ADDIS ABABA UNIVERSITY

COLLGE OF TECHNOLOGY AND BUILT ENVIRONMENT



School of Civil and Environmental Engineering Graduate studies MSc
in
Hydraulic Engineering

Evaluation of Irrigation Development based on Rain Water Harvesting at Jemma Sub-Basin, Upper Blue Nile River, Ethiopia.

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(Hydraulic Engineering)

By: Derara Gari Wakjira

Thesis Advisor: Belete Birhanu (Dr.)

Addis Ababa University

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	Name	Signature	Date
1.	_____ Advisor	_____	_____
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I hereby declare that thesis is my original work and has not previously been submitted for a degree or master's program at this or any other university.

Name: Derara Gari

Signature_____

Date_____

This thesis has been submitted for Examination with my approval as university advisor:

Name: Belete Birhanu (Dr.)

Signature_____

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ABSTRACT

In Ethiopia, where rain-fed agriculture is the major livelihood in the Jemma Sub-Basin, climate variability and water shortages persist as a continuing challenge. To address this problem, the present Research develops a geospatial and hydrological modelling solution for irrigation development assessment. This sustainable alternative can be achieved through rainwater harvesting (RWH). The approach included;

In the sub-basin, a GIS-based analysis of multiple criteria was used to find **6983.70 km^2** of irrigable land. Consideration should be given to components such as slope, soil type, and water accessibility. The Topographic Wetness Index (TWI), and the Normalized Difference Vegetation Index (NDVI) models was used. Subsequently, **2,274** potential sites were identified for water harvesting and storage combined, which can hold about **45.1** million cubic meters.

The next step involved using the CROPWAT model to compute the irrigation water duty. The Dega zone was found to have a value of **90.07 ha/cumec** and Weyna Dega zone **67.07 ha/cumec**. The investigation revealed that the demand for irrigation water is **191.54 cumec** for all identified suitable lands.

Calibration of HYPE model was done, in order to assess the water availability in the catchment, three hydro-gauging stations have been established. It is evident that total available water in the Jemma Sub-Basin is **206.222 cumec**. It is more than sufficient to meet total irrigation water demand.

Thus, water availability does not pose a limitation. This confirms that irrigation development based on rainwater harvesting is a feasible and sustainable strategy to enhance agricultural production and water security in the area.

Keywords: *Rainwater Harvesting, Irrigation Suitability, GIS, AHP, NDVI, TWI, HYPE Model, Hydrological Modeling, Crop Water Requirement, Jemma Sub-Basin, Upper Blue Nile, Ethiopia*.

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ACRONYMS

ANOVA	Analysis of Variance
CSA	Central Statics Agency
CR	Consistency Ratio
CWR	Crop Water Requirement
DEM	Digital Elevation Model
DMA	District Metering Area
ET_O	Evapotranspiration
FAO	Food and Agriculture Organization's
GIS	Geographical Information System
HYPE	Hydrological Predictions for the Environment
IWA	International Water Association
ITCZ	Inter Tropical Coverage Zone
K_C	Crop Coefficients
MCA	Mult- Criteria Analysis
MCDM	Multi-Criterial Decision Making
NGO	Non-Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NMA	National Metrological Agency
RAM	Readily Available Moisture
RLD	Rain Water Leader Design

RHA	Rain Water Harvesting
TAW	Total Water Available
TAM	Total Available Moisture
UFW	Unaccounted for Water
UBNB	Upper Blue Nile Basin
WRP	Water Resource Potential

1. INTRODUCTION

1.1 Background and Introduction

Food security and agricultural productivity are seriously threatened by the growing global problem of water scarcity. The strain on water resources has increased as a result of urbanization, industrialization, and population growth worldwide. In areas that depend significantly on agriculture, where water is an essential input for crop production, this shortage is especially severe. Although agriculture is the backbone of the economies in many African countries, it is still extremely susceptible to changes in the availability of water. These areas are especially vulnerable to the negative effects of drought and rainfall variability because they rely heavily on rain-fed agricultural systems.

Ethiopia has severe water scarcity issues that hinder the growth of its agriculture. Ethiopia experiences seasonal and variable rainfall, which frequently results in dry spells and droughts that have a detrimental effect on crop yields. The region's water scarcity issue is made worse by this variability, high runoff, and evapotranspiration losses (Gebremedhn et al., 2023).

Sustainable water management techniques that can boost agricultural output and guarantee food security are desperately needed to address these issues. These tactics ought to maximize the use of available water resources for irrigation while reducing the effects of rainfall variability.

A promising strategy to reduce water scarcity and improve agricultural output, particularly in arid and semi-arid areas, is rainwater harvesting (RWH) (Faruqi et al., 2020). RWH is the process of collecting and holding onto rainwater for later use from a variety of sources, including land surfaces and rooftops. This method improves water availability for irrigation and provides a decentralized, sustainable way to augment conventional water sources. RWH can help improve agricultural resilience and stabilize crop yields by lowering dependency on unpredictable rainfall.

Proper site selection and storage capacity are two of the many factors that affect RWH's effectiveness (Saplioglu & Kucukerdem, 2018). Maximizing the use of collected rainwater requires figuring out the ideal storage reservoir size (Saplioglu & Kucukerdem, 2018).

Finding appropriate land for irrigation is a crucial first step in the development of irrigation systems. Analyzing land suitability entails assessing a number of variables to decide whether a piece of land is suitable for a given use, like irrigation. These elements could be land cover, slope, soil properties, and the distance from water sources (Tolera et al., 2023; Hagos et al., 2022; Yalew et al., 2016).

Geographic Information Systems (GIS) and remote sensing are two examples of geospatial technologies that are essential to land suitability analysis because they make it possible to process and analyze spatial data efficiently (Tolera et al., 2023; Yalew et al., 2016). To integrate and weigh various suitability factors, GIS-based multi-criteria decision-making (MCDM) techniques, like the Analytical Hierarchy Process (AHP), are frequently used (Tolera et al., 2023; Yalew et al., 2016; Gebremedhn et al., 2023).

Finding possible RWH locations and determining whether land is suitable for irrigation development require the use of geospatial technologies (Haile & Suryabhagavan, 2019). To assess site-specific conditions, GIS enables the integration of multiple spatial data layers, including topography, soil maps, and land use information (Tolera et al., 2023). Finding appropriate water storage locations can be facilitated by using remote sensing methods like the Normalized Difference Vegetation Index (NDVI) and Topographic Wetness Index (TWI), which can offer useful data on vegetation cover and water flow patterns (Bisrat & Berhanu, 2018).

In order to assess water resources and assist with irrigation planning, hydrological modeling is yet another essential element. In order to estimate water availability and design RWH systems, the relationship between rainfall and runoff is simulated using rainfall-runoff models (Peel & McMahon, n.d.). River discharge can be simulated using hydrological models, like the HYPE model (Bui et al.).

Water scarcity and agricultural development present major challenges for Ethiopia's Jemma sub-basin, which is part of the Upper Blue Nile River basin (Gebremedhn et al., 2023; Yitea et al., 2023). Because the sub-basin's agriculture is primarily rain-fed, it is susceptible to drought and fluctuations in rainfall. The potential of RWH to promote irrigation development and raise agricultural productivity in this area needs to be assessed.

In order to meet this need, this study will assess irrigation development in the Jemma sub-basin using RWH. To determine appropriate locations for RWH, gauge water availability, and analyze the feasibility of irrigation development, the study will make use of hydrological modeling and geospatial techniques. In the Jemma sub-basin, this research can help increase agricultural productivity and food security by offering insights into sustainable water management techniques.

1.2 Statement of the Problem

The issue of water scarcity is a serious global concern, menacing agricultural production and food security. Growing industrialization, accelerated urbanization, and an expanding global population are adding to the pressures, which raise the demand on already scarce water resources. The agricultural sector, which depends heavily on water, is especially vulnerable to these pressures because water is a key input in the production of crops. Agricultural water shortage leads to reduced crop production, reduced agricultural productivity, and exacerbated food insecurity, particularly in regions where agriculture is the principal means of livelihood.

As in most countries in Africa, agriculture is a staple in Ethiopia, and it generates economic activity and livelihood for a great majority of its people. The livelihood of millions is at stake, and agricultural development is frustrated by the severe water shortage issues in the country. The country has periodic dry spells and perpetual droughts because of its extremely variable and seasonal rainfall pattern. Intensive runoff and evapotranspiration rates, combined with an unreliable pattern of precipitation, increase the risks inherent in water scarcity and render farming activities extremely vulnerable and volatile. Compounding these difficulties is the fact that there is a shortage of proper infrastructure and inefficient water management practices, which undermine the country's potential to optimize water resources for agricultural output.

Rainwater harvesting (RWH) has been identified as a viable and sustainable means of lessening the adverse effects of water scarcity on agriculture. RWH involves the collection and storage of rainwater from different surfaces such as ground areas and rooftops for subsequent use in irrigation and other uses. RWH enhances the reliability of the water supply which can stabilize crop production and enhance agricultural productivity and resilience.

The successful implementation of RWH involves proper planning and consideration of factors such as site selection, storage capacity, and use of water.

The success of irrigation development e.g. RWH-based irrigation depends on identification and usage of suitable land. The land suitability analysis refers to the analysis of a set of variables to determine whether a particular land is suitable for irrigation or not. Features such as land cover, water availability, topography (for instance, slope), soil (for instance, texture, depth, and drainage), and access to infrastructure.

Geospatial technologies are indispensable for efficacious collection, processing, and analysis of geospatial data. Land suitability analysis involves the assessment of land for varied kinds of land-uses, The precise input for land suitability analysis requires the use of geospatial technologies. Techniques such as Analytical Hierarchy Process (AHP) and other similar GIS based multi-criteria decision making (MCDM) approaches are usually adopted to enter and evaluate multiple suitability factors and to offer logical way of evaluating land suitability.

In Ethiopia, the Upper Blue Nile River Jemma sub-basin faces significant challenges that necessitate the assessment of irrigation development driven by RWH. The sub-basin is very sensitive to drought and rainfall variations because of its high reliance on rain-fed agriculture.

Water scarcity is often triggered by a region's seasonal and unpredictable rainfall, which limits the agricultural production of food. Due to the topography of sub-basins and soils, limitations will occur for conventional irrigation approaches, making RWH a more appropriate and more sustainable alternative.

RWH should be evaluated to ascertain its ability for irrigation development and agricultural production enhancement in Jemma sub-basin. In the present study, the necessity of finding suitable sites for RWH, quantifying water availability and analyzing the feasibility and advantages of RWH-based irrigation systems will be fulfilled by using hydrological modeling and geo-spatial techniques.

The results of this study can help in the sustainable water management strategies and agricultural livelihoods improvement in Jemma sub-basin.

It is necessary to assess RWH's potential to enable irrigation development and enhance agricultural production in the Jemma sub-basin. By using hydrological modeling and geospatial techniques to determine the suitability of RWH sites, quantify water availability, and analyze the feasibility and advantages of establishing RWH-based irrigation systems, this study seeks to fulfill this necessity. The development of sustainable water management strategies and improved agricultural livelihoods in the Jemma sub-basin can gain much benefit from the data-based findings and insights of this study.

1.3 Objective of the study

1.3.1 General Objective

The broad goal of these studies includes a series of inter-connected goals that are basically related to water and irrigation management. This includes assessing irrigation development based on rainwater harvesting, land suitability analysis for irrigation, geospatial mapping of rainwater harvesting sites, capacity assessment of rainwater harvesting storage and surface irrigation potential assessment.

1.3.1.1 Specific Objectives

- Assess land suitability for irrigation development using GIS and AHP techniques.
- Apply hydrological modeling using the HYPE model coupled with geospatial techniques to identify locations for rainwater harvesting.
- Determine the water requirements of the crops and create an optimal irrigation development plan through the application of irrigation scheduling models like CROPWAT.

1.4 Research Questions

- "How can AHP and GIS methods be utilized to assess land suitability for irrigation development in the Jemma sub-basin?"
- "Where are the potential sites for rainwater harvesting system implementation in the sub-basin, and how can geospatial techniques and hydrologic modeling help in their identification?"
- "What are the main agricultural crops of the Jemma sub-basin's water requirements, and how might this information be employed to develop an optimum irrigation schedule?"

1.5 Variables

Independent Variables:

- Soil characteristics (texture, depth, pH, organic carbon, available water content, salinity)
- Slope
- Land use/cover
- Runoff depth
- Drainage density
- Distance to roads
- Distance to water source
- Proximity to urban areas
- TWI (Topographic Wetness Index)
- NDVI (Normalized Difference Vegetation Index)
- Climatic data (e.g., rainfall, temperature, evapotranspiration)
- Crop type and growth stage
- Soil moisture levels
- Streamflow

Dependent Variables:

- Land suitability for irrigation
- Rainwater harvesting suitability
- Crop water requirement (CWR)
- Water Balance

1.6 Scope of the study

In order to meet the objectives of the study, several projects were undertaken.

I. Study Area: Study area was Jemma Sub-Basin, an element of Ethiopia's Upper Blue Nile River Basin.

II. Evaluation for Irrigation Suitability: Among the aspects considered in this GIS-aided multi-criteria land suitability assessment for irrigation included slope, land use/cover, type of soil, and water courses proximity.

III. Derivation of Agricultural Suitability Criteria: The requirements needed to identify agricultural land suitability thresholds were discovered and identified by the research.

IV. GIS-Based Preprocessing: Preprocessing applicable parameters for spatial analysis, as raster layers, were achieved in a GIS environment.

V. Usage of Analytical Hierarchy Process (AHP): Weights of varying criteria raster layers, to ensure a sound decision, were calculated with the aid of the AHP method.

VI. Land Suitability Classification: Land suitability was categorized based on multiple criteria using the technique of a weighted overlay analysis approach.

VII. The research classified and categorized the basin lands into four classes of suitability: not suitable, marginally suitable, moderately suitable, and highly suitable.

VIII. Rainwater Harvesting Potential Analysis: Topographic Wetness Index (TWI) and Normalized Difference Vegetation Index (NDVI) were used in the research to examine the potential of water resource points towards WRP.

IX. Identification of Storage Sites: GIS-based spatial analysis was used to determine possible sites for water storage.

X. The HYPE model is specifically designed to simulate the flow of water in a river basin.

XI. Determining when and how much water crops require. This focuses on figuring out how much water crops need and creating the best irrigation schedules, frequently with the aid of programs like CROPWA

XII. Development of an Optimized Irrigation Plan: An optimized irrigation development plan was prepared by taking into account the outcomes of land suitability and WRP potential analysis.

XIII. Sustainability and Feasibility Implications: The research guaranteed that the proposed method of irrigation was sustainable, technologically viable, and reconcilable with the Jemma Sub-Basin water resources.

XIV. Empowerment of Local Communities: The research aimed at providing local communities with a template to use rainwater harvesting for enhanced food

security, agricultural yields, and ecologically friendly water management practices.

1.7 Significance of the study

I. The research project improves agricultural planning by providing information about the optimum irrigation and rainwater harvesting in the Jemma Sub-Basin.

II. Identifying Suitable Land for Irrigation: The study reveals suitable sites for irrigation through a multi-criteria analysis of GIS that ensures effective land-use planning.

III. Rainwater Harvesting Potential Analysis: The study uses TWI and NDVI to calculate water resource potential to identify suitable sites for rainwater storage and use.

IV. This research integrates land suitability analysis and water resource availability analysis to develop an irrigation plan that is technically feasible and environmentally sustainable.

V. This research provides evidence-based information that enables agricultural planners, policy makers and water resource managers to make fully informed decisions concerning irrigation development.

VI. Encouragement of Sustainable Water Management: The study encourages sustainable water management through the evaluation of the feasibility of rainwater harvesting and the incorporation of rainwater harvesting in irrigation planning.

VII. Seventh The identification of areas where water storage and irrigation can be created enhances efforts to improve food security and agricultural productivity in the area.

VIII. Local Community Empowerment: This paper provides a framework that will enable farmers and other local stakeholders to maximize the benefit from sustainable irrigation and rainwater harvesting technologies.

IX. GIS-Based Research Development: The study demonstrates the potential of remote sensing and GIS in assessing land and water resources, paving the way for future research in this area.

X. The upper Blue Nile basin benefit from water savings mechanisms and sustainable agriculture practices contributing to climate resilience.

XI. Significance of the HYPE Model: This research used the HYPE model to estimate river discharge and simulate hydrological processes. This will help in understanding the water flow dynamics in the Jemma Sub-Basin, which is useful for water resource management and irrigation.

XII. The research uses CROPWAT 8 model to assess the consumption of water for irrigation on demand for optimal design of effective irrigation schedules. It is useful for the design of irrigation schemes of optimum water use efficiency, high crop yields and sustainable agricultural production in the region.

1.8 Research Design Frame Work

Research design frame work

1. Introduction:
   - Give a summary of the research issue.
   - Outline the objectives of the research and
   - Explain why the study is important.
2. Identification of the Problem:
   - Assessment of the Jemma Sub-Basin irrigation issues and water shortage.
   - Water resource plays a crucial role in sustainable irrigation development.
   - GIS and hydrologic modeling are essential to optimize irrigation planning.
3. Literature Review
   - Assessment of literature availability on irrigation suitability analysis by GIS and remote sensing.
   - Assessment of rainwater harvesting potentiality estimation by TWI and NDVI.
   - Assessment of dominant irrigation planning methodologies and suitability to the study region.
4. Data Collection: -

Spatial Data:

- Digital Elevation Model (DEM) for slope and watershed delineation.
- Land use/land cover (LULC) maps, soil maps, climate information.
- Hydro-meteorological data (streamflow, rainfall, evaporation).

Satellite Imagery & Remote Sensing Data:

- NDVI for a study on vegetation index.

- TWI for analysis of potential areas of water storage.

Socioeconomic Data:

- Agricultural land use trends.
- Local community-based methods and irrigation practices.

5. Data Processing and Analysis

Preprocessing:

- Conversion of spatial data to GIS-compatible form.
- Normalization and reclassification of datasets on a raster basis.

Irrigation Suitability Analysis:

- Multi-criteria analysis (MCA) of GIS.
- Weighting of attributes to criteria through Analytical Hierarchy Process (AHP).
- Weighted overlay analysis for suitability categorization of irrigation.

Water Resources Potential Analysis:

- TWI and NDVI-based identification of potential RWH storage sites.
- Association of hydrological and topographical factors.

Optimization of Irrigation Development Plan:

- Land suitability and WRP storage capacity integration.
- Scenario analysis for alternative irrigation strategies.
- Determination of feasibility for sustainable water use.

6. Results and Discussion
   - Irrigation Suitability Zone Mapping.
   - Location Identification of Suitable RWH Storage Sites.
   - Balancing Suitability and RWH for Irrigation Development.
   - Implications to Sustainable Water Management.
7. Conclusion and Recommendations
   - Summary of conclusions.
   - Policy and practical implications for irrigation development.
   - Future research directions for better water resource management.

1.9 Summary of Research Design Frame work

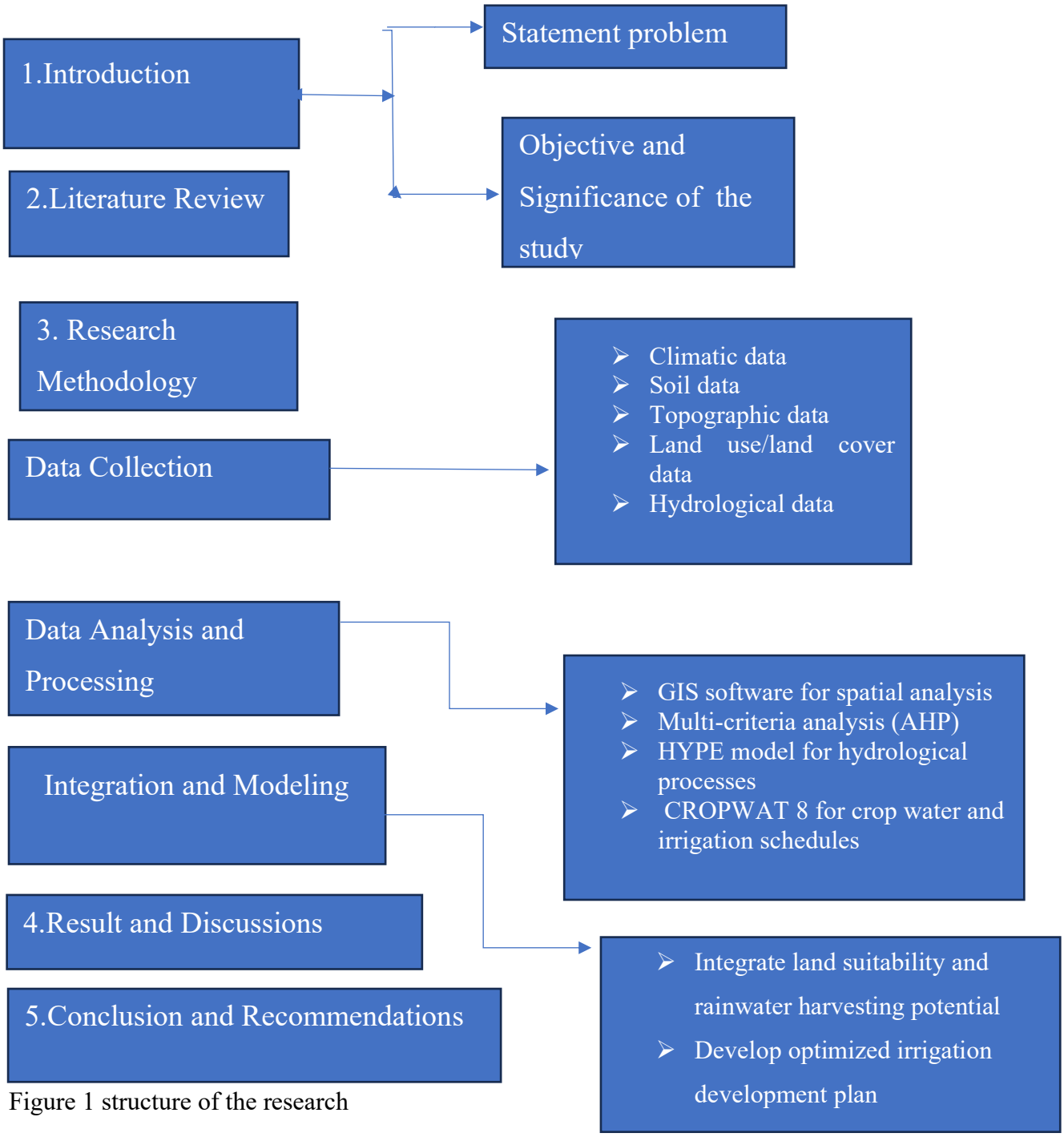


Figure 1 structure of the research

2. LITERATUREREVIEW

2.1 Introduction

A growing global population and intensifying agricultural demands are putting immense pressure on freshwater resources. This is particularly concerning in regions with limited water availability, where traditional irrigation practices often contribute to unsustainable water management. Rainwater harvesting (RWH) emerges as a promising solution, offering a reliable and eco-friendly source of water for irrigation. This literature review explores the potential of RWH for sustainable irrigation development, analyzing existing research on its benefits, challenges, and successful implementation strategies (Alene et al., 2022).

Ethiopia faces a significant challenge in ensuring water security for its growing population. Highly reliant on rain-fed agriculture, the country is vulnerable to erratic rainfall patterns and frequent droughts. These climatic uncertainties significantly impact agricultural productivity, leading to crop failures, food insecurity, and economic hardship, particularly in rural communities (Gebremichael et al., 2016). Traditional water management practices often prioritize large-scale infrastructure projects, neglecting localized solutions that could enhance water security at the community level (Woldearegay et al., 2017).

Rainwater harvesting (RWH) offers a promising approach to improve water availability at the local level. By capturing and storing rainwater during the wet season, RWH provides a supplemental source of water for irrigation during dry periods. This can significantly enhance agricultural productivity, improve food security, and empower communities to manage their water resources more effectively (Adimassu et al., 2014).

This literature review explores the potential of RWH for sustainable irrigation development in Ethiopia. It examines the existing body of research on RWH practices, their benefits and challenges, and their role in promoting sustainable water management in Ethiopian agriculture.

2.2.1 Case Studies of Successful RWH Projects in Ethiopia

Several successful RWH projects in various regions of Ethiopia serve as valuable case studies. Studies show practical applications of RWH technologies as well as their agriculture productivity effects and strong need for community involvement in RWH projects.

Here are some examples:

The Tigray Region now implements the micro-catchment rainwater harvesting systems which perform two key functions: they improve agricultural production while simultaneously enhancing food security throughout local areas (Adimassu et al., 2014).
In the Wolaita Zone rooftop rainwater harvesting systems successfully operating serve as additional water sources for vegetable farming which improves local household financial stability (Moges et al., 2018).

The Amhara Region implemented sand dams across ephemeral rivers in order to restore damaged lands and increase water levels and deliver irrigation systems to smallholder farmers (Mekonnen et al., 2018).

2.2.2 The Need for Sustainable Irrigation Development in Ethiopia

Ethiopia's agriculture remains the backbone of the nation's economy, sustaining over 80% of the population and contributing significantly to GDP (World Bank, 2023). However, the sector faces grave threats from water scarcity and irregular rainfall patterns. Rain-fed agriculture is highly vulnerable to drought and, therefore, crop failure and famine are frequent occurrences (Conway & Schipper, 2011). This underscores the imperative to embrace sustainable irrigation development initiatives toward boosting agricultural productivity and enhancing food security in Ethiopia. The predicament of water scarcity amidst rising food demand due to population growth is a principal global issue, especially in basins such as the Upper Blue Nile River Basin in Ethiopia. These issues call for encouraging sustainable agricultural production with emphasis on effective irrigation and water resource management. This literature review presents key areas of study applicable to this subject, including hydrological modeling, crop water needs, rainwater harvesting, land suitability analysis, and the combination of these considerations for optimal irrigation development.

2.2.3 Land Suitability Analysis for Irrigation

Land suitability analysis is necessary to identify areas with the potential for successful irrigation development. Many studies have emphasized the importance of using a range of factors to determine this suitability. Topography, soil characteristics, and present land use patterns are typically included in these components. The significance of aligning land attributes with the demands of particular land uses is emphasized in the Food and Agriculture Organization's (FAO) 1976 land evaluation guidelines. Yalew et al. (2016) used AHP, GIS, and remote sensing methods to perform a land suitability analysis in the Abbay basin. The study found that a sizable section of the basin was ideal for farming, underscoring the area's potential for agricultural growth. Similarly, Tolera et al. (2023) used a GIS-based analytical hierarchy process to evaluate the suitability of land for irrigation in the West Shewa zone of Oromia, Ethiopia. Their study illustrated the complex nature of land suitability evaluations by taking into account variables like slope, land use, soil characteristics, and proximity to water sources. To further highlight the importance of contemporary technology in this area, Hagos et al. (2022) also employed geospatial technology to evaluate the land's suitability for surface irrigation development in the Ethiopian highlands.

These studies show a consistent method for analyzing land suitability by integrating various spatial data layers using GIS and AHP. The results highlight the potential for agricultural development in a sizable section of the Ethiopian highlands, provided appropriate irrigation techniques are used. The procedure frequently entails dividing the land into various suitability classes according to the limiting factors and their intensity, including highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and unsuitable (N) (Hagos et al., 2022).

2.2.4 Geospatial Technology and AHP in Land Suitability Analysis

Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) are presently indispensable tools in land suitability analysis. GIS provides a management and analysis environment for spatial data, and AHP offers a systematic approach to decision-making by means of weighting and ranking of various factors (Saaty, 1977).

The integration of GIS and AHP enables researchers to manage large spatial data efficiently and incorporate multiple criteria in the decision-making process. For instance, Gebremedhn et al. (2023) utilized GIS and AHP to identify the suitable rainwater harvesting points in the Chacha watershed, Jemma sub-basin, Upper Blue Nile, Ethiopia. The study considered eleven variables, including slope, soil texture, runoff depth, and land cover, validating the capability of GIS-AHP to handle complex data. Yalew et al. (2016) and Tolera et al. (2023) also effectively used GIS and AHP. The AHP method involves developing a pairwise comparison matrix to derive the weights of different criteria.

The application of GIS and AHP in these studies demonstrates their effectiveness in providing quality and accurate results for land suitability analysis. The ability to integrate several data sets and sequentially analyze various factors makes these tools vital in sustainable land and water resource planning.

2.2.5 Rainwater Harvesting: Potential and Site Identification

Water shortage problems can be effectively managed through rainwater harvesting techniques which have emerged as essential tools for arid and semi-arid territory management. Rainwater harvesting consists of collecting and storing precipitation which becomes usable water for agricultural purposes together with residential needs along with protecting the environment. The fundamental concept of rainwater collection exists in this water balance formula:

$V = C \times R \times A$

Where: The volume of stored rainwater equals the product of runoff coefficient and rainfall depth and catchment area.

C = Runoff coefficient

R = Rainfall depth

A = Catchment area

Haile & Suryabhagavan (2019) performed a geographic information system analysis to study available rainwater collection opportunities in the Arsi Zone of Central Ethiopia. Bisrat and Berhanu (2018) executed site searches for surface water storages using topography combined with land use analysis and vegetation sensors and NDVI data and

TWI methods. The results of these investigations show how rainwater harvesting operations can help boost conventional water supplies to boost water safety security.

Identifying proper sites for rainwater harvesting operations determines its effectiveness levels. The Rainfall patterns alongside topography features together with soil properties and nearby access to demand centers must be evaluated. The researchers from Gebremedhn et al. (2023) conducted their study at the Chacha watershed in Ethiopia whereas they investigated slope, soil texture, runoff depth along with land cover as crucial factors. TWI functions as a standard approach for predicting locations where water ponding might occur. The TWI is calculated as:

$$TWI = \ln (As / \tan(\beta))$$

Where:

As = Specific catchment area

β = Slope angle

2.2.6 Rainwater Harvesting in Dryland Agriculture

For agricultural production to continue in arid areas with irregular and infrequent rainfall, rainwater harvesting is especially important. According to Yosef and Asmamaw (2015), rainfall is essential for agricultural productivity in Ethiopia, where subsistence rain-fed agriculture is prevalent. Biazin (2012) also looked at rainwater harvesting for dryland agriculture in Ethiopia's Rift Valley.

In dryland agriculture, choosing the right methods and optimizing water use are essential to the success of rainwater harvesting. Rainwater harvesting is a sustainable way to address the problem of water scarcity in agriculture, claim Faruqi et al. (2020). In these vulnerable areas, rainwater harvesting in conjunction with other water management techniques, like supplemental irrigation, can also increase crop yields and improve food security. Depending on the particular agro-ecological conditions and farming systems, a variety of rainwater harvesting techniques, including contour ridges, retention ditches, and micro-basins, can be used.

2.2.7 Determining Rainwater Harvesting Storage Capacity

Designing rainwater harvesting systems starts with selecting appropriate storage capacities that form an essential part of the system design process. The process of determining rainwater harvesting storage capacity using the particle swarm optimization method appears in Saplioglu et al. (2018). Determining the best tank capacity requires considering both local precipitation patterns and water consumption statistics according to the study. Water quantity between supply and demand requires an equal level of storage capacity.

An exact assessment of storage capacity remains vital because it establishes reliable water supply while preventing overflow-related water loss. The calculation process for determining proper storage volumes requires evaluation of demand variables alongside rainfall patterns as well as economic requirements and catchment region characteristics. The mass curve analysis serves as a method to determine storage capacity (S) by graphing the accumulated water demand and rainfall predictions into a single chart.

2.2.8 Crop Water Requirements and Irrigation Scheduling

Developing suitable irrigation schedules and having a solid grasp of crop water requirements are essential for effective irrigation techniques. The total amount of water required by a crop to reach maturity is known as its crop water requirement (CWR), whereas irrigation scheduling entails figuring out when and how much water to apply to the crop.

In the Welmera district of Ethiopia's Central Highland, Abebe and Temam (2024) estimated the water requirements and irrigation schedule for potatoes using the CROPWAT 8.0 model. By forecasting crop water needs, Baig et al. (2023) also sought to create a system that maximizes water use in agricultural irrigation. The FAO created CROPWAT, a popular program for figuring out CWR. The fundamental formula used to determine CWR is

$$ETc = ETo \times Kc = CWR$$

Where:

Crop evapotranspiration (ETc)

ETo stands for reference evapotranspiration.

Kc is the crop coefficient.

Maximizing crop yields, reducing water waste, and halting soil degradation all depend on the precise calculation of CWR and the application of efficient irrigation schedules. Irrigation planning must take into account variables that affect CWR, such as crop characteristics, soil type, and climate.

2.2.9 Rainfall-Runoff Modeling

Hydrological tools named rainfall-runoff models analyze the transformation process of catchment rainfall into runoff. These predictive tools are essential because they provide forecasts of water availability needed for different applications including irrigation together with hydrological system understanding in basin areas.

The evolution of rainfall-runoff modeling practices from the past till present is discussed by Peel & McMahon (n.d.). The relationship between rainfall-runoff was analyzed by Sebayang et al. (2018) through their implementation of an artificial neural network model. The research study employed the HYPE model according to Phuong et al. (n.d.). Conceptual and empirical methods comprise the two primary types of rainfall-runoff models with the Soil Conservation Service Curve Number method belonging to the conceptual group and the Rational Method existing as an empirical model. The rational method determines peak runoff rate (Qp) through calculation of

$$C \times I \times A = Qp$$

Where:

C is the runoff coefficient.

Rainfall intensity receives the abbreviation **I** in this equation.

A stand for catchment area.

The type of research aims together with the characteristics of the basin and data accessibilities determine which rainfall-runoff simulation model to select. The computational models help estimate water streamflow at the surface while offering benefits for water resource assessment and irrigation planning.

2.2.10 HYPE Model for Hydrological Simulation

The Hydrological Predictions for the Environment (HYPE) model functions as a dynamic process-based system that runs simulations of river basin water flow and transport procedures. The model has been designed to forecast multiple hydrological measurements with river discharge being among them alongside nutrients levels and additional water quality data.

Each sub-basin in the catchment receives individual hydrological process simulation from the HYPE model. A representation of sub-basin water balance takes this form

$ds/dt = P - ET - Q - G$

Where:

S = Water storage

t = time

P = Precipitation

ET = Evapotranspiration

Q = Discharge

G = Groundwater flow

The HYPE model demonstrated its capabilities to predict Upper Srepok River Basin River discharge according to Phuong et al. (n.d.). The HYPE model functions effectively as a resource that helps reveal basin water balances and lets users measure land use and climate change effects on water sources for supporting water resource management choices.

2.2.11 Optimization of Irrigation and Crop Planning

Effective optimization of crop planning methods together with irrigation techniques must exist to support sustainable agricultural systems. Widespread optimization of water resource use needs to produce both environmentally friendly outcomes and enough agricultural products to meet growing food requirements.

Duhan et al. (2012) proposed a simulation together with optimization approach to manage crop planning and irrigation operations. A complete method which incorporates crop needs and water resources together with environmental variables must be used for optimal

irrigation management and agricultural scheduling. Linear programming techniques help optimize the decision-making process regarding crop allocation at different times as well as irrigation programming subject to limits from land availability and water sources and market requirements.

A review of research demonstrates numerous links between land assessment methodologies and hydro-logical modeling with aspects of rainwater collection and the necessary use of water by crops within irrigation systems. Biotechnology tools such as GIS and AHP provide essential capabilities to unite various information sources for facilitating decision-making processes. Rainwater harvesting presents an effective secondary water supply method which helps regions with limited water supplies while proper crop water measurement with optimized irrigation management leads to the best possible output while preventing unnecessary water loss. The hydro-logical simulation benefits significantly from utilization of HYPE and similar models. Agricultural production needs the optimized approaches to irrigation and crop planning for keeping farming operations sustainable over the long term. A combination of various approaches enables the creation of sustainable agricultural systems which boost agricultural food security through higher income potential in water-deprived environments.

3.MATERIAL AND METHEDOLOGY

3.1 Overview of the Study Area

This research was conducted in the Jemma Sub-Basin; a part of the Upper Blue Nile Basin located in the central highlands of Ethiopia.

3.1.1 The location of the Study Area

Jemma Sub-Basin is situated in the central part of the highlands of Ethiopia that constitutes a sub-basin of the Upper Blue Nile Basin (UBNB). Geographically, this is located between 9º 12' l0.900 to 10º 57' 23.900l N latitude and 38°6'59.900" until 39°48'46.900 E longitude. The basin has a large area total about 15,000km^2 and its altitude variability is between 991 meters and 3814 meters, above sea level. This mixed topography is one of the concepts bringing about the mixed climatic conditions and patterns of land usage in the basin.

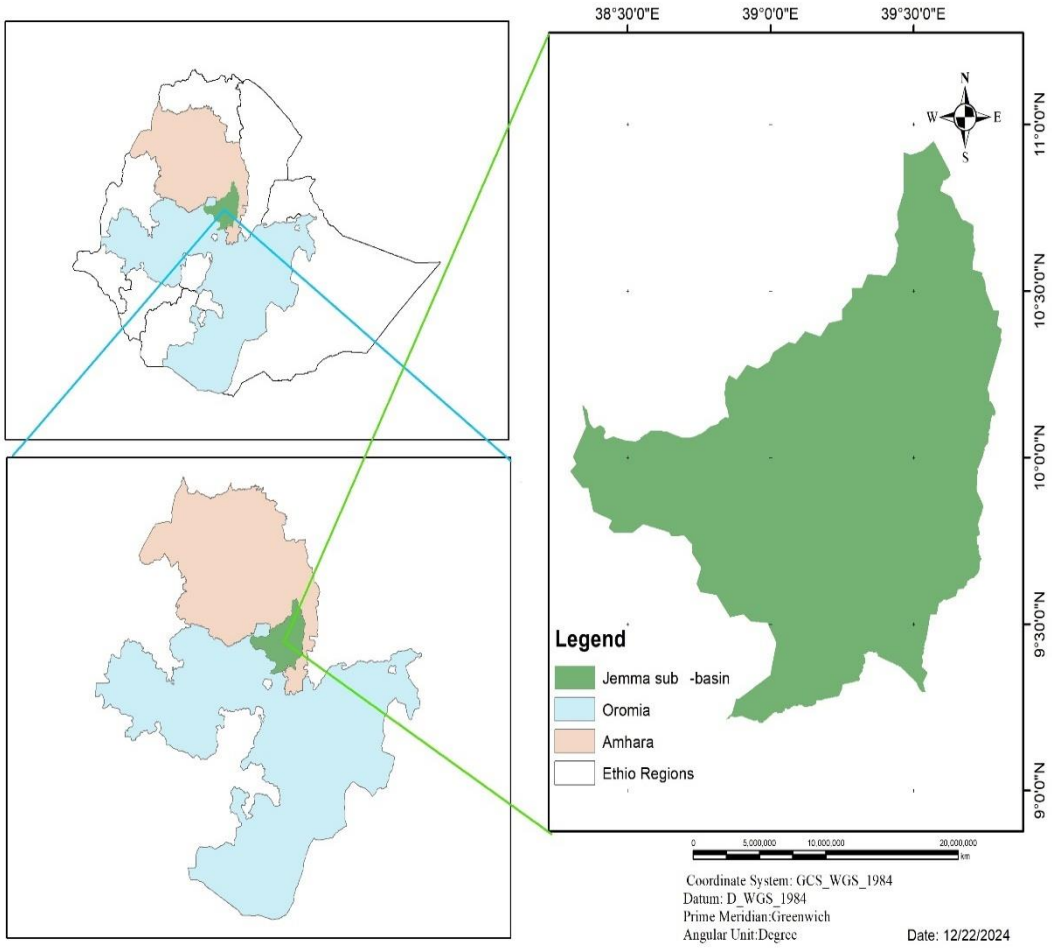


Figure 2 Location of the study area map

3.1.2 Climatic characteristics of the study area

The Jemma Sub-Basin has a diverse climate with mean annual temperatures ranging from 9°C to 24°C. The rainfall in the area also varies from 697 mm to 1475 mm annually. The area has two rainy seasons that dictate the farming activity. The short rainy season, commonly known as Belg, occurs between February and May, and the main rainy season, Kiremt, runs from June to September and accounts for the majority of the nation's annual rainfall. The bimodal rainfall pattern allows for two harvesting seasons.

3.1.3 Land Use and Land Cover of the Study Area

Land use and land cover were established as significant factors in land suitability determination for irrigation development. The research utilized spatial data, specifically European Space Agency Sentinel-2 Imagery, to preprocess and analyze land cover and land use data in the GIS environment. Land use/land cover was also used as a mask to exclude areas that were not agriculturally viable or irrigable. This comparison was a crucial step to generate the final suitability map of the sub-basin.

3.2 Data Collection and Sources

Data	Source
Digital Elevation Model	USGS https //earth-explorer.usgs.gov/
Soil Properties	Harmonized World Soil Database, version 1.2
Soil Depth	AfSoilGrids250m
Land Use/Cover	European Space Agency Sentinel-2 Imagery
River Network	Ministry of water and Energy Bureau
Road Network and Urban Areas	https://www.ethiogis-mapserver.org/dataDownload.php
River flow data	Ministry of water and Energy Bureau
Climate data	CLIMWAT 2.0 for CROPWAT

Table 1 Data and data source

The research relied on different kinds of data from diverse sources to conduct comprehensive analysis. These data were necessary for the geospatial analysis, hydrologic modeling, and estimating crop water requirements.

Spatial Data:

- Digital Elevation Model (DEM): Used in the computation of topographic variables like slope. The DEM data was preprocessed to correct errors before use.
- Soil properties: Data on soil properties such as texture, depth, and water-holding capacity were acquired from the Harmonized World Soil Database.
- Land Use/Land Cover (LULC): It was acquired from European Space Agency Sentinel-2 Imagery. It was used as a masking factor for the exclusion of non-agricultural areas and was preprocessed through image classification and geometric correction.
- River Network: River network data was obtained from the Ministry of Water and Energy Bureau.
- Road Network and Urban Areas: These layers were obtained from the Ethiopia GIS map server.

Hydrological and Climatic Data:

- River flow data: Long-term River flow data was obtained from the Ministry of Water and Energy Bureau.
- Climatic data: These data, which include rainfall, temperature, and evapotranspiration, were utilized in the CROPWAT model and were obtained from CLIMWAT 2.0.

3.2.1 Preparing GIS and Preprocessing Data

The research preparation phase involved a systematic process of preparing and pre-processing the various geospatial data within a GIS environment. This step was crucial to ensure data accuracy and usability for the subsequent analysis phase.

Preprocessed data used were:

- Digital Elevation Model (DEM): The DEM was the foundation dataset to investigate topographic variables. DEM was preprocessed to fix data errors, e.g., sinks, and correctly derive slope, an important variable in irrigation suitability analysis, before application.
- Land Use/Land Cover (LULC): The information was acquired from European Space Agency Sentinel-2 Imagery. Raw images were rectified and classified

through image classification and geometric correction to create an accurate LULC map of the interested area. The resultant LULC data were then used as a masking factor in excluding land that cannot be cultivated, i.e., urban, forest, and wetland.

- Other Thematic Layers: Other spatial data like soil properties, river and road networks, and urban areas were also prepared and organized as thematic layers in the GIS. These thematic layers were then utilized in the multi-criteria analysis to assess irrigation land suitability.
- Weighted Overlay Analysis: As part of the GIS preprocessing, an essential step was preparing these layers for a weighted overlay analysis. Each of the factors (slope, soil, water distance, etc.) was assigned weights through the Analytical Hierarchy Process (AHP). The layers were merged and reclassified into one composite suitability map. This approach synthesized several biophysical and socioeconomic factors into one irrigation suitability index.

3.3 Land Suitability Analysis for Irrigation Development

Land suitability analysis was a significant process in the research study, as per a multi-criteria analysis (MCA) in a Geographic Information System (GIS) setting. This process, aided by the Analytical Hierarchy Process (AHP), objectively examined and combined multiple factors in an effort to determine areas that were most appropriate for irrigation.

Step-by-step procedure is as follows:

Step 1: Factor Selection: The research first identified significant factors influencing land suitability for irrigation. They comprised biophysical factors such as slope, and soil characteristics (texture, depth, drainage, and available water content), and socioeconomic factors such as proximity to water sources, roads, and towns. These are needed to assess the sustainability and feasibility of an irrigation scheme.

Step 2: AHP-based Weight Assignment: To capture the relative importance of each factor, the AHP technique was employed. This involved creating a pairwise comparison matrix for the purpose of determining the weightage of each criterion. The consistency ratio (CR) was calculated to ensure the validity of the weightages assigned; if the CR was below 0.10, then the comparisons were consistent and the weights could be used for the subsequent level of analysis.

Step 3: Weighted Overlay and Suitability Classification: After the standardization and reclassing of factors into suitability classes (e.g., highly suitable, moderately suitable, etc.), weighted overlay analysis was performed in ArcGIS. The process overlayed all the spatial layers based on their AHP-derived weights to generate a single composite suitability map. Final values of suitability were ultimately classified into four broad categories: Highly Suitable (S1), Moderately Suitable (S2), Marginally Suitable (S3), and Not Suitable (N1).

Order	Suitability classes	Details
Suitable (S)	Highly suitable (S1)	Land having no substantial restrictions for specific land use activities
	Moderately suitable (S2)	Land with slight restrictions for specific land use activities
	Marginally suitable (S3)	Land with extreme restrictions for specific land use activities
Not Suitable (N)	Currently not suitable (N1)	Land with restrictions can be resolved in time rather than fixed with knowledge at a reasonable cost
	Permanently not suitable (N2)	Land which has severe restrictions that cannot be prevented using any possible solution

Table 2 Land suitability classification (FAO, 1976)

Step 4: Land Use/Land Cover (LULC) Masking: To make the final map conceptually sound and pragmatically feasible, a LULC masking operation was performed. Post-processing eliminated land units which are unapproachable or unsuitable for agricultural production, such as forests, urban areas, wetlands, and aquatic systems, though they also had high suitability scores during the initial assessment. The final map therefore only identified the parcels of land where irrigation development is theoretically possible and is realistically available for cultivation.

3.3.1 Factors in Irrigation Suitability Analysis

Analysts used GIS-based multi-criteria decision analysis (MCDA) for studying key physical and infrastructure-related properties that would guide the search for suitable land for irrigation development in the Jemma Sub-Basin. The selected factors directly affect

surface irrigation system feasibility and sustainability alongside operational efficiency so these were the main criteria for selection. Selection fulfillment relied on FAO land evaluation guidelines together with expert-based knowledge and research results from Ethiopia and similar areas in semi-arid regions.

Positional as well as structural elements consisting of slope, soil features, river accessibility, access to roads, and closeness to towns form the core selection for suitability determination. The study used Analytical Hierarchy Process (AHP) to determine weights of each factor while reclassifying raster layers into suitability classes.

3.3.1.1 Slope

Analysis of slopes through Digital Elevation Model (DEM) allowed slope division into five irrigation suitability categories. Surface irrigation performed best on slopes ranging from 0 to 5 percent since these regions offered easy irrigation methods and low erosion potential. At the same time steep slopes exceeding 30 percent were entirely unsuitable for irrigation purposes. The evaluation followed the land classification system provided by FAO.

- Highly suitable (S1): 0–5%
- Moderately suitable (S2): 5–8%
- Marginally suitable (S3): 8–15%
- Currently not suitable (N1): 15–30%
- Permanently not suitable (N2): >30%

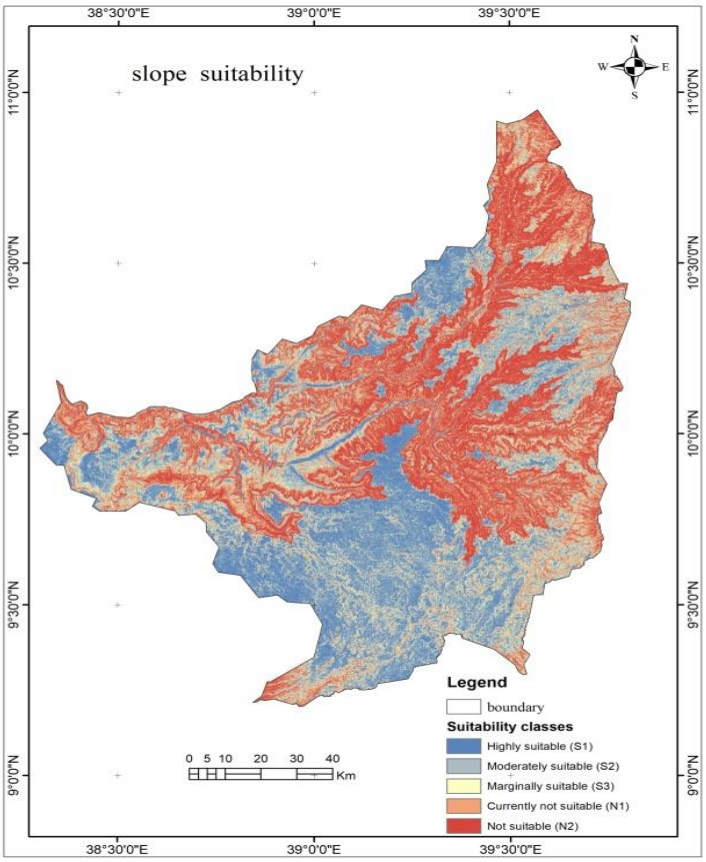


Figure 3 slope suitability map

The region contains significant areas which fall into moderate to marginal suitable categories because of their slopes spanning between 5% and 15%. Surface irrigation systems would work best for the majority of terrain areas which contain 0–5% slope and which occupy river plains and valley bottoms and gentle slopes.

The steep slopes greater than 15% which characterize highland and escarpment regions resulted in a classification as N1 and N2 permanent unsuitability zones because construction projects were difficult to implement and erosion risks became elevated.

The development of irrigation should focus on immediate implementation within the 0–5% slope areas because of their advantageous topography combined with cheaper construction costs. There are chances to implement irrigation practices in areas featuring slopes between 5% to 15% but additional soil conservation measures like contouring and terracing will be required to make it feasible.

Preference is to exclude land segments exceeding 15% slope from irrigation development and apply these areas to grazing or forestry purposes to combat land destruction.

A substantial portion of land in the Jemma Sub-Basin can be developed for irrigation due to suitable slope gradients that exceed the available flat terrain. The slope integration factor earns its position as the multi-criteria analysis highest-weighted criterion (39.5%) since it influences system design and cost and sustainability effectiveness.

3.3.1.2. Soil Factors in Irrigation Suitability Analysis

The characteristics of soil act as primary factors that determine how well land holds and provides water for agricultural crop needs. The evaluation in this study regarded five crucial soil indicators which included soil depth as well as texture and pH levels together with drainage properties and available water content (AWC). A standard agricultural threshold system divided the examined values into suitable categories which received distribution analysis for the entire study area.

a) Soil Depth

The measurement of soil depth indicates the length of vertical space between the ground surface and an obstruction layer like bedrock while reflecting the size of the available soil moisture storage area.

Suitability Classification:

- Highly Suitable (S1): 120–200 cm
- Moderately Suitable (S2): 60–120 cm

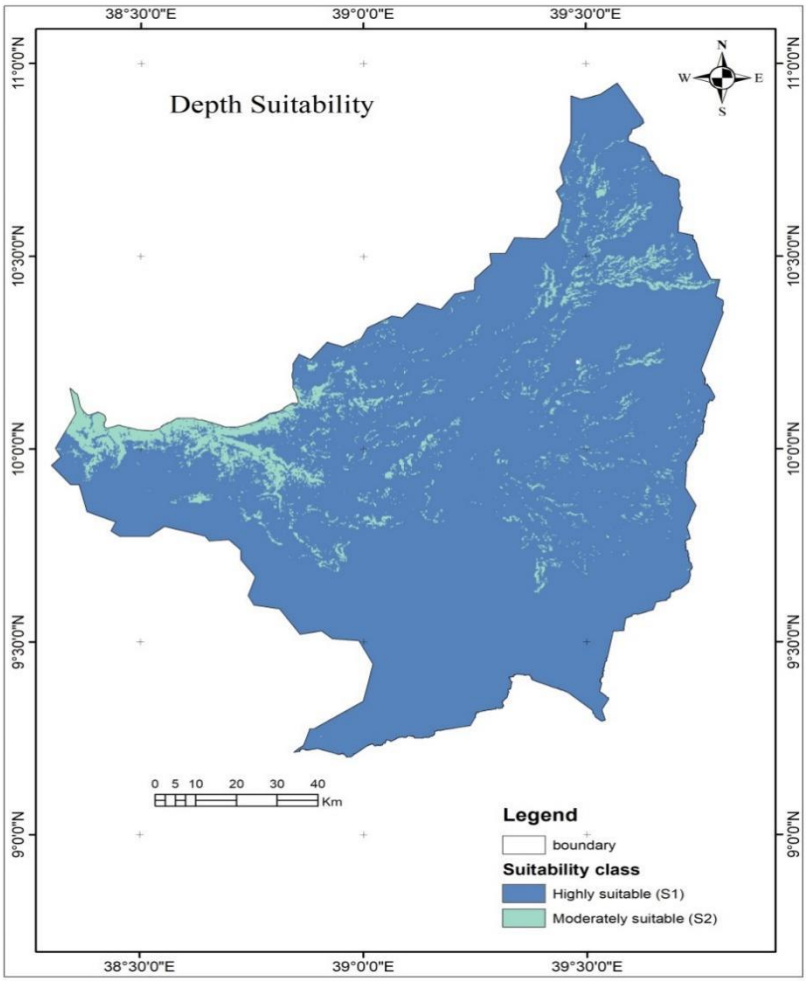


Figure 4 Soil depth Suitability map

Deep soils that surpass 120 cm reach extensive coverage throughout the research region where Eutric Nitisols and Cambisols control its majority extent. These soils excel in irrigation applications. The deep water-absorbing capacity along with extended growing season potential of these soils makes them ideal for teff and maize crops because shallow roots can penetrate deep while retaining water effectively.

b) Soil Texture

Soil texture refers to the relative proportion of sand, silt, and clay particles and affects water infiltration, water holding capacity, and aeration.

Classification of Suitability (based on FAO and field data):

- Be**9-3c**: Eutric Cambisols
- Qc**10-1c**: Chromic Luvisols
- Be**48-3c**: Eutric Cambisols

- Qc**2-1bc**: Chromic Luvisols
- Qc**2-1bc**: Chromic Luvisols
- Ne**13-3b**: Eutric Nitisols
- Vp**14-3a**: Pellic Vertisols
- Vp**14-3a**: Pellic Vertisols
- Ne**10-3b**: Eutric Nitisols
- **Eutric Cambisols (Be9-3c, Be48-3c)**: These soils are generally well-drained and have a loamy texture, making them highly suitable for farming.
- **Eutric Nitisols (Ne13-3b, Ne10-3b)**: Known for their deep, well-drained profiles and loamy texture, these soils are also highly suitable for farming.
- **Chromic Luvisols (Qc10-1c, Qc2-1bc, Qc2-1bc)**: These soils often have a clayey texture and are moderately suitable for farming.
- **Pellic Vertisols (Vp14-3a, Vp14-3a)**: These heavy clay soils are not typically classified as highly suitable for farming due to their poor drainage and tendency to crack when dry.

- Highly suitable (S1): Clay loam, silt loam
- Moderately suitable (S2): Silty clay loam, sandy clay, loam
- Marginally suitable (S3**)**: Light clay, sandy clay loam, sandy loam

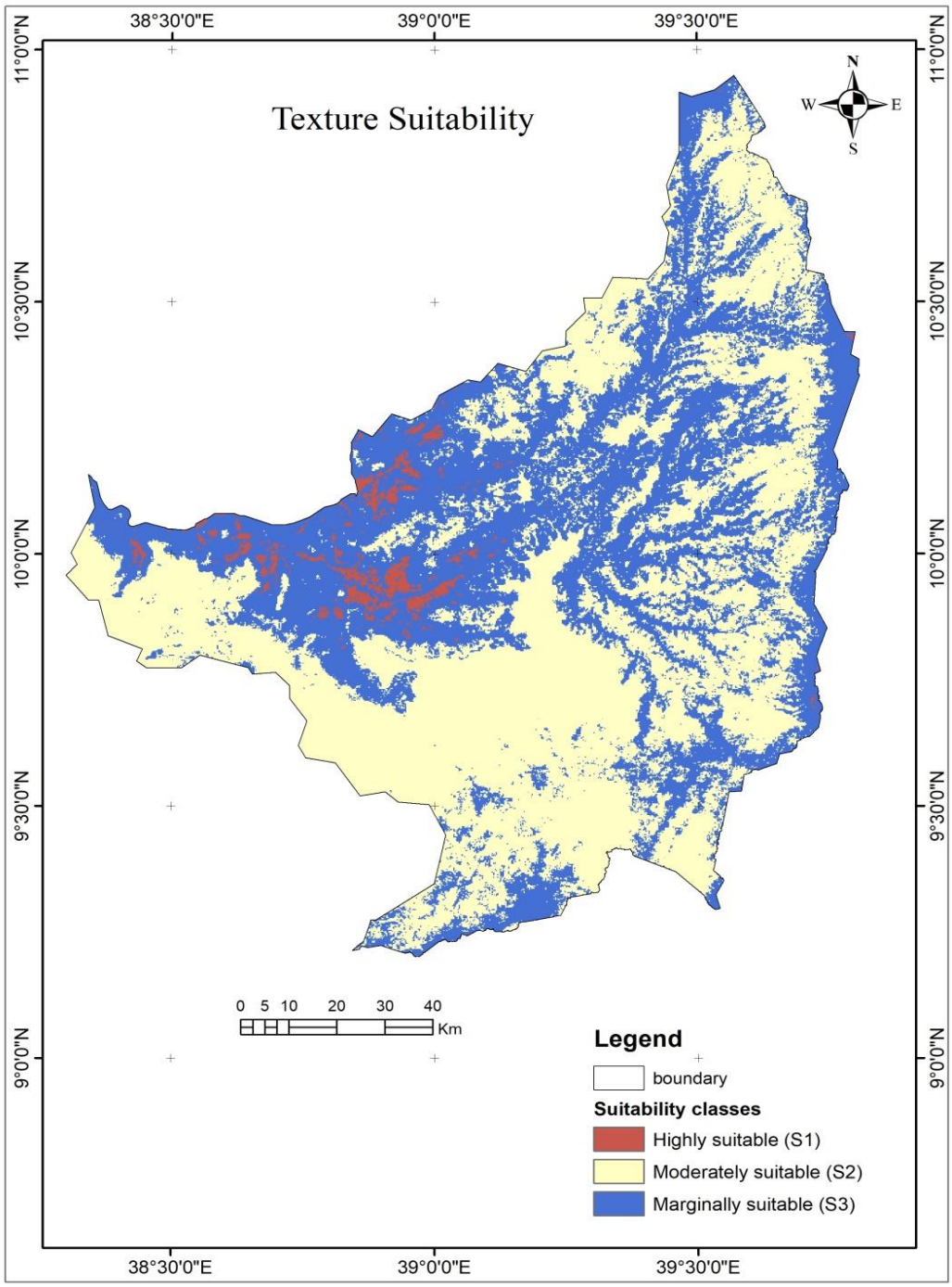


Figure 5 Soil texture suitability map

The most conspicuous soil textures of the Jemma Sub-Basin are loamy to silty loam, especially where Eutric Cambisols and Nitisols are found, which are considered highly suitable due to their water-retaining and drainage capacity at equilibrium. Those areas with Pellic Vertisols (heavy clay) are less suitable due to poor drainage and cracking during dry spells.

c) Soil pH

Soil pH is a measure of the soil's acidity or alkalinity, affecting nutrient availability and microbial activity.

Suitability Classification:

- Extremely Suitable (S1): pH 5.5–7.3
- Moderately Suitable (S2): 4–5.5 or 7.3–8.5
- Not Suitable (N1): <4 or >8.5

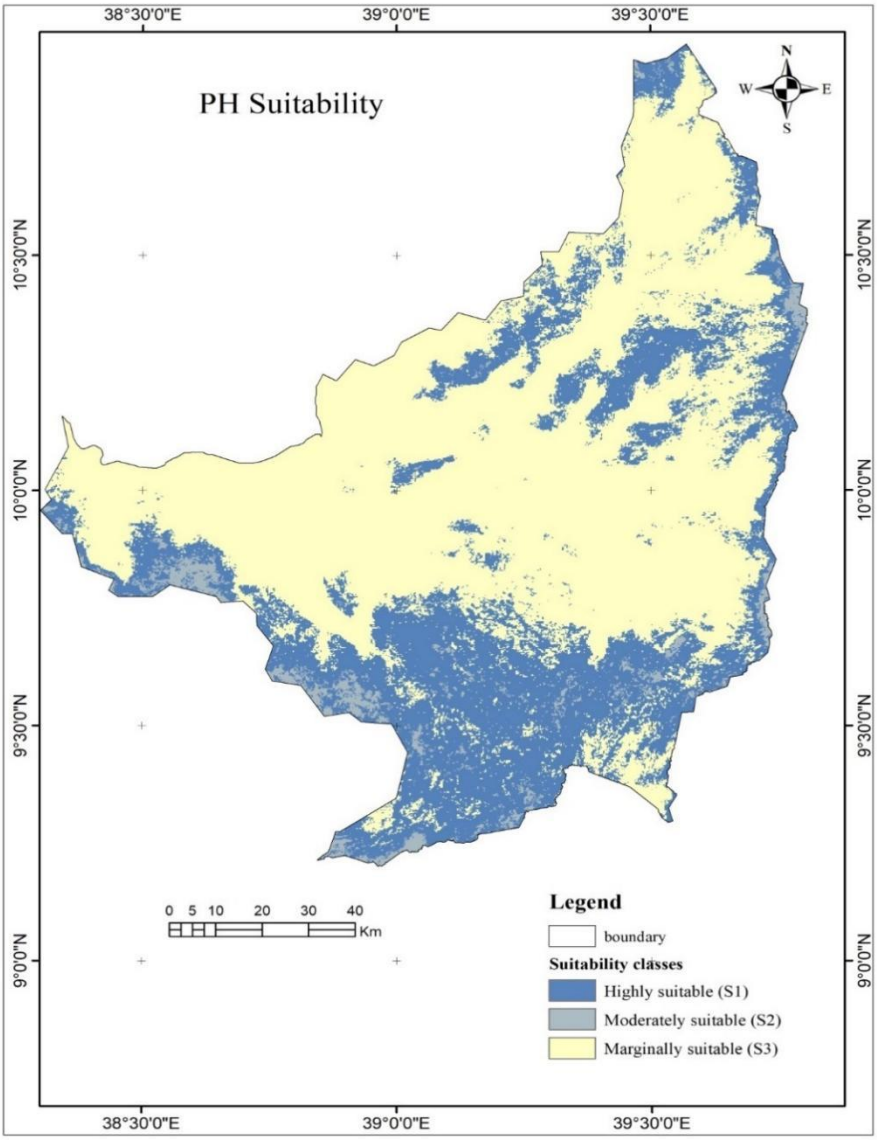


Figure 6 Soil PH Suitability map

The majority of the Jemma Sub-Basin is within the neutral to slightly acidic (5.5–7.3) range, which favors optimum nutrient availability and microbial activity. Only a few

locations in the lower basin recorded slightly acidic (<5.5) conditions, which may indicate that soil amendments would be necessary for successful irrigation.

d) **Drainage**

Drainage indicates how well excess water is removed from the soil profile, preventing water-logging.

- Suitability Classification:
- Moderately Well-Drained (S2): Moderately well-drained
- Marginally Suitable (S3): Imperfectly or poorly drained
- Not Suitable (N2): Highly poorly drained or over drained

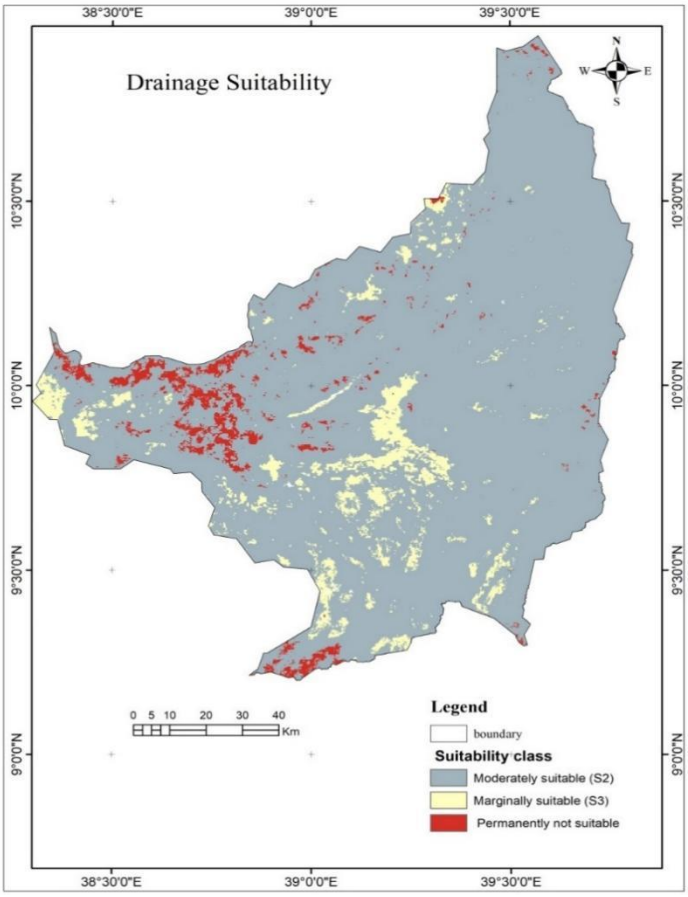


Figure 7 Soil Drainage Suitability Map

The majority of soils, especially Nitisols and Cambisols, are moderately drained well, and these can be irrigated without danger of water-logging. Vertisols, however, which frequently occur in valley bottoms with lower topography, exhibit poor drainage and

become cracked in their dry state, creating problems for uniform moisture supply and irrigation management.

e) Available Water Content (AWC)

AWC is the water which the soil will retain and make available to crops between field capacity and wilting point.

Suitability Classification

- Very Suitable (S1): >150 mm/m
- Moderately Suitable (S2): 125–150 mm/m

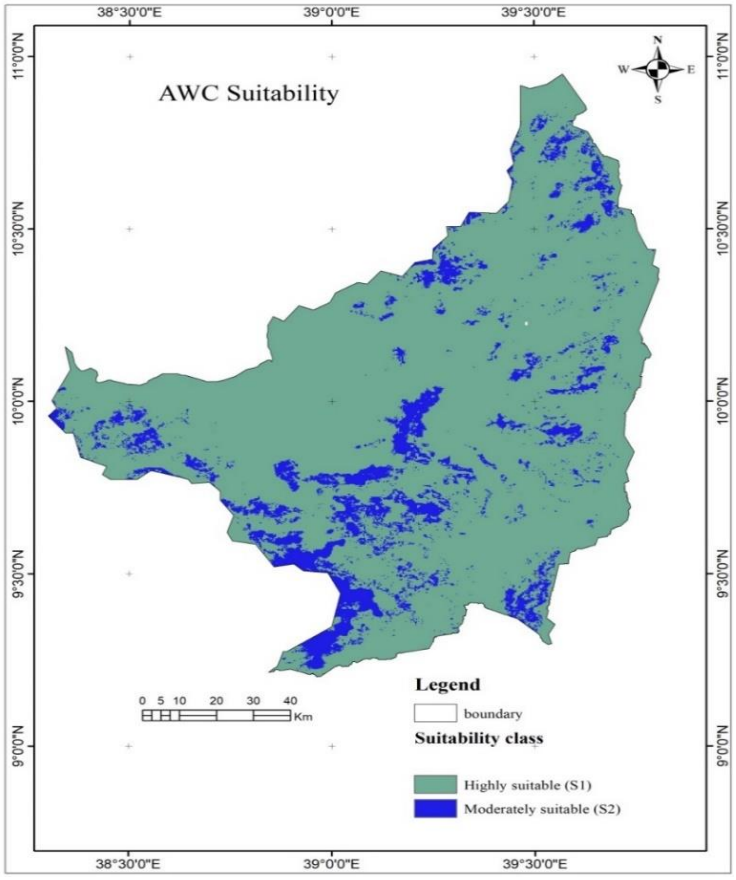


Figure 8 Soil Available Water Content map

AWC distribution by soil texture and depth. Deep profile-dominant and loamy soil regions are regions of high AWC (>150 mm/m) with prolonged duration of water available to crops. As a result of reduction in loss of water and frequency of irrigation, seasonal irrigation is most efficient in these regions.

Composite soil suitability layer was derived by integrating all the five factors through AHP. It reflected extensive unbroken areas in the sub-basin as highly or moderately suitable for irrigation. Soil factors were the second most influential factor, and AWC (37.1%) and drainage (35%) contributed the maximum to the final weight since they have a direct impact on irrigation efficiency and crop yield.

The overall evaluation of the soil facilitated the maintenance of the farming system and minimized agronomic risks by ensuring that the development of irrigation concentrated on areas with appropriate physical and chemical characteristics.

Criterion		Weights
1	Depth	6.3%
2	AWC	37.1%
3	Texture	10.1%
4	PH	11.5%
5	Drainage	35.0%

Matrix		Depth	AWC	Texture	PH	Drainage
		1	2	3	4	5
Depth	1	1	1/5	1	1/3	1/7
AWC	2	5	1	3	5	1
Texture	3	1	1/3	1	1	1/3
PH	4	3	1/5	1	1	1/3
Drainage	5	7	1	3	3	1

Table 3 soil suitability factors weight assigning by Matrix

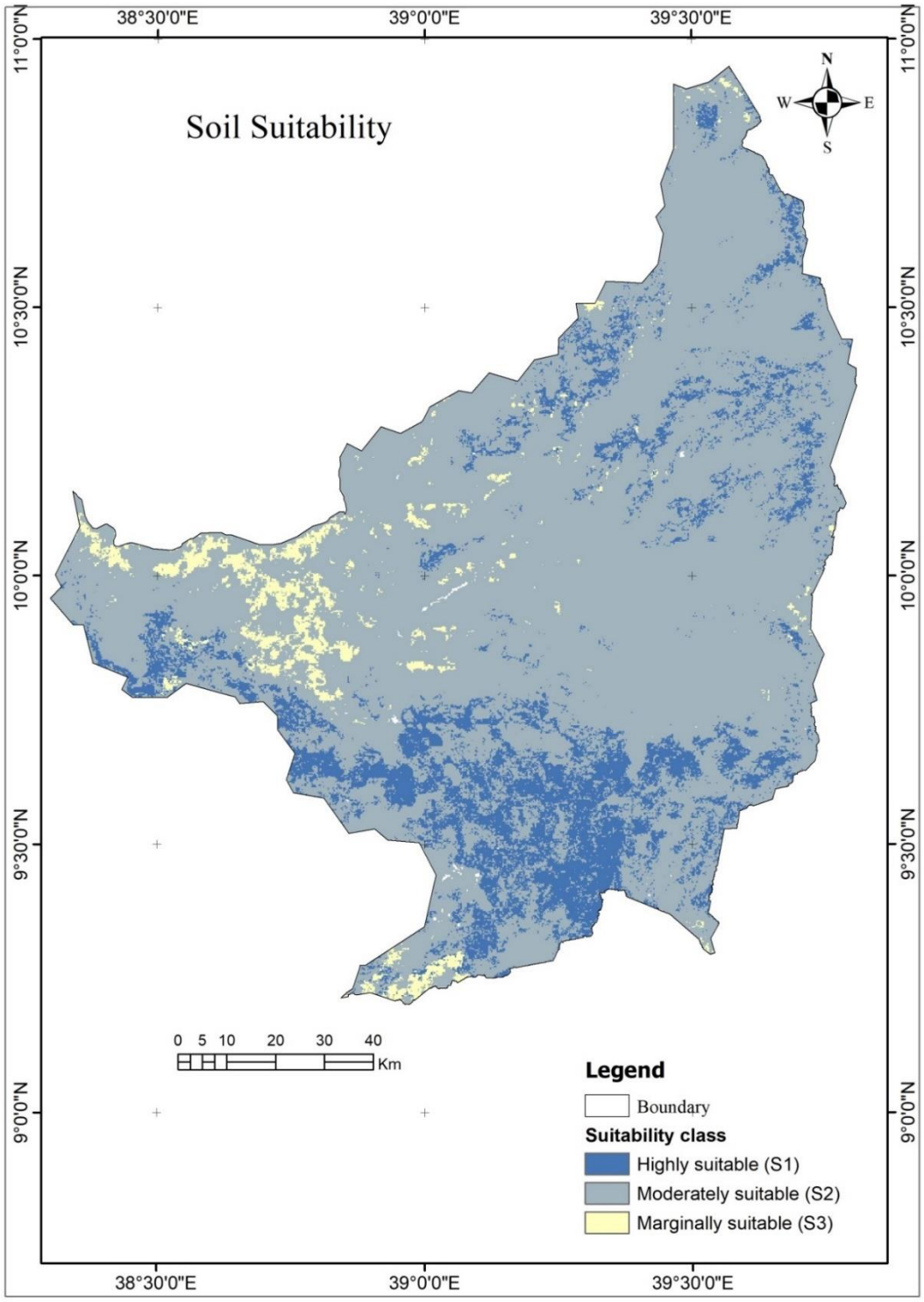


Figure 9 Soil suitability Map

Sn	Soil factors	Suitability	Area(km^2)	% Percentage per each suitability
1	Texture	**S1**	274.5	1.9%
		S2	7875.9	54.5%
		S3	6347.33	43.9%
2	PH	**S1**	4567.8	31.6%
		S2	494.5	3.42%
		S3	9435.4	65.24%
3	Drainage	**S2**	13068.3	90.4%
		S3	930.7	6.2%
		N2	487.8	3.4%
4	Depth	**S1**	13525.8	93.5%
		S2	971.8	6.7%
5	AWC	**S1**	12726.7	88%
		S2	1770.98	12%

Table 4 Soil factors suitability coverage

3.3.1.2.1 Interpretation and Discussion of Soil Factor Suitability

AWC refers to the water retained and provided by the soil to the plants. It is between the field capacity and wilting point.

Suitability Classification

- Extremely Suitable (S1): >150 mm/m
- Moderately Suitable (S2): 125–150 mm/m

AWC variation with soil depth and texture. Areas with deep profile-dominant and loam soil possess high AWC (>150 mm/m), with a long moisture supply to crops. Seasonal irrigation is most effective in these areas because of the reduction in loss of water as well as in irrigation frequency.

The composite soil suitability layer was created by combining all five soil factors through the Analytic Hierarchy Process (AHP). The research identified extensive continuous areas in the sub-basin that were highly suitable or moderately suitable for irrigation. Soil factors are important, but they are less important than slope. Available Water Capacity (AWC) makes up 37.1%, and drainage makes up 35% of the total weight because both affect irrigation efficiency and farming success directly.

The meticulous examination of soils enhanced the sustainability of the system and reduced farming risks through ensuring that the irrigation was concentrated only in areas with favorable physical and chemical attributes.

Soil Factor	Dominant Suitability Class	% Coverage	Implication
Texture	Moderately suitable (S2)	54.5%	Generally favorable but some S3 areas may need crop-specific adjustments.
pH	Marginally suitable (S3)	65.2%	Soil amendments recommended in many areas to optimize nutrient uptake.
Drainage	Moderately suitable (S2)	90.4%	Mostly favorable, with minor risk zones requiring drainage management.
Depth	Highly suitable (S1)	93.5%	Excellent rooting conditions for most crops.
Available Water Content (AWC)	Highly suitable (S1)	88%	Supports water-efficient irrigation; reduces irrigation frequency.

Table 5 Soil Factors Summary and Implications

The analysis shows that Jemma Sub-Basin possesses high suitability of soils for irrigation, particularly with regards to depth and water-holding capacity. Although pH and texture are moderate constraints in certain places, these can be dealt with through proper soil and crop management practices. These findings were employed to build a composite layer of soil suitability, which had a high impact on the total irrigation suitability map.

3.3.1.3 River Proximity

Proximity to rivers is a significant factor in determining land suitability for irrigation, especially in surface water abstraction systems. Shorter distances to rivers reduce infrastructure costs, energy requirements, and water conveyance losses. This was determined by Euclidean distance from the river network in GIS and classified into five suitability classes:

- Highly suitable (S1): 0–3 km
- Moderately suitable (S2): 3–6 km
- Marginally suitable (S3): 6–9 km
- Not presently suitable (N1): 9–12 km
- Permanent not suitable (N2): >12 k

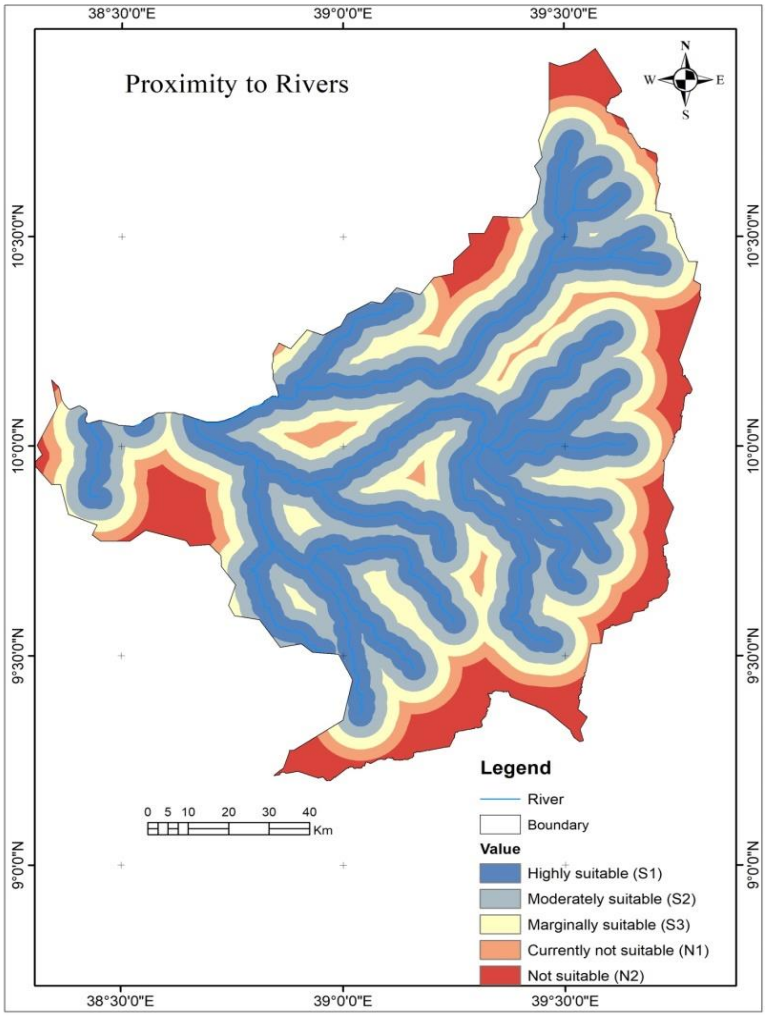


Figure 10 River proximity map

Based on the river proximity analysis:

Areas between 0–3 km of rivers, which are highly suitable, occur along the major river courses and tributaries such as the Jemma River and its feeders. These are most suitable for direct surface water off-take and gravity schemes.

Moderately suitable areas (3–6 km) constitute a transition zone where surface water access is feasible but may require intermediate-scale conveyance facilities (e.g., canals or low-lift pumping).

Marginally suitable areas (6–9 km) begin to present logistical and economic constraints, requiring long water conveyance systems or pumping stations, especially in rolling or irregular terrain.

Areas beyond 9 km are currently or permanently not suitable due to excessive distance from rivers, making surface irrigation impossible without enormous capital investment or alternative water sources (e.g., groundwater or RWH storage reservoirs).

3.3.1.4 Road Proximity

Proximity to roads is one of the major socioeconomic criteria used in land suitability for irrigation. It indicates the ease with which agricultural lands are connected to transport infrastructure, which has a direct implication on the ease of transporting irrigation facilities, farm inputs (seeds, fertilizers), and getting produce to markets. Lands that are nearer to roads lower logistical expenses and enhance the viability of implementing projects.

The suitability classes were determined based on distance from existing road infrastructure using Euclidean distance in GIS:

- Highly suitable (S1): 0–7 km
- Moderately suitable (S2): 7–14 km
- Marginally suitable (S3): 14–21 km
- Currently not suitable (N1): 21–28 km
- Permanently not suitable (N2): >28 km

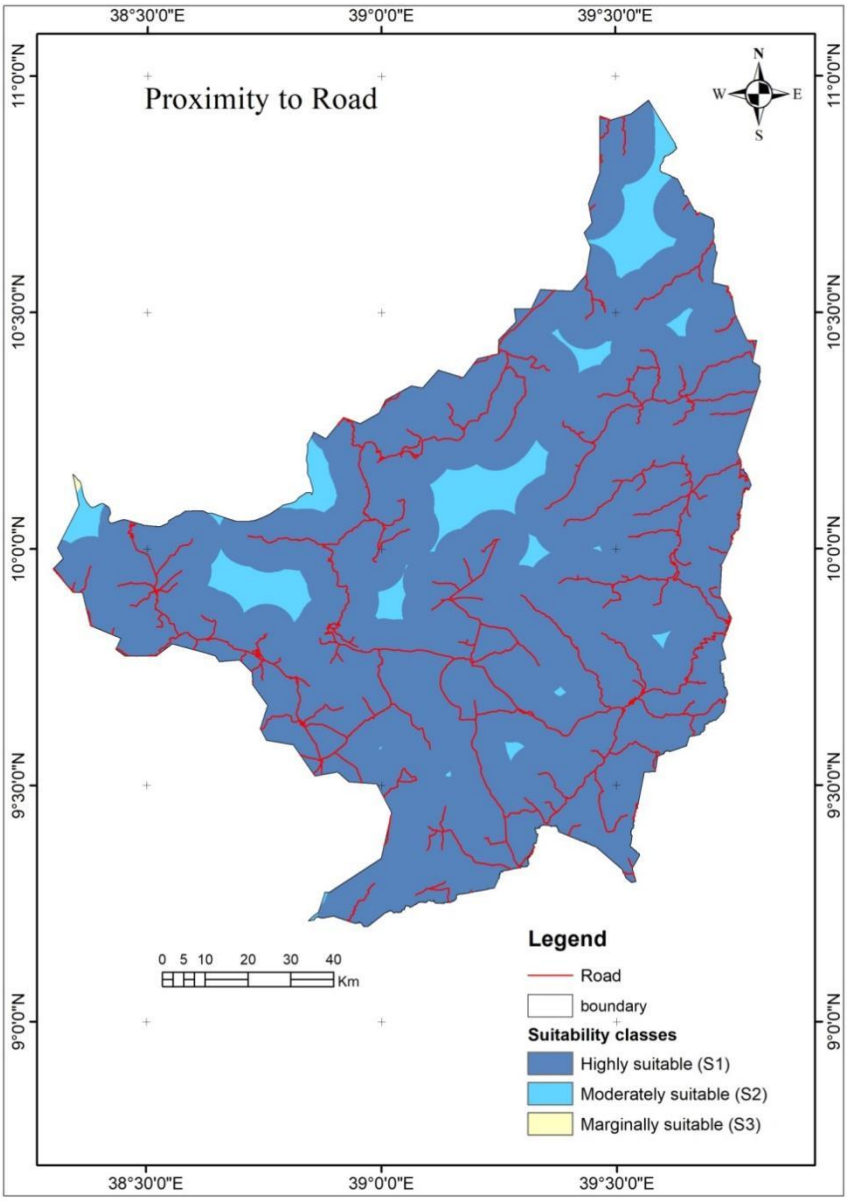


Figure 11 Road proximity Map

Based on spatial analysis:

Most irrigable land occurs between 0–14 km from roads, i.e., the majority of areas with irri-gable potential are moderately or highly accessible. They are well-located for irrigation growth with minimal hindrances to movement.

The 14–21 km (S3) regions are still reachable, but they may have poorer market integration and higher transportation costs. If irrigation investment is chosen, they may also need road extensions or maintenance plans.

N1 and N2 zones (>21 km from roads) are far and mostly located in more distant highland or hilly sections of the sub-basin. Such locations are not acceptable for immediate development due to restricted accessibility, other than with the potential for major infrastructure investment.

3.3.1.5 Town

Socio-economic town proximity is taken into account in land suitability assessment for irrigation. Town proximity enhances access to:

- Agricultural extension services
- Maintenance support for irrigation systems
- Selling markets for fruits
- Labor, administration, and finance services

Locations well networked to towns tend to be apt for irrigation schemes, especially commercial and community farming. For the purposes of this study, proximity to towns was computed using Euclidean distance in GIS and coded as follows:

- Very favorable (S1): 0–7 km
- Favorable (S2): 7–14 km
- Marginally favorable (S3): 14–21 km
- Not suitable at present (N1): 21–28 km
- Not suitable at all (N2): >28 km

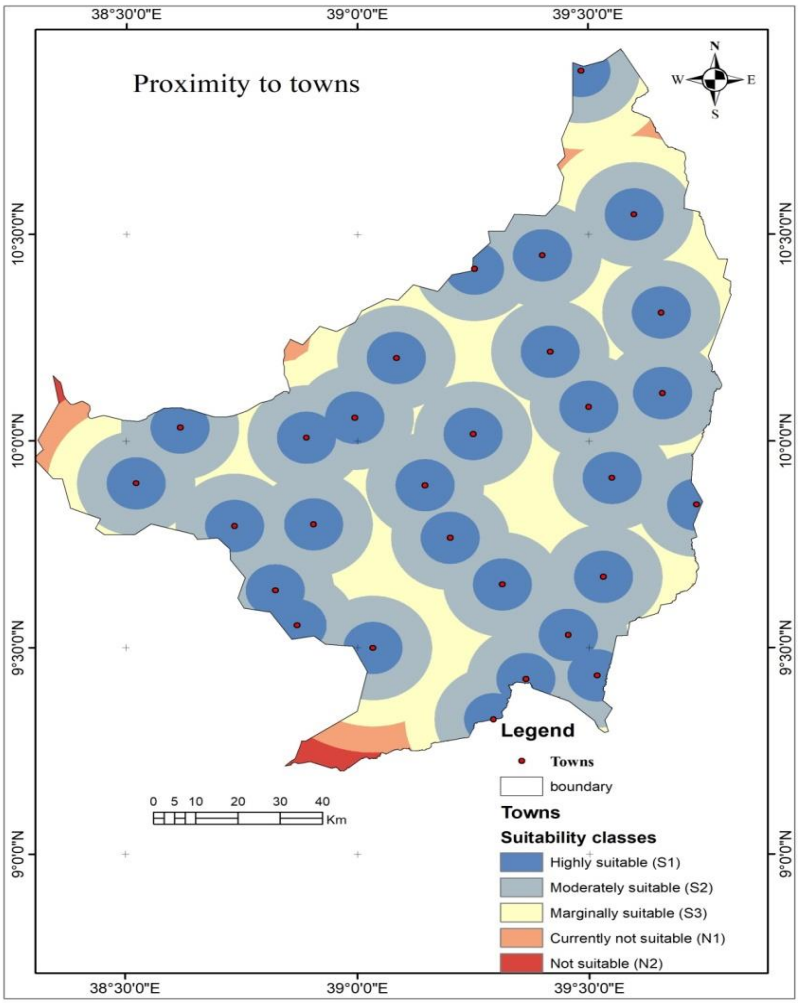


Figure 12 Town proximity map

From the spatial analysis:

A relatively limited extent of the total is within the very suitable zone (0–7 km) from towns. These are mainly surroundings of the larger urban centers of the Jemma Sub-Basin.

The majority of the moderately and marginally suitable zones (7–21 km) still enjoy good access to town-based services and can be considered viable for irrigation development, especially where rural road networks exist.

More than 21 km, referred to as N1 and N2, are typically found in more remote or hilly terrain where service delivery is inconvenient. These areas struggle to obtain administrative and technical services unless there are mobile services or decentralized administrative structures.

Implications for Irrigation Development:

Investment and initial expansion of irrigation facilities prioritize S1 and S2 areas due to their institutional and logistic access.

Marginal areas (S3) may be feasible with mobile extension services and improved rural accessibility. N1 and N2 areas may require institutional outreach programs or sequential development approaches due to inaccessibility.

3.3.2 Weight Assignment using AHP

Land suitability for irrigation development in this research was assessed against a number of key factors. The conditions stipulated for suitability assessment include both topography (slope) and soil characteristics (depth, texture, and water-holding capacity) and proximity to water sources. The criteria chosen are significant in quantifying irrigation feasibility and sustainability.

To integrate multiple factors for irrigation suitability, the Analytical Hierarchy Process (AHP) was employed to assign weights to each criterion regarding their relative importance. AHP is a structured decision-making approach founded on pairwise comparisons to express expert judgments and ensure consistency in multi-criteria analysis. In this study, five factors affecting—slope, soil characteristics, distance to river, distance to road, and distance to town—were evaluated by AHP. Pairwise comparison matrices were created and a consistency ratio (CR) was calculated to establish the rational consistency of judgments. Factors bearing greater impact on irrigation feasibility, like slope (39.5%) and soil characteristics (26.2%), were given high weights, whereas socio-economic criteria like town proximity (4.3%) were given low weights.

The weights were subsequently utilized in the weighted overlay analysis in GIS to generate a composite land suitability map. This enabled data-driven decision-making and compliance with expert opinion.

AHP Pairwise Comparison Scale

According to the AHP model, the factors of irrigation suitability are compared in pairs using a standard scale that assigns numbers to convey the relative importance of one factor over another. The 1 to 9 scale is such that:

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two criteria contribute equally to the goal
3	Weak importance	One criterion is slightly more important than the other based on expert judgment
5	Strong importance	One criterion is strongly favored
7	Very strong importance	Demonstrated and proven importance in practical applications
9	Extreme importance	Highest level of favoring one criterion over another with confident justification
2, 4, 6, 8	Intermediate values	Used when compromise between two judgments is necessary

Table 6 AHP weight assigning using Pairwise Comparison

This scale was applied in literature-informed assessment and expert consultations to build the pairwise comparison matrix. The derived weights are the relative contribution of each factor (e.g., slope, soil, proximity to rivers, etc.) toward the achievement of the goal to identify suitable land for irrigation development.

Let me know if you would like me to format this as a table in Word or if you would like me to write out the paragraph explaining how the Consistency Ratio (CR) was checked in your AHP.

Consistency Ratio (CR)

The consistency ratio (CR) is a key component of the analytical hierarchy process (AHP), used to determine the logical consistency of judgments made during pairwise comparisons. Since the AHP relies on subjective relative importance judgments, it's essential to ensure that these comparisons are not made randomly or inconsistently.

$$CR = CI / RCI$$

Where RCI is the random consistency index and CI is the consistency index, which is given as:

$$CI = (\lambda max - n\ n) / (-1)$$

Where λ_{max} is the principal eigenvalue computed by the eigenvector technique and *n* is the number of criteria (factors), Number of criteria (in this case, 5)

A CR value of 0.10 (10%) or lower is typically acceptable. When CR > 0.10, the pairwise comparisons may have to be re-scaled to enhance consistency

In this research, a 5 × 5 comparison matrix was constructed in order to determine the relative importance of slope, soil characteristics, river proximity, road proximity, and town proximity. After calculating the eigenvalue and consistency index, the final consistency ratio was found to be less than 0.10, thus confirming that the made comparisons were consistent and reliable. This made it justifiable to use the derived weights in the GIS-based weighted overlay analysis for suitability mapping of irrigation.

3.3.3 Weighted Overlay and Suitability Classification Analysis

After standardization and reclassification of all the selected factors—i.e., slope, soil type, distance to rivers, distance to roads, and distance to towns—they were integrated into one composite map through a weighted overlay analysis in ArcGIS. This technique enables the combination of numerous spatial layers based on weight values, which are calculated through the Analytic Hierarchy Process (AHP), that express the relative importance of each factor in relation to irrigation suitability.

Criterion		Weights
1	Soil factor	26.2%
2	Slope	39.5%
3	Town proximity	4.3%
4	Road proximity	8.8%
5	River proximity	21.1%

Matrix		Soil factor	Slope	Town proximity	Road proximity	River proximity
		1	2	3	4	5
Soil factor	1	1	1	5	3	1
Slope	2	1	1	7	5	3
Town proximity	3	1/5	1/7	1	1/3	1/5
Road proximity	4	1/3	1/5	3	1	1/3
River proximity	5	1	1/3	5	3	1

Table 7 Over all factors weight assigning by matrix

The raster layer of each factor was reclassified into five different suitability classes, with higher values indicating greater suitability:

- Particularly suitable (S1) = 4
- Moderately suitable (S2) = 3
- Marginally suitable (S3) = 2
- Now deemed inappropriate (N1) = 1
- Permanent not suitable (N2) = 0 (where relevant, i.e., slope > 30%)

Weighted Overlay Analysis:

The last suitability map was created with the Weighted Overlay Tool in ArcGIS that uses the formula:

$$\text{Suitability Index} = \sum(wi \times ri)$$

Where:

Wi = weight of factor *i* (from AHP)

ri = reclassified raster value of factor *i*

The calculated composite suitability values were also categorized into four major classes by natural breaks (Jenks classification) or expert-specified thresholds:

- Highly Suitable (S1)
- Moderately Suitable (S2)
- Marginally Suitable (S3)
- Not Suitable (N1)

Weighted overlay technique had provided a firm basis to integrate diverse spatial parameters—biophysical and socioeconomic—into a single irrigation suitability index. The land suitability distribution as observed after analysis and classification was done as following: Very Suitable (S1, Moderately Suitable (S2), Marginally Suitable (S3) and Not Suitable (N1).

S1 is utilized to refer to highly suitable lands that are found within the lowlands and gently sloping sections of the basin and are characterized by deep loamy soils in river and road proximity. The lands need minimum modification and are most suitable for the immediate utilization of irrigation schemes. Moderately suitable areas (S2) are those with suitability and slight constraints—e.g., moderate slopes, less-than-optimal pH levels of the soil, or

medium distance to infrastructure. With proper planning and investment, these areas can function well. Marginally suitable areas (S3) may possess constraints like steeper slopes, lower AWC soils, or greater distance from roads/towns. Such areas can still be utilized but would require adaptive irrigation systems and supporting infrastructure to mitigate risk. Lands not suitable (N1) are steep slopes, poorly drained or very shallow soils, and lands far away from roads and urban centers. Sites are not appropriate for standard irrigation methods and may be more appropriate for alternative land uses like grazing or forestry. Conclusion: Suitability classification and weighted overlay analysis generated a detailed, site-specific basis for the determination of the most suitable areas for the development of irrigation projects. The procedure illustrates the intricate relationship between topography, soil characteristics, and accessibility, enabling policymakers to target areas of priority for investment. The output serves as a strategic planning tool, enabling the realization of sustainable and economically viable irrigation projects in the Jemma Sub-Basin.

3.3.4 Land Use/Cover Masking and Final Suitability Map

After the creation of the composite irrigation suitability map through weighted overlay analysis, a land use/cover (LULC) masking operation was performed as a post-processing operation. The aim of the masking operation was to enhance the accuracy of the final irrigation suitability map by eliminating land areas that are not available or not suitable for cultivation, including urban, forests, wetlands, and aquatic systems. LULC details were retrieved from Sentinel-2 satellite data and classified under the following two broad classes:

Appropriate land use classes (value = 1):

- Agricultural land
- Grassland
- Shrubland

Inappropriate land use classes (value = 0):

- Forests
- Urban and built-up areas
- Wetlands
- Aquatic ecosystems

The reclassified LULC raster layer was then used as a mask in GIS to extract only those parts of the suitability map that fell under suitable land cover types. In this manner, even if a place had high values in the biophysical and accessibility-based suitability analysis, it was excluded from final consideration if it matched non-agricultural land use.

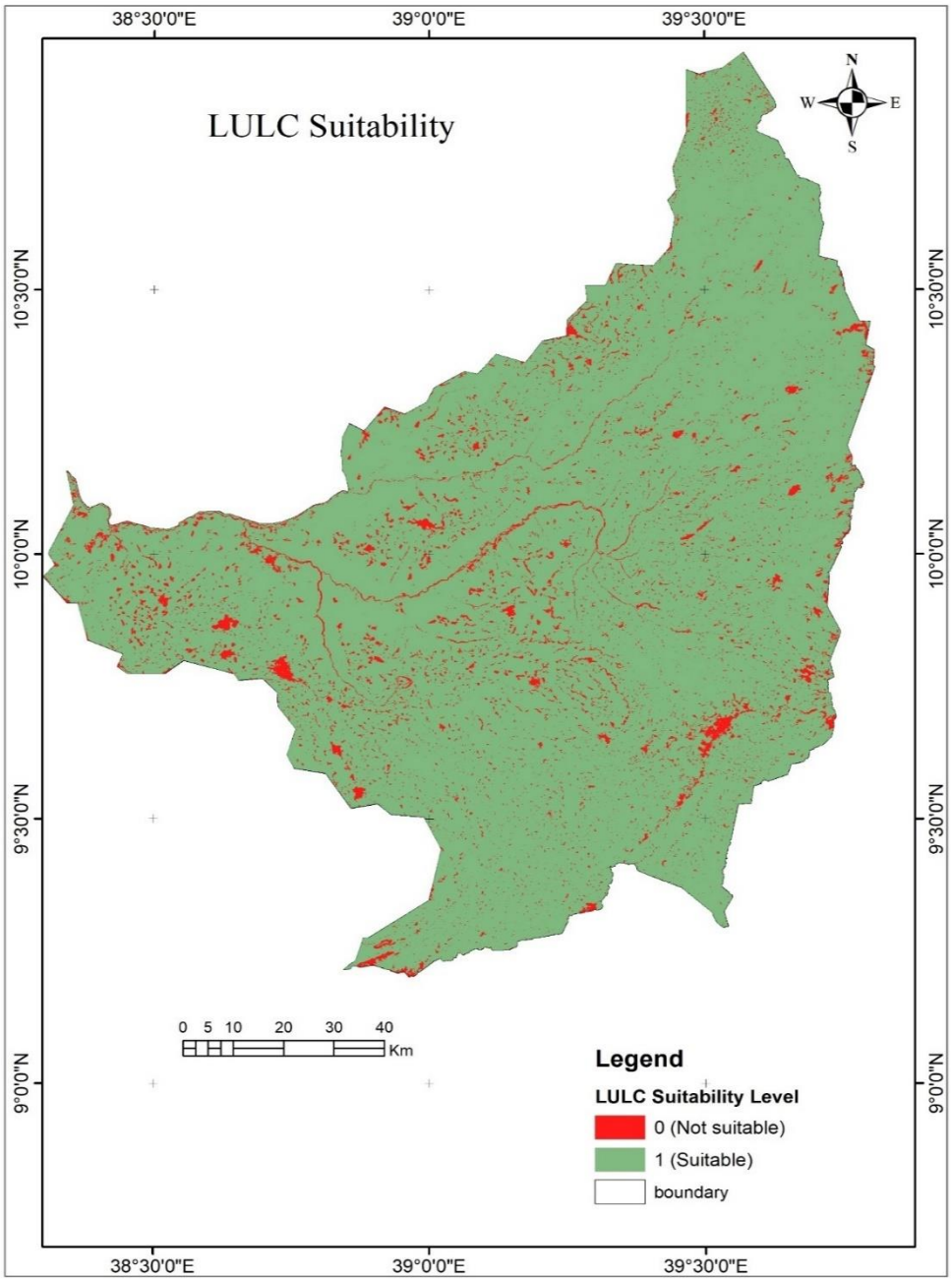


Figure 13 LULC Suitability map

3.4 Rainwater Harvesting Potential Assessment

Rainwater harvesting (RWH) potential assessment employed a planned geospatial evaluation to identify locations where water could be stored and accumulated. The method was founded on the merging of two key biophysical indicators: the Topographic Wetness Index (TWI) and the Normalized Difference Vegetation Index (NDVI).

The process is outlined step by step below:

- Indicator Selection:

Topographic Wetness Index (TWI): TWI was utilized for the identification of areas where natural convergence of surface flow occurs. It quantifies the potential for water to accumulate at a specific point in a basin as a function of topography, with higher values indicating greater water accumulation tendency.

Normalized Difference Vegetation Index (NDVI): NDVI was employed to quantify vegetation cover, a factor that is pivotal in determining the potential of a land to generate or receive runoff. Low vegetation cover (and, therefore, low values of NDVI) will have high surface runoff and will be favorably suitable for rainwater harvesting.

- Geospatial Integration:

The two indicators, TWI and NDVI, were integrated using GIS overlay operations on raster data. It involved overlaying the classified TWI and NDVI layers to generate one composite RWH suitability map.

This composite map classified the entire sub-basin into several likely classes for rainwater harvesting. For example, areas with extremely high potential were characterized by a high value of TWI (more than 25) and low vegetation cover (minimum value of NDVI), which rendered them appropriate places for water accumulation.

- Storage Site Location:

Following the initial analysis, there was an additional hydrological investigation to identify individual potential storage sites. Using the Digital Elevation Model (DEM), natural depressions or "sinks" within the basin can be identified. The changes were mapped for every sink identified, and the potential storage volume was computed.

3.4.1 Derivation of Topographic Wetness Index (TWI)

Topographic Wetness Index (TWI) is a widely used hydrological index that quantifies the spatial variation in soil moisture and the likelihood of water convergence in specific locations. TWI is typically useful for mapping probable areas of surface runoff convergence and water collection. The 30-meter resolution Digital Elevation Model (DEM) was used to derive TWI from the formula:

$$TWI = \ln\left(\frac{(Flow_accumulation + 1) \times Pixlesize^2}{\text{"}0.00565\text{"} + \tan(Slope(rad))}\right)$$

Flow direction and flow accumulation raster were extracted from the preprocessed DEM using hydrological tools in ArcGIS. Slope raster was computed in degrees and converted to radians for use in the formula. The TWI raster was then generated using raster calculator by performing the natural logarithm function on the flow accumulation and slope ratio.

The TWI values ranged from approximately 4.86 to 28.18 in the Jemma Sub-Basin. These were classified into three suitability classes for rainwater harvesting:

- Moderate Potential: TWI 15-20
- High Potential: TWI 20-25
- Very High Potential: TWI > 25

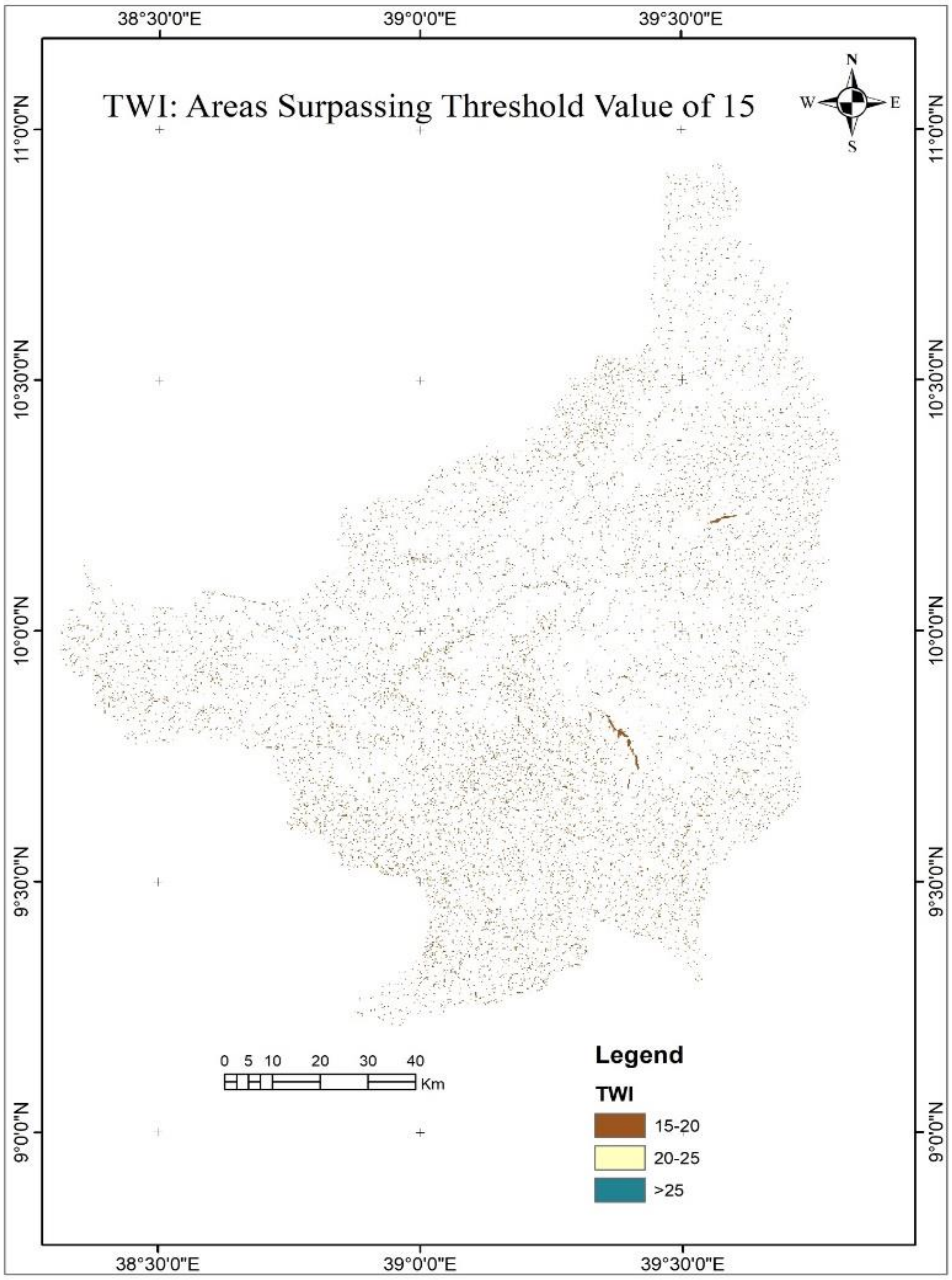


Figure 14 TWI Areas surpassing threshold values of 15 map

Areas with greater values of TWI indicate areas of greater potential for surface water accumulation due to a combination of greater contributing area and lesser slope and therefore are optimum locations for discovering water resource potential locations.

3.4.2 NDVI Classification

$$NDVI = \left(\frac{Band5 - Band4}{Band5 + Band4} \right)$$

NDVI ranges were classified as

- Water Bodies: – 1.0 to – 0.046
- Swampy/Wetland Areas: – 0.046 to 0.025
- Light Green Vegetation: 0.090 to 0.14

s. n	Type	Area (ha)
1	Light Green Vegetation	163,665.53
2	Swampy Areas	7,501.00
3	Water Bodies	245.15

Table 8 Area's coverage of NDVI Classifications

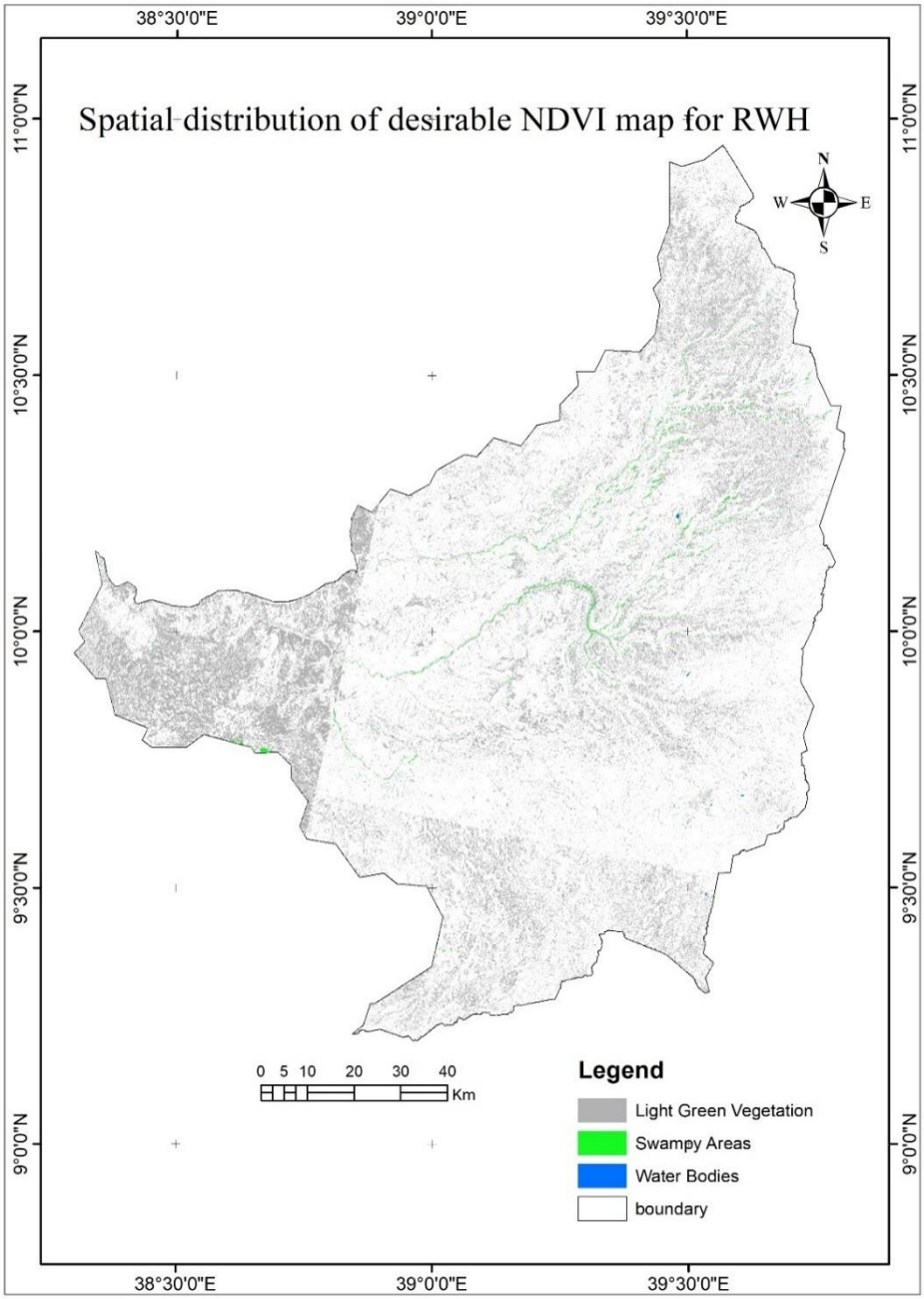


Figure 15 Spatial distribution of desirable NDVI map for RWH

These classes provide informative data regarding surface wetness conditions. Water bodies exhibit systematically low or even negative NDVI values due to the lack of photosynthetic activity, and swampy or wetland environments exhibit somewhat higher NDVI values associated with waterlogged soil conditions and open cover. Light green vegetation, the NDVI range of which ranges from 0.090 to up to 0.14, is characterized by low to average

vegetation cover. These areas have a higher tendency to produce more surface runoff during rain occasions and thus are optimal locations for rainwater harvesting.

By targeting these vegetation classes, the analysis succeeds in distinguishing land with low vegetation cover and high available moisture, two important parameters for effective RWH planning. NDVI can be used as a substitute for the capacity of land surfaces to generate runoff or to take it up, helping to differentiate fruitful locations for upcoming water resource initiatives.

3.4.3 GIS-Based Integration of TWI and NDVI

The fusion of TWI and NDVI through GIS was a crucial process towards the identification of high surface water accumulation potential and surface rainwater harvesting area favorable conditions. The fusion was conducted within ArcGIS utilizing raster overlay techniques and conditional logic tools (Con tools) to overlay the classified TWI and NDVI layers to produce a composite suitability map. All the pixels in the raster dataset were evaluated based on their corresponding TWI and NDVI value, and nine varying class combinations were produced. These were then coded to reflect the degree of water resource development suitability:

- Class 1: TWI > 25 and NDVI = Water Body → Very High Potential
- Class 5: TWI 20–25 and NDVI = Light Green Vegetation → High Potential
- Class 9: TWI 15–20 and NDVI = Swampy Areas → Moderate Potential

The numbers are not just simple sequential ranking 1-9. They will probably serve to represent sets of TWI and NDVI values with a larger scheme of classifications.

Class 1: This shows the highest potential and is characterized by TWI value > 25 as well as being classified under NDVI as Water Body. The combination denotes a natural water body or place with high chance of water collection thus, "Very High Potential."

The TWI of such a class is 20-25, and the NDVI is Light Green Vegetation. The highest potential area is still rather good, but compared to Class 1, it is not ideal since the vegetation indicates some water absorption or not the strongest accumulation.

In Class 9, the TWI is lesser (1520) and NDVI is Swampy Areas. This set implies a medium potential, because despite water occurs, its possible significant accumulation to be used, as a source of water is not so numerous as it can be in case of a defined water body.

The rest of the combinations were interpreted in a similar way to show various degrees of RWH appropriateness, placing greater emphasis on combinations with high TWI and low NDVI vegetation cover (e.g., sparse vegetation or exposed land).

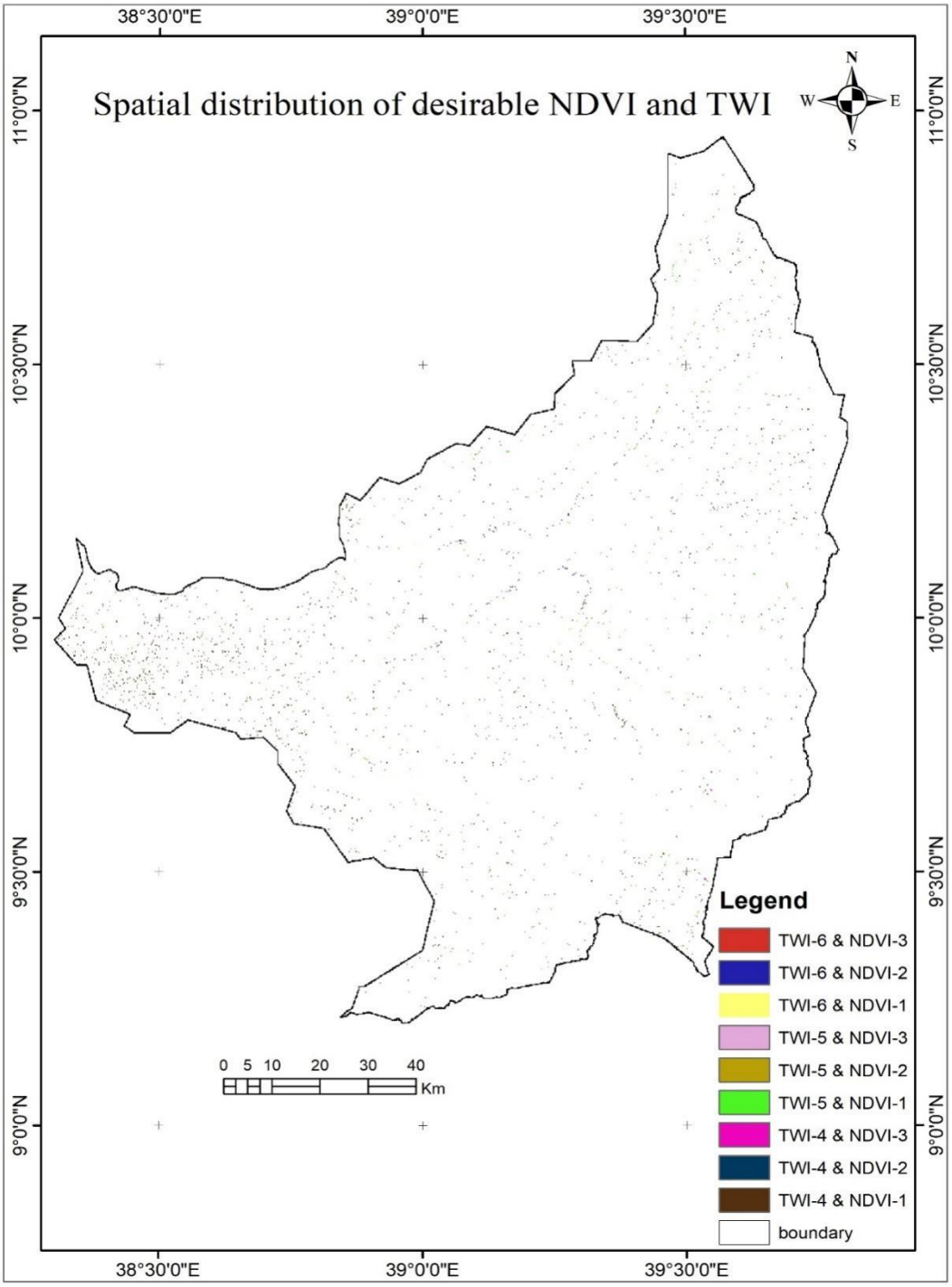


Figure 16 Spatial distribution of desirable NDVI and TWI map

This spatial overlap analysis allowed precise targeting of areas where surface runoff naturally converges and the land topography is conducive to the construction of water harvesting structures. This composite map as an output has been a very significant input in selecting zones to identify RWH sites and ascertain storage volume.

3.4.4 Identification of Storage Sites

Following the integration of TWI and NDVI, regions that might be potential areas for runoff accumulation were examined to identify the potential rainwater harvesting (RWH) storage areas. Surface depressions, where the storage basins could be utilized, were identified using hydrological modeling techniques, including sink detection, flow direction, and watershed delineation in ArcGIS.

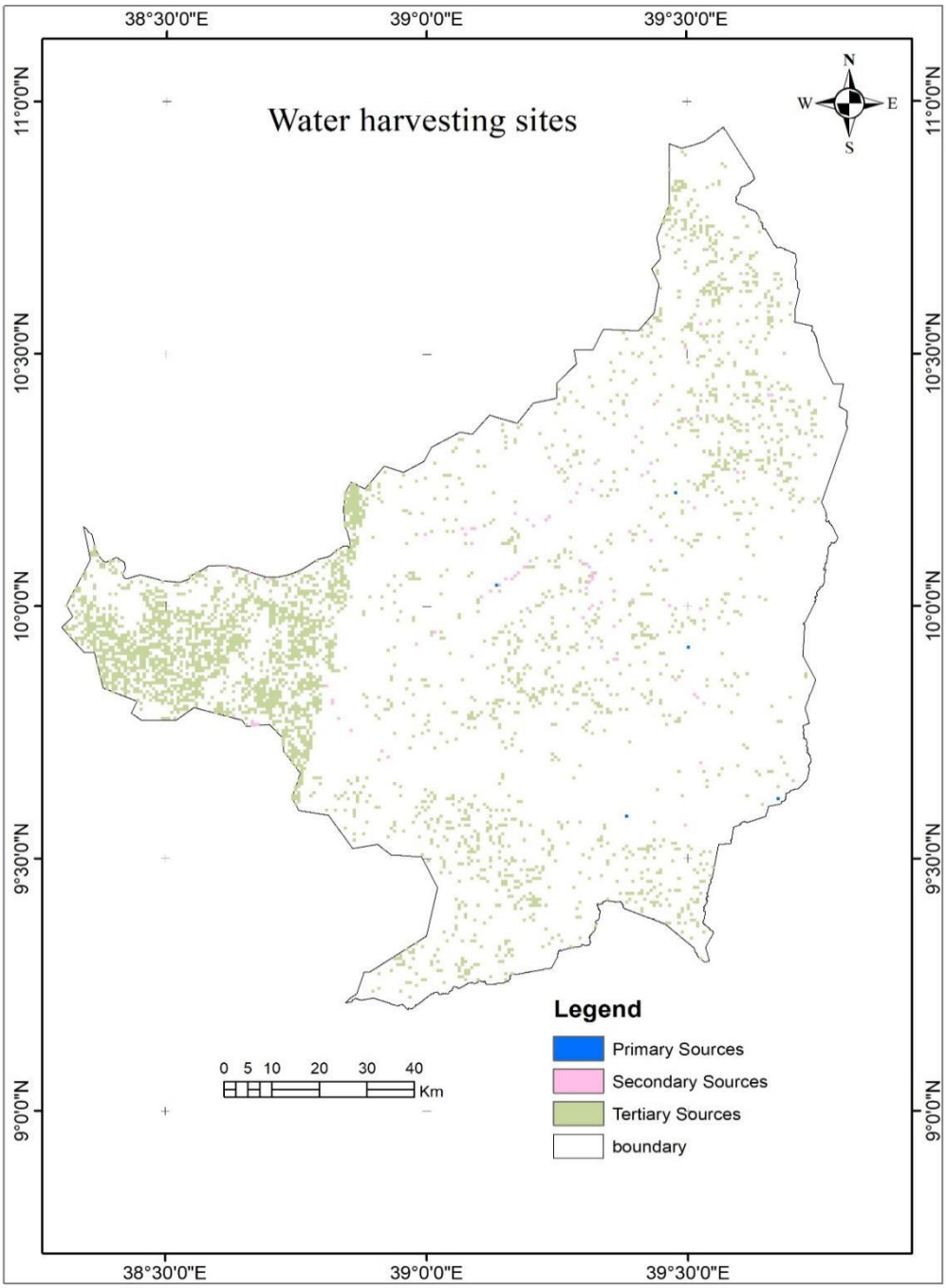


Figure 17 Water Harvesting Sites Map

3.5 Crop Water Requirement Analysis

This study applied the CROPWAT model to determine the crop water requirements and prepare an optimum irrigation development scheme. Model analysis was a crucial part of preparing a sustainable water resource management scheme for the Jemma Sub-Basin. To

have a clear view of this analysis, the climatic zones of the study area were initially determined and quantified.

The Jemma Sub-Basin is grouped into three broad climatic zones:

- Dega: This area, which covers 63.37% of the country's surface area, is characterized by a cool highland climate.
- Weyna Dega: This area covers 22.64% of the country's surface area and is characterized by a temperate climate.
- Kola: This area, covering the remaining 13.99% of the area, has a hot, dry lowland climate.

The position of these zones is graphically presented in the climatic map of classification for the Jemma Sub-Basin. The simulation of every zone by the CROPWAT model was therefore carried out based on its specific climatic data to ensure that the water requirement and irrigation regime were made specific to local conditions.

Climatic Zone	**value**	**count**	**Area_sqkm**	**percent__%**
Kola	1	2,163,518.00	2,028.88	13.99
Weyna Dega	2	3,500,718.00	3,282.87	22.64
Dega	3	9,798,903.00	9,189.13	63.37

Table 9 Climatic Zone Coverage

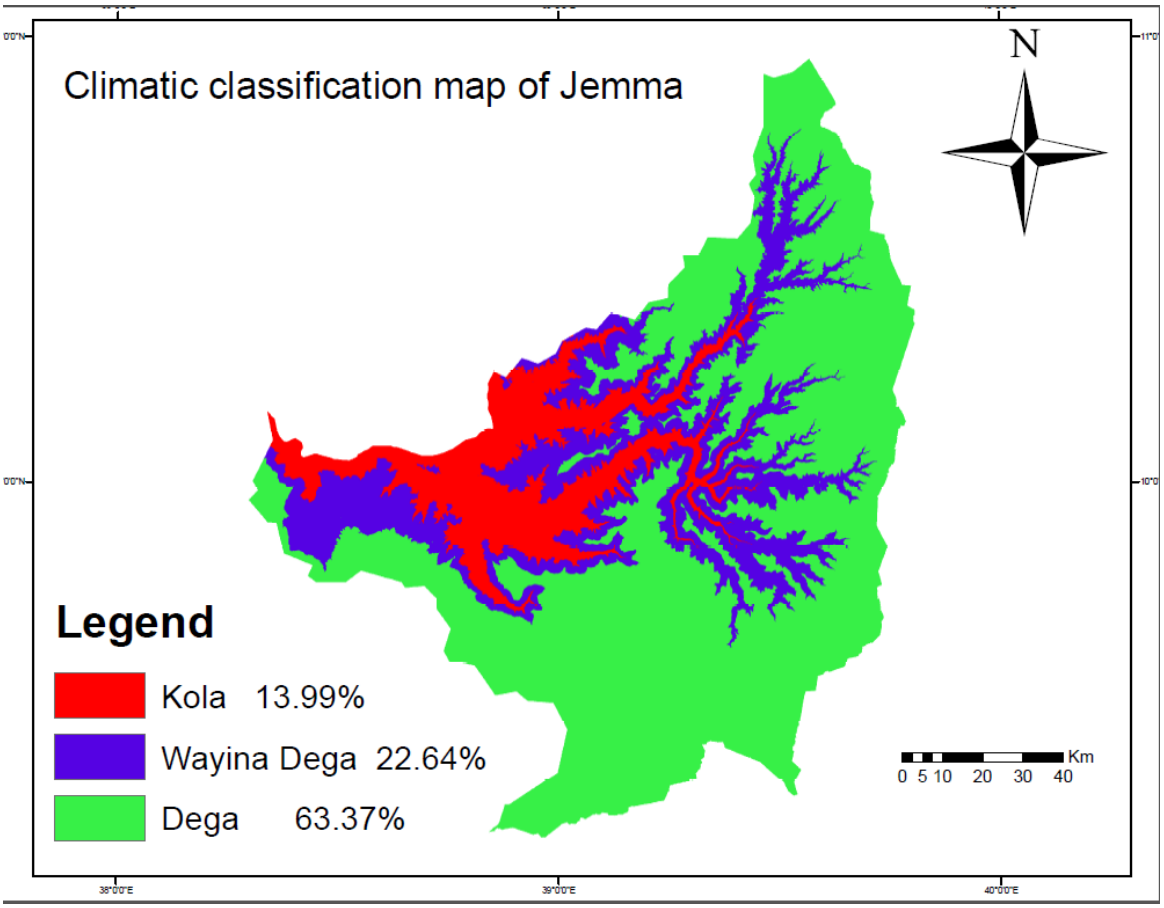


Figure 18 Climatic zone map

3.5.1 Purpose of the CROPWAT Model

The CROPWAT model has been used to estimate the irrigation water duty for the specific climatic zones of the Jemma Sub-Basin. It is also used in the optimal design of irrigation schedules. This information is required for irrigation scheme design and operation as well as for general water resource planning.

3.5.2 Input Data and Parameters

The CROPWAT model requires the combination of three main data types for its estimation:

- Climatic Data: These have information on temperature, rainfall, and evapotranspiration. The data source was the CLIMWAT 2.0 program. This climatic data is used to calculate the reference evapotranspiration (ETo), which is also the atmospheric water demand and the basis for all other water requirement estimates.

- Soil Data: The model applies significant soil characteristics such as texture, water-holding capacity, and maximum infiltration rate. This data is significant, as soil characteristics have a direct effect on the quantity of water crops can store and use. The soil data came from sources including the Harmonized World Soil Database.
- Crop Data: The model requires certain crop data like the planting date, duration of each growth stage (initial, development, mid-season, and late-season), and their corresponding crop coefficients. They are used for deriving the reference evapotranspiration (ETo) to actual crop evapotranspiration (ET), i.e., the actual amount of water utilized by the crop.

3.5.3 Output and Key Findings

The CROPWAT model gave a series of principal outputs, which were the principal findings of the research:

- **Effective Rainfall**: The model estimated the amount of effective rainfall that can be utilized by the crop.
- **Net Irrigation Requirements**: This is a critical output that represents the water deficit with regard to effective rain. The model determines the time at which additional irrigation becomes a requirement.
- **Irrigation Duty:** The study approximated the irrigation duty for two out of the three climatic zones, namely Dega and Weyna Dega. The Kola climatic zone was excluded from analysis because of the following reasons:

The Kola climatic zone is of extremely small area in the study area, and thus it is of lesser significance for a project of large-scale irrigation development. The characteristics of the zone are not suitable for irrigation development. There are no climatic or weather stations in the Kola zone (below 1500 m sea level) in the area under study, and it is not possible to gather the necessary data for use in the CROPWAT model.

3.5.3.1 Weyna Dega Evapotranspiration Data

Reference evapotranspiration (ETo) data of the Weyna Dega climatic zone was accessed from the CLIMWAT program for the Filílik station, which is at elevation 1800 m. Analysis showed a distinct seasonal trend of ETo values, which is crucial in describing atmospheric water demand and estimating crop water requirements.

Seasonal Trends

- Peak Water Demand: Peak ETo values are experienced during the dry season of February to May. This is a result of high air temperatures, low relative humidity, and prolonged sunshine hours, all of which contribute to high evaporation rates from soil and plant transpiration.
- Low Water Demand: Conversely, the lowest ETo values are experienced during the main rainy season of June to September. This reduction in water demand is a result of ample cloud cover, which diminishes sunshine hours and solar radiation. The rains also cause temperatures to be lower and humidity to be higher, reducing the ability of the atmosphere to evaporate. This seasonal survey indicates that supplemental irrigation is needed most during the dry season and that the rainy season contains sufficient water for the majority of crops.

Country: Location 10 Station: FILIKLIK

Altitude: 1800 m. Latitude: 10.05 °N Longitude: 38.21 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	13.0	28.4	50	147	7.5	18.5	4.26
February	13.8	29.9	49	156	7.6	19.8	4.77
March	15.0	30.5	49	156	6.5	19.2	4.91
April	15.1	30.6	56	156	6.7	19.8	4.91
May	14.7	29.8	52	147	7.7	21.0	5.04
June	13.7	27.4	65	121	6.0	18.0	4.06
July	12.0	23.2	77	104	3.6	14.7	3.04
August	11.8	22.6	79	112	3.7	15.0	2.97
September	11.2	24.6	72	138	5.0	17.0	3.50
October	12.1	26.3	54	190	7.3	19.6	4.54
November	12.1	27.2	51	190	9.3	21.1	4.75
December	11.9	27.4	49	156	8.4	19.1	4.28
Average	**13.0**	**27.3**	**59**	**148**	**6.6**	**18.6**	**4.25**

Table 10 Weyna Dega Evapotranspiration Data

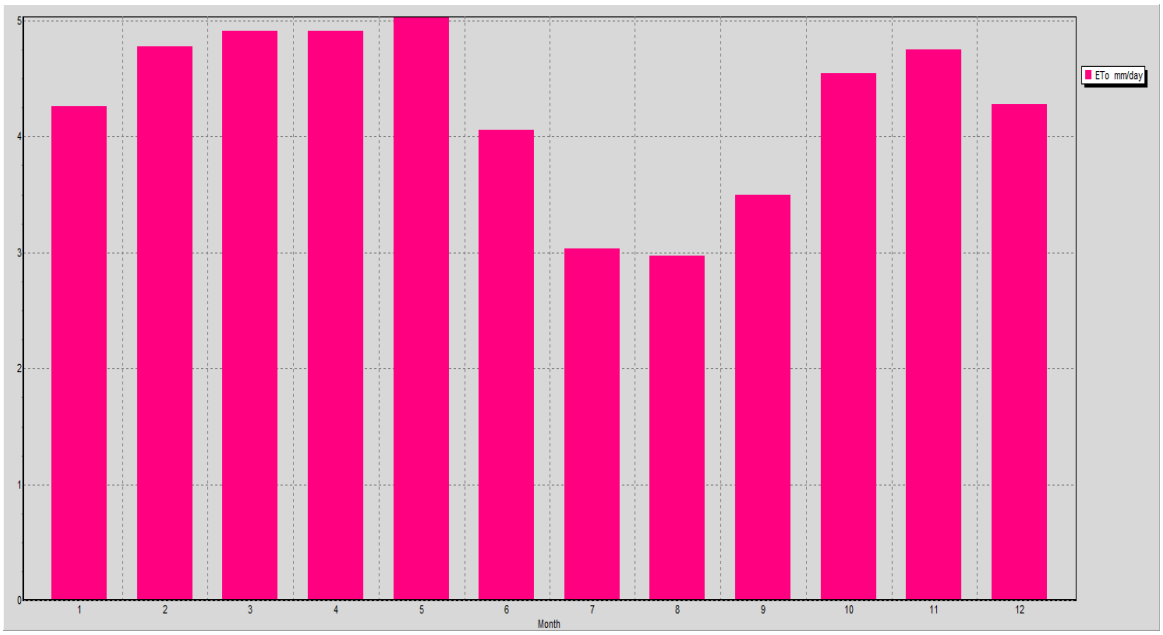


Figure 19 Monthly Evapotranspiration chart

3.5.3.2 Weyna Dega Effective Rainfall Data

Effective rainfall is that portion of the total rainfall which is utilized effectively by a crop. Effective rainfall is a key parameter in irrigation scheduling as it reduces the amount of water that needs to be supplied through irrigation. Effective rainfall for Weyna Dega, a climatic zone that receives bimodal rainfall, was estimated using the CROPWAT model.

The research discovered that the rainfall in the Weyna Dega region is extremely variable intra-annually. The most valuable rainfall is obtained from June to September during the Kiremt rainy season, and a large amount of water is accessible for crops during this period. The effective rainfall during the dry season, which spans from December to February, is very low. This inter-seasonal variability is a valuable finding for designing an efficient irrigation scheme.

Successful computation of the CROPWAT model's effective rainfall for the Weyna Dega region confirmed that supplemental irrigation is most necessary during the dry season to alleviate the water shortage and preserve crop yields.

Station FILIKLIK Eff. rain method USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	0.0	0.0
February	7.0	6.9
March	35.0	33.0
April	34.0	32.2
May	101.0	84.7
June	130.0	103.0
July	280.0	153.0
August	243.0	148.5
September	110.0	90.6
October	17.0	16.5
November	17.0	16.5
December	5.0	5.0
Total	979.0	689.9

Table 11 Weyna Dega Effective Rainfall and Rainfall Data

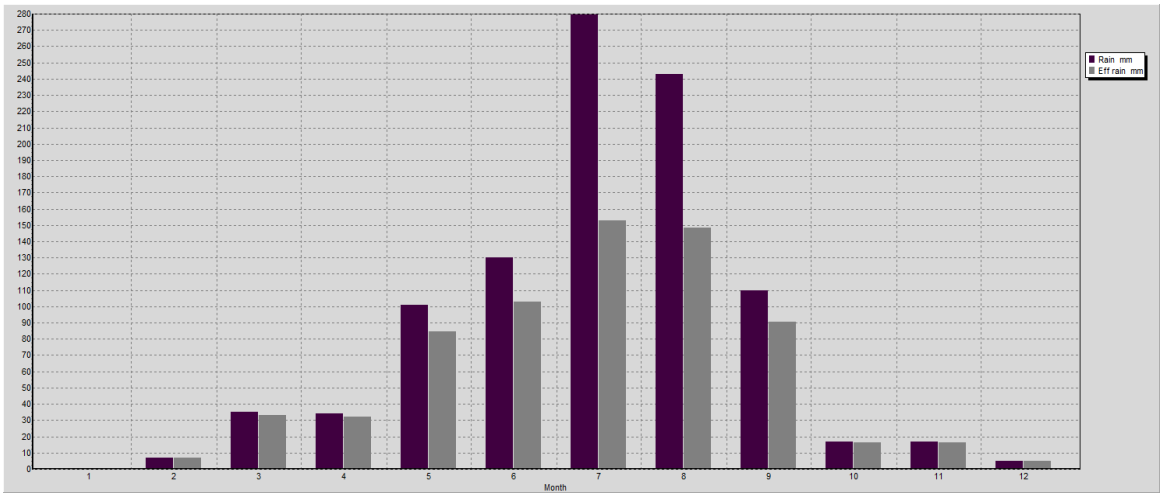


Figure 20 Rainfall and Effective rainfall chart

3.5.3.3 Weyna Dega for the chosen crop—wheat

The CROPWAT model was used to quantify the water needs of wheat, which was taken as a representative crop of Weyna Dega climatic zone. The computation of this specific crop is vital for the development of a precise and effective irrigation schedule.

Crop Growth Stages

The study identified four key growth stages of wheat:

- Initial Stage: The initial stage continues for about 30 days.
- Crop Development Stage: The crop development stage continues for 35 days.
- Mid-Season Stage: This stage lasts 40 days.
- Late-Season Stage: The final growth stage lasts 30 days.

Crop Coefficients (Kc)

Every growth stage also has a specific crop coefficient (Kc) in order to compare the crop evapotranspiration (ET) with the reference evapotranspiration (ETo). The Kc values of wheat were calculated as follows:

- Initial Stage: 0.30
- Crop Development Stage: 0.70
- Mid-Season Stage: 1.15
- Late-Season Stage: 0.30

These parameters were important for the CROPWAT model to accurately calculate the crop water requirements during the crop growth season in the Weyna Dega region.

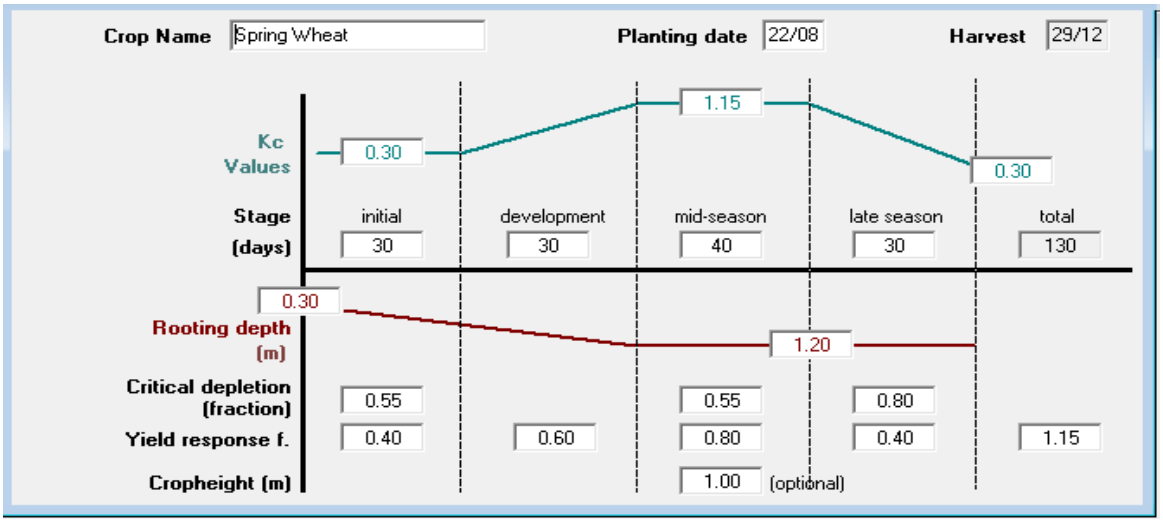


Figure 21 Crop Coefficients (Kc) Diagram

3.5.3.4 Weyna Dega soil data

Specific soil information is required by the CROPWAT model in order to accurately calculate effective rainfall and irrigation requirement. For the Weyna Dega climatic zone,

soil information used was provided by the Harmonized World Soil Database. The parameters used were those deemed as necessary for the analysis:

- Total available soil water: This is the maximum amount of water a soil can hold which is also available to the plant.
- Initial soil water deficit: This is the water shortage at the start of the crop growth season in the soil.
- Maximum infiltration rate of rainfall: This is the factor that will regulate the rate at which water infiltrates the soil and affect how much water is available to the crops versus how much water becomes runoff.

These soils, in conjunction with the climatic and crop data, allowed for the model to simulate the water balance and derive the precise amount of irrigation to supplement natural rainfall in the Weyna Dega area.

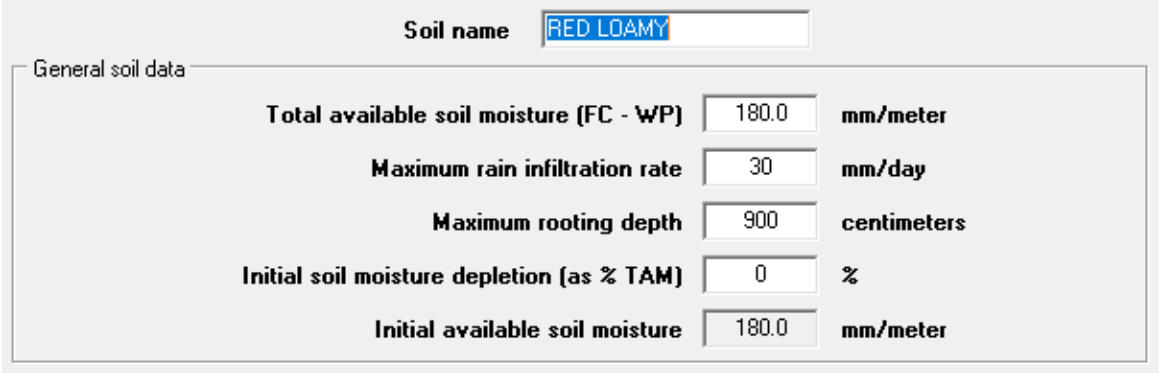


Figure 22 General soil data diagram

3.5.3.4 Weyna Dega Crop water Requirements

Key Data and Parameters

Crop water requirement of wheat was determined based on a set of the following data:

- **Climatic Data:** Reference evapotranspiration (ETo) values were sourced from the CLIMWAT program for the station Fililik. The highest values of ETo are received between the months of the dry season (February to May), indicating highest water demand in the mentioned months.
- **Soil Data**: Soil data, including the maximum infiltration rate and total available water (TAW), were used by the model to simulate water balance in the soil.

- **Crop Data:** The wheat crop was simulated for 135 days of crop growth. Four growth stages of wheat were used in the study:
- Initial Stage: 30 days, Crop coefficient (Kc) = 0.30.
- Crop Development Stage: 35 days, Kc = 0.70.
- Mid-Season Stage: 40 days, and Kc of 1.15.
- Late-Season Stage: 30 days, and Kc of 0.30.

ETo station	FILIKLIK	**Crop**	Spring Wheat
Rain station	FILIKLIK	**Planting date**	22/08

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Aug	3	Init	0.30	0.94	9.4	40.7	0.0
Sep	1	Init	0.30	1.00	10.0	37.1	0.0
Sep	2	Init	0.30	1.05	10.5	31.0	0.0
Sep	3	Deve	0.46	1.77	17.7	22.5	0.0
Oct	1	Deve	0.75	3.15	31.5	11.4	20.0
Oct	2	Deve	1.04	4.73	47.3	2.0	45.2
Oct	3	Mid	1.17	5.40	59.4	3.2	56.2
Nov	1	Mid	1.17	5.48	54.8	5.8	49.0
Nov	2	Mid	1.17	5.56	55.6	6.0	49.6
Nov	3	Late	1.17	5.37	53.7	4.6	49.1
Dec	1	Late	0.98	4.36	43.6	2.7	40.9
Dec	2	Late	0.69	2.96	29.6	1.4	28.3
Dec	3	Late	0.42	1.78	16.0	0.7	15.1
					439.0	**169.1**	**353.5**

Table 12 Weyna Dega Crop water requirement data

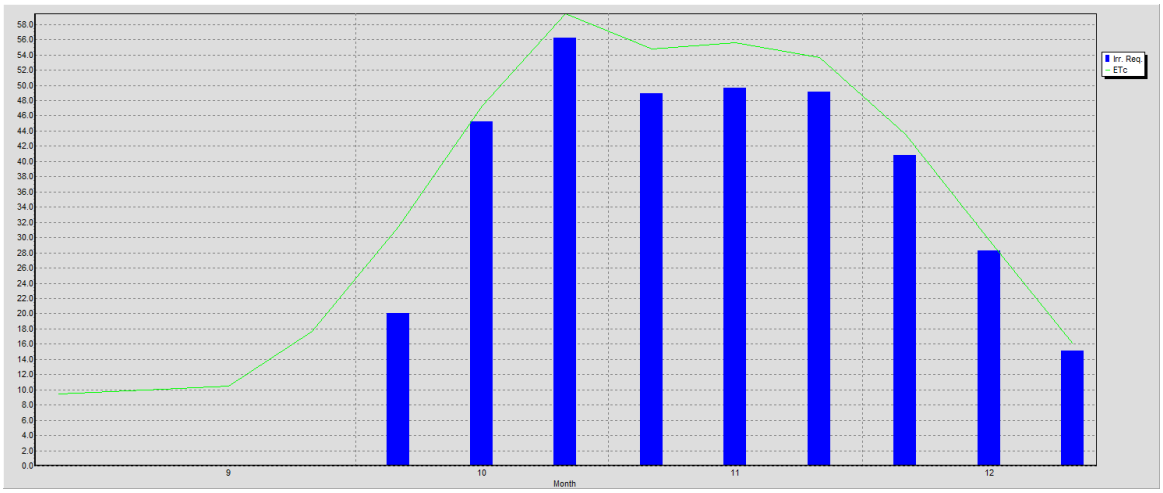


Figure 23 Weyna Dega Crop water requirement chart

3.5.3.5 Weyna Dega Schedule

The CROPWAT model was used to develop a precise irrigation schedule for wheat, the chosen crop for Weyna Dega climatic zone. The schedule, which is calculated from climatic, soil, and crop data, provides a precise analysis of the water requirements and effective rain during the growing period. The date of planting spring wheat was August 22.

The schedule provides the following information for every decade and month in the growth cycle of the crop:

- Crop Stage: The schedule outlines the four phases of the growth of the wheat crop: Initial, Development, Mid-Season, and Late-Season.
- Crop Coefficient (Kc): The values of Kc, which are the crop water requirement in relation to the reference evapotranspiration (ETo), are different at every stage of development. The first stage, for instance, is 0.30, while the mid-season stage is at its peak at 1.17.
- Effective Rainfall (Eff rain): This represents the amount of rainfall that is effectively used by the crop. Effective rainfall during the initial months (August and September) is very high (40.7 mm/dec) and hence there is no irrigation requirement.
- Irrigation Requirement (Irr. Req.): This refers to the total water requirement that must be met through irrigation. The calendar specifies that irrigation must be carried out starting from the first decade of October (20.0 mm/dec) and continuing through to December harvest.

The total net irrigation requirement throughout the entire growth period totals 353.5 mm. This accurate calendar is extremely important in an attempt to optimize water usage and allow the crop to receive the proper amount of water at each stage of its life cycle.

ETo station: FILIKLIK | Crop: Spring Wheat | Planting date: 22/08 | Yield red.: 0.0 %
Rain station: FILIKLIK | Soil: RED LOAMY | Harvest date: 29/12

Table format
- Irrigation schedule
- Daily soil moisture balance

Timing: Irrigate at critical depletion
Application: Refill soil to field capacity
Field eff. 70 %

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
30 Oct	70	Mid	0.0	1.00	100	57	122.7	0.0	0.0	175.3	0.29
24 Nov	95	Mid	0.0	1.00	100	57	122.7	0.0	0.0	175.3	0.81
29 Dec	End	End	0.0	1.00	0	52					

Totals

Total gross irrigation	350.6	mm	Total rainfall	218.5	mm
Total net irrigation	245.5	mm	Effective rainfall	79.6	mm
Total irrigation losses	0.0	mm	Total rain loss	138.9	mm
Actual water use by crop	437.2	mm	Moist deficit at harvest	112.2	mm
Potential water use by crop	437.2	mm	Actual irrigation requirement	357.7	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	36.4	%
Deficiency irrigation schedule	0.0	%			

Yield reductions

Stagelabel	A	B	C	D	Season	
Reductions in ETc	0.0	0.0	0.0	0.0	0.0	%
Yield response factor	0.40	0.60	0.80	0.40	1.15	
Yield reduction	0.0	0.0	0.0	0.0		%
Cumulative yield reduction	0.0	0.0	0.0	0.0	0.0	%

Table 13 Weyna Dega Irrigation schedule data

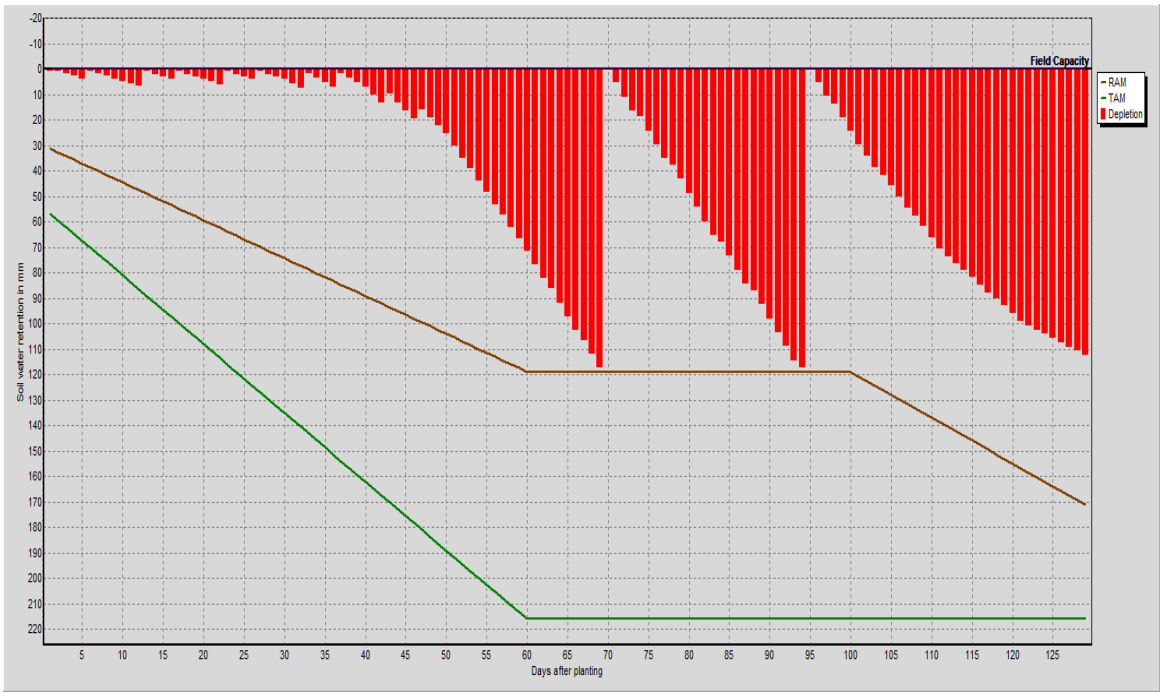


Figure 24 Weyna Dega Irrigation schedule chart

3.5.3.6 Weyna Dega Crop pattern

The temporal and spatial arrangement of crops within a given land area is known as the crop pattern. It deals with the order in which crops are planted in a field over a specific period of time, usually a season or a year. The definition is broken down into important elements that can be looked at in the chart you gave, which displays a particular crop pattern.

- **Planting Date:** This is when the crop's life cycle begins. Because it dictates when the crop will experience the wet or dry season, this variable is extremely important.
- **Crop Type:** This establishes what kind of crop—in this example, wheat—should be planted. Different crops require different amounts of water and have different growth patterns.
- **Growth Stages:** There are four stages of crop life: early, mid-season, late-season, and crop development. Every phase has a set water requirement and lasts for a different amount of time.
- **Crop Coefficient (Kc):** This unitless number represents the amount of water needed by a particular crop at different stages of growth. The reference evapotranspiration (ETo) is converted into the crop water requirement (Eto) using the Kc.

Cropping pattern name: pattern1

No.	Crop file		Crop name	Planting date	Harvest date	Area %
1.	...a\CROPWAT\data\crops\FAO\WHEAT.CRO	...	Spring Wheat	22/08	29/12	60
2.	...ata\CROPWAT\data\crops\FAO\MAIZE.CRO	...	MAIZE (Grain)	22/08	24/12	20
3.	...\CROPWAT\data\crops\FAO\POTATO.CRO	...	Potato	22/08	29/12	10
4.	...a\CROPWAT\data\crops\FAO\BARLEY.CRO	...	Barley	22/08	19/12	10
5.		...		22/08		
6.		...		22/08		
7.		...		22/08		
8.		...		22/08		
9.		...		22/08		
10.		...		22/08		

Table 14 Weyna Dega Crop pattern

3.5.3.7 Weyna Dega Scheme Supply

Calculation of the Weyna Dega zone irrigation water supply was a part of the methodology for establishing whether the proposed irrigation system was feasible. It was conducted through a two-stage process:

- Computing Water Demand: The research commenced by using the CROPWAT model to calculate the irrigation duty of the Weyna Dega zone. It is a measure of the land (in hectares) that can be irrigated with a flow rate of one cubic meter per second. This was crucial in estimating the total water required to sustain a potential irrigation project.
- Water Availability Estimation: The research further involved a standalone methodology for estimating the total water availability of the entire Jemma Sub-Basin. This was meant to determine if the aggregate available water from the catchment was sufficient enough to meet the computed irrigation demand.

By setting up a particular procedure to estimate both the supply and demand, the research set up a template for a final water balance analysis.

Scheme Supply

ETo station FILIKLIK Cropping pattern Pattern1

Rain station FILIKLIK

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Spring Wheat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	121.5	147.7	84.2
2. MAIZE (Grain)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.8	140.8	152.6	67.3
3. Potato	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.7	134.8	147.3	114.8
4. Barley	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.4	144.8	138.2	39.7
Net scheme irr.req.												
in mm/day	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	4.2	4.9	2.6
in mm/month	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	129.0	147.7	79.4
in l/s/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.48	0.57	0.30
Irrigated area	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0	100.0	100.0	100.0
(% of total area)												
Irr.req. for actual area	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.48	0.57	0.30
(l/s/h)												

Table 15 weyna Dega Irrigation Scheme Supply

3.5.3.2 Dega Climatic Zone Crop water analysis

The same process was followed as the one explained for the Weyna Dega zone, the only difference being that specific climatic data and parameters applicable to the Dega region were used. The focus of this study is the Dega climatic zone, which is the largest agricultural area of the Jemma Sub-Basin, and it occupies approximately 63.37% of the entire study area. Its height and unique climatic attributes are central to the agricultural operations and water management justifications in this region. Proper understanding of this region is therefore a prerequisite to understanding and planning irrigation development activities for the entire sub-basin.

3.5.3.2.1 Location and Climate Characteristics of Dega zone

The Dega zone possesses a highland climate due to the zone's high elevation, and the reference station, Debre Berhan, is at an elevation of 2820 meters and coordinates 39.5°E and 9.63°N. The climatically cold to cool weather conditions quite substantially influence the type of crops that are producible and their respective growing seasons. The precipitation patterns and reference evapotranspiration (ETo) data for this region are primarily derived from the climatic data obtained from this station, as provided by the CLIMWAT program.

3.5.3.2.2 Agricultural Potential and Challenges of Dega Climate Zone

The Dega zone has a huge potential for agriculture but under unique constraints. While a cooler climate can reduce the evapotranspiration rate, low temperatures can similarly restrict the type of crop that may be produced. Proper water management is, therefore, critical to establish agricultural productivity. Proper water harvesting and distribution, and in particular rainwater harvesting, in this highland climate requires specialized irrigation methods.

3.5.3.2.3 Application of the CROPWAT Model to Dega Zone

The CROPWAT model was applied to the Dega climatic zone to estimate the exact water needs of the crops for this climate. Utilizing information from the CLIMWAT application and other pertinent details, an extensive water balance analysis was conducted. This comprised:

- Estimating the crop water requirement (ETo).
- Defining the soil and crop parameters.

- Creating an optimal irrigation schedule.

The final output of this exercise will be the calculation of the irrigation duty for the Dega zone. This value provides a base number for irrigation scheme design and operation and water resource planning in the Jemma Sub-Basin as a whole.

3.6 Hydrological Modeling

This study used the Hydrological Predictions of the Environment (HYPE) as the hydrological modeling used in this research. This semi-distributed process-based model is very appropriate to examine hydrological processes and can be applied to small catchments to large river basins.

The Hydrological Predictions for the Environment (HYPE) model is a process-based, semi-distributed hydrological model for water movement and substance transport simulation at catchment and basin scales. The HYPE model was developed by SMHI (Swedish Meteorological and Hydrological Institute), a tool of great utility to study a very wide range of hydrological processes including snowmelt, soil moisture dynamics, evapotranspiration, groundwater recharge, and streamflow generation. It is particularly well-suited to investigations requiring an integrated approach to water resource management, as it can be applied from small catchments to vast river basins and also for current as well as future climate conditions.

One of the key features of the HYPE model is its flexible spatial operation scale, which is of utmost importance in detailed water balance analysis in a sub-basin such as Jemma. The model divides a river basin into a number of sub-basins, each with properties of its own. Sub-basins are also classified into different Soil and Land Use Classes (SLCs) so that high spatial resolution in the simulations is possible. This semi-distributed structure enables the model to account for rainfall, soil, and land use heterogeneities, which are all critical in appropriately simulating the basin's hydrologic response. The model's flexible structure also enables it to be used for evaluating land use change, climate change, as well as various water management interventions.

Within the context of this study, the HYPE model is an essential tool for quantifying rainwater harvesting (RWH) capacity in the Jemma sub-basin. Through integration with GIS-based land suitability analysis, the research will simulate the water storage and flow

and the hydrology and water balance at the identified RWH locations. By the simulation capacities of the model for water storage and flow, the volume of available water will be calculated for irrigation. This goes beyond the simple water balance calculation by mimicking in a dynamic way how water accumulates and conveys through the basin, hence providing for a more realistic calculation of the RWH system's capability to meet crop water demands.

The application of the HYPE model within this research comes close to filling the divide between theoretical CROPWAT calculations and a more realistic hydrological assessment on a large scale. While CROPWAT will provide a definite, point-based value of crop water requirements, the HYPE model will provide a general idea of the water availability within the basin. It will execute the rainfall-runoff process and model the available water resources to be stored in the provided RWH sites. This integration makes it possible to create an optimized irrigation plan that not only takes into account the requirements of the crop but also the dynamically simulated water availability, ensuring the feasibility and sustainability of planned irrigation development.

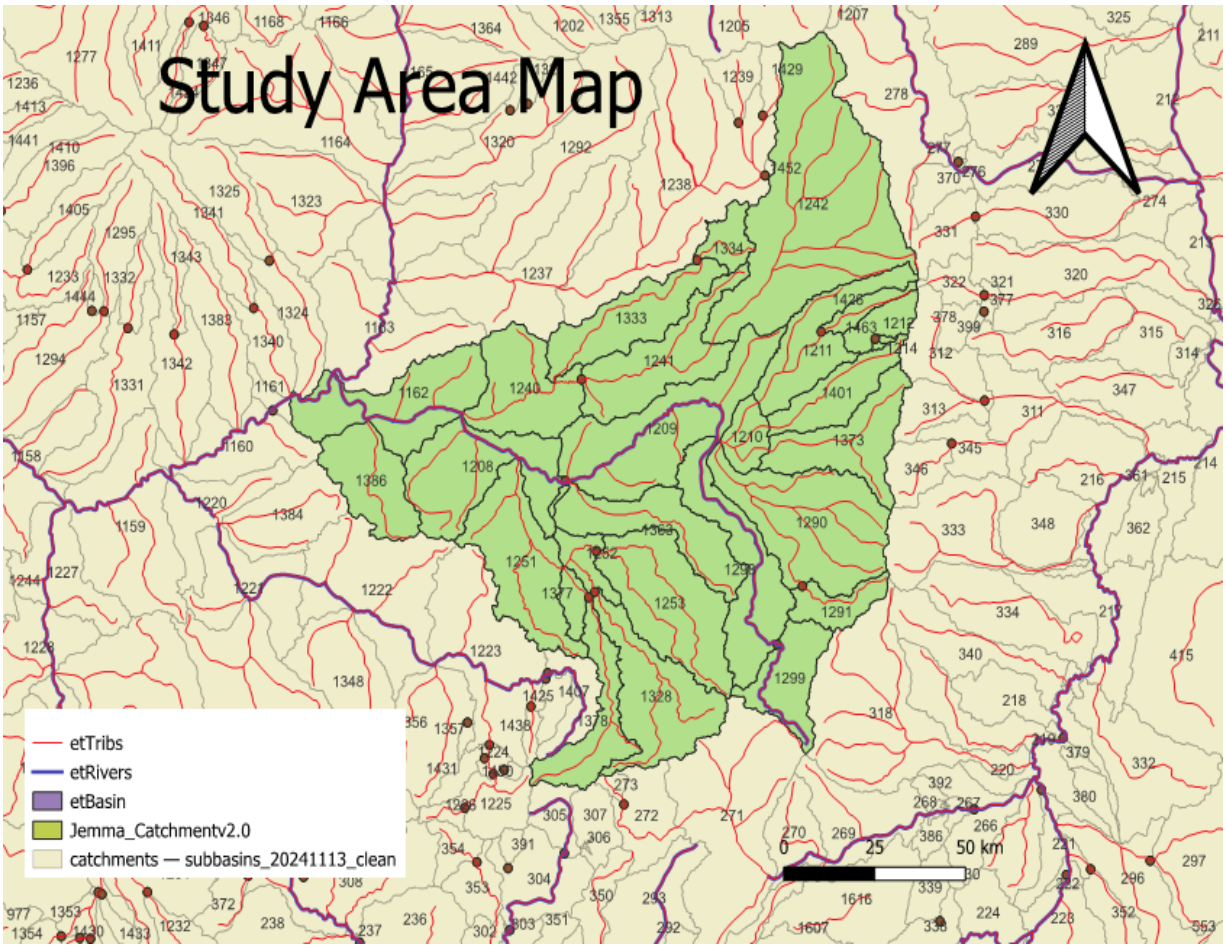


FIGURE 25 JEMMA SUBID MAP

3.6.1 Selection of Model and Framework

The specific use of HYPE and not a "lumped" hydrological model was chosen. Lumped models entail the representation of a watershed as a whole unit, which would attribute a single value of runoff to a specific location. Thus, it fails to capture the local variations in the runoff that occur in rugged terrains. As opposed to this HYPE, which is semi-distributed, divides the Jemma sub basin into smaller sub-basins. The units can be further categorized into Soil and Land use Classes (SLCs). This enables the model to replicate the hydrological footprints linked to different land use types, such as high-altitude grazing land and valley-bottom agriculture, with specified soil types, Nations and Camisole. The model, which takes into account this spatial heterogeneity, paints a picture of the physical reality of the catchment.

3.6.2 Jemma Sub-Basin Simulation of Physical Processes

The HYPE model is a digital representation of the water cycle in the basin, showing the water movement through several interconnected storages. The simulation comprises a combination of key processes.

- The model determines the partitioning of rainfall between surface runoff and infiltration based on soil moisture and slope of the land.
- Evapotranspiration (ET) can be defined as the calculation by which the model determines the actual ET by comparing the potential demand at a particular location to the moisture available in the root zone. The model recognizes that the evaporation demand of the Blue Nile Basin is very high.
- HYPE represents the vertical movement of water through three different layers of soil. It allows simulating inter flow and deep percolation, two important processes for estimating the water available for irrigation at late stages of the season.

3.6.3 Data collection and simulation period 1995-2014.

The simulation was conducted in a continuous mode from 1995 to 2014 for a duration of 20 years. This duration allows the results to be statistically robust and captures long-term climatic cycles. Furthermore, this period covers a wide range of hydrologic conditions, ranging from severe drought years to high-intensity flood years. The driving force behind the model was a high-resolution 30m Digital Elevation Model (DEM), ESA Sentinel-2 land cover data and daily climatic records.

The model has been calibrated at three internal gauging stations to represent all the hydrologic response zones in the basin.

- Cha-cha (SU BID 1291) the highland headwaters.
- Barsha (SU BID 1299): Understanding tributary dynamics.
- Robin located near Lamp (SU BID 1252): Current Observation of cumulative flow in middle reach.

3.6.4. Parameter Descriptions

The successful calibration results should be attributed to the accurate adjustment of the vertical and horizontal water movement parameters. In Jemma deep Nations, a vertical movement is a multi-stage process. The **mperc1** variable controls the water movement from the upper soil layer to the middle layer, while **mperc2** controls drainage from the middle layer to the deep groundwater zone.

NO.	Parameter	Description	Default	Min (Lower Band)	Max (Upper Band)
1	srrcs	Surface runoff coefficient; determines the fraction of rainfall that becomes immediate overland flow.	0.1	0.01	0.5
2	mperc1	Percolation coefficient for Layer 1; controls vertical drainage rate from the first to the second soil layer.	1	0.01	10
3	mperc2	Percolation coefficient for Layer 2; controls vertical drainage from the second to the third soil layer (deep recharge).	1	0.01	10
4	rrcs1	Regional runoff coefficient for Layer 1; dictates the speed of shallow inter flow reaching the stream.	0.05	0.001	0.2
5	rrcs2	Regional runoff coefficient for Layer 2; dictates the horizontal flow originating from the middle soil profile.	0.01	0.0001	0.1
6	koc	Groundwater recession coefficient; the primary constant used in the RGB method to calculate base flow discharge.	0.005	0.0001	0.05

7	mpe	Multiplier for Potential Evaporate-transpiration; adjusts the evaporation demand based on local catchment characteristics.	1	0.5	1.5
8	wcap	Soil water capacity; defines the amount of water the soil can hold before saturation-excess runoff occurs.	0.15	0.05	0.4
9	lp	Limit for potential evaporate-transpiration; the soil moisture threshold below which actual ET starts to decrease.	0.7	0.3	0.9

Table of Parameters Description

3.6.4.1 The methodology for Evaluating

The model was calibrated on a monthly basis, which is an appropriate scale to cope with daily variability and seasonal contrasts for irrigation design. The “goodness of fit” of the model was assessed using Nash-Sutcliffe Efficiency (NSE), along with monitoring the volume bias using Relative Error (RE) were used as two primary criteria. A low RE indicates a slightly conservative underestimation, which is a safer baseline for infrastructure planning. Results of model performance were assessed to be in the “Very Good” to “Excellent” range at all three observation points.

4.0 RESULTS AND DISCUSSION

4.1 Land Suitability Analysis

A land suitability map of the Jemma Sub-Basin was generated by overlaying a number of biophysical and infrastructural elements, including slope, soil type, and proximity to rivers, roads, and towns, using a weighted overlay analysis in a GIS environment. To render the map functional and not theoretical, a land use/cover (LULC) masking procedure was implemented to remove lands that were not arable, such as forestland, urban land, and wetlands. The procedure guaranteed that the resulting map would identify only those land parcels that were theoretically and practically qualified for irrigation development.

The analysis located a total of 6,983.70 km² of irrigable land available in the sub-basin. The previous classification based on land suitability is as follows:

- Highly Suitable (S1): These locations, with a total area of 1,567.82 km² (10.84%), lie in the lowlands and gentle slopes and are edged by deep loamy soils and good infrastructural accessibility. They require only minor adjustments and are most suitable for instant investment in irrigation.
- Moderately Suitable (S2): These areas cover 5,415.88 km² (37.45%) with limited difficulties, such as moderate slopes or sub-optimum soil pH status. They have adequate development potential with moderate input and infrastructure support.
- Marginally Suitable (S3): These, the largest class at 6,207.07 km² (42.92%), have major constraints like steeper slopes or greater distances from infrastructure. They would require flexible irrigation systems or be best suited to drought-resistant crops.
- Presently Not Suitable (N1): These zones, with an area of 1,270.96 km² (8.79%), have severe limitations such as high slopes or water-logging, or are included under conserved land use categories such as high-density forests or towns. They are not available for development of irrigation.

The ultimate classification of irrigation suitability classes is presented below:

No	Suitability	Area(km^2)	Percent (%)
1	Highly suitable (S1)	1,567.82	10.84%
2	Moderately suitable (S2)	5,415.88	37.45%
3	Marginally suitable (S3)	6,207.07	42.92%
4	Currently not suitable (N1)	1,270.96	8.79%

Table 16 Area's Irrigation land suitability Coverage

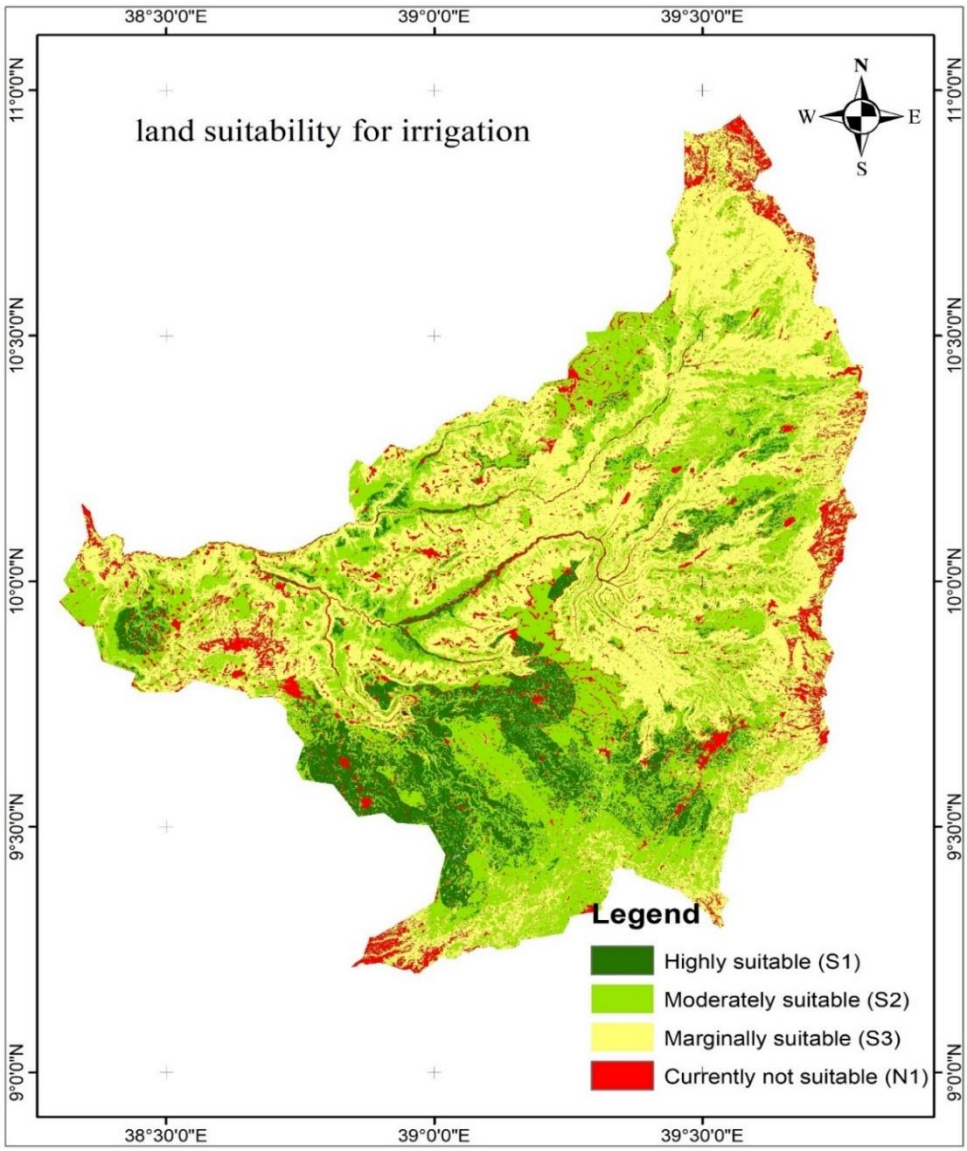


Figure 26 Irrigation land suitability map

4.1.2 Total Relevance of the Final Suitability Map

The enhanced suitability map offers a real-world, practical spatial planning method that can assist decision-makers, agricultural planners, NGOs, and water resource planners in making decisions about where and how to invest in irrigation development. Unlike theoretical models, which do not consider land use constraints, this map offers suggestions based on physical feasibility and available land availability.

Furthermore, it facilitates phased irrigation planning:

- Short-term investment in S1 regions
- Medium-term expansion into S2 regions
- Long-term or adaptive measures in S3 regions

By the integration of spatial suitability and land use context, the final map enables sustainable and climate-resilient intensification of agriculture within the Jemma Sub-Basin.

4.1.1 Interpretation of Land Suitability Analysis

The LULC masking step is an important refinement procedure that enhances the realism and practical usefulness of the irrigation suitability map. Whereas the initial suitability analysis proceeds from theoretical potential, LULC masking guarantees that only lands presently available for agricultural use are preserved.

- Well-suited locations (10.84%), which are highly concentrated in the central and lowland regions of the basin, provide both physical suitability and land availability, hence are of prime importance for irrigation investment.
- Moderately suitable areas form a noteworthy part of the landscape, representing 37.45%, and portray good chances for development, given moderate input and infrastructure support.
- Marginally suitable areas (42.92%) require more intensive management or would be optimally used for restricted irrigation or drought tolerant cropping systems.
- The unsuitable areas (8.79%) could be ecologically sensitive, have steep slopes, or fall under specified land use limitations (like dense forest or urban areas) and should be precluded from irrigation planning considerations.

Conclusion Land cover and use masking greatly improved the spatial precision and decision-making worth of the ultimate irrigation suitability map. This process guaranteed that only areas that are environmentally suitable and agriculturally viable were retained.

Thus, this final output is a viable and actionable spatial tool for policymakers, planners, and development partners who are striving to promote sustainable irrigation practices in the Jemma Sub-Basin.

4.2 Rainwater Harvesting Potential Assessment Analysis

Analysis for the identification of rainwater harvesting (RWH) potential sites was conducted on a GIS-based hydrological analysis, seeking to locate natural sinks or low places by using a Digital Elevation Model (DEM). This was a crucial process in determining places where surface runoff tends to gather naturally. Upon detection of sinks, the upstream contributing area of the watershed of each sink was mapped and the likely volume of storage was calculated from elevation profiles and area.

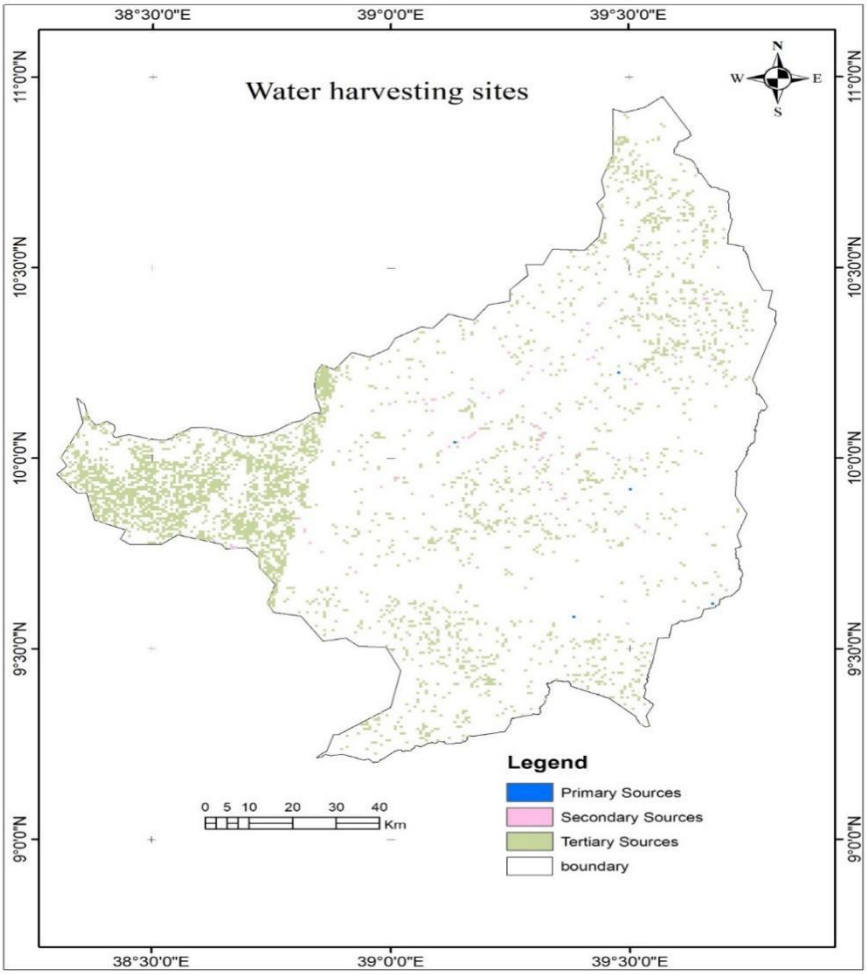


Figure 27 Final water harvesting sites map

Areal range	Number of identified storage sites	Area(ha)	Average Volume (BCM)
Below 1ha	2047	137.29	0.067
From 1ha to 5 ha	219	324.1	1.5
From 5 ha to 10ha	4	26.3	6.6
From 10ha to 18ha	3	36.6	12.2
Over 18 ha	1	24.8	24.8
Total	2274	549.1	45.1

Table 17 Storage sites Identified

Such intensive analysis found 2,274 potential points of storage in the Jemma Sub-Basin, confirming the vast scope for decentralized water harvesting there. These points were then graded according to surface area in order to ensure that implementation could be scaled up and infrastructure built in a targeted way:

- **Small-Scale Sites**: 2,047 sites with less than 1 hectare in size were discovered. These are largely suitable for micro-irrigation and domestic use at home level.
- **Medium-Scale Sites**: 219 sites with 1 to 5 hectares in size were discovered. These are suitable for small to medium-scale schemes for a community.
- **Large-Scale Sites**: 8 sites covering an area of 5 hectares or more were found. These 4 sites ranging from 5 to 10 hectares, 3 sites ranging from 10 to 18 hectares, and 1 site larger than 18 hectares can accommodate large-scale, multi-purpose reservoirs that can meet regional irrigation and water security needs.

The overall water storage capacity of all the sites identified is approximately 45.1 million cubic meters (MCM). The high capacity is regarded as a critical impeller in promoting water security in the basin, especially during dry spells when supplemental irrigation is

most required. Site classification on scale provides a critical basis for strategic investment and infrastructure planning, enabling phased development of irrigation in the region.

4.3 Crop Water Requirements and Irrigation Scheduling

CROPWAT model was employed to calculate the crop water demand and irrigation duty of each of the major climatic zones in the Jemma Sub-Basin. Irrigation duty is a significant parameter that calculates the area irrigable (in hectares) which might be supplied with a unit flow rate of water (in cubic meters per second, or cumec).

The equation for calculating irrigation duty (D) is as given below:

$$D = A / Q$$

Where:

- D = Duty of Irrigation (ha/cumec)
- A = Command Area (hectares)
- Q = Required Discharge at the Head of the Canal (cumec)

The discharge required (Q) can be determined using the following formula:

Q = (Total Net Irrigation Requirement (mm) × Command Area (ha)) / (1000 × 86400 × Number of Days)

The constants 1000 and 86400 are used to convert the units from millimeters and hectares to cubic meters and seconds, respectively (1 ha=10,000m2 and 1 day=86,400 seconds).

Using this technique, CROPWAT model yielded the following outputs for the two primary climatic regions:

4.3.1 Weyna Dega Climatic Zone

The Weyna Dega climatic zone irrigation duty was calculated by the CROPWAT model computation. The calculation was also similar to the one for the Dega zone, but with the actual data for the Weyna Dega region.

The most significant values used in the calculation were:

- Base Period: The whole wheat crop growing period is 135 days.
- Total Gross Irrigation Requirement (GIR): The crop requires a total water of 173.9 mm during this duration.
- Using the formula: Duty (ha/cumec) = (86.4 × Base Period (days)) / Total Gross Irrigation Requirement of the crop is 173.9 mm, as calculated in chapter 3.

- Duty = (86.4 × 135) / 173.9
- Duty = 11664 / 173.9
- Duty = 67.07 ha/cumec

This result implies that approximately 67.07 hectares of land would be irrigated with an uninterrupted flow of one cubic meter per second of water. This is a significant factor to be considered in the design and upkeep of any irrigation system since it provides a concrete figure of the effectiveness of water usage in an area.

4.3.2 Dega Climatic Zone

By the CROPWAT model analysis, the irrigation duty for the Dega climatic zone was calculated. The same steps that were taken for the Weyna Dega zone were followed but with data specific to Dega.

The critical figures used in the calculation were:

- Base Period: The normal growing period of the wheat crop is 135 days, as Calculated by Model.
- Total Gross Irrigation Requirement (GIR): The total quantity of water to be diverted from the source in order to meet the requirement of the crop is 129.5 mm, as calculated in chapter 3.

By using the formula: Duty (ha/cumec) = (86.4 × Base Period (days)) / Total Gross Irrigation Requirement (mm), the calculation is as given below:

- Duty = (86.4 × 135) / 129.5
- Duty = 11664 / 129.5
- Duty = 90.07 ha/cumec

4.3.3 Comparative Analysis: Dega vs. Weyna Dega Climatic Zones

A comparison of the irrigation duties of the Dega and Weyna Dega climatic areas recognizes extreme differences based directly upon each of their respective climates.

- Dega Climatic Zone (90.07 ha/cumec): The high irrigation duty of this zone is a direct result of its highland, cool climate. Low temperature and high effective rainfall in the region lower the total crop water requirement. One unit of water can, thus, irrigate more land, and thus a more efficient irrigation system.

- Weyna Dega Climatic Zone (67.07 ha/cumec): The higher duty in this zone is due to its increased temperature and increased evapotranspiration. The increased atmospheric demand for water means that a unit of water can irrigate only a small area since more water per hectare must be used in order to meet the crop demand.

Overall, comparative analysis highlighted the role of climate as a deciding factor in determining the irrigation efficiency. The findings reveal that although both zones favor irrigation, the climate of the Dega zone is naturally favorable as far as water efficiency is concerned, and it is a key parameter for the sustainable development of irrigation systems in the Jemma Sub-Basin.

4.4 Hydrological Modeling and Water Availability

The section provides the findings of the hydrological modeling conducted with the HYPE model that are essential to comprehending the water resources of the Jemma Sub-Basin, as well as evaluating the possibility of the development of large-scale irrigation. The methodology used was to have a strong and factual foundation on the conclusions of the study.

4.4.1 Statistical Performance Metrics

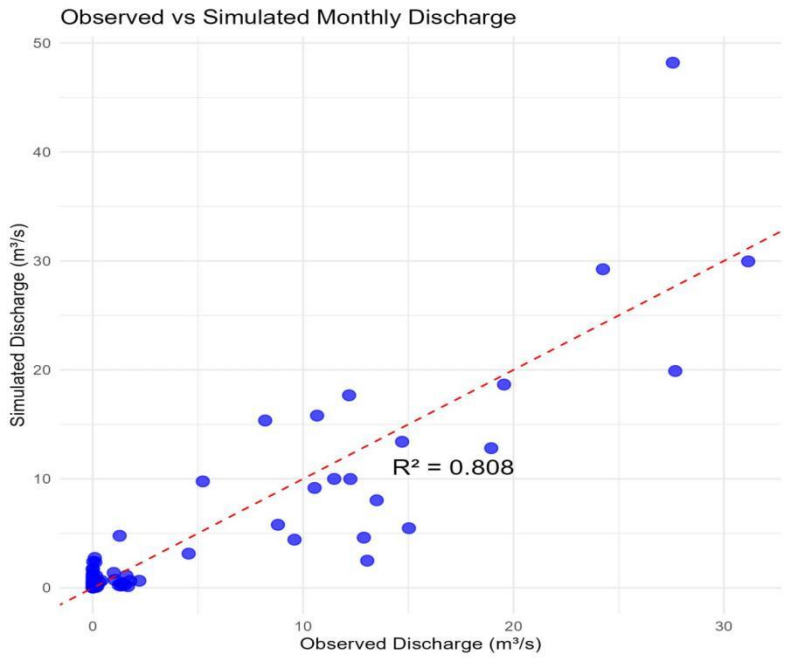
The River Murray model was calibrated against observed flow at three stations. The findings, especially SUBID 1299 with USE 0.85, demonstrate the model's predictive accuracy is "Excellent" according to international standards.

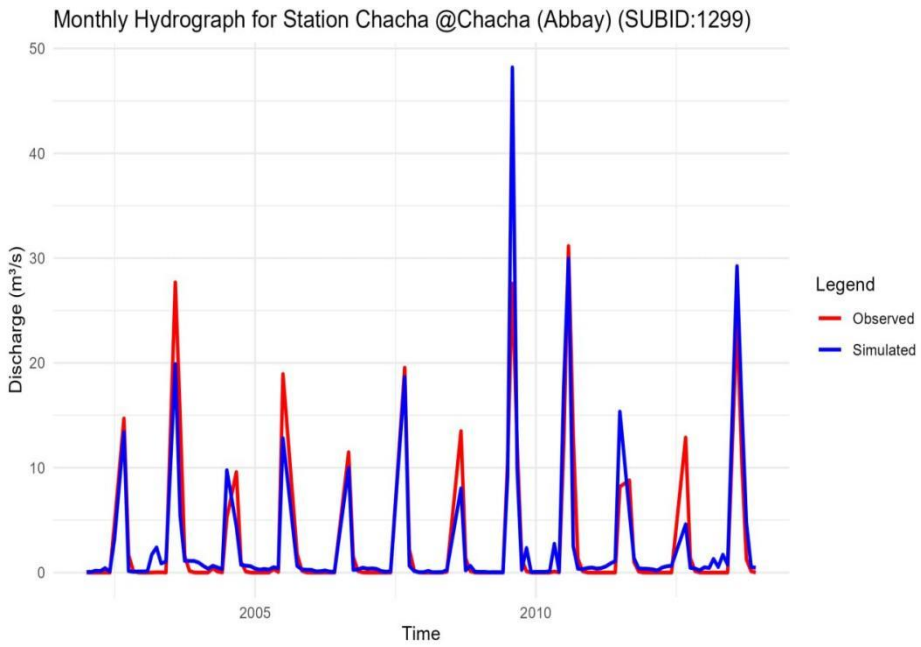
Station Name	**SUBID**	**Nash-Sutcliffe Efficiency (NSE)**	**Relative Error (RE %)**
Chacha	1291	0.75	-9.97
Baressa	1299	0.85	-11.51
Robi near Lami	1252	0.77	-6.46

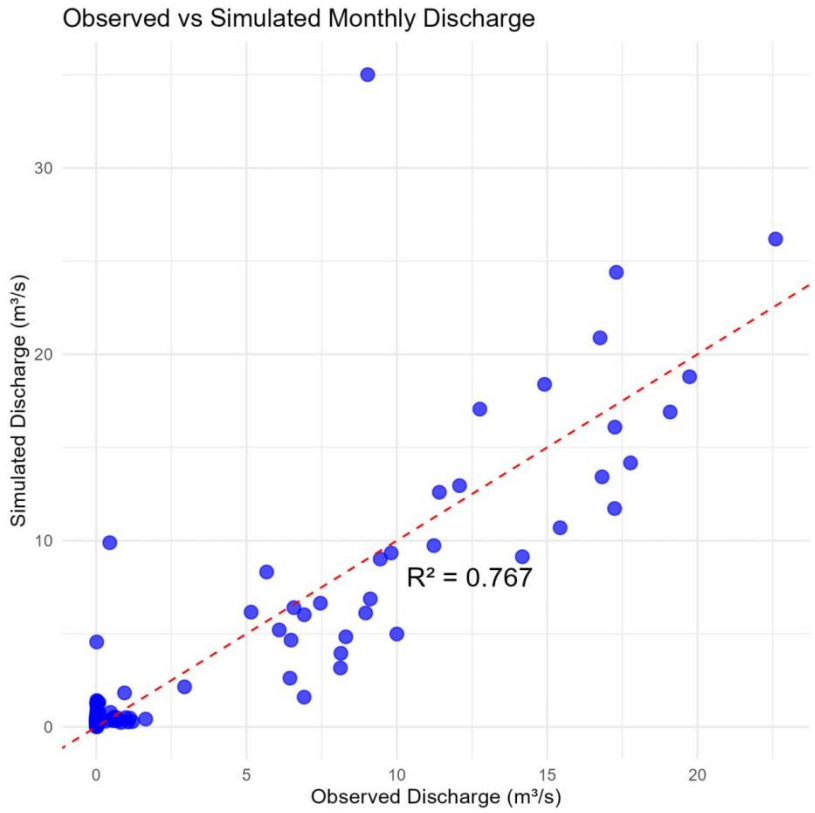
Table 19 Monthly Performance Metrics for Selected Gauging Stations

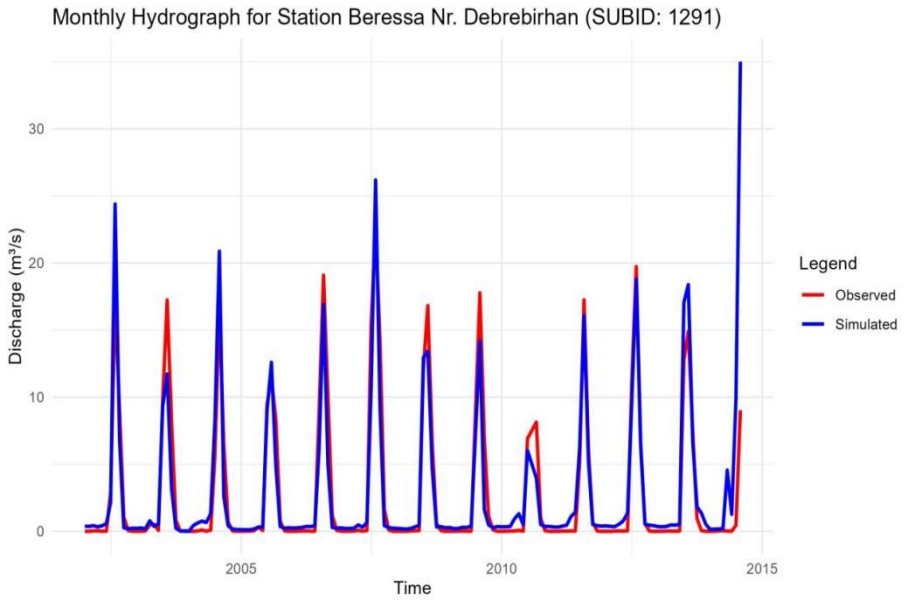
4.4.2 Graphical Analysis

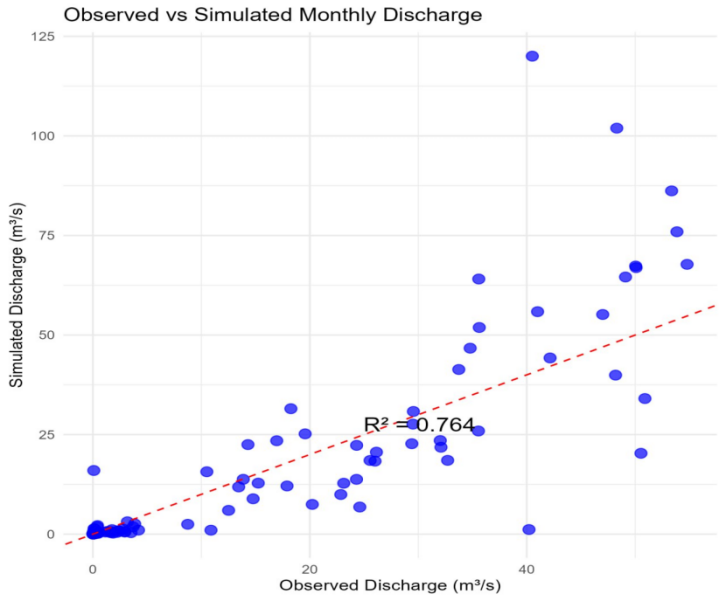
The visual display showing the correlation between observed and simulated discharge further reinforces model reliability.

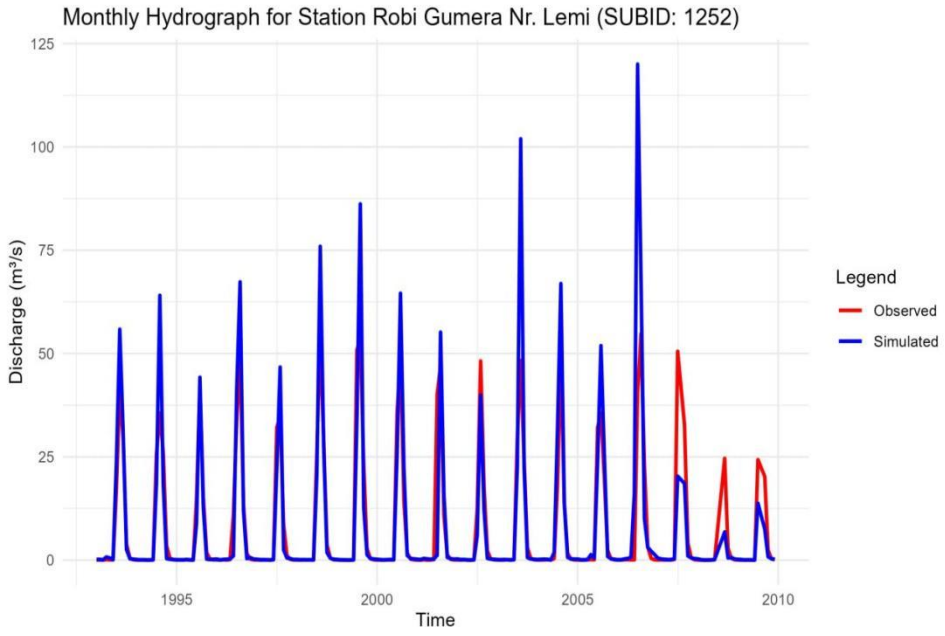





Observed vs Simulated Monthly Discharge
Simulated Discharge (m³/s)
Observed Discharge (m³/s)
R² = 0.767
0
10
20
30
0
5
10
15
20


Monthly Hydrograph for Station Beressa Nr. Debrebirhan (SUBID: 1291)
Discharge (m³/s)
Time
Legend
Observed
Simulated
0
10
20
30
2005
2010
2015





4.4.2 Total Available Water at the Outlet

The purpose of the HYPE simulation was to compute the total water yield at the Basin Outlet (**SUBID 1208)**. Using the RGB (Recession Groundwater Base flow) Method, the model separated the sustainable flow components from transient storm peaks. The Total **Available Water (Q)** for the Jemma Sub-Basin was estimated at **206.222** cumec from **1995 to 2014** simulation. Accordingly, the outcome of the hydrology is the "hydrological ceiling" to the water balance mistake, which shows the total supply to meet agricultural and environmental requirements.

4.5 Water Balance and Irrigation Scheme Analysis

This part looks at total behavior being linked to land suitability, crop water requirements (CROAT) and hydrology to comment on whether the supply of the catchment will sustain the identified irrigable land.

4.5.1 Total Irrigation Water Demand Calculation

The total irrigation water demand was assessed by aggregating all the requirement of the 6,983.70km^2 area of suitable land identified in Chapter 3. The climatic draft for Sega and Weyna Sega was used to assess the peak discharge needed to sustain the crops on this land. In the total irrigation, water demand was calculated as **191.54 cumec**. The total water requirement refers to the total volume of water needed to meet the crop water requirement of the entire cultivable area of the sub-basin.

4.5.2 Viability of Rain Water Harvesting (RWH)

Rain water harvesting is a very important supplementary source of irrigation apart from river water. The study showed the potential storage structures of 2,274 numbers having 45.1 million cubic Meter (MCM) of capacity. Using water from several seasonal streams for irrigation helps bolster water security in the dry "Began" season, and this decentralization helps stabilize the irrigation system even in wet years when rainfall is more variable.

4.5.3 Water Supply vs. Water Demand

The comparison of gross water yield (supplied by proposed irrigation development) and total irrigation demand confirmed the feasibility of the proposed irrigation development.

Parameters	**Value**
Total Irrigable land	6,983.7km^2
Required Discharge (Weyna Dega Duty)	67.07 ha/cumec
Required Discharge (Dega Duty)	90.07 ha/cumec

Total irrigation Water Demand(Q-demand)	191.54cumec
Total Available water (Q-supply at SUBID 1208)	206.222 cumec
Hydrological Surplus	14.68 cumec

TABLE 18 WATER SUPPLY AND DEMAND

The analysis of the basin's available water 206.222 cumec and total irrigation demand (191.54 cumec) established the availability surplus of 14.682 cumec. A surplus is a good sign of sustainability, as it permits environmental flow needs and provides a safeguard against future climate uncertainty.

4.5.4 Conclusion of the Water Balance Analysis

The conclusion of the Water Balance Analysis proves that the future of Jemma Sub-Basin irrigation development is technically feasible and hydrologically sound.

- Sufficient Water Availability: The 206.222 cumec mean yield from hydrological modeling provides comfortable water availability for suitable lands requiring 191.54 cumec water availability.
- Having an ample natural water supply and the potential for decentralized water storage (45.1 MCM) indicates whether the proposed irrigation schemes are feasible or not. These findings provide a solid rationale for investing in water infrastructure to enhance agricultural production and improve water security at the regional level.

5.0 RECOMMENDATION AND CONCLUSION

This section outlines the key findings of the study and gives a set of recommendations based on land suitability and crop water requirement, rainwater harvesting and water availability in the Jemma Sub-Basin.

5.1 Conclusion

Therefore, the potential for irrigation development in the Jemma Sub-Basin is high as shown by study. The key conclusions are:

- The research has found that a very extensive extent of land for irrigation suitability is 6,983.70 km2, which consists of Highly Suitable (S1) and Moderately Suitable (S2) land. This attests that there are land resources available for expansion.
- The hydrological modeling carried out using the HYPE model showed that the available water from the catchment is 206.222 cumec which is sufficient to supply water for the identified suitable land.
- According to the analysis of rainwater harvesting potential, there are huge numbers of storage sites in this area, having 2,274 possible sites with total storage capacity of about 45.1 MCM. This is to confirm that rainwater harvesting is a feasible and meaningful step towards irrigation supplementing and water security.
- The results of the study suggest a very positive water balance. Based on the HYPE model, the catchment ought to supply 206.222 cumec of water which is a lot. This supply is significantly more than the combined irrigation water demand of 191.54 cumec for irrigation of the total land which can be irrigated.

5.2 Recommendations

Consequently, the following recommendations are advanced to guide future irrigation development within Jemma sub-basin.

- Give preference to investment and infrastructure development in the Highly Suitable (S1) areas, as they require very few inputs and have the maximum likelihood of achieving immediate results.
- Using a phased approach to the development of irrigation based on the location of storage identified. The rainwater harvesting has to be scalable.
- Use the 2047 sites of less than 1 hectare for micro-irrigation and other uses.

- Developing a plot for small and medium scale community schemes with an area between 1 and 5 hectares (219 plots). Creating a sizable reservoirs for multiple purposes at eight sites greater than five hectares in area.
- Integrating rainwater harvesting with irrigation schemes so that their utilization as an additional source for irrigation may take place, especially in dry seasons, to reduce the pressure on river flow, and overall water management efficiency will improve.
- Further research should include ongoing monitoring of hydrological and climate data for further development of the CROPWAT and HYPE models. This can ensure that future irrigation planning makes use of accurate data.

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Appendix 1 Suitability of Soil Factors

AHP Analytic Hierarchy Process (EVM multiple inputs)
K. D. Goepel Version Free web based
07.07.2022 AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	5	Number of criteria (2 to 10)	Scale:	1		AHP 1-9
N=	1	Number of Participants (1 to 20)	*a:*	0.1	Consensus:	n/a
p=	0	selected Participant (0=consol.)			Consolidated	

Objective	weight of soil factors					
Author						
Date		Thresh:	1E-08	Iterations:	6	EVM check: 3.2E-10

Table

	Criterion	Comment	Weights	+/-
1	Depth		6.3%	2.3%
2	AWC		37.1%	10.8 %
3	Texture		10.1%	2.3%

4	PH		11.5%	4.1%
5	Drainage		35.0%	5.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

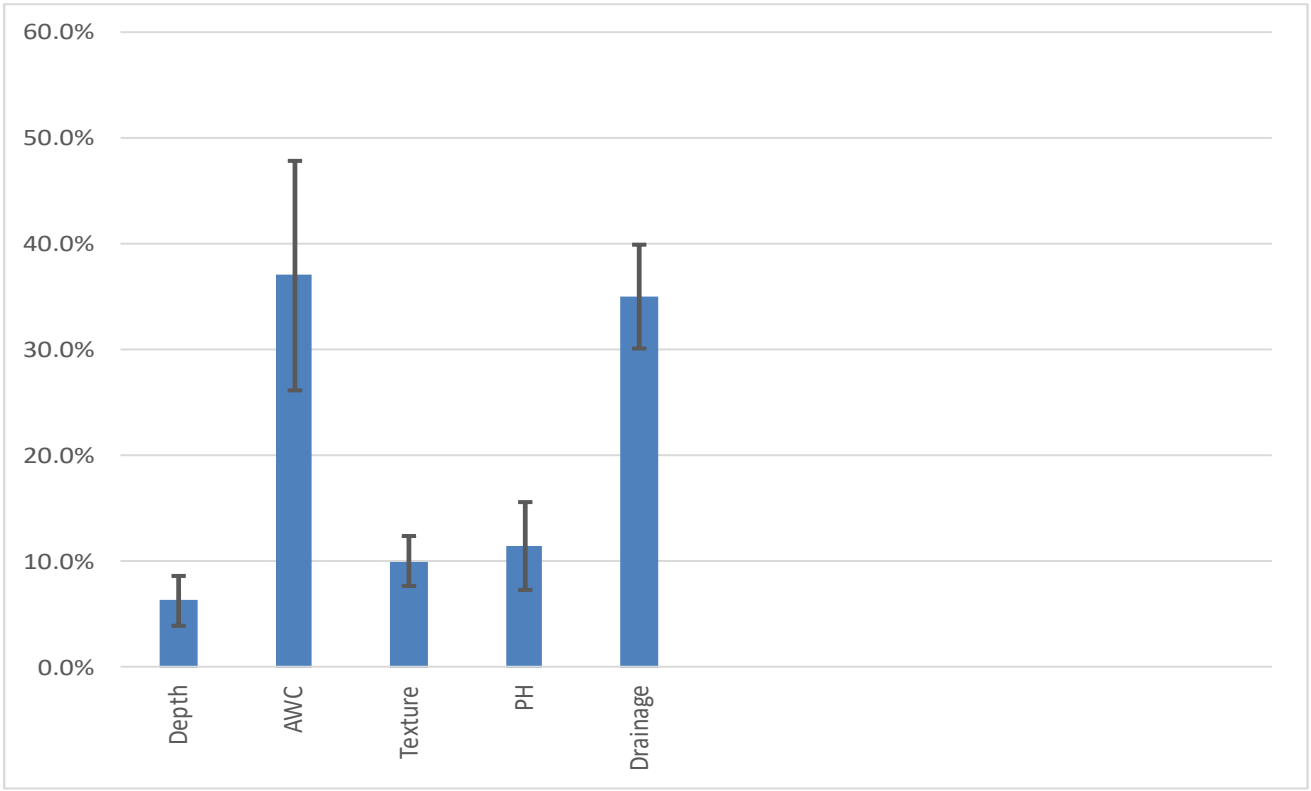
Result

Eigenvalue				Lambda :	5.168	MRE:	29.1 %	
Consistency Ratio	0.37	GCI :	0.14	Psi:	0.0%	CR :	3.7%	

Matrix

		1 Depth	2 AWC	3 Texture	4 PH	5 Drainage	6 0	7 0	8 0	9 0	10 0	normalized Eigenvector	principal
Depth	1	1	1/5	1	1/3	1/7	0	0	0	0	0		6.31%
AWC	2	5	1	3	5	1	0	0	0	0	0		37.06 %
Texture	3	1	1/3	1	1	1/3	0	0	0	0	0		10.05 %

PH	4	3	1/5	1	1	1/3	0	0	0	0	0	11.54 %
Drainage	5	7	1	3	3	1	0	0	0	0	0	35.04 %
0	6	0	0	0	0	0	1	0	0	0	0	0.00%
0	7	0	0	0	0	0	0	1	0	0	0	0.00%
0	8	0	0	0	0	0	0	0	1	0	0	0.00%
0	9	0	0	0	0	0	0	0	0	1	0	0.00%
0	10	0	0	0	0	0	0	0	0	0	1	0.00%



AHP Analytic Hierarchy Process (10x10 Matrix)
Power Method (Dominant Eigenvalue)

5

Iterations

	1	2	3	4	5	6	7	8	9	10	0	20
1	1.00	0.20	1.00	0.33	0.14	-	-	-	-	-	0.27	0.88
2	5.00	1.00	3.00	5.00	1.00	-	-	-	-	-	1.50	5.17

3	1.00	0.33	1.00	1.00	0.33	-	-	-	-	-	0.37	1.40
4	3.00	0.20	1.00	1.00	0.33	-	-	-	-	-	0.55	1.61
5	7.00	1.00	3.00	3.00	1.00	-	-	-	-	-	1.50	4.89
6	-	-	-	-	-	1.00	-	-	-	-	0.10	0.00
7	-	-	-	-	-	-	1.00	-	-	-	0.10	0.00
8	-	-	-	-	-	-	-	1.00	-	-	0.10	0.00
9	-	-	-	-	-	-	-	-	1.00	-	0.10	0.00
10	-	-	-	-	-	-	-	-	-	1.00	0.10	0.00
Sum (col)	17	2.7333	9	10.333	2.8095	0	0	0	0	0	Scaling	
											0.18	0.17
											1.00	1.00
											0.24	0.27
											0.37	0.31
											1.00	0.95
											0.07	0.00

											0.07	0.00
											0.07	0.00
											0.07	0.00
											0.07	0.00
											3.13	2.70
											Normalization	
	0.06	0.07	0.11	0.03	0.05	-	-	-	-	-	0.0571	0.06314
	0.29	0.37	0.33	0.48	0.36	-	-	-	-	-	0.3200	0.370599
	0.06	0.12	0.11	0.10	0.12	-	-	-	-	-	0.0782	0.100502
	0.18	0.07	0.11	0.10	0.12	-	-	-	-	-	0.1180	0.115377
	0.41	0.37	0.33	0.29	0.36	-	-	-	-	-	0.3200	0.350381
	-	-	-	-	-	-	-	-	-	-	0.0213	1.29E-16
	-	-	-	-	-	-	-	-	-	-	0.0213	1.29E-16
	-	-	-	-	-	-	-	-	-	-	0.0213	1.29E-16
	-	-	-	-	-	-	-	-	-	-	0.0213	1.29E-16
	-	-	-	-	-	-	-	-	-	-	0.0213	1.29E-16
											Eigenvalue:	5.167506
Check	3E-10										err:	1.0E-08	3.38E-30
	5.1675										Iterations:	6.0E+00	1.23E-32

		5.1675									check:	3.2E-10	1.11E-30
			5.1675										6.24E-32
I*I				5.1675									4.93E-32
					5.1675								6.93E-31
						5.1675							2.89E-31
							5.1675						2.89E-31
								5.1675					2.89E-31
									5.1675				2.89E-31
										5.1675			2.89E-31
		-4.168	0.20	1.00	0.33	0.14	-	-	-	-	-		
		5.00	-4.168	3.00	5.00	1.00	-	-	-	-	-		
		1.00	0.33	-4.168	1.00	0.33	-	-	-	-	-		
A-I*I		3.00	0.20	1.00	-4.17	0.33	-	-	-	-	-		
		7.00	1.00	3.00	3.00	-4.17	-	-	-	-	-		
		-	-	-	-	-	-4.17	-	-	-	-		
		-	-	-	-	-	-	-4.17	-	-	-		
		-	-	-	-	-	-	-	-4.168	-	-		
		-	-	-	-	-	-	-	-	-4.168	-		
		-	-	-	-	-	-	-	-	-	-4.168		
(A-I*I)x		4E-15	4E-15	4E-15	4E-15	4E-15	4E-15	4E-15	4E-15	4E-15	4E-15		

Appendix 2 Over all Suitability Factors

AHP Analytic Hierarchy Process (EVM multiple inputs)
K. D. Goepel Version Free web based
07.07.2022 AHP software on: https://bpmsg.com

Only input data in the light green fields and worksheets!

n=	5	Number of criteria (2 to 10)	Scale:	1		AHP 1-9
N=	1	Number of Participants (1 to 20)	*a:*	0.1	Consensus:	n/a
p=	0	selected Participant (0=consol.)	2	7	Consolidated	
Objective						
Author						
Date		Thresh:	1E-08	Iterations:	5	EVM check: 9.0E-09

Table

	Criterion	Comment	Weights	+/-
1	Soil factor		26.2%	7.2%
2	Slope		39.5%	14.1 %
3	Town proximity		4.3%	1.0%

4	Road proximity		8.8%	2.2%
5	River proximity		21.1%	5.2%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9		for 9&10 unprotect the input sheets and expand the	0.0%	0.0%
10		question section ("+" in row 66)	0.0%	0.0%

Result

Eigenvalue				Lambda:	5.153	MRE:	27.7 %
Consistency Ratio	0.37	GCI:	0.13	Psi:	0.0%	CR:	3.4%

Matrix

		1 Soil factor	2 Slope	3 Town	4 Road	5 River proximity	6 0	7 0	8 0	9 0	10 0	normalized Eigenvector	principal
Soil factor	1	1	1	5	3	1	0	0	0	0	0		26.21 %
Slope	2	1	1	7	5	3	0	0	0	0	0		39.51 %

Town proximity	3	1/5	1/7	1	1/3	1/5	0	0	0	0	0	4.35%
Road proximity	4	1/3	1/5	3	1	1/3	0	0	0	0	0	8.84%
River proximity	5	1	1/3	5	3	1	0	0	0	0	0	21.10 %
0	6	0	0	0	0	0	1	0	0	0	0	0.00%
0	7	0	0	0	0	0	0	1	0	0	0	0.00%
0	8	0	0	0	0	0	0	0	1	0	0	0.00%
0	9	0	0	0	0	0	0	0	0	1	0	0.00%
0	10	0	0	0	0	0	0	0	0	0	1	0.00%

AHP Analytic Hierarchy Process (10x10 Matrix)

Power Method (Dominant Eigenvalue)

5

Iterations 0 20

	1	2	3	4	5	6	7	8	9	10		
1	1.00	1.00	5.00	3.00	1.00	-	-	-	-	-	1.10	3.42

2	1.00	1.00	7.00	5.00	3.00	-	-	-	-	-	1.70	5.15
3	0.20	0.14	1.00	0.33	0.20	-	-	-	-	-	0.19	0.57
4	0.33	0.20	3.00	1.00	0.33	-	-	-	-	-	0.49	1.15
5	1.00	0.33	5.00	3.00	1.00	-	-	-	-	-	1.03	2.75
6	-	-	-	-	-	1.00	-	-	-	-	0.10	0.00
7	-	-	-	-	-	-	1.00	-	-	-	0.10	0.00
8	-	-	-	-	-	-	-	1.00	-	-	0.10	0.00
9	-	-	-	-	-	-	-	-	1.00	-	0.10	0.00
10	-	-	-	-	-	-	-	-	-	1.00	0.10	0.00
Sum	3.53 33	2.67 62	21	12.3 33	5.53 33	0	0	0	0	0	Scaling	

(col
)

0.65	0.66
1.00	1.00
0.11	0.11
0.29	0.22
0.61	0.53
0.06	0.00
0.06	0.00
0.06	0.00
0.06	0.00

										0.06	0.00
										2.95	2.53
										Normalization	
0.28	0.37	0.24	0.24	0.18	-	-	-	-	-	0.2197	0.20677
0.28	0.37	0.33	0.41	0.54	-	-	-	-	-	0.3395	0.30117
0.06	0.05	0.05	0.03	0.04	-	-	-	-	-	0.0375	0.00461
0.09	0.07	0.14	0.08	0.06	-	-	-	-	-	0.0972	0.00881
0.28	0.12	0.24	0.24	0.18	-	-	-	-	-	0.2064	0.20964
-	-	-	-	-	-	-	-	-	-	0.0200	1.23E-16
-	-	-	-	-	-	-	-	-	-	0.0200	1.23E-16

											0.0200	1.23E-16
-	-	-	-	-	-	-	-	-	-		0.0200	1.23E-16
-	-	-	-	-	-	-	-	-	-		0.0200	1.23E-16
-	-	-	-	-	-	-	-	-	-		Eigenvalue:	5.153462
Check	9E-09									err:	1.0E-08	3.5E-30
	5.1535									Iterations:	5.0E+00	6.04E-31
		5.1535								check:	9E-09	1.23E-30
			5.1535									1.23E-32
				5.1535								5.57E-32
I*I												

		5.15 35								2.78E-31
			5.15 35							2.63E-31
				5.15 35						2.63E-31
					5.15 35					2.63E-31
						5.15 35				2.63E-31
							5.15 35			2.63E-31
								5.153 5		2.63E-31
-4.153	1.00	5.00	3.00	1.00	-	-	-	-	-	
1.00	-4.153	7.00	5.00	3.00	-	-	-	-	-	
0.20	0.14	-4.	0.33	0.20	-	-	-	-	-	

A-I*I	0.33	0.20	3.00	-4.153	0.33	-	-	-	-	-
	1.00	0.33	5.00	3.00	-4.15	-	-	-	-	-
	-	-	-	-	-	-4.15	-	-	-	-
	-	-	-	-	-	-	-4.15	-	-	-
	-	-	-	-	-	-	-	-4.153	-	-
	-	-	-	-	-	-	-	-	-4.153	-
	-	-	-	-	-	-	-	-	-	-4.153
(A-I*I) x	2E-14	2E-14	2E-14	2E-14	2E-14	2E-14	2E-14	2E-14	2E-14	2E-14

Appendix 3 HYPE Model Parameters

!! Par.txt for ET-HYPE v2.0

!! HYPE WIKI
http://www.smhi.net/hype/wiki/doku.php?id=start:hype_file_reference:par.txt

!! METEOROLOGICAL INPUTS

!! General elevation correction parameters

pcelevadd 0.01

pcelevth 500

pcelevmax 0.7

!! EVAPOTRANSPIRATION

!! General evapotranspiration parameters

lp 0.9

epotdist 3

krs 0.1

alfapt 2.4

fepotglac 0

jhtadd 5

jhtscale 76

!! Landuse dependent evapotranspiration parameter

!! LUSE	Agriculture	(Rainfed)		Agriculture	(Irrigated)		Bare/Desert			
	Urban	Grassland	Shrubland		Closed forest		Open	forest	Olake	Ilake
	Mainriver									
kc2	1.5	1.21	1.13	0.73	1.05	1.21	0.73	0.73	1.13	1.13	1.13
kc3	1.34	1.34	1.02	0.9	1.02	1.27	1.33	1.33	0.58	0.58	0.58
kc4	1.57	1.57	1.04	0.2	1.12	1.26	1.09	1.09	0.89	0.89	0.89
alb	0.4	0.4	0.45	0.2	0.5	0.67	0.45	0.45	0.4	0.4	0.4
ttrig	0	0	0	0	0	0	0	0	0	0	0
treda	0.9	0.9	0.8	0.8	0.95	0.95	0.84	0.84	0.8	0.8	0.8
tredb	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
cevp	0.21	0.21	0.07	0.07	0.07	0.17	1.6	1.6	0.17	0.17	0.17
fepotsnow	0.21	0.21	0.2	0.44	0.16	0.46	0.53	0.53	0.44	0.44	0.44

!! SOIL/LANDUSE HYDRAULIC RESPONSE

!! Soil type parameters

!! SOIL	Fine	Moderately	Fine	Medium	Moderately	Coarse	Coarse

wcwp	0.1	0.18	0.09	0.07	0.05	
wcfc	0.5	0.4	0.35	0.25	0.15	
wcep3	0.1815	0.12	0.03	0.05	0.08	
wcep2	0.0218	0.13	0.025	0.06	0.1	
wcep1	0.1042	0.17	0.1	0.15	0.2	
trrcs	0.2	0.15	0.15	0.15	0.15	
srrate	0.2	0.065	0.06	0.06	0.045	
sfrost	0	0	0	0	0	
rrcs2	0.076	0.0711	0.01	0.009	0.008	
rrcs1	0.07207		0.0312	0.1	0.08	0.05
mperc2		15.2961		16.1	15	18 20
mperc1		15.7835		16.72	15	18 20
mactrsm		0.4	0.9	0.6	0.6	0.6
Mactrinf	10	10	10	10	10	10
macrate		0.8876	0.876	0.3	0.3	0.3

!! Landuse parameters (but controls runoff processes)

```
!!      LUSE  Agriculture  (Rainfed)  Agriculture  (Irrigated)  Bare/Desert
        Urban Grassland    Shrubland  Closed Forest Open forest  Olake Ilake
        Mainriver
srrcs   0.12  0.15  0.01  0.5  0.15  0.15  0.15  0.15  1  0.2  1

!!      Global parameters

gldepi  5

gldepo  15

gicatch 0.3

gratp   1.8

gratk   5

grata   0

limqprod        0.25

!!      Regional        parameters
ilratk  1.834

ilratp  1.426

illdepth        5

ilicatch0.3

olratk  100

olratp  2
```

olldepth 15

!! RIVER ROUTING

damp 0.6

rivvel 1

qmean 200

!! SNOW PARAMETERS

!! General snow parameters

ttpd 1

ttpi 1

sdnsnew 0.13

snowdensdt 0.0016

fsceff 1

cmrefr 0.05

!! Landuse dependent snow melt parameters

!! LUSE Agriculture (Rainfed) Agriculture (Irrigated) Bare/Desert Urban Grassland Shrubland Closed Forest Open forest Olake Ilake Mainriver

ttmp 0 0 0 0 0 0 0 0 0 0 0

cmlt 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5 2.5

cmrad 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25

snalbmin 0.45 0.45 0.45 0.45 0.45 0.45 0.45 0.45 0.45 0.45 0.45
0.45

snalbmax 0.85 0.85 0.85 0.85 0.85 0.85 0.85 0.85 0.85 0.85 0.85
0.85

snalbkexp 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
0.1

!!---

!! Landuse dependent and general fractional snow cover parameters

!!---

!! LUSE Agriculture (Rainfed) Agriculture (Irrigated) Bare/Desert Urban Grassland Shrubland Closed Forest Open forest Olake Ilake Mainriver

fscdistmax 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8 0.8
0.8

fscdist0 0.6 0.6 0.6 0.6 0.6 0.6 0.6 0.6 0.6 0.6
0.6

fscdist1 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001
0.001

fscmax 1

fscmin 0.01

fsclim 0.001

fsck1 0.2

fsckexp 0.000001

!! PARAMETER REGIONS

!! REGION 1 2 3

rrcscorr 0 0 0

cevpcorr 0 0 0

preccorr 0 0.685 0