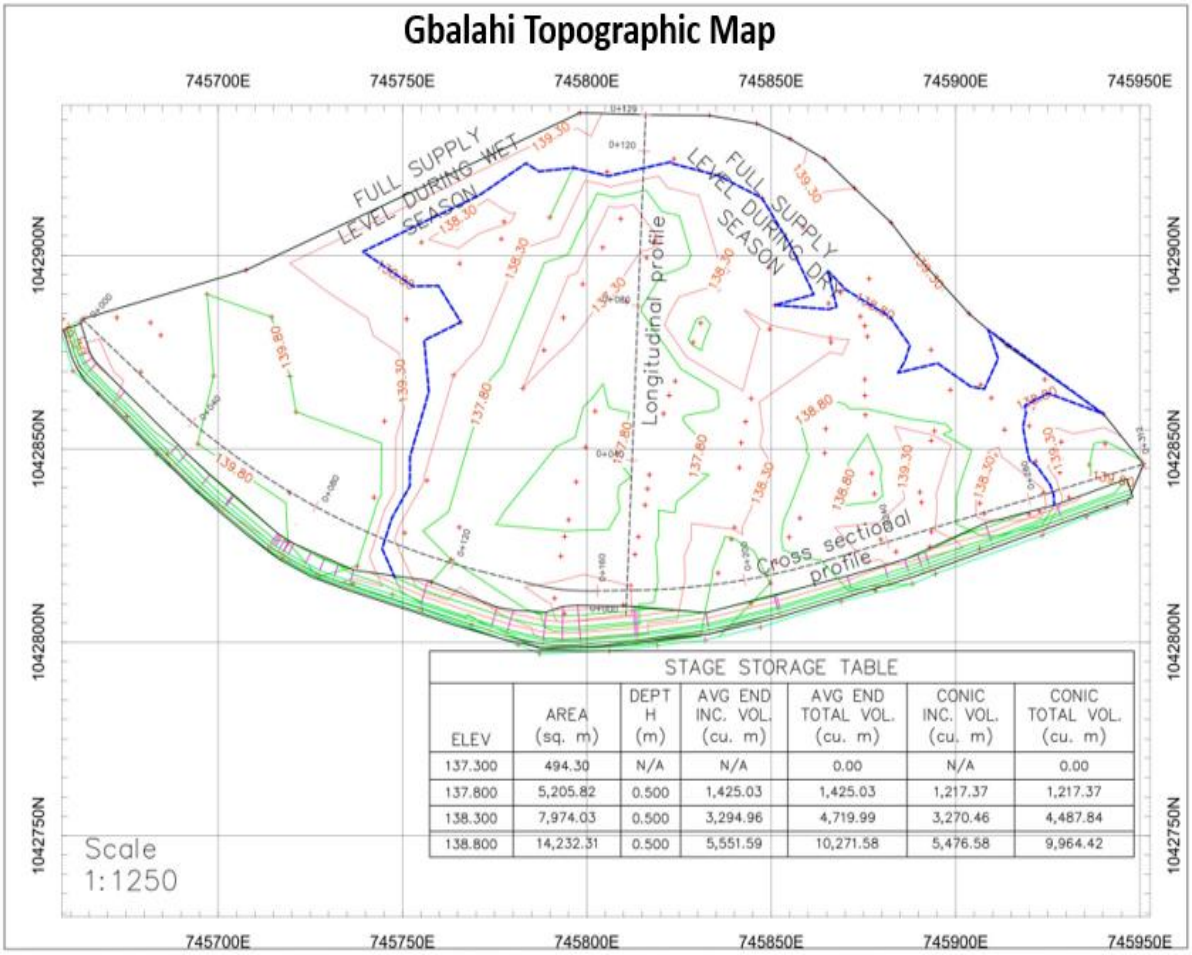
TOPOGRAPHICAL MAP OF DINASO BOO RESERVOIR

STAGE STORAGE TABLE						
ELEV	AREA (sq. m)	DEPT H (m)	AVG END INC. VOL. (cu. m)	AVG END TOTAL VOL. (cu. m)	CONIC INC. VOL. (cu. m)	CONIC TOTAL VOL. (cu. m)
314.300	2,476.87	N/A	N/A	0.00	N/A	0.00
315.300	4,979.65	1.000	3728.26	3728.26	3656.16	3656.16
316.300	14,705.31	1.000	9842.48	13570.74	9414.09	13070.25
317.300	23,583.26	1.000	19144.28	32715.03	18970.37	32040.62
318.300	29,977.51	1.000	26780.39	59495.41	26716.54	58757.17



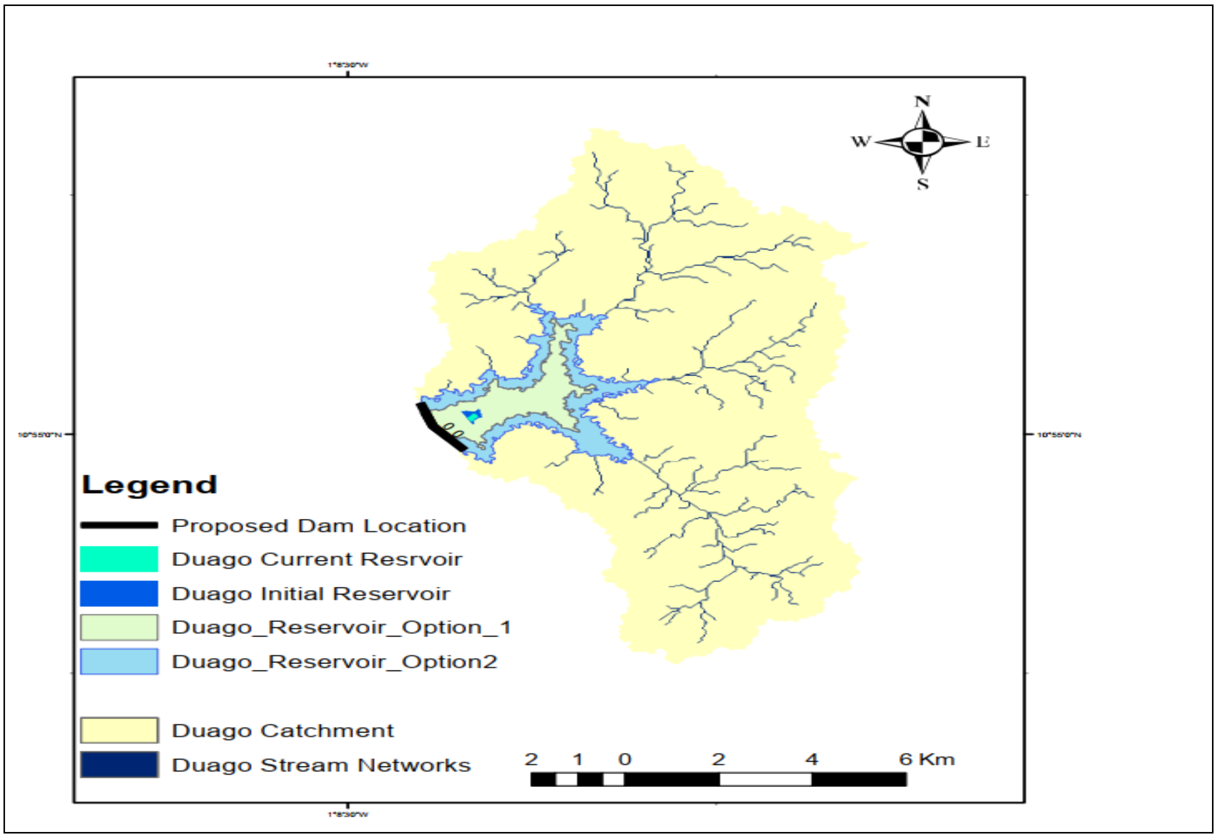
Duago

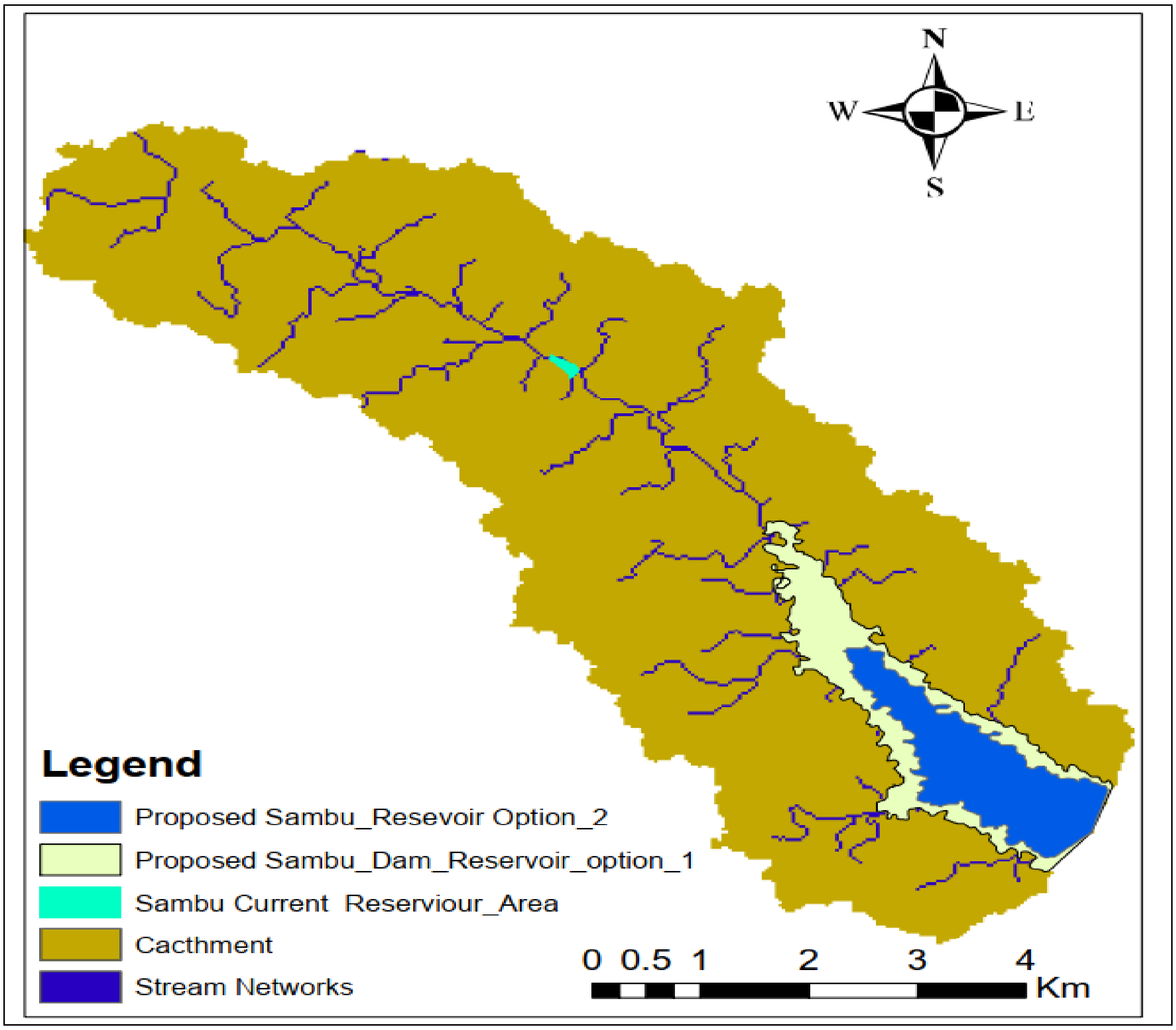
STAGE STORAGE TABLE						
ELEV	AREA (sq. m)	DEPTH (m)	AVG END INC. VOL. (cu. m)	AVG END TOTAL VOL. (cu. m)	CONIC INC. VOL. (cu. m)	CONIC TOTAL VOL. (cu. m)
271.620	7,624.01	N/A	N/A	0.00	N/A	0.00
272.620	12,205.73	1.000	9914.87	9914.87	9825.44	9825.44
273.120	21,146.36	0.500	8338.02	18252.89	8236.30	18061.74
273.620	25,724.99	0.500	11717.84	29970.73	11699.16	29760.90
274.620	32,511.35	1.000	29118.17	59088.90	29052.05	58812.94
275.120	36,381.54	0.500	17223.22	76312.12	17214.16	76027.10



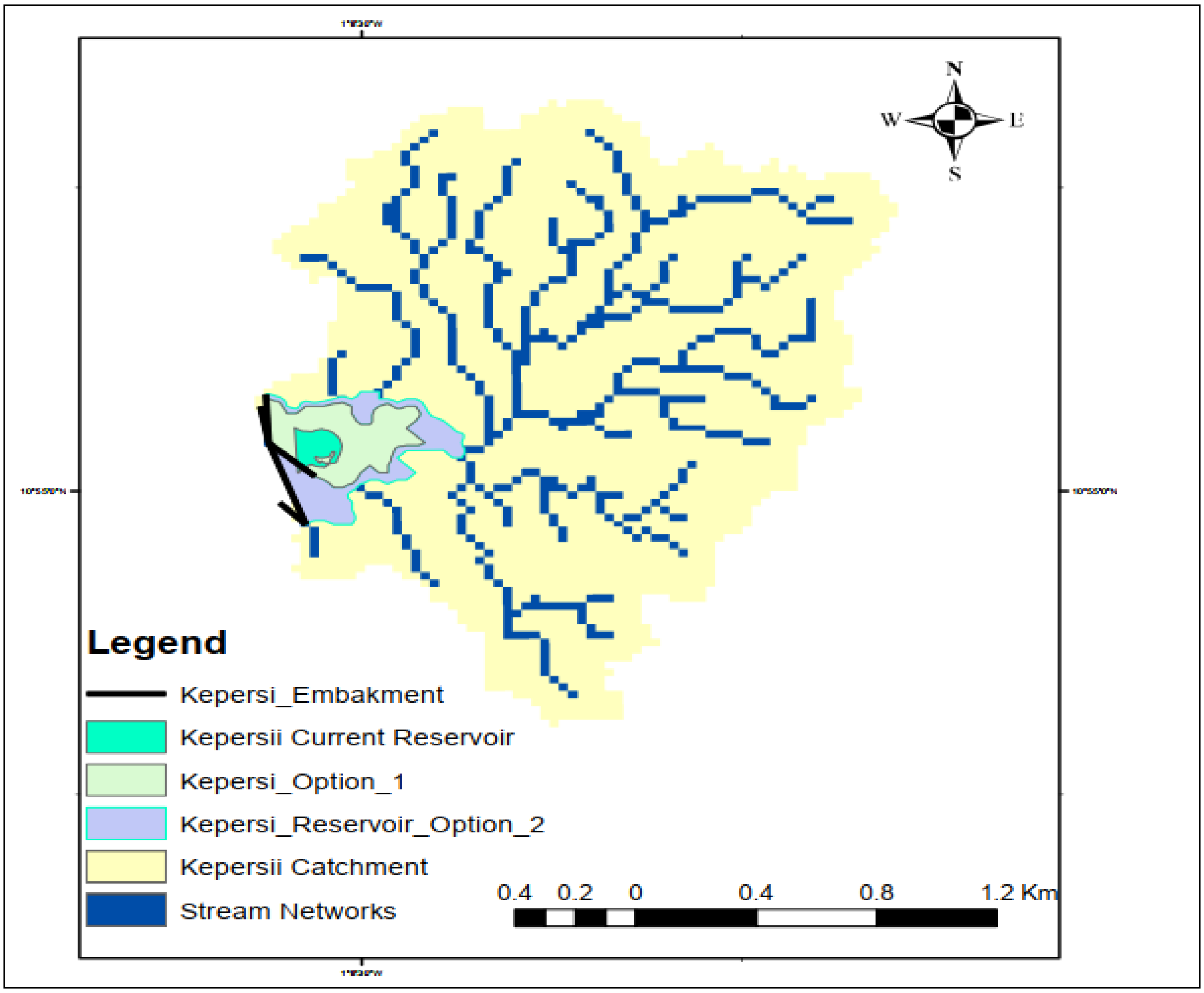
ELEV	AREA (sq. m)	DEPTH (m)	AVG END INC. VOL. (cu. m)	AVG END TOTAL VOL. (cu. m)	CONIC INC. VOL. (cu. m)	CONIC TOTAL VOL. (cu. m)
137.300	494.30	N/A	N/A	0.00	N/A	0.00
137.800	5,205.82	0.500	1,425.03	1,425.03	1,217.37	1,217.37
138.300	7,974.03	0.500	3,294.96	4,719.99	3,270.46	4,487.84
138.800	14,232.31	0.500	5,551.59	10,271.58	5,476.58	9,964.42

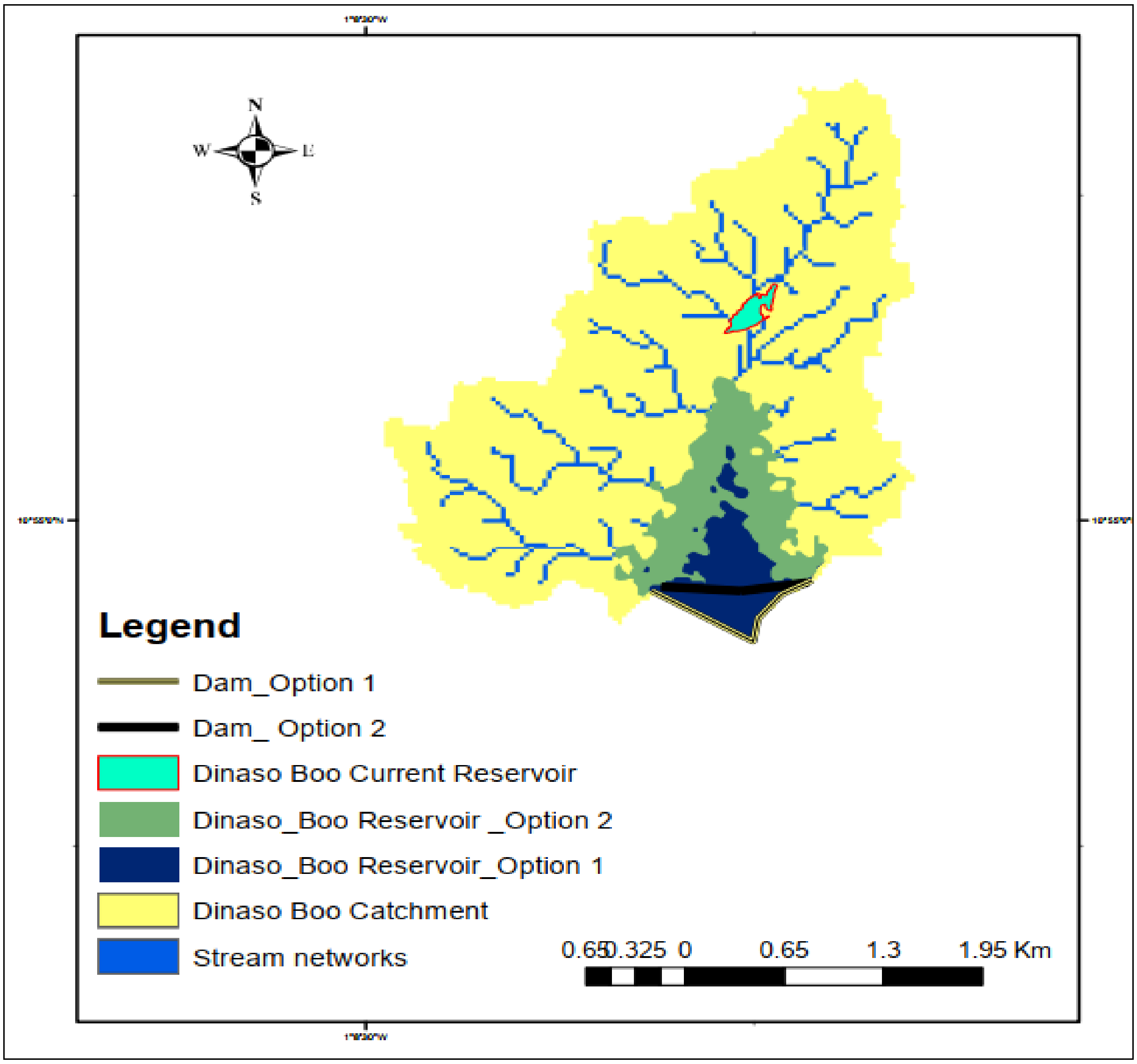
Appendix 6 b: Comparison Maps of Dams Location in Catchment

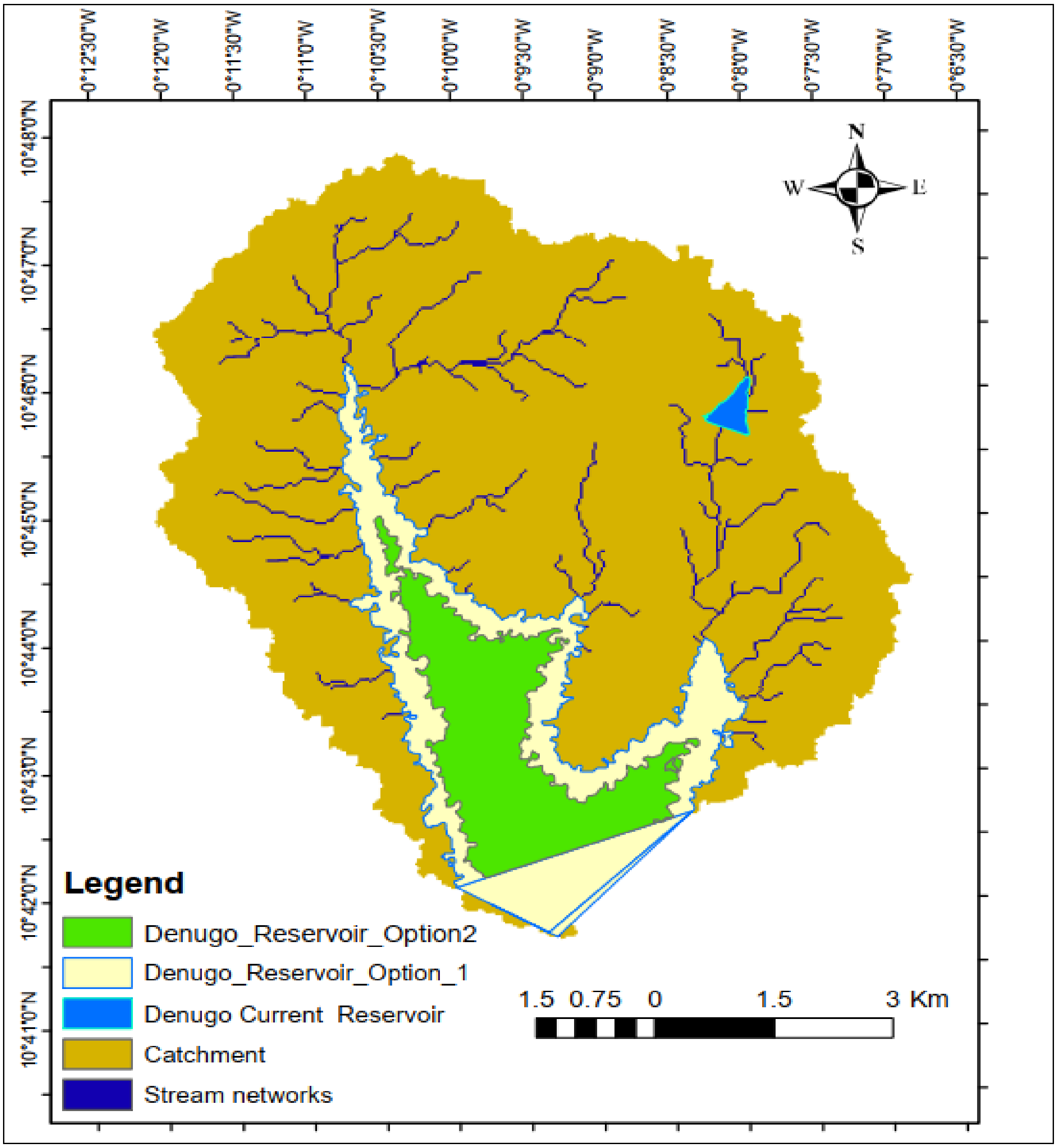


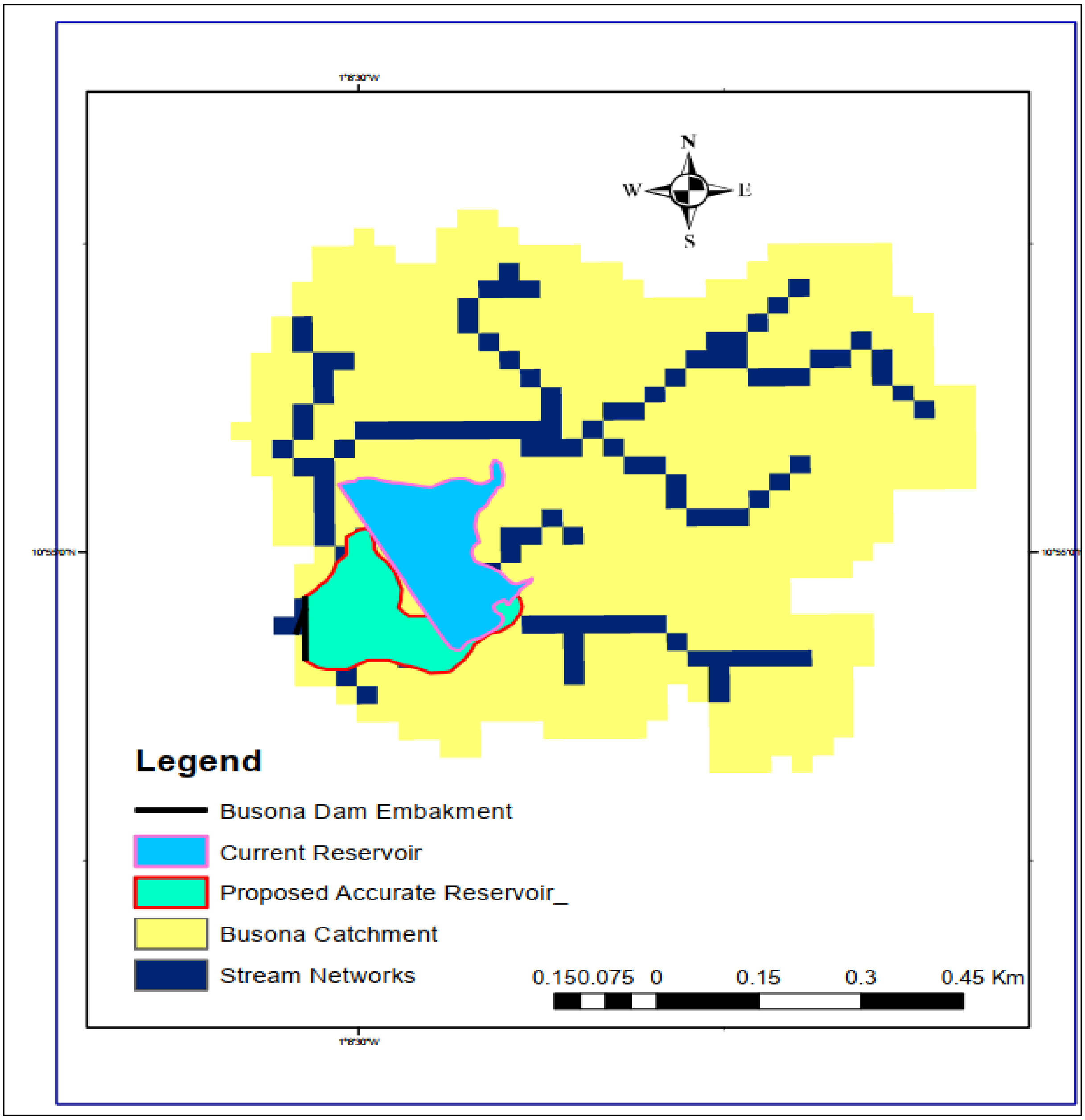


N
W
E
S
Legend
Proposed Sambu_Resevoir Option_2
Proposed Sambu_Dam_Reservoir_option_1
Sambu Current Reserviour_Area
Cacthment
Stream Networks
0 0.5 1 2 3 4
Km


N
W
E
S
Legend
Kepersi_Embakment
Kepersii Current Reservoir
Kepersi_Option_1
Kepersi_Reservoir_Option_2
Kepersii Catchment
Stream Networks
0.4 0.2 0 0.4 0.8 1.2 Km


N
W
E
S
Legend
Dam_Option 1
Dam_ Option 2
Dinaso Boo Current Reservoir
Dinaso_Boo Reservoir _Option 2
Dinaso_Boo Reservoir_Option 1
Dinaso Boo Catchment
Stream networks
0.650.325 0 0.65 1.3 1.95 Km


0°12'30"W
0°12'0"W
0°11'30"W
0°11'0"W
0°10'30"W
0°10'0"W
0°9'30"W
0°9'0"W
0°8'30"W
0°8'0"W
0°7'30"W
0°7'0"W
0°6'30"W
10°48'0"N
10°47'0"N
10°46'0"N
10°45'0"N
10°44'0"N
10°43'0"N
10°42'0"N
10°41'0"N
N
W
E
S
Legend
Denugo_Reservoir_Option2
Denugo_Reservoir_Option_1
Denugo Current Reservoir
Catchment
Stream networks
1.5 0.75 0 1.5 3 Km



Appendix 7(a): Determination of Curve Number Characteristics of the Study Areas 2023

Sub-catchment	LUC Classes (2023)	Area in 2023	Area in %	CN	Area (%) *CN	Weighted CN
	Built-up	2.1	7	82	5.8	
Guno	Grasslands	1.46	5	74	3.7	79
	Agricultural lands	25.64	87	80	69.5	
	Built up	80	73	82	59.6	
Gbahali	Grasslands	19	17	74	12.8	80
	Agricultural land	10.5	10	80	7.6	
	Built up	4.5	12	82	9.6	

Sambu	Grasslands	5.5	14	74	10.6	79
	Agricultural and	28.5	74	80	59.2	
Duago Upper west	Agricultural lands	58.21	55	82	45.0	
	Built up Area	4.32	4	80	3.3	79
	Grassland Areas	43.46	41	74	30.3	
Denugo	Agricultural lands	50.17	74	80	59.2	
	Built up Areas	6.48	10	82	7.8	79
	Grasslands	11.16	16	74	12.2	
Kwisini	Agricultural lands	1.61	62	80	49.7	
	Grasslands	0.67	26	74	19.2	78
	Open trees	0.31	12	79	9.4	
Sandu -	Agricultural lands	6.43	61	80	48.7	
	Built up Area	0.54	5	82	4.2	79
	Grassland	1.55	15	74	10.8	
	Open Space	2.04	19	79	15.3	
Nyeko	Agricultural lands	44.07	37	80	29.2	
	Grasslands	19.32	16	74	11.8	79
	Open Lands	57.26	47	79	37.5	
Dinaso Boo	Agricultural lands	8	91	80	72.8	
	Grasslands	1	7	74	5.5	80
	Water Body	0	1	100	1.5	
Busa Dampu	Agricultural lands	29.73	77	80	61.9	
	Built up	2.49	6	82	5.2	80
	Grasslands	5.86	15	74	12.5	
	Water Body	0.33	1	100	0.0	
Siiru Balawa	Agricultural land	0.86	19	80	15.4	
	Built up	2.81	63	82	51.7	
	Grassland	0.79	18	74	13.1	80
	Waterbody	0	0	100	0.0	
Kepersii	Agricultural lands	2.45	71	80	57.2	
	Bare Lands	0.70	20	79	16.0	80
	Mixed forest	0.29	8	79	6.6	

Appendix (7b): Determined Curve Number Characteristics of the Study Areas in 2015

Subcatchment	LUC Classes (2023)	Area in 2023	Area in %	Correspondent CN	Area (%)*CN	Weighted CN	Weighted CN
	Built up	2,1	7	82	5,8		
Guno	Glasslands	3,1	11	74	7,8	79	79
	Agricultural Lands	24,1	82	80	65,4		
	Built up	68,72	62	82	51,2		
Gbalahi	Glasslands	21	19	74	14,1	80	80
	Agricultural Land	20	18	80	14,5		
	Built up	3,96	10	82	8,4		
Sambu	Glasslands	7,3	19	74	14,0	79	79
	Agricultural Land	27,24	71	80	56,6		
	Agricultural Lands	39,53	37	80	29,8		
Duago	Built up Area	4,29	4	82	3,3	77	77
	Grass Lands Areas	62,18	59	74	43,4		
	Agricultural Lands	22,29	33	80	26,3		
Denugo	Built up Areas	5,34	8	82	6,5	77	77
	Grass lands	40,18	59	74	43,8		
	Agricultural lands	1,15	44	80	35,5		
Kwisini	Grasslands	1,16	45	74	33,1	78	78
	Open trees	0,29	11	79	8,8		
	Agricultural lands	5,65	54	80	42,8		
	Built up Area	0,54	5	82	4,2	78	78
Sandu - Sandu	Grass land	3,43	32	74	24,0		
	Open Space	0,93	9	79	7,0		
	Agricultural lands	40,52	34	80	26,9		
Nyeko	Grass lands	37,10	31	74	22,8	78	78
	Open Lands	43,03	36	79	28,2		
	open forest	1	6	79	4,5		
	Agriculture	6	71	80	56,9		
Dinaso Boo	Grass lands	2	22	74	16,2		78
	Water Body	0	0	100	0,0		

Busa Dampu	Agriculture	22,16	58	80	46,2	80
	Built up	2,82	7	82	6,0	
	Grass lands	13,15	34	82	28,1	
	Water Body	0,27	1	1	0,0	
Siiru Balawa	Agricultural land	0,80	18	80	14,3	79
	Built up	2,57	58	82	47,3	
	Grass land	1,07	24	74	17,8	
	Mixed forest	0	0	79	0,0	
	Waterbody	0	0	100	0,0	
Kepersii	Agricultural Land	2,30	67	80	53,6	79
	Bare Lands	0,83	24	79	19,1	
	Mixed trees	0,29	8	79	6,7	

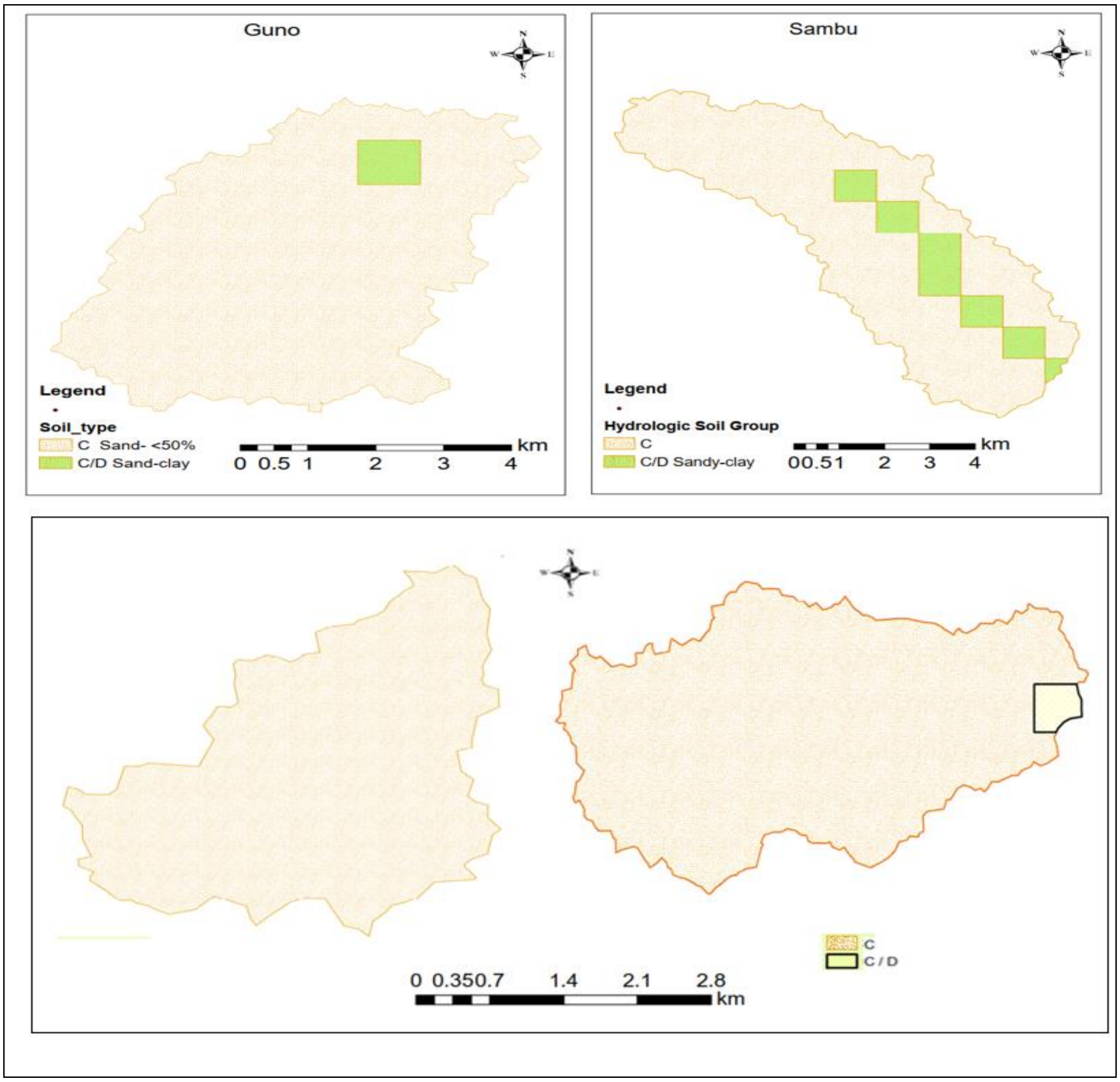
Appendix (7C): Determined Curve Number Characteristics of the Study Areas in 2005

Subcathcment	LUC Classes (2023)	Area in 2023	Area in %	Correspondent CN	Area (%) x CN	Weighted CN
Guno	Built up	2	7	82	5.6	78
	Glasslands	5.1	17	74	12.8	
	Agricultural Lands	22.1	75	80	59.9	
Gbalahi	Built up	36.86	34	82	27.5	79
	Glasslands	24	22	74	16.1	
	Agricultural Land	48.9	44	80	35.6	
Sambu	Built up	3.5	9	82	7.5	77
	Glasslands	18	47	74	34.6	
	Agricultural Land	17	44	80	35.3	
Duago	Agricultural Lands	35.87	34	82	27.7	77
	Built up Area	3.64	3	80	2.7	
	Grass Lands Areas	66.49	63	74	46.4	
Denugo	Agricultural Lands	14.66	22	80	17.3	75
	Built up Areas	4.97	7	82	6.0	
	Grass lands	47.64	70	74	52.0	
Kwisini	Agricultural lands	0.69	27	80	21.3	77
	Grasslands	1.36	53	74	38.9	

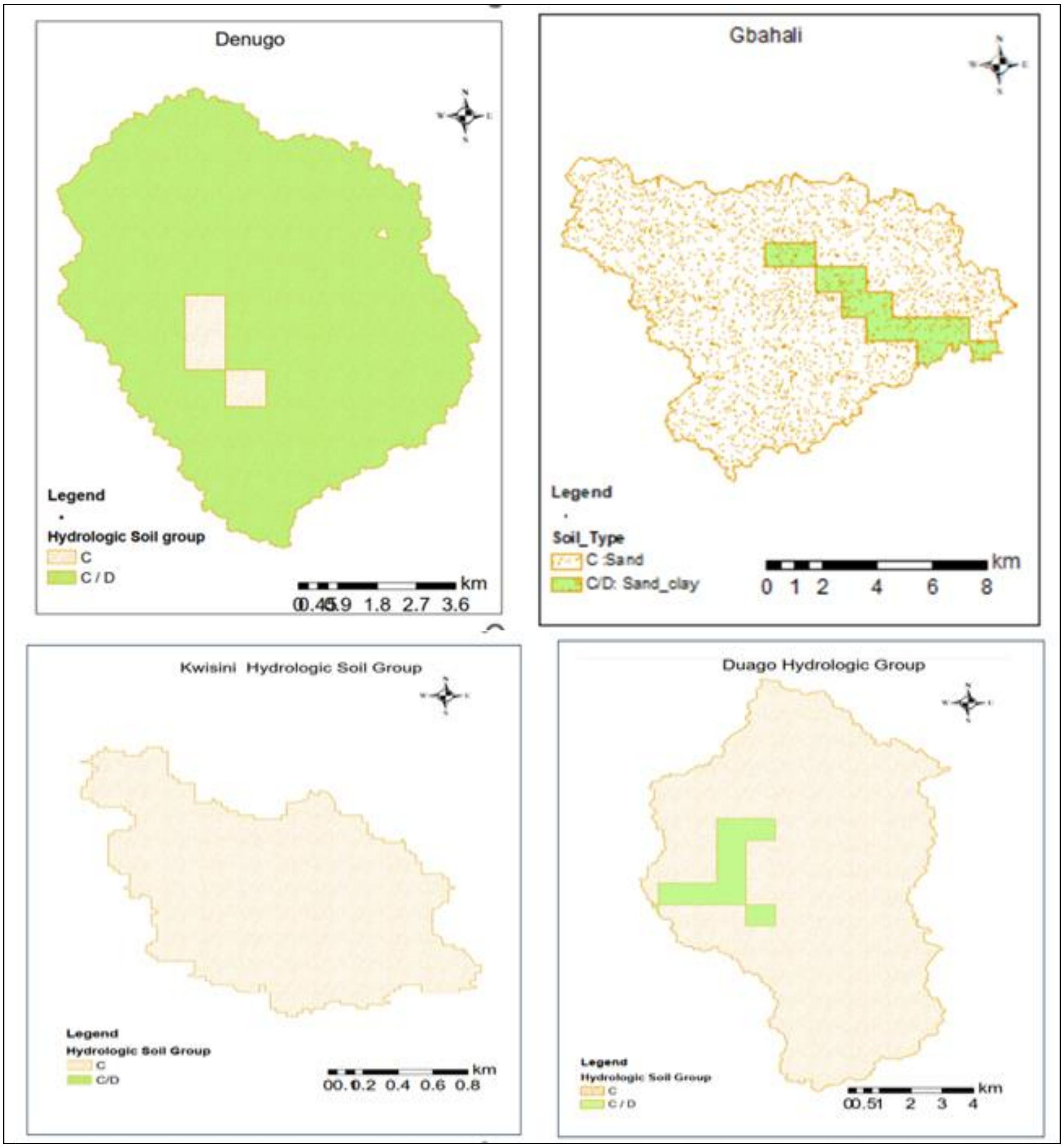
	Open trees	0.54	21	79	16.5	
Sandu - Sandu	Agricultural lands	4.05	38	80	30.7	78
	Built up Area	0.50	5	82	3.9	
	Grass land	4.01	38	74	28.1	
	Open Space	2.00	19	79	15.0	
Nyeko	Agricultural lands	26.47	22	80	17.6	77
	Grass lands	54.74	45	74	33.6	
	Open Space	39.45	33	79	25.8	
Dinaso Boo	Mixed forest	2	23	79	18.2	77
	Agriculture	3	39	80	31.3	
	Grass lands	3	37	74	27.2	
	Water Body	0	0	100	0.0	
Busa Dampu	Agriculture	17.56	46	80	36.6	80
	Built up	1.42	4	80	3.0	
	Grass lands	19.13	50	82	40.9	
	Water Body	0.28	1	1	0.0	
Siiru Balawa	Agricultural land	0.50	11	80	9.0	79
	Built up	2.15	48	82	39.5	
	Grass land	1.81	41	74	30.0	
	Mixed trees	0	0	79	0.0	
	Waterbody	0	0	100	0.0	
Kepersii	Agricultural Land	2.18	64	80	50.8	80
	Bare Lands	0.96	28	79	22.1	
	Mixed trees	0.29	8	79	6.7	

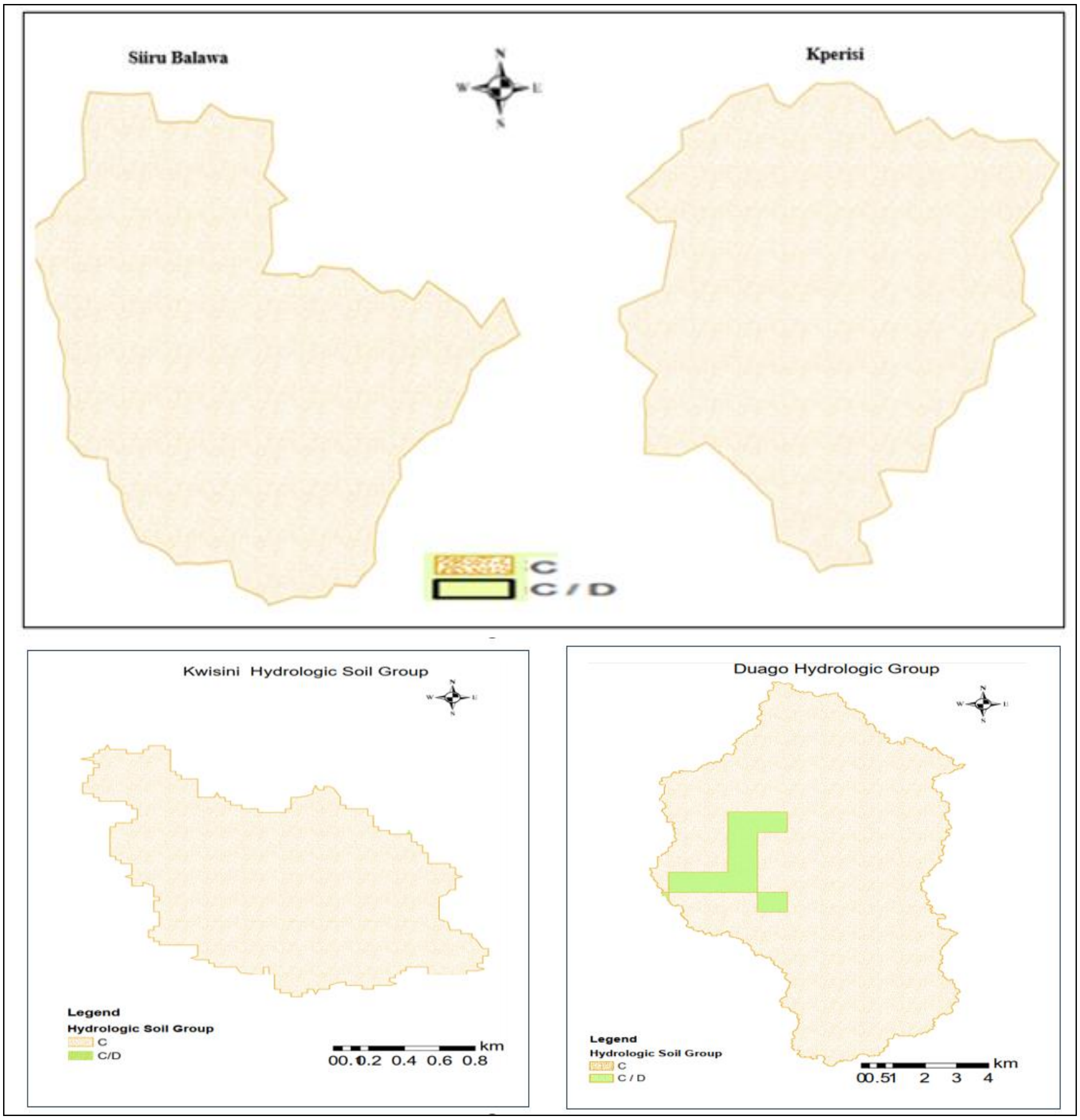
Appendix 7: Hydrologic Soil Group from the Study Areas.

	Catchment							
HSGs	Guno	Gbahali	Sambu	Duago	Denugo	Kwisini	Sandu	Nyeko
C (%)	96.5	95	97	96	98	100	97.2	94.4
D (%)	3.5	5	3	4	2	0	2.8	5.6

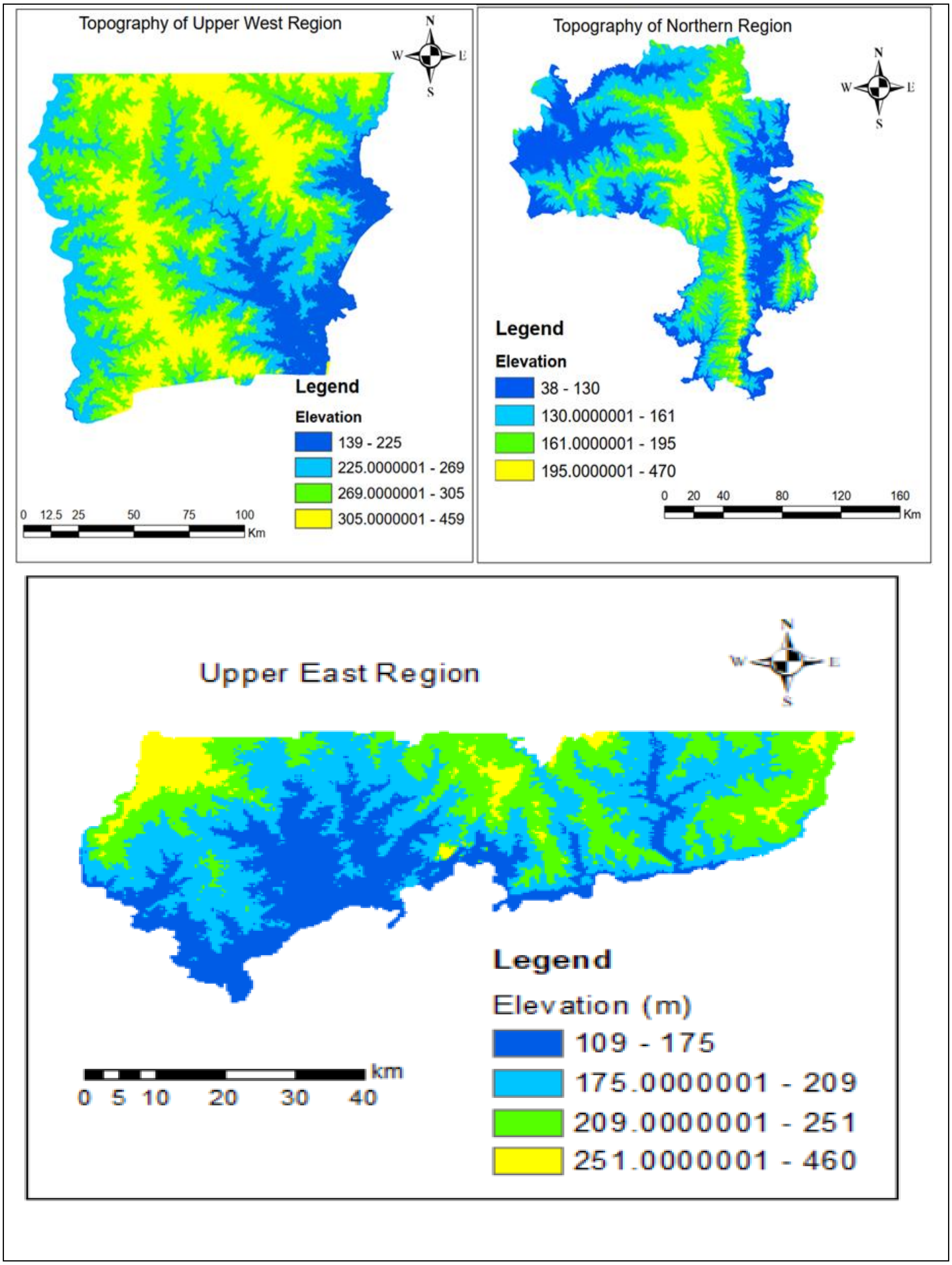


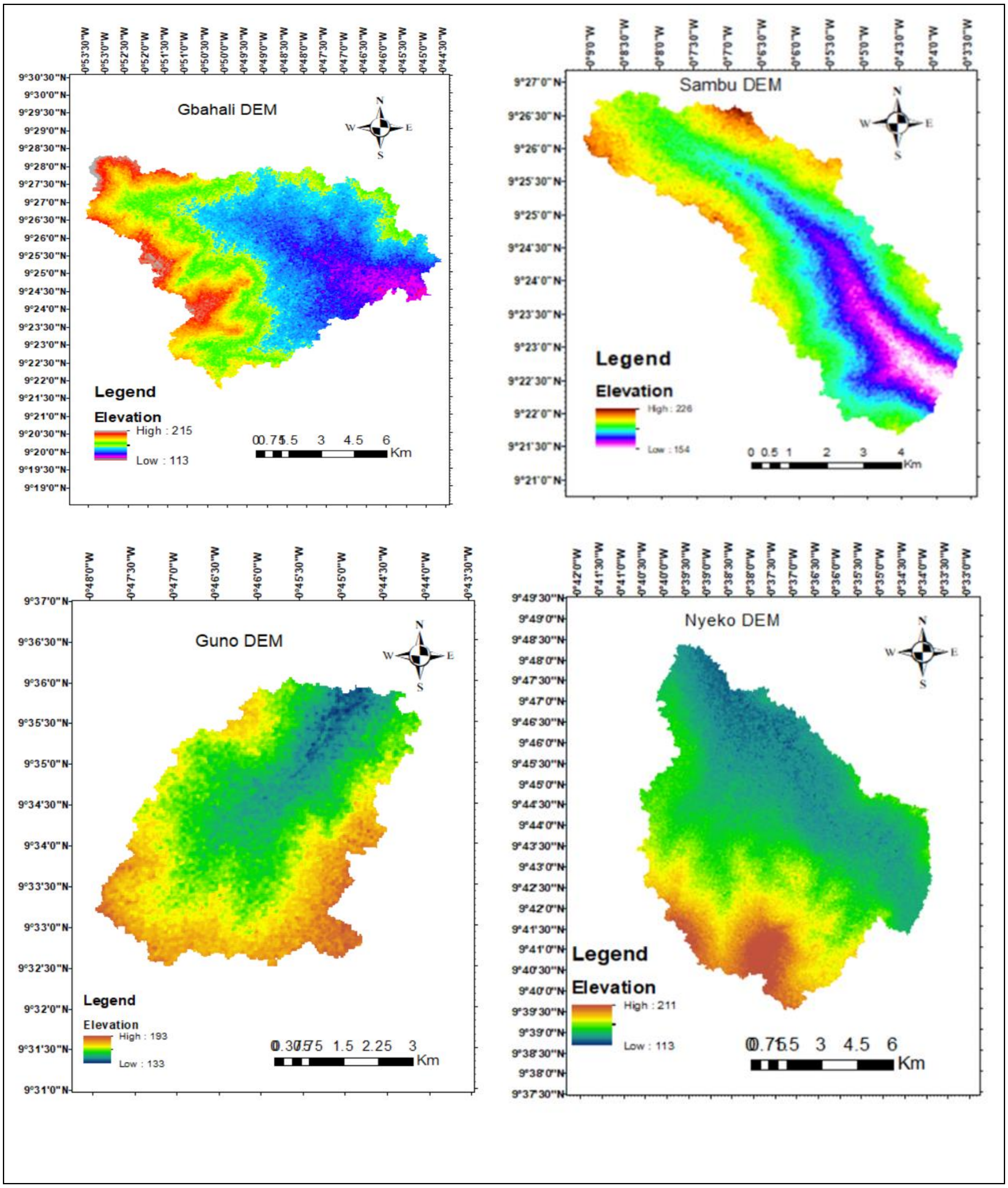
Guno
Legend
Soil_type
C Sand- <50%
C/D Sand-clay
0 0.5 1 2 3 4
km
Sambu
Legend
Hydrologic Soil Group
C
C/D Sandy-clay
00.51 2 3 4
km
C
C / D
0 0.350.7 1.4 2.1 2.8
km

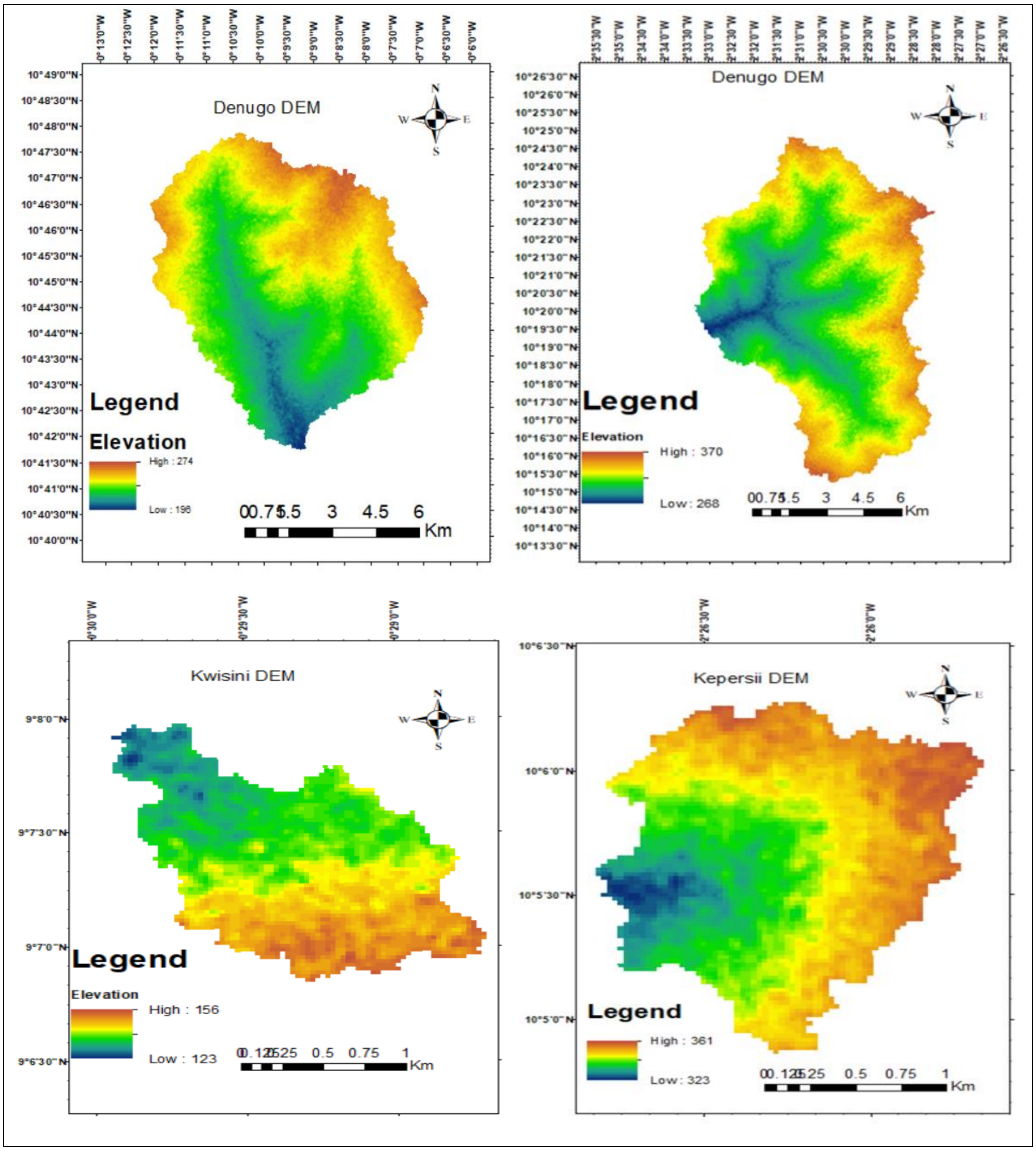

Denugo
Legend
Hydrologic Soil group
C
C / D
km
0 0.45 0.9 1.8 2.7 3.6
Gbahali
Legend
Soil_Type
C :Sand
C/D: Sand_clay
km
0 1 2 4 6 8
Kwisini Hydrologic Soil Group
Legend
Hydrologic Soil Group
C
C/D
km
0 0.1 0.2 0.4 0.6 0.8
Duago Hydrologic Group
Legend
Hydrologic Soil Group
C
C / D
km
0 0.5 1 2 3 4

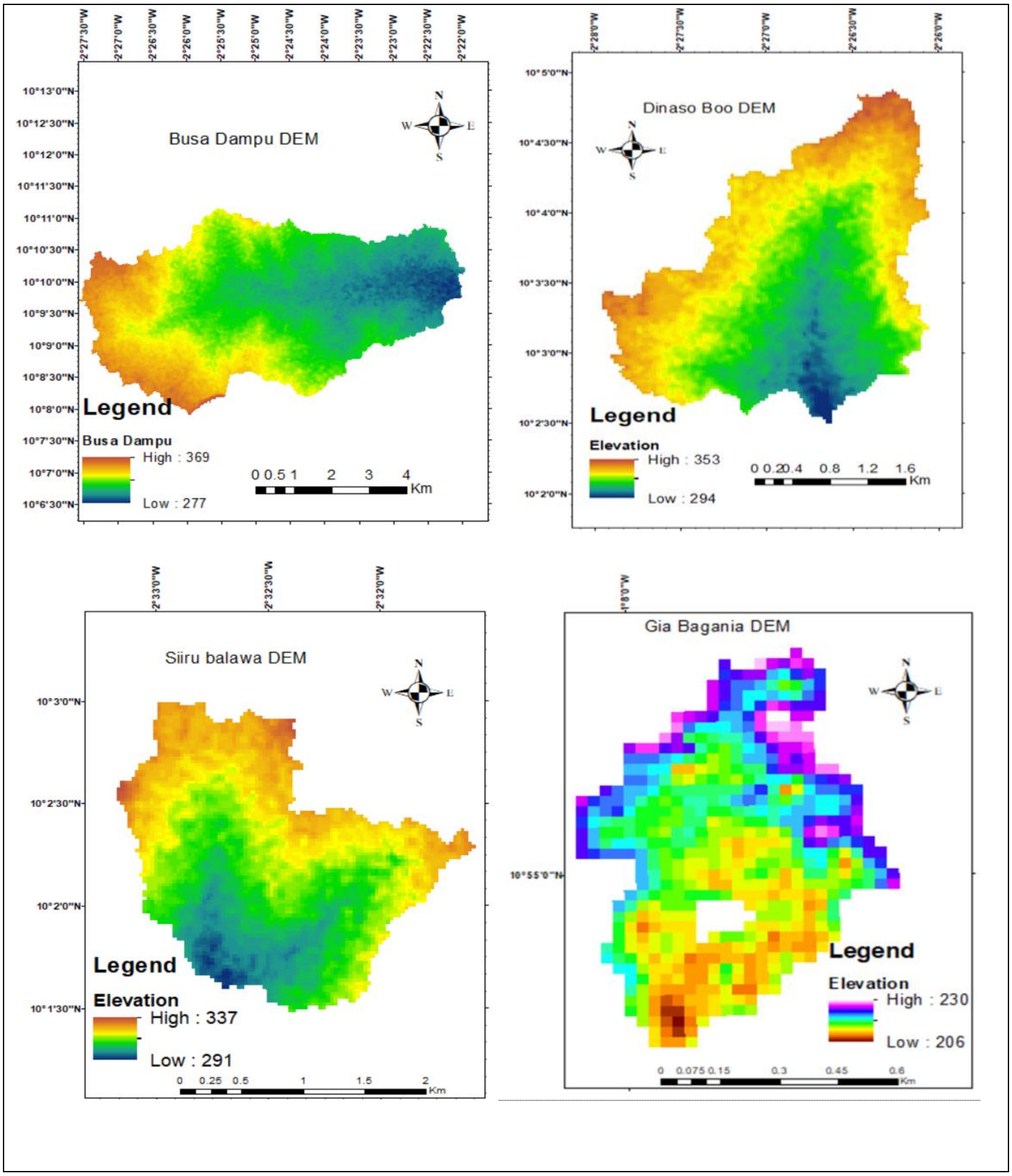

Siiru Balawa
Kperisi
C
C / D
Kwisini Hydrologic Soil Group
Legend
Hydrologic Soil Group
C
C/D
km
0 0.1 0.2 0.4 0.6 0.8
Duago Hydrologic Group
Legend
Hydrologic Soil Group
C
C / D
km
0 0.5 1 2 3 4

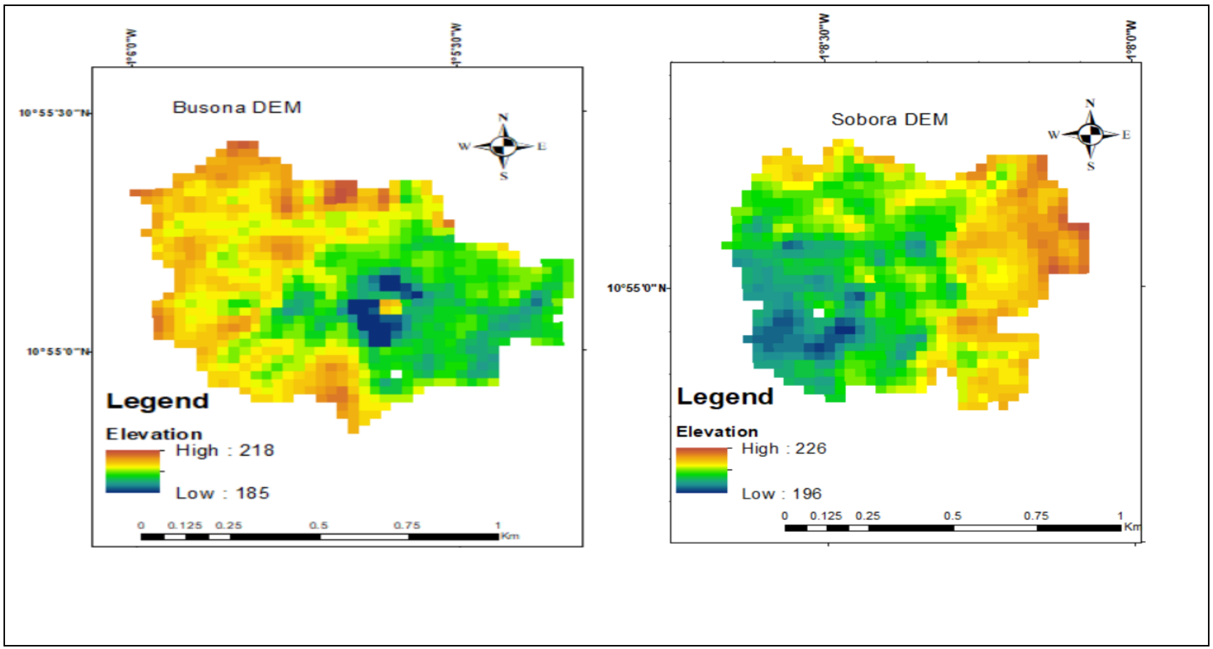
Appendix 8: Topographical Maps of the Studied Regions and Catchments




Gbahali DEM
Legend
Elevation
High : 215
Low : 113
Sambu DEM
Legend
Elevation
High : 226
Low : 154
Guno DEM
Legend
Elevation
High : 193
Low : 133
Nyeko DEM
Legend
Elevation
High : 211
Low : 113


Denugo DEM
Legend
Elevation
High : 274
Low : 196
0 0.75 1.5 3 4.5 6
Km
Denugo DEM
Legend
Elevation
High : 370
Low : 268
0 0.75 1.5 3 4.5 6
Km
Kwisini DEM
Legend
Elevation
High : 156
Low : 123
0 0.125 0.25 0.5 0.75 1
Km
Kepersii DEM
Legend
High : 361
Low : 323
0 0.125 0.25 0.5 0.75 1
Km


Busa Dampu DEM
Legend
Busa Dampu
High : 369
Low : 277
Dinaso Boo DEM
Legend
Elevation
High : 353
Low : 294
Siiru balawa DEM
Legend
Elevation
High : 337
Low : 291
Gia Bagania DEM
Legend
Elevation
High : 230
Low : 206


Busona DEM
Legend
Elevation
High : 218
Low : 185
Sobora DEM
Legend
Elevation
High : 226
Low : 196