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INSTITUTE OF TECHNOLOGY

Assessment of Land Suitability and Water Availability for Surface Irrigation in North Wollo Zones of Amhara Region.

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DECLARATION

We researchers, the signed hereby declare that this research entitled **Assessment of Land Suitability and Water Availability for Surface Irrigation in North Wollo Zones of Amhara Region** is the final report submitted to the Research, Publication, Ethics, and System Directorate of WOLDIA University. The original work was done under the supervision of this directorate. This study has not been published or submitted elsewhere for the requirement of a degree program to improve our knowledge and development. Ideas or materials of other scholars or institutions used for this study have been appropriately accredited and cited.

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ABBREVIATIONS AND ACRONYMS

ADSWE	Amhara Design and Supervision Work Enterprise
AHP	Analytical Hierarchy Process
BGS	Britain Geological Survey
CIESIN	Center for International Earth Science Network
DEM	Digital Elevation Model
ENMA	Ethiopia National Metrological Agency
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
GIWR	Gross Irrigation Water Requirement
GLCN	Global Land Cover Network
HWSD	Harmonized World Soil Dataset
IDW	Inverse Distance Weight interpolation
IFAD	International Fund for Agricultural Development
IWR	Irrigation Water Requirement
LULC	Land Use Land Cover
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
MCE	multi-criteria Evaluation
MOA	Ministry of Agriculture
MOWR	Ministry of Water Resources, Irrigation and Energy
P_{eff}	Effective rainfall
RWA	Rain Water Harvesting
SCI	Soil Capability Index
STRM	Shuttle Radar Topography Mission
USGS	United States Geographic Survey
WSM	Weight Sum Model

ABSTRACT

Despite Ethiopia's abundant land, water resources, and labor potential, only a small fraction of its irrigable land is currently utilized. All rural Woreda of North Wollo Zone have been grouped as the most drought-prone and food insecure in the Amhara Region. To combat increasing droughts and improve crop yields, the potential expansion irrigation projects will be the promising tools. This study assessed land suitability and water availability for surface irrigation in the North Wollo Zone using a GIS-based Analytical Hierarchy Process (AHP). Key physical and socio-economic factors including land use/land cover, soil capability index (SCI), slope, accessibility, climate variables, population density, and proximity to rivers were considered. Groundwater suitability was evaluated based on depth, aquifer storage, and salinity. A pairwise comparison matrix was used to assign weights to each factor, and the resulting data were reclassified into different suitability categories based on FAO guidelines and relevant literature. Weighted overlay analysis, revealed that 2,303 km² (18%) of the area is suitable for surface irrigation from rivers, while 3,326 km² (26%) is suitable using groundwater. Kobo, Habru, and Wadla were most suitable for surface irrigation, whereas Meket, Kobo, and Habru showed high potential for groundwater use. Among the limiting factors, slope had the greatest impact, followed by river proximity (for surface water) and groundwater depth (for groundwater use). Hydrological analysis showed that 51 km² could be irrigated without storage infrastructure. The Alawha River alone could support 42 km² (82%) of this potential area, while the remaining three rivers could irrigate only 9 km² (18%). The suitability analysis was validated using existing irrigation projects in the study area, all of which (100%) fell within the identified suitable zones. Additionally, nearly all wells were located in areas deemed suitable for groundwater-based irrigation. This study highlights significant areas with potential for surface irrigation using both river and groundwater sources. It recommends that future development prioritize these zones while addressing slope, river proximity, and groundwater depth to enhance irrigation efficiency.

Keywords: North Wollo Zone, Land suitability, surface and groundwater, GIS-Based AHP, Surface Irrigation

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1 INTRODUCTION

1.1 Background

In Ethiopia the primary mechanism to achieve food security is Agriculture, it contributes 43% of the national GDP (Kassa and Andualem, 2020). The food production system is mainly on rain-fed agriculture with limited irrigation practices (Tilahun *et al.*, 2011). Rainfall variability hampers the traditional rain fed production system in the country (Yang *et al.*, 2020). Food insecurity and frequent drought caused by unreliable rainfall distribution affect the livelihoods of the rural community (Asrat and Anteneh, 2020) which depicts the need to expand irrigated agriculture for sustainable food supply in the nation (Assefa *et al.*, 2021). Adequate suitable land resources and water availability are key to transforming the rain fed agricultural system into irrigated agriculture (Jägermeyr, 2020).

Irrigated agriculture is critical to reducing the adverse effect of rainfall variability and improving agricultural production (Yimam *et al.*, 2020). To maximize crop production through irrigated agriculture, understanding the potential of water resources (surface water and groundwater sources) will take priority (Alattar *et al.*, 2020). Surface water is the main source of irrigation and the use of groundwater is limited to irrigation use (Reyes, *et al.*, 2019). However, groundwater is more reliable for irrigation than surface water due to its slow reaction to climate change and contaminants (Assefa et al., 2018). Besides, it is evidenced that about 8% of the irrigable land in Ethiopia could be addressed using only shallow groundwater (Worqlul et al., 2017). Even though groundwater is a reliable resource, the lack of technology and knowledge on the potential of the resource hampers its use for irrigation (Walker *et al.*, 2019). Besides, the method of irrigation practice also influences the potential of water resources (Porhemmat et al., 2018).

Water resource planning for surface irrigation requires information about the land suitability, water availability, and water requirements of crops in irrigable areas in time and space (Gonfa et al., 2021). Evaluating the potential of water resources and areas suitable for irrigation helps to increase water and crop productivity and cost-effective use of land (Suênio *et al.*, 2021). Identifying suitable land for surface irrigation requires the evaluation of multiple factors that

affect irrigated agriculture using Multi-Criteria Evaluation (MCE) in a GIS (Geographic Information System) environment.

Several studies used the GIS-based MCE technique for hydropower potential site selection, erosion hotspot identification, irrigation suitable site assessment, and wastewater disposal site selection. Several studies have been done in Ethiopian highlands on the assessment of irrigable land potential using either groundwater or surface water sources (Kassie et al., 2022). However, there was no study found on the integrated assessment of land suitability and water availability for irrigation considering multiple factors for the North Wollo Zone. In addition, the low flow potential of the major rivers and groundwater yield in the study area for surface irrigation is still unknown. Therefore, this study aims to evaluate land suitability and water availability for irrigation in the North Wollo Zone of Ethiopia.

1.2 Statement of the problem

The livelihoods of Ethiopia and the North Wollo zone or the current study area depend on rain-fed agriculture. However, in the case of seasonal or annual climate variability, farmers of the study area are engaged in a mono-cropping cultivation system(Awulachew et al., 2010). Irrigation development is very important for refining the livelihood of the people (Mitiku et al., 2024). According to Azemeraw (2021), the combination of population growth, land degradation, and more frequent droughts will result in more frequent food-related crises. All rural Woreda of North Wollo Zone have been grouped as the most drought-prone and food insecure in the Amhara Region. To combat increasing droughts and improve crop yields, the potential expansion irrigation projects can be the promising tools (Haile & Kasa, 2015). Identifying suitable area water sources and Irrigation development is therefore perceived as one of the most important strategies to solve food-related crises and increase national income. Besides, the initiation of this study, there are no clear assessments of both surface water and groundwater resource potential for irrigation suitability. Therefore, the integrated assessment of land suitability and water availability for irrigation is important for decision makers and stakeholders irrigated agriculture expansion to improve crop productivity.

1.3 Objectives of the study

The general objective of the study was to assess land suitability and water availability for surface irrigation in the North Wollo Zone of Ethiopia using the MCE technique in a GIS environment.

The specific objectives of the study were:

- To assess potential irrigation areas from surface water sources in the North Wollo Zone;
- To assess potential irrigation areas from shallow groundwater sources in the North Wollo Zone;
- To evaluate the surface water potential for irrigation use in potentially suitable areas along selected gauged rivers.

1.4 Research Questions

- How much land in the zone is potentially suitable for surface irrigation from surface water?
- How much of the land is potentially suitable for surface irrigation from shallow groundwater wells?
- How much area can surface water irrigate in the zone using surface irrigation methods?

1.5 Scope and Limitation of the Study

The study was conducted at the North Wollo Zone in Ethiopia. The scope of the study is mainly limited to assessing potentially suitable irrigable land from surface and groundwater sources for surface irrigation at North Wollo, Ethiopia by implementing a digital elevation model (DEM) on Arc GIS considering slope map, land use land cover, soil data, socio-economic parameter, and groundwater data.

There was a limitation to conducting the study. Shortage of data in the study area was the main problem faced during the study and data collection. This study integrates physical land characteristics, economic considerations, social factors, and climatic conditions to assess the suitability of the area for irrigation development from both surface water and shallow groundwater sources. In addition, selected soil physical properties were analyzed to evaluate

soil suitability; however, chemical soil properties were excluded due to data unavailability. Furthermore, the assessment of water resource potential was not carried out, as the relevant data were inaccessible and the responsible data provider declined to release the information.

1.6 Significance of the Study

The study area is drought-prone. This makes the area the most important area to study. This study suitability evaluation for surface irrigation will guide in cases of conflict between rural land use and urban or industrial expansion, by indicating which areas of land covers /uses are most suitable for irrigation. This study will have significant importance in raising the production and productivity of the community to achieve food self-sufficiency at the household level in particular and the country level in general by pointing to suitable areas and available water for the community or irrigators. The study also will provide information for governments to expand and construct irrigation projects by identifying the potential suitable area and the potential water source. Identification of suitable irrigable land and evaluation of available water resources are very important and boosters for policy and decision-makers. The research will provide input for future irrigation project expansion/development and support the decision maker by providing facts on the suitability of the area for surface irrigation using available water sources.

Finally, an irrigation system improves low agricultural productivity (rain-fed agriculture), alleviates famine and drought, alleviates the outcome of overpopulation, mitigates land degradation, and contributes to gender equality. Therefore, to get these advantages irrigation development and expansion are very important and this study will contribute a lot by addressing potential suitable areas and water availability for irrigation.

2 LITERATURE REVIEW

2.1 Role of Irrigation in Advancing Ethiopia's Agricultural Sector

Irrigation and improved water management are crucial for enhancing agricultural productivity and reducing vulnerability to climate variability in Ethiopia. Despite having abundant water resources, the country's agriculture remains largely rain-fed and underutilizes modern irrigation technologies. Most rural communities face poverty due to limited access to infrastructure, markets, and agricultural innovations. Degraded natural resources, poor soil fertility management, and high rainfall variability, especially in the highlands, further exacerbate food insecurity (Tukura & Feyissa, 2020). With declining seasonal rainfall and rising temperatures, reliance on subsistence farming increases the sector's exposure to climate risks (Asrat & Anteneh, 2020). Expanding irrigation offers a key solution to boost yields, stabilize food production, and build resilience (Awulachew et al., 2010; Sinore & Wang, 2024; Asaye et al., 2025).

Irrigation in agricultural production is 20% of the total cultivated land but it gives 40% of the total nutrition produced globally (Mcguire, 2015). Thus, irrigation will play a significant role in the substantial increase in food production for food security enhancement and economic development of Ethiopia with the efficient use of land and water resources (Haile & Kasa, 2015). The production function analysis done by Makombe et al. (2007), shows that irrigation could shift the agricultural production frontier to a higher level. But rain-fed agriculture plays a significant role compared with irrigation. But global agricultural production has doubled within an area that has only increased by 12% and a part of this gain can be attributed to an increase in irrigation (Getahun et al., 2023). Increasing irrigation has long been seen as the most direct strategy to alleviate the impact of drought and ensure food security (Girma et al., 2020). The report emphasizes without increased irrigation, the unpredictability of rains in Ethiopia is an overwhelming disincentive to investment in agricultural improvements. Also explained that well-managed irrigation development is key in helping Ethiopia overcome major challenges of population pressure, soil and land degradation, high climate variability, and low agricultural productivity. Research in the Lake Tana Basin revealed that, on average, the household incomes of those who practiced irrigation were 27 percent higher than those who did not (Haile & Kasa,

2015). In another study in the Gubalafto district, North Wollo Mengistie and Kidane (2016), indicated that irrigation has a great impact on enhancing farmer's livelihoods through different dimensions, such as the possibility to grow different crops, and improving agricultural products, increasing income and crate employment opportunity.

2.2 Irrigation Potential in Ethiopia

The estimations of the irrigation potential of Ethiopia differ from one source to the other, due to a lack of standard or agreed criteria for estimating irrigation potential in the country. Ethiopia covers 112 million hectares (Mha) of land. The former report, for example from Ramanathan (2001), showed the irrigation potential at a lowest of 1.0 and 1.5 million hectares, and a highest of 4.3 million hectares. There have also been different estimates of the irrigation potential in Ethiopia. According to McCornick et al. (2003), the total irrigable land in the country measures 2.3 million hectares. Tilahun *et al.* (2011), alternatively give a figure of 2.8 million hectares. A total of 3.7 million hectares had been identified as potentially irrigable land (Awulachew et al., 2010). According to Awulachew et al. (2010), Ethiopia has huge cultivable land (30 to 70 Mha), but only about a third of that is currently cultivated (approximately 15 Mha), with the current irrigation scheme covering about 640,000 hectares across the country from 640,000 hectares of irrigation nationwide includes 128,000 hectares from RWH, 383,000 hectares from SSI and 129,000 hectares MSI/LSI. The MSI/LSI includes the Fentale and Tibila schemes. However, the study estimates that the total irrigable land potential in Ethiopia is 5.3Mha assuming the use of existing technology, including 1.6 Mha through RWH and ground water. Most of these figures are derived by adding up the irrigation potential of the country's twelve river basin (Awulachew et al., 2007).

2.2.1 Surface water potential

Ethiopia is endowed with considerable surface water resources, owing to its diverse topography and climatic conditions that contribute to the formation of numerous rivers, lakes, and reservoirs (Awulachew et al., 2007). Major river basins such as the Abay (Blue Nile), Baro-Akobo, Tekeze, Awash, Omo-Gibe, and others collectively contribute significant volumes of surface runoff. However, despite this natural endowment, there have been limited and fragmented efforts to systematically assess and quantify the surface water potential available for irrigation development in the country.

Most existing estimates of surface water irrigation potential in Ethiopia are derived from national master plan studies and government-sponsored reports, such as those conducted by the Ministry of Water and Energy and international development partners. One of the notable references is the study by Awulachew et al. (2007), which highlights that these estimations are often based on broad assumptions, outdated hydrological data, and generalized assessments. As a result, the figures reported vary significantly between sources, creating confusion and inconsistency in planning and decision-making processes.

Furthermore, detailed and up-to-date basin-level investigations that incorporate both hydrological and socio-economic parameters remain scarce. There is a clear gap in comprehensive research that integrates seasonal variability, climate change impacts, and environmental sustainability into the assessment of water potential. Assefa et al. (2021) emphasize that Ethiopia still lacks a harmonized and universally accepted framework for evaluating surface water resources. The absence of consensus and coordinated methodology among stakeholders including government agencies, researchers, and development organizations continues to hinder efforts to fully understand and effectively utilize the country's surface water potential for irrigation and other productive uses.

Consequently, the underutilization of available surface water resources persists, and many irrigation projects suffer from poor planning, inadequate feasibility studies, and unsustainable practices. Addressing this issue requires a concerted national effort to develop robust, scientifically grounded assessments of surface water availability, supported by reliable hydrological monitoring, modeling, and participatory planning that reflect local conditions and development priorities.

2.2.2 Groundwater potential

Groundwater represents a critical yet underexploited water resource in Ethiopia's quest for agricultural intensification and water security. It can be accessed through both shallow and deep aquifers using hand-dug wells, boreholes, and motorized pumps, offering considerable potential for smallholder and commercial irrigation. Compared to surface water, groundwater is often more reliable, less affected by seasonal variability, and available even in areas where surface

sources are scarce or erratic (Altchenko & Villholth, 2015). The strategic advantage of groundwater lies in its buffer capacity during dry seasons and drought periods, as well as its spatial distribution across diverse agro ecological zones. It is also frequently used for multiple purposes, including domestic supply, livestock watering, and industrial use, thereby enhancing its socioeconomic value (Foster & MacDonald, 2014).

Despite these advantages, the use of groundwater for irrigation in Ethiopia remains limited. Several constraints hinder its development, including high capital and operational costs, especially for drilling deep wells; the need for specialized equipment and skilled personnel; and a lack of reliable hydrogeological data (Awulachew et al., 2010). In rural and remote areas, the technical and financial barriers are even more pronounced, limiting the adoption of groundwater-based irrigation technologies.

A major challenge is the insufficient understanding of the country's groundwater systems. National-scale studies are scarce, and existing assessments are often fragmented or outdated. Consequently, decision-makers lack a clear picture of groundwater availability, recharge rates, and safe yield thresholds (MacDonald et al., 2012). This knowledge gap increases the risk of over-abstraction, especially in intensively used aquifers with poor monitoring systems.

Awulachew et al. (2010), indicate that Ethiopia's groundwater irrigation potential may significantly exceed the current estimate of 1.1 million hectares, underscoring the opportunity for expanding irrigated agriculture if barriers are addressed. However, unlocking this potential requires integrated and sustainable groundwater management, improved institutional coordination, and investments in groundwater mapping, drilling technologies, and farmer capacity building (Altchenko & Villholth, 2015). A national effort to integrate groundwater into the broader water resource development agenda is essential. This includes the promotion of conjunctive water use, policy reforms, and the establishment of monitoring systems to ensure the long-term sustainability of groundwater for irrigation and other uses.

2.3 Land evaluation and suitability classification

Land evaluation is a method for matching the features of land resources for certain uses using a scientific standard technique. The result of land evaluation and classification can be used by

planners as guidance to identify the land for different uses. Land suitability is the ability or suitability of a given land for defense uses. The procedure of land suitability classification is the assessment and grouping of specific areas of the land in terms of their fitness for a certain use. Suitability is measured by the evaluation of land use requirements with the land qualities (Pönka et al., 2009). Land suitability can be evaluated for current condition (actual land suitability) or after improvement (potential land suitability) (Mesfin & Asnake, 2022).

Reza et al. (2020), classifies the land into four suitability classes (S1, S2, S3, and S4). Land Suitability Orders indicate in the simplest of whether the land is suitable (S) or not suitable (N) for specified use. Land Suitability Classes show the degree of suitability within an order; Land Suitability Sub-classes reflect the kinds of limitation or required improvement measures within classes; and Land Suitability Units indicate differences in required management within sub-classes.

A Land Suitability order indicates or reflects a kind of suitability, whether the land is assessed as suitable or not suitable for the use under consideration (i.e. S or N.) respectively. According to the FAO framework of land suitability classes, there are two orders Suitable and not suitable represented in maps, tables, etc. by the symbols S and N respectively. Order S suitability: land suitable for defined uses and expected to yield benefits that justify the inputs, without unacceptable risk of damage to land resources. Order N not suitable: Land that has qualities that appear to preclude sustained use of the kind under consideration.

Order S - suitability. The classes under this order are:

S1 (highly suitable) - land without significant limitation for a given use. This land has the best potential and does not reduce productivity or require increased input.

S2 (moderately suitable) - land having a moderate limitation for a given use. Land that is suitable but has limitations that either reduce productivity or require an increase of inputs to sustain productivity compared with those needed on S1 land.

S3 (marginally suitable) - land having limitations for a given use and will reduce productivity or benefits. Land with limitations so severe that benefits are reduced and/or the inputs required to sustain production need to be increased so that this cost is only marginally justified.

Order N suitability classification

N (currently not suitable) - land that is not suitable for a given use. Land that cannot support the particular land use on a sustained basis or land on which benefits do not justify inputs.

2.4 Irrigation Land Suitability Evaluation Factors

Land evaluation is the assessment and evaluation of land by analyzing land feature data including soil, climate, land use/ land cover, and other socio-economic factors in terms of realistic alternatives for improving the use of that land (Girmay et al., 2018; Reza et al., 2020). For irrigation land suitability analysis, particular attention is given to the physical properties of the soil, the distance from available water sources, and the terrain conditions of methods of irrigation considered (Grunwald et al., 2011; Mitiku et al., 2024). In addition to these factors, land use/land cover types are considered limiting factors in evaluating the suitability of land for irrigation (Assefa et al., 2018). The factors considered for surface irrigation land suitability evaluation are narrated separately in subsequent sub-sections.

2.4.1 Slope

The slope is the percentage change in the elevation over a certain distance and is expressed by percent. The slope of the land affects the suitability of an area in terms of land preparation for irrigation and irrigation operation and also influences runoff, drainage, erosion, and choice of irrigation types. The land slope affects the choice of irrigation methods. According to FAO (1999), slopes are classified into four classes for suitability evaluation, Slopes from 0-2% were classified as S1, from 2-4% as S2, from 4-8% as S3, and slopes above 8% are classified as S4.

2.4.2 Soils

Soil is a very important factor for irrigation suitability assessment and also influences the choice of irrigation methods. Soil is a key factor in determining the suitability of an area for agriculture in general and irrigation in particular. The assessment of soils for irrigation involves using permanent properties that cannot be changed or modified. Such properties include drainage, texture, depth, salinity, and alkalinity (Fasina & Aruleba, 2008). According to (Hartemink, 2015), soil is also classified into four suitability classes for analysis. Even though salinity and alkalinity hazards are possibly improved by soil amendments or management practices, they could be considered as limiting factors in evaluating the soils for irrigation (Yee et al., 2012).

2.4.3 Land cover or land use

Land use data helps to identify the productivity of an area for irrigation. Herold *et al.* (2006) define land cover as the observed (bio) physical cover, as seen from the ground or through remote sensing, including vegetation (natural or planted) and human construction (buildings, roads, etc.) which cover the earth's surface. Water, ice, bare rock, or sand surfaces also count as land cover. The definitions of land cover and land use provide a basis for identifying the possible land suitability for irrigation with precise and quantitative economic evaluation. Therefore, matching existing land cover/use with topographic and soil characteristics to evaluate land suitability for irrigation with land suitability classes, presents possible lands for new agricultural production (Pohekar & Ramachandran, 2004). The suitability of the land for surface irrigation is categorized into four classes according to the Food and Agricultural Organization (FAO) framework.

2.4.4 Population density, Road proximity, and urban center

The development and sustainability of irrigation projects are strongly influenced by socioeconomic and infrastructural factors such as population density, proximity to roads, and distance from urban centers. These elements collectively determine the feasibility, accessibility, and profitability of irrigated agricultural production, especially in rural and semi-arid regions.

Population density serves as a proxy for labor availability and local market size. Areas with higher population densities are more likely to provide the necessary workforce for the operation and maintenance of irrigation schemes, while also offering local demand for agricultural produce (Yee et al., 2012). In addition, dense populations often correspond to regions with better access to public services and infrastructure, creating a more enabling environment for agricultural intensification.

Road proximity, especially to all-weather or paved roads, plays a critical role in reducing transportation costs and improving farmers' access to input and output markets. Reliable road infrastructure enables timely delivery of agricultural inputs such as seeds, fertilizers, and equipment, and facilitates the movement of perishable goods to local and regional markets

(Awulachew et al., 2010). In contrast, remote areas with limited or poor road access face high transaction costs, which can hinder the commercial viability of irrigation schemes.

Likewise, **proximity to urban centers** enhances access to market opportunities, financial services, extension support, and agro-processing industries. Urban centers act as economic hubs that provide broader and more diversified markets for irrigated crops, and often serve as focal points for investment in value chain development (FAO, 1997). Therefore, irrigated agriculture near urban areas is more likely to be economically sustainable due to better market integration and institutional linkages.

For irrigation planning and prioritization, spatial criteria such as population density, road proximity, and urban access are frequently used in Geographic Information System (GIS)-based analyses to identify high-potential zones. Integrating these variables into irrigation development strategies supports efficient allocation of resources, reduces production and marketing risks, and promotes inclusive growth in rural areas (Yee et al., 2012).

2.4.5 Water availability

River proximity is another important factor that decides and prioritizes the areas to be irrigated using surface irrigation. It is important to make sure that there is no lack of irrigation water. If water is in short supply during some part of the irrigation season, crop production may suffer, returns may decline and part of the scheme's investment may lay idle (Schaible, 1956). Therefore, water supply is an important factor in evaluating the land suitability for irrigation according to the volume of water during the year when it is available. According to (Albaji et al., 2015), available water resources will not be able to meet various demands shortly and without doubt result in the looking for newer lands for irrigation to achieve sustainable global food security. The important question is whether there will be adequate fresh water to satisfy the growing needs of agriculture and non-agricultural uses (Alexandratos & Fao, 2012). The reality is water has at all times been the main factor limiting crop production in much of the world where rainfall is insufficient to meet crop demand (Steduto et al., 2012). Therefore, the assessment of irrigation potential should take into account water limitations.

2.4.6 Rainfall deficit

Rainfall deficit, a key factor in irrigation suitability assessment, is calculated by subtracting potential evapotranspiration (PET) from precipitation (P). It reflects the balance between water

supply and atmospheric demand. A positive rainfall deficit indicates sufficient rainfall with no irrigation requirement, whereas a negative value suggests the need for supplementary irrigation, with more negative values signifying greater irrigation demand (Allen et al., 1998). This indicator is particularly important in arid and semi-arid areas of Ethiopia, where rainfall is often inadequate and irregular. Spatial analysis of rainfall deficit using GIS can help identify high-priority zones for irrigation development (Awulachew et al., 2005).

2.5 GIS-based Land Suitability Analysis for Irrigation

GIS is a computer-based system that offers a suitable and influential platform for execution suitability evaluation. GIS technique and procedure have a significant role to play in analyzing and decision on problems. Certainly, GIS is frequently recognized as a decision support system concerning the integration of spatially referenced data in a problem-solving environment. Site suitability assessment is integrally a multi-criteria problem that includes several capable factors appearing at the same time. GIS, done by its spatial analysis tools that are mainly suited for an overlay analysis of various capable factors, comforts the task of the decision maker. Therefore, an important advantage of using GIS technology is to perform a spatial Multi-criteria evaluation (MCE) study. Without the knowledge and expertise of the operator and decision maker, and appropriate data, such tools will be useless (Carver, 1991). However, GIS and MCE applications seem to represent potentially effective areas for further research and development.

Land suitability is the suitability of a given category of land for appropriate use. The land may be classified in its present condition or after improvements for its specified use. The procedure of land suitability classification is the assessment and grouping of specific areas of land in terms of their suitability for defined uses. Land evaluation is the assessment and analysis of land by considering different factors such as soils, climate, vegetation, etc. in terms of truthful alternatives for improving the use of that land. For irrigation, and land suitability analysis, particular attention is given to the physical properties of the soil, the distance from available water sources, and the terrain conditions of methods of irrigation considered (Grunwald et al., 2011).

Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. They considered multiple factors such as climate, soils, land covers, topography, road network, and population density. Additionally, they consider Groundwater depth and Potential borehole yield

for assessment of groundwater potential. Their finding indicates that there is a modest amount of land suitable for irrigation using groundwater. A large portion of the suitable land is located in the Upper Blue Nile, Rift Valley, Omo Ghibe, and Awash River basins. The available groundwater would only irrigate 8% of the suitable land (Worqlul et al., 2017).

2.6 Crop and Irrigation Water Requirement

Crop water requirement (CWR) is defined as the amount of water needed to compensate for the evapotranspiration from a cropped field, and it is essentially equal in magnitude but opposite in sign to crop evapotranspiration (ETc), which reflects water lost through evaporation and transpiration. The relationship between ETc and reference evapotranspiration (ETo), an atmospheric parameter, is expressed through the crop coefficient (Kc. Since rainfall is often uncertain in timing and amount, especially in arid and semi-arid regions, irrigation becomes essential to supplement natural rainfall to ensure optimal crop growth. Net irrigation requirement (IR) is the difference between CWR and effective rainfall and represents the actual volume of water that must be delivered through an irrigation system. CWR varies by crop type, climate, soil conditions, and growth stage from low water use during initial stages to peak demand at mid-season, followed by a decline towards maturity. Accurately estimating total water demand from sowing to harvest is crucial for designing irrigation systems, and models like FAO's CROPWAT are commonly used for such computations, integrating ETc, application losses (La), conveyance losses (Lc), and special needs such as land preparation or leaching (Yee et al., 2012).

2.7 Evaluation of surface water potential

There is no reliable record, documented and detailed study regarding water potential in the Ethiopia context (Haile & Kasa, 2015). Also, available water resources will not be able to meet various demands shortly inevitably resulting in the seeking of newer lands for irrigation to achieve sustainable global food security (Albaji et al., 2015). Water is a main limiting factor for crop production in much of the world where rainfall is insufficient to meet crop evapotranspiration needs (Steduto et al., 2012). Groundwater is also a source of irrigation water where the surface water is relatively low and not enough. Applied a methodology that assumes groundwater as the sole source of irrigation water and hence gives an estimate of the area that could potentially be irrigated by groundwater disregarding any existing irrigation, whether from

groundwater or surface water. Groundwater irrigation potential is calculated as a ratio of available groundwater to crop water requirement in the area; where groundwater availability is calculated as an excess of groundwater recharge and considering other extra demands from humans and the environment. Crop type grown in the area, planting date, crop coefficient, and other crop parameters are essential to calculate crop water requirements.

The potential area that can be irrigated from the rivers in the irrigation season was calculated as the quotient of Q90 (discharge exceeds 9 out of 10 years) and crop water requirement in the growing season (Worqlul et al., 2015). To find the irrigable area, they divided the average flow of the river by the crop water requirements. The study recommended, increasing the potentially irrigable areas, and storing or harvesting river water in the rainy season for dray season use. Similarly, the groundwater potential is estimated as the quotient of the potential average borehole yield and the total crop water requirement of the dominant crop in the area for the growing season.

2.8 Application of Geo-Spatial Tools for Irrigation Planning

The application of geo-spatial tools, particularly Geographic Information Systems (GIS) and remote sensing, has become integral to modern irrigation planning. These technologies enable the efficient analysis and integration of various spatial and non-spatial data such as soil characteristics, land use, slope, climate variables, groundwater depth, and proximity to infrastructure to assess land suitability and water availability for irrigation. By leveraging satellite imagery and digital elevation models (e.g., ALOS PALSAR, USGS DEM), along with multi-criteria evaluation techniques in GIS, decision-makers can identify optimal areas for irrigation development and sustainably manage water resources (Assefa et al., 2021; Dinku & Kebede, 2023; Duguma & Duguma, 2022; Fasina & Aruleba, 2008; Hussien et al., 2019; Kassie et al., 2022; Malczewski, 2004; Nigussie et al., 2019; Worqlul et al., 2015; Yimam et al., 2021).

The integration of GIS and remote sensing facilitates the handling of large and diverse datasets that are critical for effective irrigation management in complex environments. These tools enable spatial analysis of hydrological parameters such as rainfall distribution, evapotranspiration, and river network density, which are essential for estimating water availability and demand (Nigussie et al., 2019; Worqlul et al., 2015; Yimam et al., 2021). Furthermore, socio-economic factors including proximity to roads, markets, and population

density can be incorporated to assess the feasibility and sustainability of irrigation projects (Melesse, 2022). Multi-criteria decision-making models within GIS, such as weighted overlay analysis, support prioritizing areas based on combined suitability criteria, thus optimizing resource allocation (Hussien et al., 2019a; Malczewski, 2004). The adoption of these technologies has proven effective in various regions, notably in Ethiopia and other parts of Sub-Saharan Africa, contributing to improved agricultural productivity and water resource management under changing climatic conditions (Kassie et al., 2022).

3 MATERIALS AND METHODOLOGY

3.1 Description of the Study Area

3.1.1 Location

North Wollo central area is one of the eleven zones of Amara Regional state. It is in the northern part of the country and geographically located at 11°50′N 39°15′E and 11.833°N 39.250°E. It is found in three larger Ethiopian basins which are the Abay, Denakil, Awash, and Tekezie basins. It shares a border with the South Wollo Zone, South Gondar Zone, Wag Hamra Zone, Tigray Region, and Afar Region. In addition to these neighboring areas, part of North Wollo's southern border is defined by the Mille River (Aragie & Genanu, 2017). Currently, North Wollo Zone has 11 rural woredas and six city administrations i.e., Raya Kobo, Gidan, Habru, Gubalafto, Angot, Gzaobelay, Wadla, Lasta, Meket, Bugna, and Dawunt; and Woldiya city, Kobo city, Hara city, Mersa city, Gashena city and Lalibela city respectively.

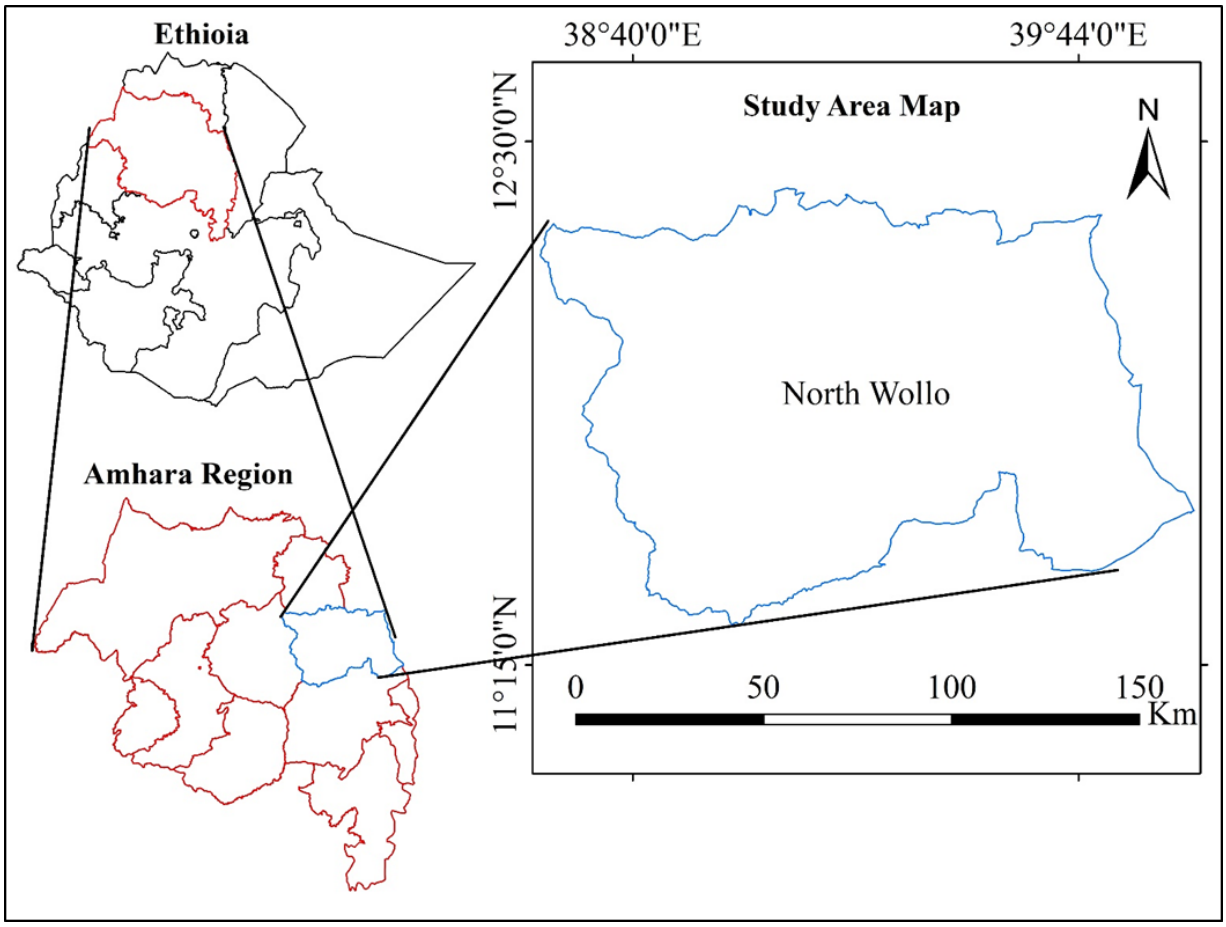


Figure 3:1 Location of the study area

3.2 Datasets

To achieve the objectives of the study different data inputs, including biophysical (e.g., climate, soil characteristics, groundwater, land use type, and topography) and socio-economic (e.g., market access such as proximity to a road and population density) were collected from the online source and different governmental and non-governmental office. These suitability factors were selected from other factors by considering literature and expert opinion on irrigation potential assessment. The material used to effectively execute the research include ArcGIS10.4, and CROPWAT 8.0.

3.2.1 Hydro-meteorological data

The hydro-meteorological datasets, such as Rainfall, temperature (max, min), wind speed, sunshine, and humidity for 2013-2022 daily data were obtained from the Ethiopian meteorological institute of Ethiopia. The climate datasets were used from eighteen (18) metrological stations which are the most influential climatic factors for crop water requirement calculation of the crop and finding the suitability of land for irrigation from a ground and surface water source. These climatic data were used in CROPWAT 8.0 to calculate the water requirement of the crop majorly grown in the study area and also used to calculate potential evapotranspiration of the area to find rain deficit for irrigation suitability assessment. For calculating evaporation with the Penman–Monteith equation (Monteith, 1965) the daily measurements of temperature, humidity, wind speed and sunshine hours were collected from two of the synoptic stations at Chifra, and Sirinka stations. The streamflow data from 1996-2014 of the Four hydrological gauging stations were obtained from the Ministry of Water and Energy of Ethiopia.

3.2.2 Spatial datasets and GIS file

The various land uses, soils, slopes, road network and city accessibility, Population density, river network, stream discharge, groundwater data (depth, aquifer productivity, storage, and salinity from the British Geological Survey (BGS) were obtained from different sources. The physical properties of the soils: namely, soil drainage, soil depth, and texture classes with a spatial resolution of 250 m, were downloaded from Africa Soil Information Service (AfSIS) and Amhara Design and Supervision Work Enterprise.

For the land use cover change analysis, Sentinel-2 Images were downloaded from the platform Copernicus http://www.Copernicus.com. The pre-processed imagery of the year 2023 with a resolution of 10 × 10 m, which was acquired on March 28, was further processed for land use cover change detection using ArcGIS 10.4. Similarly, the PALSAR Digital Elevation Model (DEM) from the Alaska Satellite Facility Distributed Active Archive Data Center (ASF DAAC) with a resolution of 12.5 m was downloaded from (https://search.asf.alaska.edu/#/) was used to assess the suitability of land using slope. The road network, streamline, and other necessary GIS files were obtained from the Ministry of Water Resources and Energy of Ethiopia.

Table 1 Factors consider for land suitability analysis

Data	Source	Spatial Resolution (meter)
Digital Elevation Model (DEM)	https://search.asf.alaska.edu/#/	12.5
Sentinel-2 Images	http://www.Copernicus.com	10
Climate Data	Ethiopian meteorological institute	
Hydrological	Ministry of Water and Energy	
Soil	Africa Soil Information Service (AfSIS)	250
Population density	Global Gridded Population Database	1000
Road network	Ethiopian Road Authority (ERA)	-
MODIS PET (mm)	(https://search.earthdata.nasa.gov/search)	500
Climate	Ethiopian National Meteorological Agency (ENMA)	-
Streamflow Data	Ethiopian Minster of Water and Energy	-
Borehole data	Water and Energy Office	-
Groundwater depth (m)	British Geological Survey (BGS), 2012	5000
Potential borehole yield (l/s)	British Geological Survey (BGS), 2012	5000
Groundwater storage (mm)	British Geological Survey (BGS), 2012	5000
GPS Data	Field Survey	-

3.3 Methodology and data analysis

The general method includes three main parts: (1) assessing the land that is suitable for surface irrigation using the Multi-Criteria Evaluation (MCE) technique in Geographical Information System, GIS; (2) determining crop water requirement for the selected crop; (3) evaluating the

potential of surface water irrigable area during the dry season. After all the necessary data were collected from different sources, further analysis was conducted for each physical and socio-economic land suitability factor to evaluate the suitability of the study area for surface irrigation both surface and groundwater sources. Besides, each ach parameter was assessed by different guidelines and prepared for the final overlay.

3.3.1 Irrigation Suitable Land Potential

To find suitable land for irrigation using surface and groundwater sources, individual suitability factors were analyzed through a multi-criteria evaluation approach. Seven common factors were selected for both water sources: soil capability index (a function of soil characteristics), land cover, slope, climate (rainfall deficit), proximity to urban centers, population density, and road networks (Malczewski, 2004). For surface water-based irrigation, an additional factor—proximity to river networks was considered (Senay et al., 2014). Groundwater-based irrigation suitability included four more factors: groundwater depth, salinity, yield, and storage capacity (Jha et al., 2010). All factors were prepared, standardized, and integrated using a weighted overlay analysis in ArcGIS 10.4, enabling spatial prioritization of suitable irrigation zones based on expert-driven and literature-supported criteria.

Table 2 Framework of Land Suitability Classification

Class	Name	Land Description
S1	Highly suitable	Land without significant limits, this land is the best possible and does not reduce productivity or require increased inputs.
S2	Moderately suitable	Land that is suitable but has a limitation that either reduces productivity or requires an increase of inputs to sustain productivity compared with those needed on S1 land.
S3	Marginally suitable	Land with limitations so severe that benefits are reduced and/or the input required to sustain production needs to be increased so that this cost is only marginally justified.
S4 (N1)	Currently not suitable	land having limitations that may be surmountable in time but which cannot be corrected with existing knowledge at a currently acceptable cost
S5 (N2)	Not suitable	land having limitations that appear as severe as to preclude any possibilities of successful sustained use of the land of a given land use

Source: (Worqlul et al., 2015)

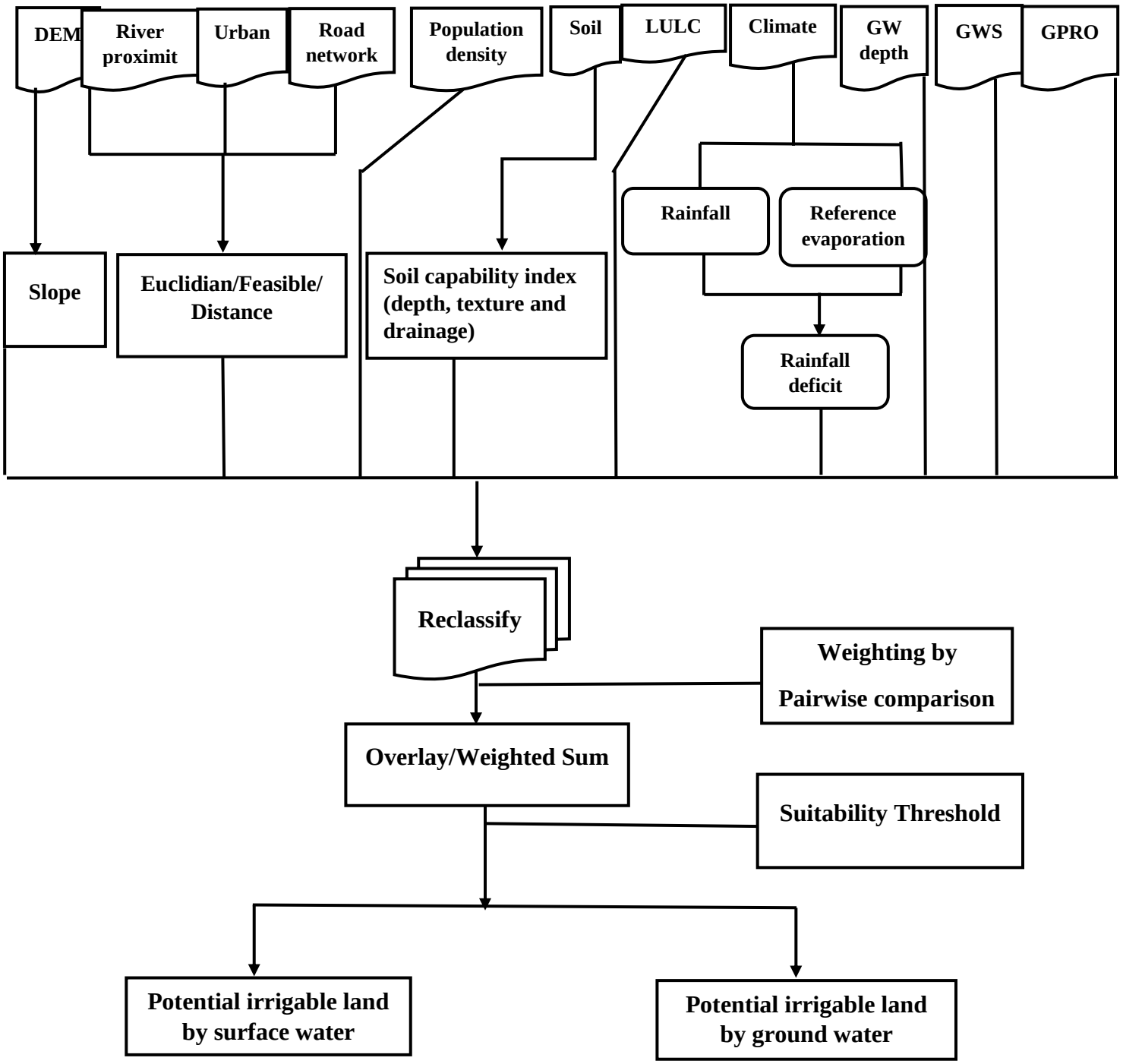


Figure 2 Irrigation suitability model

3.3.1.1 Watershed delineation

The study area is rugged and mountainous and ranges from the highest elevation of 4260m in the central part of the study area to 913m of lowest elevation on the eastern and northwestern part of the area from mean sea level (Figure 3). Gidan, Lasta, Wadla, Delanta, and other woreda in the central part of the study are characterized by high elevation and high slope whereas Kobo, Habru, and some parts of Meket and Bogna woreda have the lowest elevation.

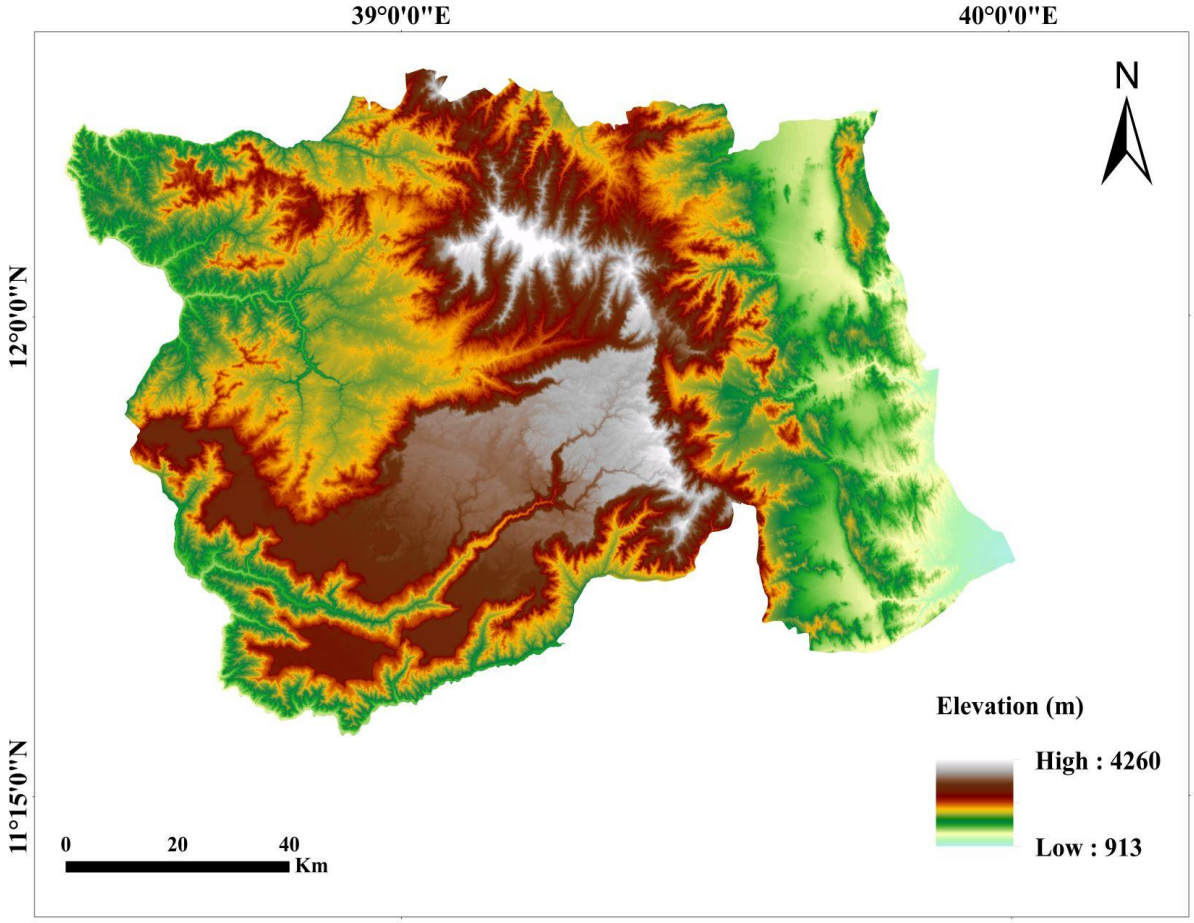


Figure 3 DEM of the study area

3.3.1.2 Slope suitability analysis

The percentage slope map of the study area was derived from 12.5m resolution DEM (Figure 3 above) using the "Spatial Analysis Slope" tool in ArcGIS 10.4 and slopes were re-classified based on Worqlul *et al.* (2015), using the "Reclassification" tool into five classes (Table 3).

Indicating suitability for surface irrigation finally, the slope suitability map was developed and data layers were prepared for further overlay analysis.

Table 3 Slope suitability framework

Slope (%)	suitability class
0-2	S1
2-8	S2
8-12	S3
12-30	S4
>30	S5

Source: (Worqlul et al., 2015)

The topography of the study area is shown in (Figure 4), 8% of the area has slopes below 5%, 12% of the study area has a slope between 5% and 10%, 18% of the area coverage has slope between 10% to 20% of the slope, and 15% of the area is between 20% to 30% and the rest 47% of the area have slope above 30% and it is a steep slope. Kobo, Habru, and Wadla have flat slopes than other areas.

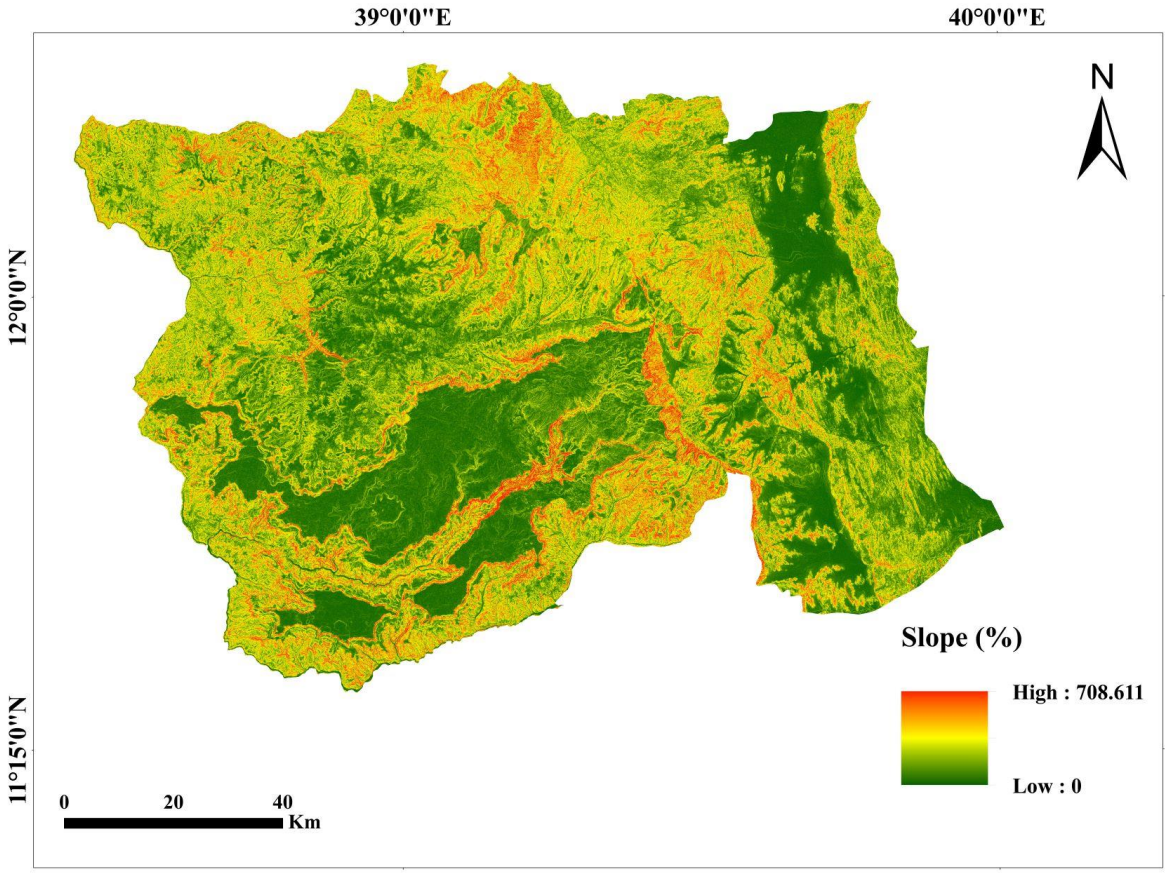


Figure 4 Slope of the study area (%)

3.3.1.3 Soil suitability classification

Soil is a key factor in determining the suitability of land for agriculture and irrigation. Its primary influence is on the productive capacity, but it also influences production and development/investment costs. It provides structural support to plants and is also a source of water and nutrients. Soil affects irrigation by influencing infiltration, drainage, water-holding capacity, and others.

Soil texture, soil drainage, and soil depth are the major physical properties of soil that are very significant for the assessment of the irrigation potential of the study area. They affect the suitability by controlling the root growth of the plant, infiltration of water into the soil, drainage characteristics, moisture, or water holding capacity for the production of crops. The soil physical properties of the study area (soil texture, soil depth, and soil drainage) are obtained from the online source of the Africa Soil Information System (AfSIS). The soil data from AfSIS has six layers (i.e., 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm, and 100-200 cm) with 250m resolution. Each layer contains the above-listed soil physical parameters. By considering the root depth of the crop mostly grown in the zone, select five layers (100 cm) from six-layer data of AfSIS and aggregated by weighted average and classified using the USDA soil classification method to get the texture of the study area. Soil depth and drainage are also obtained from the AfSIS data source. The soil suitability of the study area for irrigation was analyzed by taking the soil physical and chemical properties collected from the online source of the Africa Soil Information System (AfSIS).

Based on its particle size soils, soils are divided into three major types of soil textures. These include clay, silt, and sandy soils. These major types have mixtures of particles like silt-clay, clay-loam, sandy loam, etc. Generally, clay, clay loam, and silty clay loam are classified as fine-textured soils while sandy clay loam, loam, and silt loam are classified as medium-textured soils and others like sandy soils are classified as coarser-textured soils. The most important irrigation parameter (Water holding, movement of water through the soil, water availability, and inflation capacity) is influenced by soil texture. This infiltration and water holding parameter affect the irrigation type selection, irrigation interval, and other design parameters like furrow length, size, etc.

The soil texture of the area was clay, clay loam, loam, and silty clay loam. As shown from the map (Figure 5) of the texture, clay loam (88.71%) was the dominant followed by clay (9.37%). The other 0.04% and 1.88% of the area are covered by silty clay loam and loam respectively. According to Worqlul *et al.* (2017), the soil texture was classified into four groups based on the soil water holding capacity, namely very high holding capacity (e.g. silt, silt loam, and silty clay loam), high capacity (e.g. silty clay, and clay), low capacity (e.g. loamy sands), and very low (e.g. sands, and loamy sands).

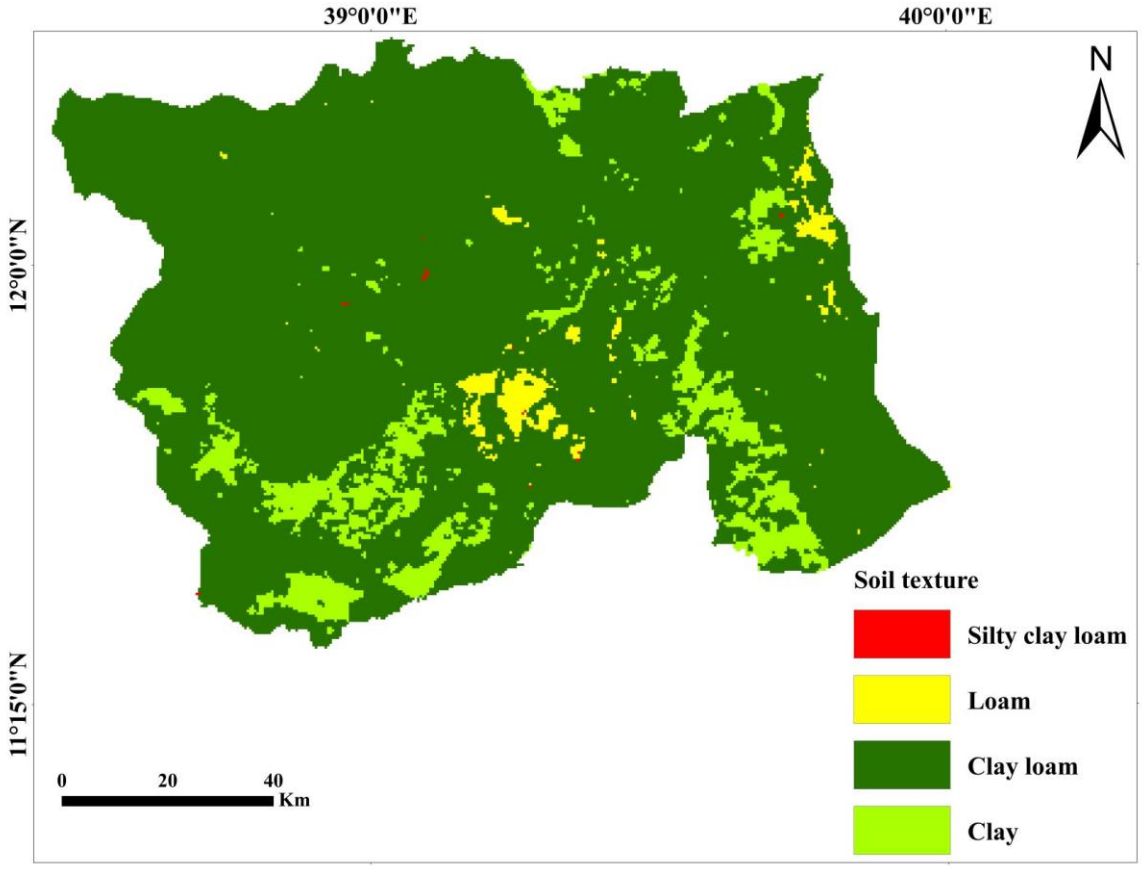


Figure 5 Soil texture of the basin

Soil capability index (SCI)

The effect of soil physical and chemical characteristics was expressed using the soil capability index (SCI), which is described as the suitability of soil for irrigation. Soil texture (A), soil depth (B), and drainage (C) were used to determine the soil capability index (SCI) and used for suitability analysis as a soil suitability factor. The classification of SCI was done based on Teka

et al. (2010) for suitability analysis. SCI was then reclassified into five suitability classes for surface irrigation based on Teka et al. (2010) to suitability classes.

$$SCI = A * \left(\frac{B}{100}\right) * \left(\frac{C}{100}\right) \quad \text{Equation 1}$$

Where: - SCI is soil capability index; A is soil texture rating; B is soil depth rating; C is soil drainage class rating,

Table 4 Soil capability index suitability class and range based on Teka et al. (2010)

Capability index	Suitability classes	Definition
> 80	S1	highly suitable
60-80	S2	moderately suitable
45-60	S3	marginally suitable
30-45	S4	less suitable
< 30	S5	unsuitable

3.3.1.4 Land use/land cover

Land use and land cover are also one of the potential factors for irrigation land suitability assessment (Mitiku et al., 2024). The image pre-processing was made using ArcGIS 10.4 and ERDAS imagine 2015 software. Three bands (B_3, B_4, and B_8) of the image were combined to create a mosaic raster of the study area.

Ground control points were collected by a global positioning system (GPS) then imported to Google Earth, a paper review such as (Daniel *et al.*, 2019), ESRI 2020 land cover map having 10 by 10 meter resolution were used for the classification of LULC. The Supervised maximum likelihood classification was used to produce the land cover map of the study area based on the pixel-based.

Predefined sampling points within the selected area of the study area were randomly assigned using ERDAS imagine 2015 for accuracy assessment. The combined shape file and predefined sampling points were converted to a KML file to import the data to google earth. After importing to google earth, LULC types were targeted and recorded. Hence, predefined sampling points falling LULC types were used for field data collection. Therefore, depending on this, a total of 304 sampling points covering 11 rural woredas of the study were generated for sample collection.

During survey work, the pre-defined sample locations were surveyed in the field and the location was geo-referenced using the GPS receiver (AndroiTS GPS test) with Arc GIS 10.4. Once, the sampling points are navigated and reached, a description of the selected study

watershed was performed through LULC types, and an analysis of the confusion matrix was done.

A confusion matrix was used to assess the classification accuracy and indicate the nature of the classification error (Geremew, 2013). The produced accuracy was figured by dividing the total number of correct pixels in a category by the total number of pixels in that group as derived from the reference data (Jonathan, 2015). It indicates how well a certain area can be categorized. Also, the user's accuracy was computed by dividing the total number of correct pixels in a category by the total number of pixels that were classified in that category. Kappa coefficient indicates a strong agreement between observed LULC, and classified land cover classes (Fantaye et al., 2017). A value nearest to one indicates that the classification is significantly better than random. The kappa coefficient can be obtained using Equation 2.

$$kappa\ coefficient = \frac{P_o - P_e}{1 - P_e} \qquad \text{Equation 2}$$

Where, Po is the proportion of correctly classified classes, and Pe is the proportion of correctly classified classes expected by chance.

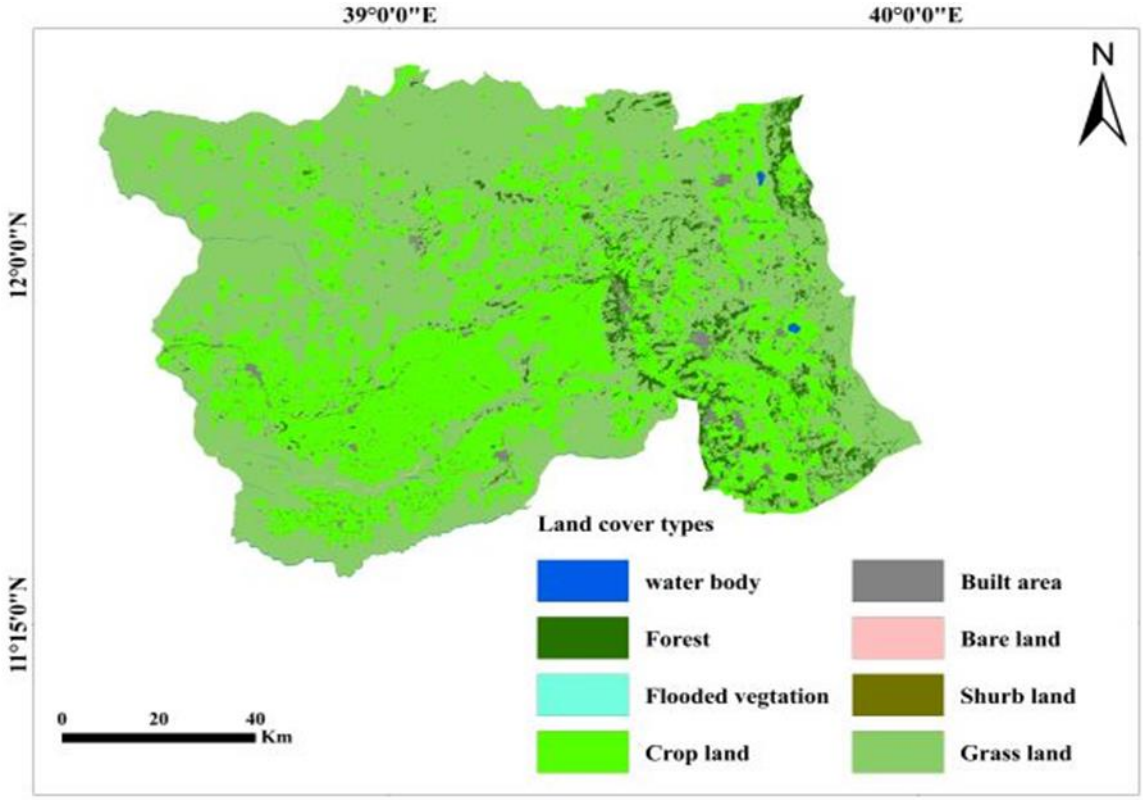


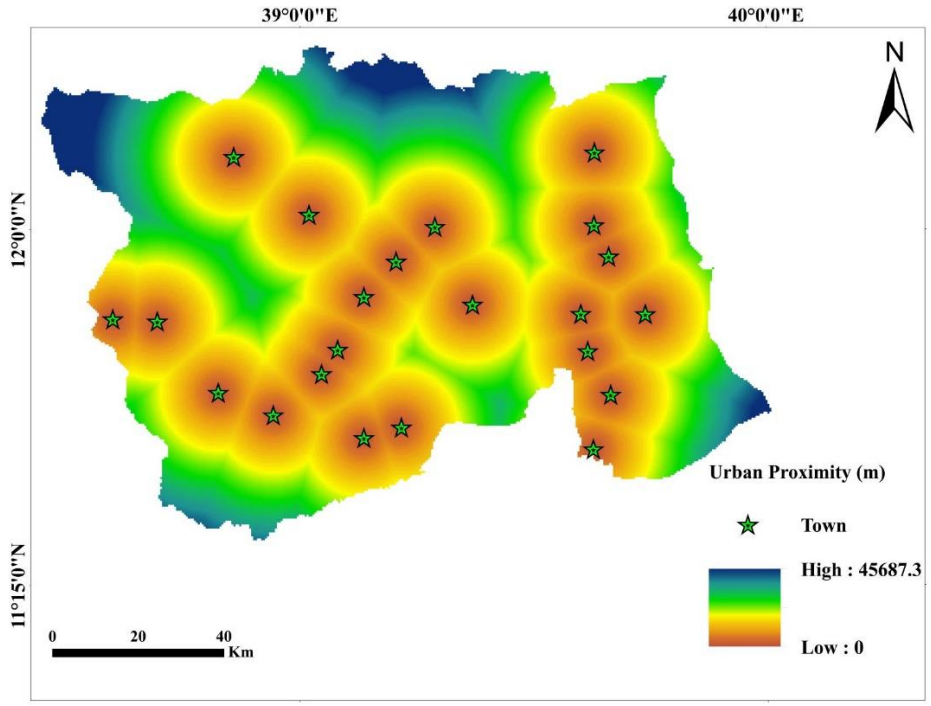
Figure 6 Land use and cover of North Wollo

The overall accuracy is 92.81 % and the kappa statistics is 0.87 is as shown in Appendix table VI. This indicates that the LULC classes are properly classified. According to Shiferaw et al. (2019), kappa coefficient which greater than 0.8 represents a strong agreement between observed LULC and classified land cover classes. Tessema et al. (2020), suggested that the minimum threshold of overall accuracies should be not less than 85%.

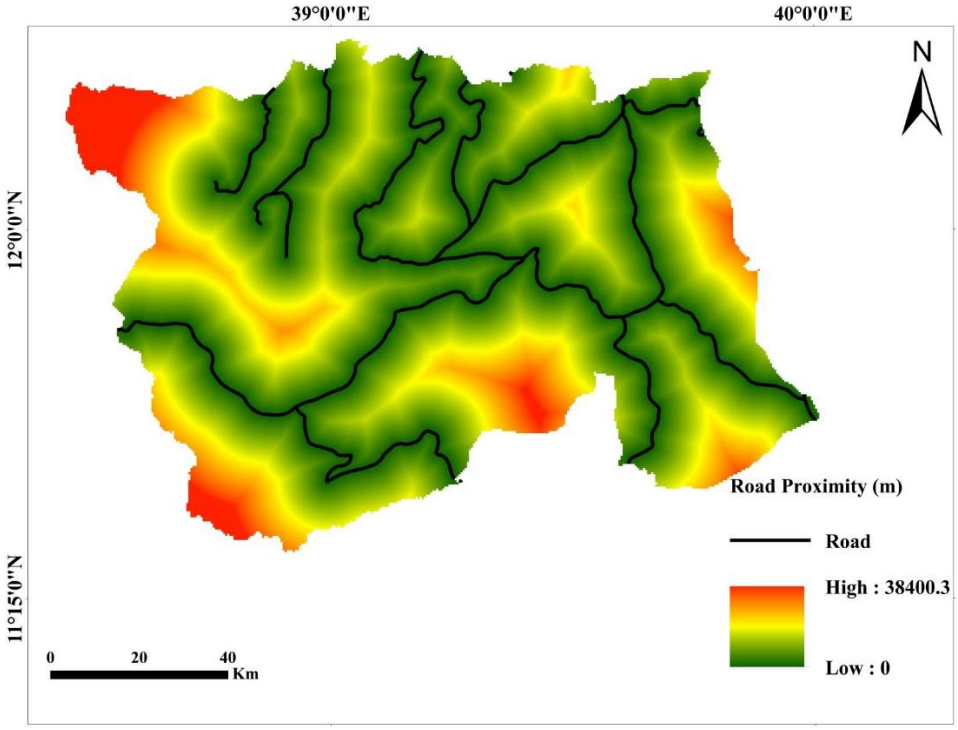
The suitability of land use for surface irrigation was categorized into four classes according to Oumer (2009), ranging from highly suitable class (S1) to not suitable class (S4). Cropland and bare land use cover 36.555% of the zone, and 55.90% of the study area is covered by grassland and small vegetation. Shrub land and bushland cover 4.45 % of the area from the total. Forest, water bodies, and built-up areas cover 3.09% of the study area (Figure 6).

3.3.1.5 Road proximity and urban center

The market outlet is the most dominant factor that affects irrigation suitability of surface irrigation because agricultural products and inputs need markets and road access to reach users and farmers. These market outlets are expressed by proximity to road networks and urban centers.



(a)



(b)

Figure 7 Urban (a) and Road (b) proximity of the area

Urban centers and road networks that are included within the basin are considered in this study. Euclidean distances were calculated from road networks and urban centers and then classified into suitability classes based on the equal interval approach for suitability analysis (Worqlul et al., 2015).

The lands close to the market and road are most suitable for surface irrigation according to market accesses because they can get agricultural input and sell their output easily in the market through road and city. The map of urban and road proximity showed that the farthest irrigated area in the basin is found 45.7 km from the city and 38.4 km from the road, in this area it is difficult to address the agricultural outputs from the farmers to the market and agricultural input to farmers (Figure7 a, and b).

3.3.1.6 River Proximity

River proximity is a significant factor that decides and ranks the areas to be irrigated using surface irrigation from a surface water source. Agricultural land close to river networks can get access to water easily for crop production and the area found far from the river cannot get water

for crop production. The major river network was downloaded from an online source of Hydro sheds which includes 10km^2 drainage area coverage and o.1m^3/sec flow.

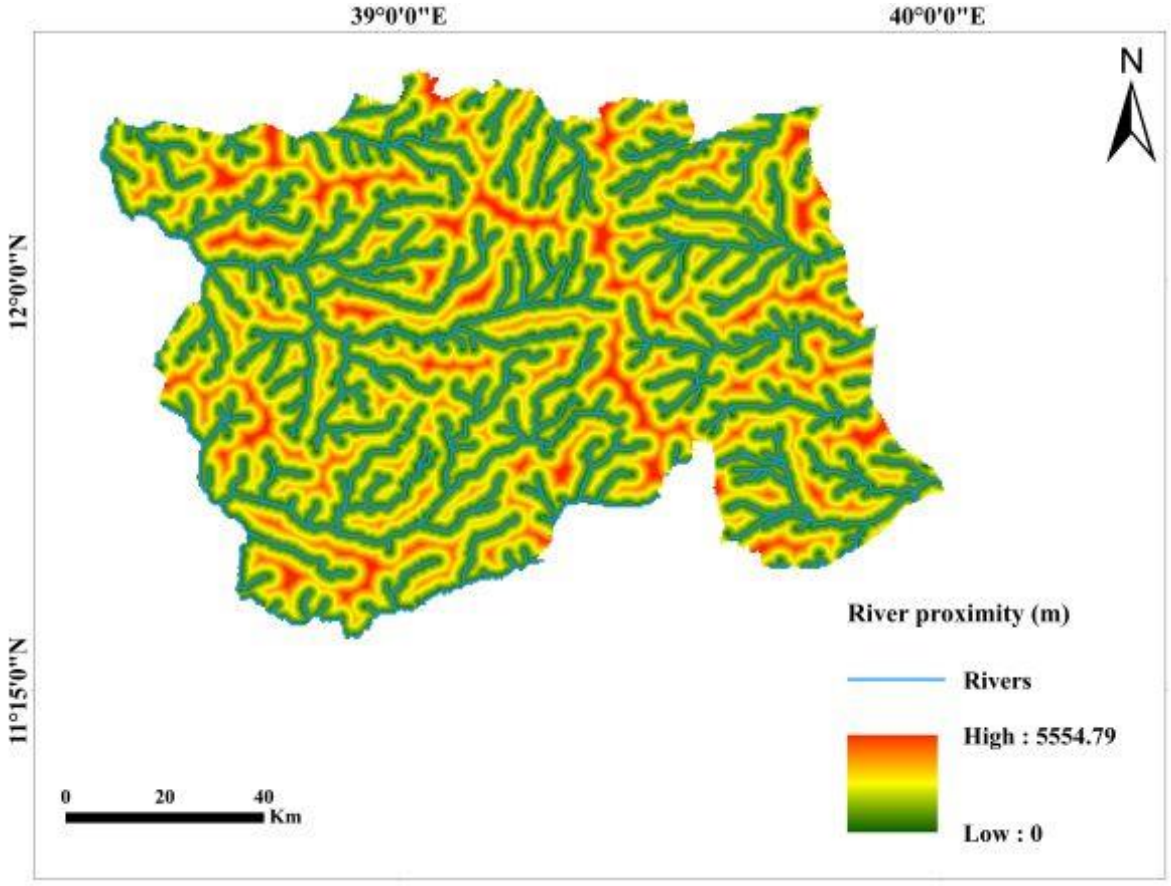


Figure 8 River proximity (m)

Euclidean distances were calculated for each river in the study area and then an equal interval method was used for classification into suitability classes for suitability analysis. The farthest area is 55.5 km far from the river and can get water after 55 km of transport to address irrigation water (Figure 8). The furthest point is found on the boundary of the basin and it is not suitable according to the river proximity factor.

3.3.1.7 Population density

The irrigation project requires market access for users. This market access is represented by roads, cities, and population density. The population density for the study area was collected from the Global Gridded Population Database from the Center for International Earth Science Network (CIESIN). The population density of the study ranges from 0 to 14200.8 persons per square kilometer, The population density map indicates that in the city, Kobo woreda, Habru,

Gubalafto, Wadla, and some parts of Delanta, Meket of the study area the people lives densely and on the other part of the study area like Bugna and north part of the area the community lives sparsely (Figure 9). Due to high variability and skewed into one side geometric interval classification techniques with eight classes are used for suitability assessment classification.

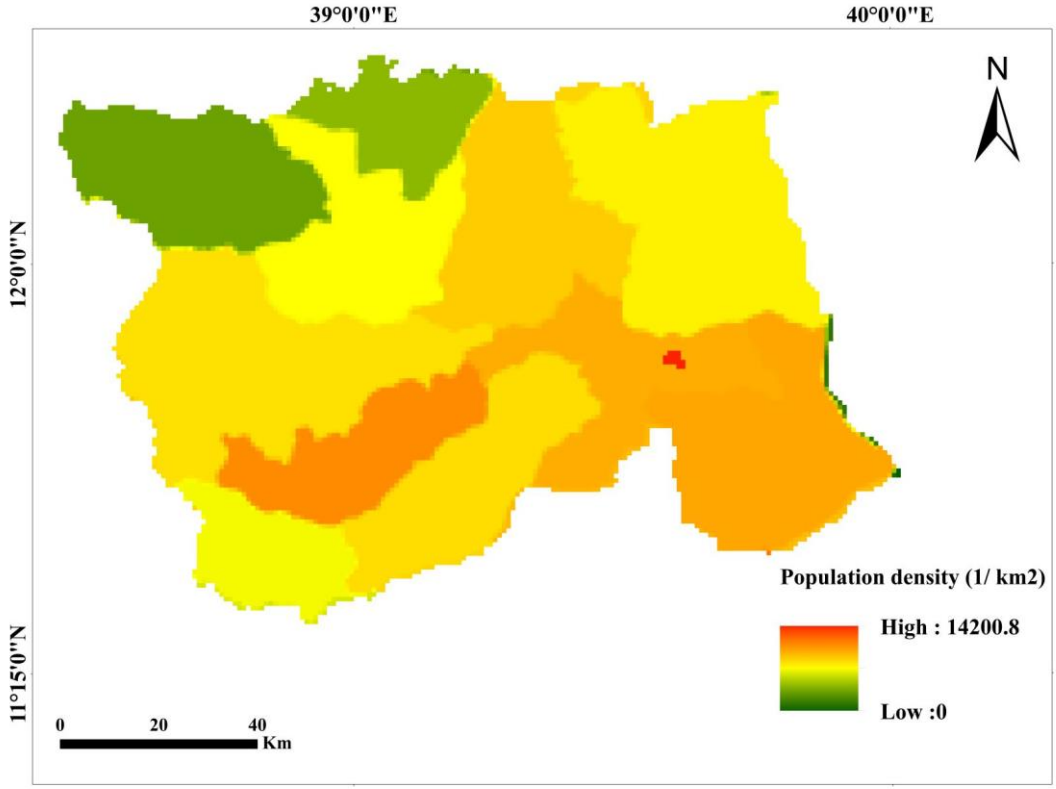


Figure 9 Population density of the basin

3.3.1.8 Climate

Potential evapotranspiration of the study area was downloaded from the MOD16 Global Terrestrial Evapotranspiration Data Set. Rainfall data of North Wollo was collected from the metrological stations of zones in the Ethiopian National Meteorological Agency (ENMA), the annual rainfall of the study area was obtained by interpolation using the Inverse Distance Weighting interpolation (IDW) method, and Rainfall deficit was calculated by subtracting potential evapotranspiration from rainfall. A positive monthly rainfall deficit value indicates no irrigation requirement, while the negative values suggest an irrigation requirement; the higher the negative value, the higher the irrigation requirement. These data were classified by equal interval approach into suitability classes for surface irrigation.

3.3.1.9 Groundwater depth, salinity, aquifer productivity and storage

Groundwater is the main source of water for domestic use in our country. But now it is widely used for irrigation also. This study used Groundwater data such as groundwater depth, salinity, aquifer productivity, Groundwater storage, and potential borehole yield collected from the British Geological Survey (BGS) to assess the potential irrigable land using groundwater. Within 5km resolution, the groundwater data listed above in Africa is available (MacDonald et al., 2012). To publish this map they use hydrological maps, literature, and publicly available data. The data were downloaded from BGS in ASCII file format. The ASCII file was converted to a grid format of 5 km resolution by the information on the dataset can be found in data download from BGS. According to the groundwater table map downloaded from BGS, 60% of the study area accesses groundwater within very shallow depth (VS) which is below 7 m depth, and 15% of the area accesses water in a shallow depth (S) between 7-25 m depth and the rest 25% of the basin get water within small to medium depth (SM) below 50 m depth and above 25 m depth (Figure 10).

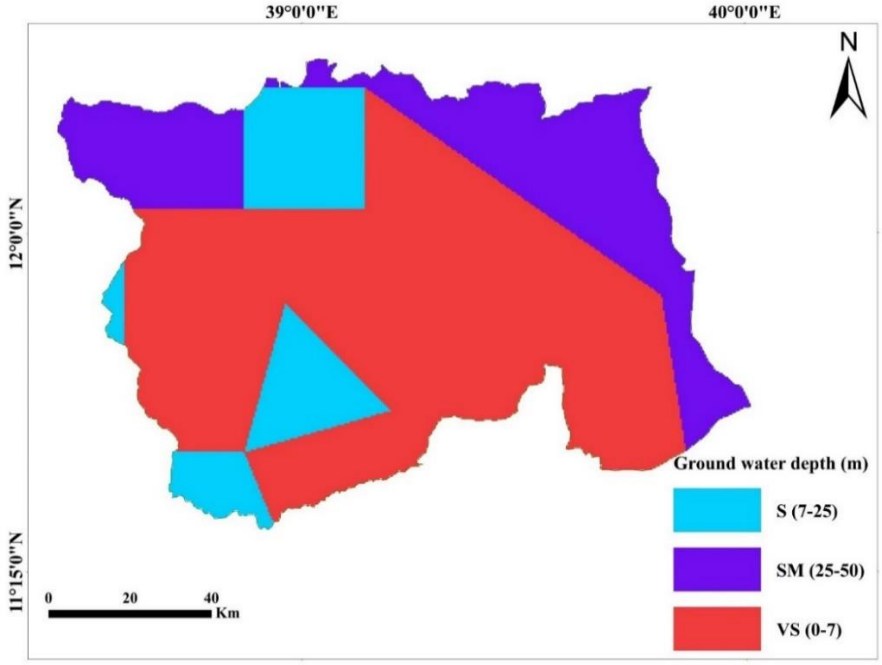


Figure10 Groundwater depth (source: BGS)

According to the groundwater storage map (Figure 11) downloaded from BGS, 0.45% of the study area has medium water storage and the rest 99.55% of the area has large to medium water storage. Figure 12 shows that 0.05% of the study area has high aquifer productivity which is

between 5 to 20 l/s and the remaining 99.95 of the study area has medium aquifer productivity which is between 1-5 l/s.

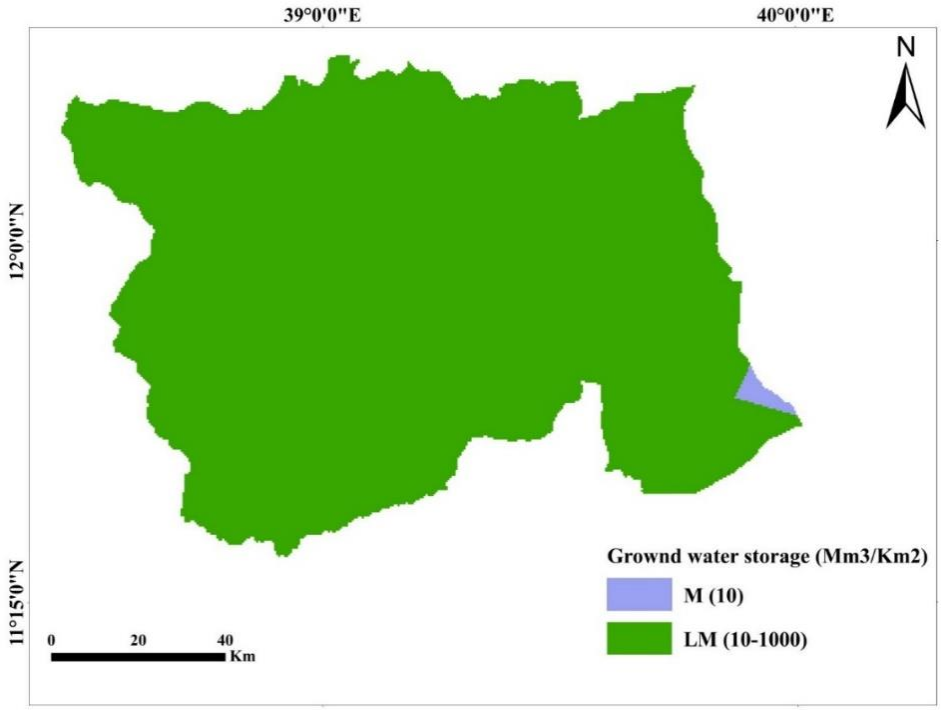


Figure 11 Groundwater storage (source: BGS)

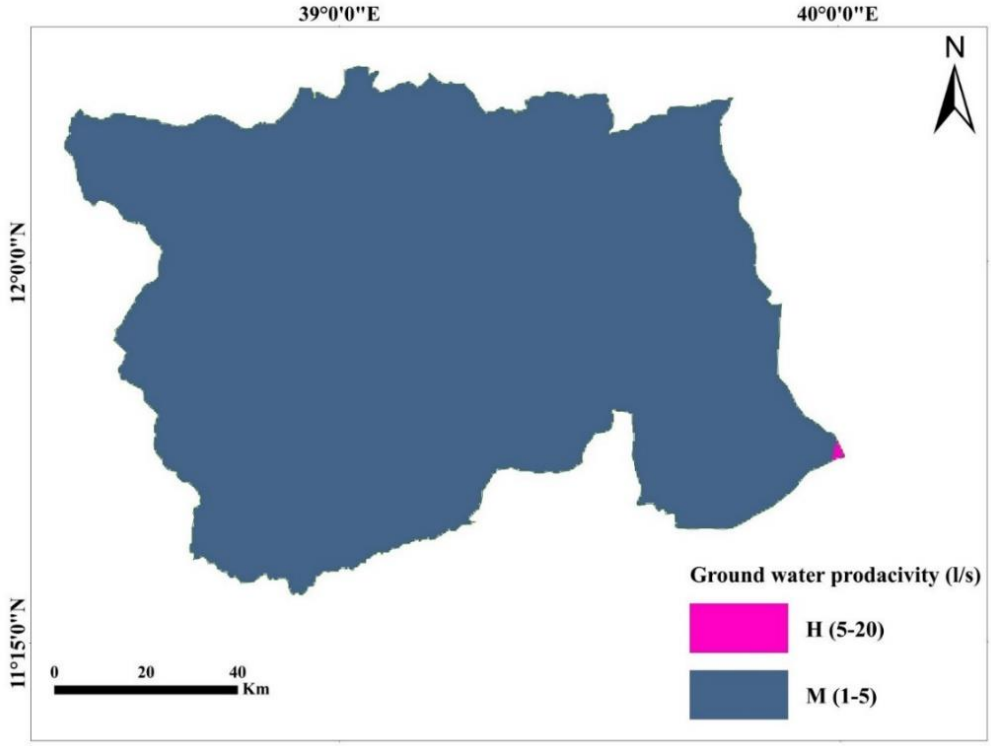


Figure 12 Aquifer productivity (source: BGS)

3.3.1.10 Weighted Overlay Analysis of the Factors

After the irrigation suitability of each parameter was assessed and the suitability map layer of each criterion was developed separately, an overlay analysis was done to generate one suitability map using "model builder" in Arc toolbox and tools from spatial analysis toolsets. The weights were developed by providing a series of pair-wise comparisons of the relative importance of factors to the suitability of pixels for the activity being evaluated. The logic developed by Saaty (1977), is used to produce weights under the Analytical Hierarchy Process (AHP) with a weighted linear combination. The steps involved in the AHP processes used in this study can be pairwise comparison, calculation of weight, and weight overlay analysis. The average of expert opinions and literature were used for the comparison of factors one-to-one. A scale of importance was divided from a value of 1 to 9 (Table 5). The highest value 9 corresponds to absolute importance and the reciprocal of all scaled ratios will be entered in the transpose position (1/9) and shows an absolute triviality.

Table 5 Intensity of importance class definition Pairwise scale based

Intensity of Importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	somewhat more important	Experience and judgment are slightly favorable one over the other
5	Much more important	Experience and judgment strongly favorable one over the other
7	Very much more important	Experience and judgment strongly favor one over the other, its importance is demonstrated in practice.
9	More important	The evidence favoring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

The column factors were compared with the factors in the rows for their significance to surface irrigation, and then using the scoring indicated in the Table above, a pair-wise matrix was prepared. After the pair-wise comparison matrices were filled, the weights of the factors were computed by normalizing the respective eigenvector. To ensure the credibility of the relative influence ranking used the consistency ratio index (CR) was calculated. The consistency ratio (CR) were calculated according to (Saaty, 1977) and the acceptable CR value is up to 0.1 based on (Saaty, 1977).

$$CR = \frac{CI}{RI}, \qquad \text{Equation 3}$$

Where: - CR = consistency ratio, CI = consistency index, and RI = consistency index of randomly generated matrix

The consistency ratio was used to check the consistency of the pairwise matrix. The weights were distributed to individual factors' suitability classes based on an equal interval ranging technique, and the factors were combined using a weighted sum overlay technique to produce a suitability map (0% to 100%). The value of the suitability index ranges from 0 (permanently unsuitable land) to 100 (most suitable land).

3.3.2 Irrigation Water Requirement

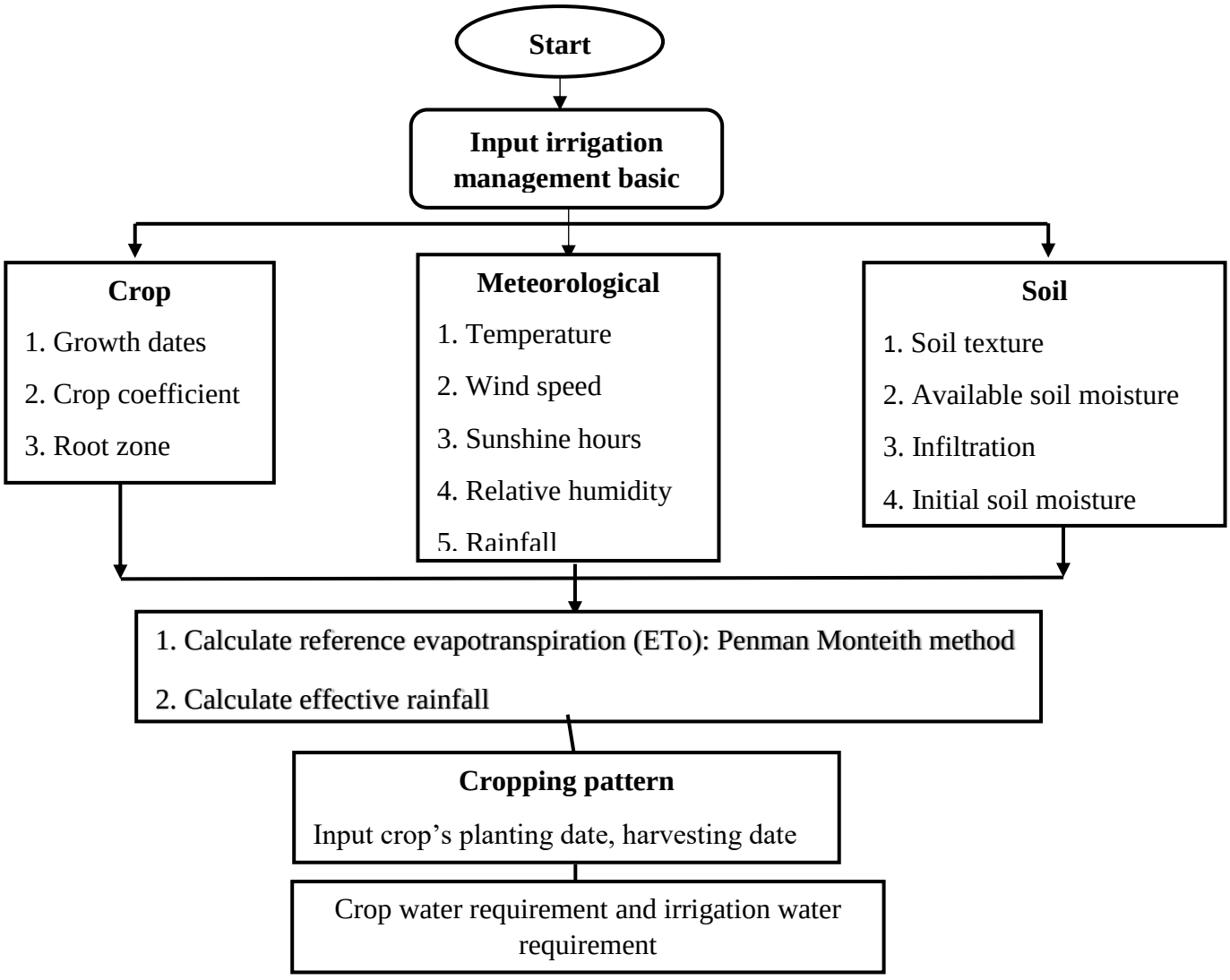


Figure13 CROPWAT model

After evaluating the suitability of the land for surface irrigation, it is very necessary to evaluate the water potential for crops produced in the study area. Therefore, the study aimed to evaluate suitable land and water resources by considering major crops in the study area. The baseline to select types of crops, which are grown in the study area were types of crops, which are widely grown in the area and used by many farmers as commercial crops. According to DAs that work in the study area Sorghum, wheat, teff, and maize are major crops grown in most of Woreda and were selected to evaluate the potential of water resources in the study area. Sorghum, teff, and maize are widely grown in the study area. The farmers use rainwater and sometimes use irrigation water to grow cereal crops. Wheat is a crop majorly grown by irrigation in the study area. The evapotranspiration (ETc) for the dominant crop was calculated using CROPWAT 8.0 with climatic data for the area grown from the Ethiopian National Metrological Agency weather station. The crop water requirement of the crop is calculated by multiplying the crop coefficient by evapotranspiration. The crop coefficients for the initial, mid, and late seasons and growing periods were extracted from the FAO - 56 manual (Allen et al., 1998).

According to this manual, most of the cereal crops have a close crop coefficient of 0.3, 1.15, and 0.4 for initial, mid, and late growing seasons, respectively. The growing period of the irrigated crops ranges between 130 and 140 days. The rain-fed crops that are planted in the summer season (Meher) are harvested between September and December (Allen et al., 1998). Irrigated crops were planted in the dry season from December to April. Irrigation water requirement (IWR) was calculated, taking into account the effective precipitation (P_{eff}). Net irrigation requirement is the difference between crop water requirement and effective rainfall. The crop water requirement depends on the prevailing climate condition, crop type, stage of crop growth, and soil properties. CROPWAT 8.0 software was used for analyzing the ETo, and ETc of the selected crop in the study area. Root depth, depletion level, and other agronomic parameters were obtained from FAO guidelines. Generally, the crop water requirement (CWR) was calculated as a product of the potential evapotranspiration (ETo) and the crop coefficient (Kc).

$$CWR\ (ETc) = ETo * Kc \quad \text{Equation 4}$$

$$IWR = ETc - Peff \quad \text{Equation 5}$$

The total crop water requirement or gross water requirement was computed with a 60% irrigation inefficiency of water application and water requirement for special needs such as land preparation and leaching (F. Yohannes & Tadesse, 1998).

$$NIR = 1.6 * Kc * ETo - Peff$$ Equation 6

3.4 Surface Water Resources Potential

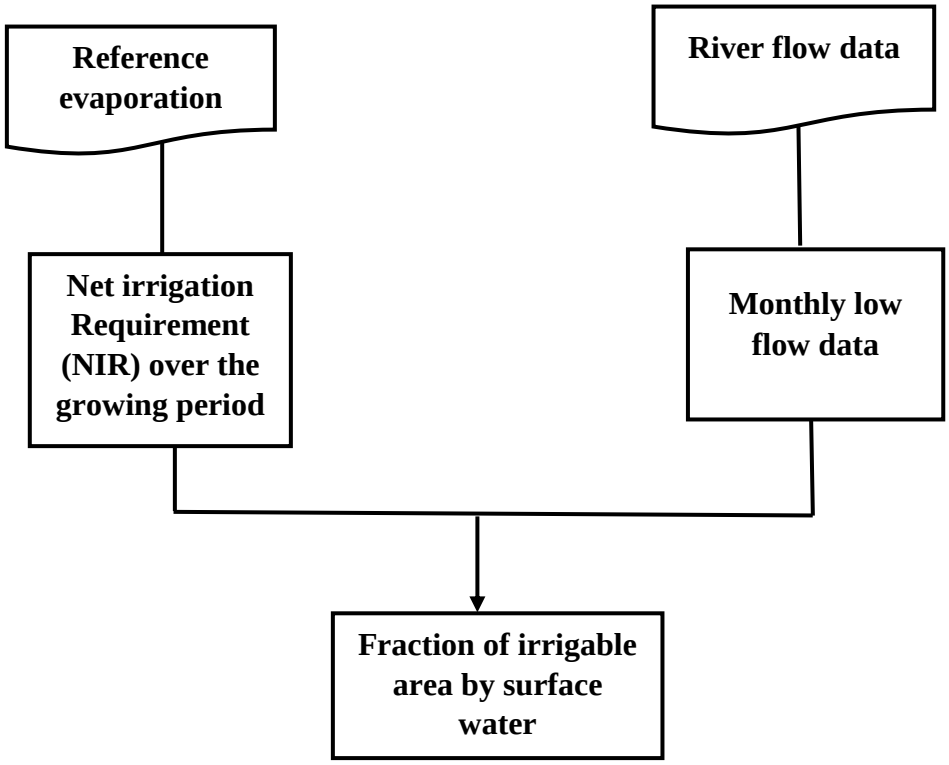


Figure 14 Evaluation of surface potential

Irrigation development requires assessment of the potential of the rivers and groundwater because assessing the suitability of land is critical to the development of productive and economically viable irrigation schemes (Verheye et al., 2014). The available surface water stream flow discharges of the major river were obtained from the Minster of Water and Energy. The Low-flow (Q90) potential of rivers was analyzed and compared with crop water requirement in the study area to know the irrigable area by water without constructing storage. To find the irrigable area, divide the average daily flow by the crop water requirement.

4 RESULTS AND DISCUSSION

4.1 Irrigation Suitability Evaluation

The suitable land for surface irrigation is evaluated by the suitability factor of the slope, soil characteristics (SCI), land uses, climate, urban and road proximity, population density and River proximity for surface water source and groundwater depth, storage, yield and salinity for groundwater sources additionally from surface water source factor except for River proximity. Each factor was assessed separately below based on suitability guidelines of FAO and other literature.

4.1.1 Slope Suitability

The slope is the incline or gradient of a surface and is commonly expressed in percent. The slope of the land affects the suitability of an area in terms of irrigation method selection, land preparation for irrigation, and irrigation operation and surface irrigation require a suitable slope for gravity flow. Additionally, important for soil formation and management because it influences runoff, drainage, erosion, and choice of crops. Higher slope land results increase runoff and erosion; water management is more difficult and land preparation cost is very high. So steep slope results in lower productivity and high production costs. According to FAO standard guidelines for surface irrigation slopes greater than 8% are not suitable and slopes less than 2% are very suitable. For the surface, the irrigation slope is the main driving factor.

The slope of the study area was derived using the ArcGIS 10.4 by spatial analysis tool importing DEM with 30m resolution downloaded from USGS. The slope derived from the DEM with 10m resolution was classified into five classes indicating the suitability class for surface irrigation based on (Worqlul et al., 2015) using the reclassification tool in ArcGIS 10.4. The slope from 0-2% was classified as highly suitable (S1), from 2-8% as moderately suitable (S2), from 8-12% as marginal (S3), slope from 12-30% was classified as less suitable (S4) and slop above 30% were classified as not suitable (S5). After the reclassification, a slope suitability map of the basin was developed for surface irrigation suitability assessment.

Table 6 Slope Suitability and Area Coverage

N0_	Suitability classes	Area coverage (km^2)	% of total area coverage
1	S1	298	2.34
2	S2	1636	12.89
3	S3	1002	7.90
4	S4	3746	29.51
5	S5	6012	47.36

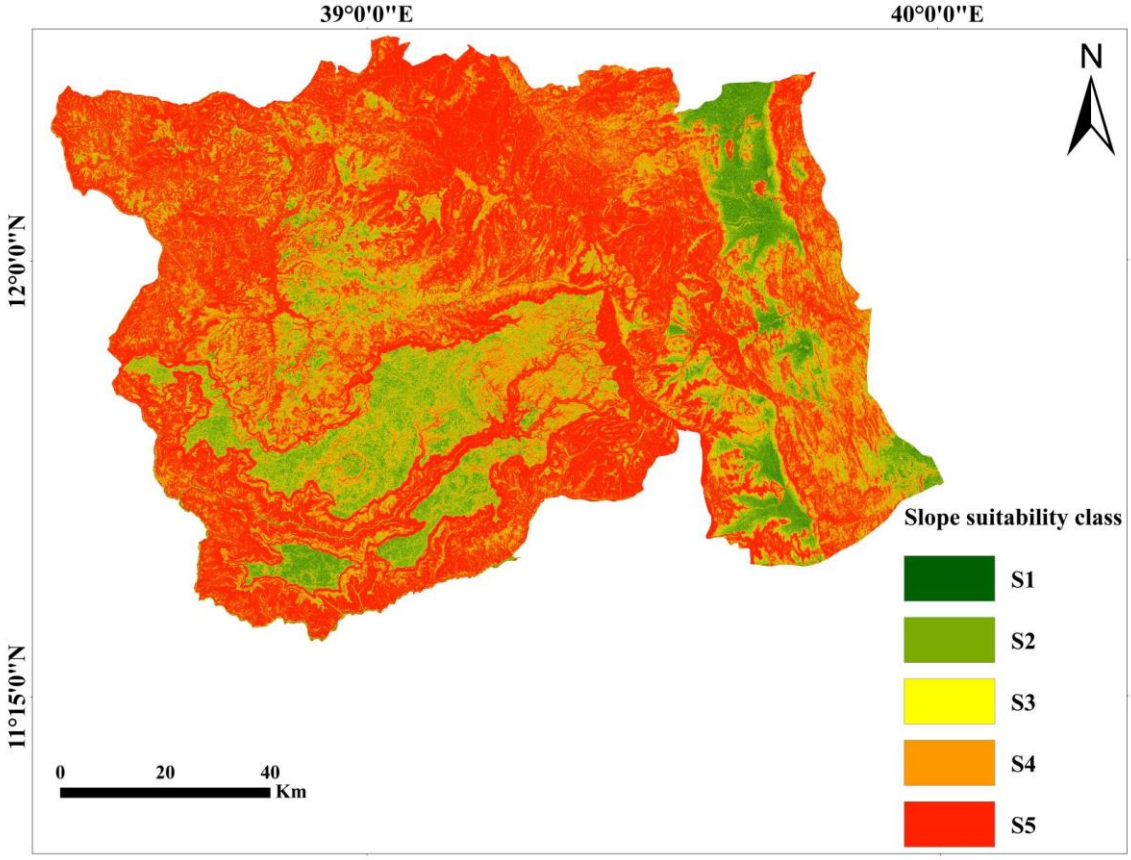


Figure 15 Slope suitability map

The slope suitability result in Figure 15 and Table 6 showed that 2.34% of the area of the study area found within 0-2% slope and it is highly suitable for surface irrigation, does not need land leveling and irrigates the area with low initial cost and is classified as (S1) and very suitable for surface irrigation according to with slope suitability and 12.89% of the area with the slope between 2%-8% is classified moderately suitable and requires a small quantity of land leveling for gravity water flow and classified as (S2). 7.9% zone has a slope between 8%-12% and is classified as marginally suitable classes (S3). It requires a large quantity of land leveling to fit the area for irrigation and needs a high initial cost for these operations. 29.51% of the area is

less suitable and the slope is between 12%-30%, this area requires a very high cost for land leveling to turn these less suitable areas into a suitable area and this practice is done after a comparison of cost and benefit. Whereas the remaining 47.36% of the area is not suitable for surface irrigation and the slope is above 30% and steep slope. Most of the area (84%) is covered by a slope that is greater than 8% not suitable for surface irrigation and requires land leveling.

4.1.2 Land use/land cover

Land use and land cover are some of the potential factors for irrigation land suitability assessment. Land use/land cover influences the cost of irrigation practice to prepare the land for agriculture and tillage practice. The land cover like cultivated is very suitable and the other land cover types shrub and bushland can become suitable for irrigation by removing the cover by high initial investment cost compared with cost-benefit. The land use/ cover type of the study area was ranked based on their importance for surface irrigation potential, costs to remove or change for cultivation, and environmental impacts under the study area.

The suitability of land use for surface irrigation is categorized into four classes according to Verheye et al. (2014), ranging from highly suitable class (S1) to not suitable class (S4). The land use map of the study area is prepared using the image downloaded from USGS, Based on Verheye et al. (2014) guidelines for surface irrigation suitability assessment the land cover data are reclassified, cultivated cropland or farmland uses were grouped into highly suitable (S1) and do not need an extra cost and already prepared for tillage, grassland, and flooded vegetation, which requires a small amount of land clearing and leveling to come irrigable land was classified as moderately suitable (S2), it needs a small amount of land leveling cost. Shrub land, which requires a higher initial investment for land clearing and preparation, was reclassified as marginally suitable (S3), whereas the rest of the land cover type forest, town, rock land, and water body were classified as un-suitable (S4) by considering the environment and conserving them.

Table 7 Land cover suitability result

N0_	Suitability classes	Area coverage (km^2)	% of total area coverage
1	S1	4623	36.44
2	S2	7109	56.03
3	S3	≈0	≈0.00
4	S4	956	7.53

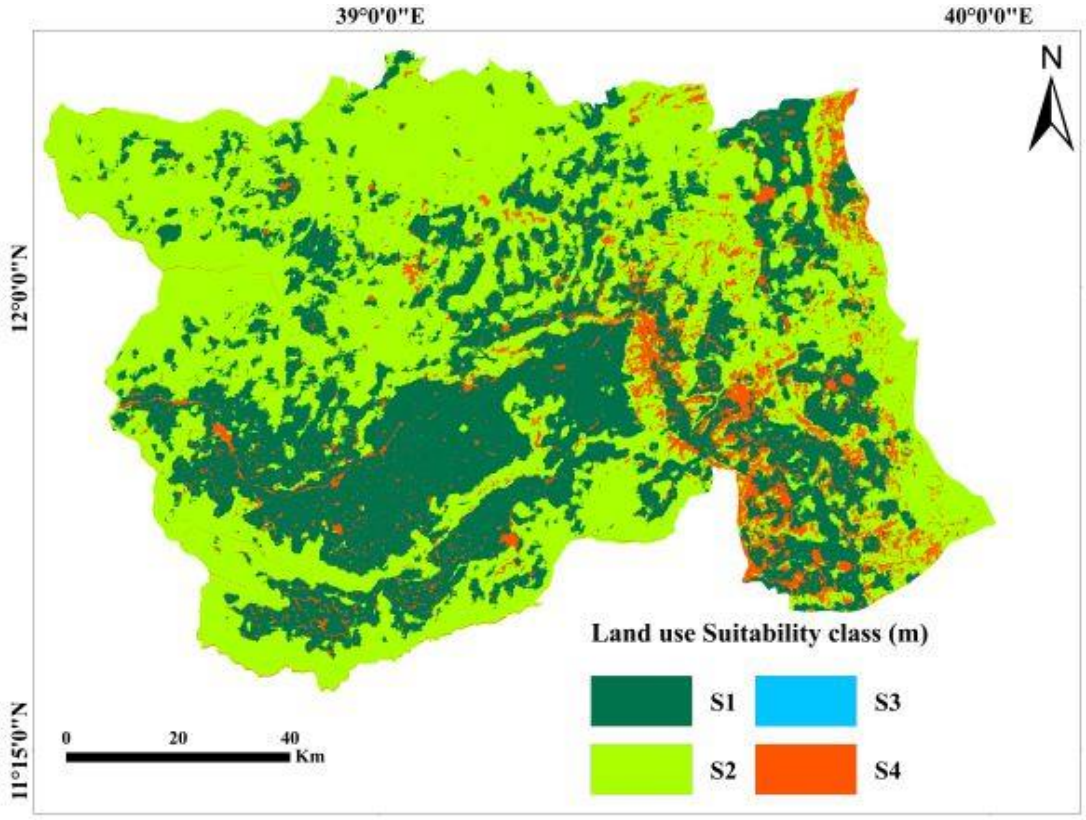


Figure 16 Land use suitability map

The results in (Table 7 and Figure 16) showed that 36% of the study area was classified as highly suitable (S1), cultivated land cropland and very suitable for surface irrigation, and does not need land preparation according to land cover. The highest portion which is half of the study area 56% is classified under moderately suitable area (S2), covered by grassland, and requires a small amount of land preparation. 4ha of the study area is covered by shrub land, this type of land requires high cost for land preparation and is classified under marginally suitable classes (S3). The remaining 8% of the area is not suitable for irrigation and covered with forest, water, hard rock, and other unsuitable covers for irrigation.

4.1.3 Physical properties of Soil

The soil suitability of the study area for irrigation was analyzed by taking soil physical properties collected from the online source of the Africa Soil Information System (AfSIS). According to Worqlul et al. (2017), The soil texture was classified into four groups based on the soil water holding capacity, namely very high holding capacity (e.g. silt, silt loam, and silty

clay loam), high capacity (e.g. silty clay, and clay), low capacity (e.g. loamy sands), and very low (e.g. sands, and loamy sands).

4.1.3.1 Soil capability index

After individual soil factors obtained from AfSIS were assessed, SCI was calculated by rating individual soil factors (soil texture, soil depth, and drainage) from 100% based on their importance to surface irrigation to assess the soil suitability of the study area for irrigation. The effect of soil physical characteristics was expressed using the soil capability index (SCI), which is described as the suitability of soil for irrigation. Soil texture (A), soil depth (B), and Drainage (C) were used to determine the soil capability index (SCI) and used for suitability analysis as a soil suitability factor. The classification of SCI was done based on Teka et al. (2010) for suitability analysis. The highest SCI value indicates that the area is suitable for irrigation and the lower value indicates that the area is less suitable, high soil capability index means that the soil has deeper soil depth, high water holding capacity, and well-drained soil whereas a lower value indicates that the soil is poorly drained, shallow depth and low water holding capacity (Figure 17).

The soil capability index of the study area was calculated (Figure 17) and the calculated SCI value was then reclassified into five suitability classes for surface irrigation based on Teka et al. (2010) to suitability classes (Table 8).

Table 8 Soil capability index suitability range

Capability index	Suitability classes	Definition
> 80	S1	highly suitable
60-80	S2	moderately suitable
45-60	S3	marginally suitable
30-45	S4	less suitable
< 30	S5	unsuitable

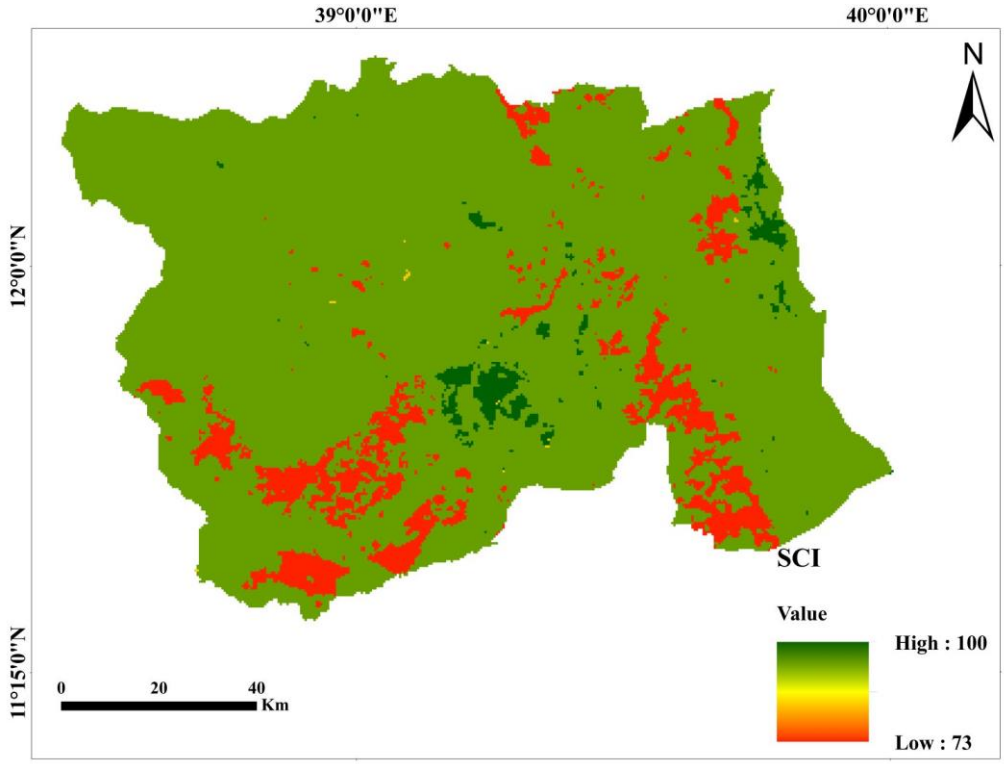


Figure 17 Soil capability index

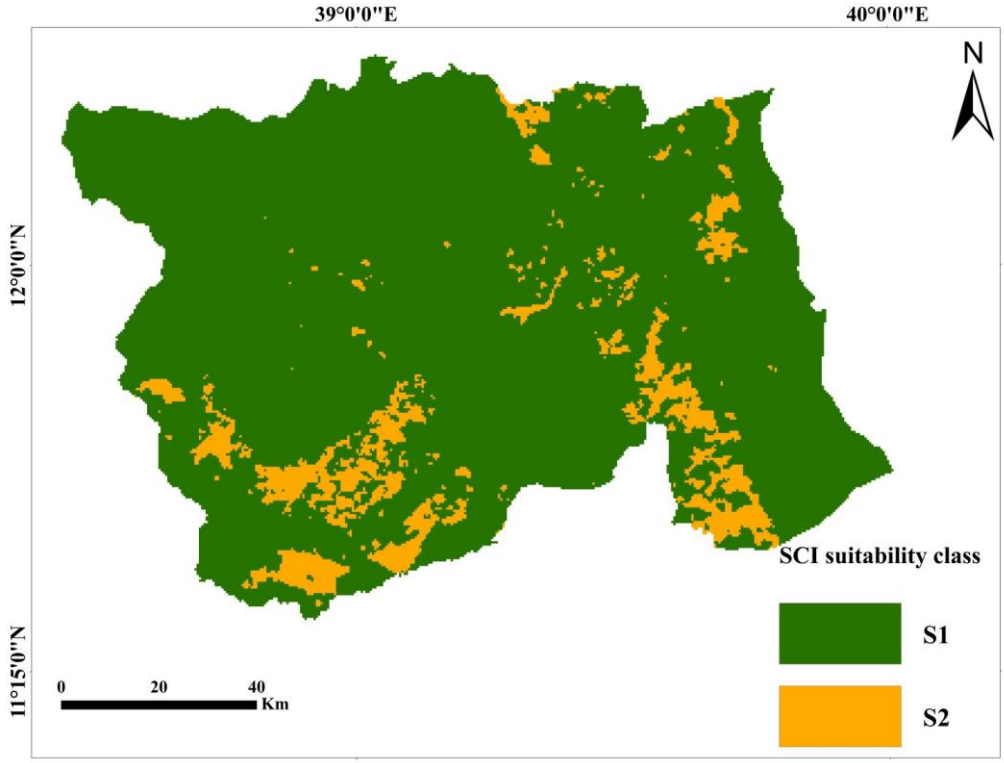


Figure 18 Soil capability index suitability

Table 9 Soil capability suitability result

N0_	Suitability classes	Area coverage (km^2)	% of total area coverage
1	S1	11500	90.63
2	S2	1189	9.37

According to SCI suitability results (Figure 18 and Table 9) showed that 90.63% of the basin is highly suitable (S1) and it has very good soil for crop production and is characterized by good water holding capacity soil, deep soil depth, and well-drained soil, and the reaming area coverage 1198km which is 9% of the area is classified under moderately suitable (S2), and have moderate water-holding, soil depth and moderate drainage characteristics.

4.1.4 Road proximity and urban center

Implementation of irrigation requires access to the market to purchase agricultural inputs and to sell agricultural outputs. The market outlet is the most dominant factor that affects irrigation suitability of surface irrigation because agricultural products and inputs need markets and roads to access users. These market outlets are expressed by population density, proximity to road networks, and urban centers. The lands close to the market and road can get inputs and sell their products easily and the area where the people live densely is good and get market quickly without consuming time and other resources. So, the area near roads, cities, and people living densely are most suitable for surface irrigation based on market access. These three factors (i.e. road proximity, city proximity, and population density) do not identify the physical potential of the land but are used to assess market availability, because an irrigation scheme needs a market to sell the outputs and purchase the inputs. Every irrigation project is installed to increase the income of the users, the community, and also the country so to study the benefit of the project asses market availability using urban and rod proximity is essential.

Euclidean distances were calculated from road networks and urban centers (Figure 7 a and b) and then classified into five suitability classes (Figure 19 a and b) due to high variability based on the equal interval approach for suitability analysis (Worqlul et al., 2017). The urban proximity map showed that the farthest point is located at a distance of 45.7 km away from the town and road proximity showed that the farthest point is 38.4 km far away from the road. The suitability of the market outlet was assessed by dividing the proximity map of the road and

urban center calculated using calculated Euclidean distance, with the nearest proximity assigned as highly suitable (S1) to the farthest proximity which is not suitable (S5) (Figure 19 a and b). The nearest proximity area gets market access within a short distance for their input and output to purchase and sell and the furthest proximity indicates that the users or irrigators are fussing to purchase the agricultural inputs and to sell their output.

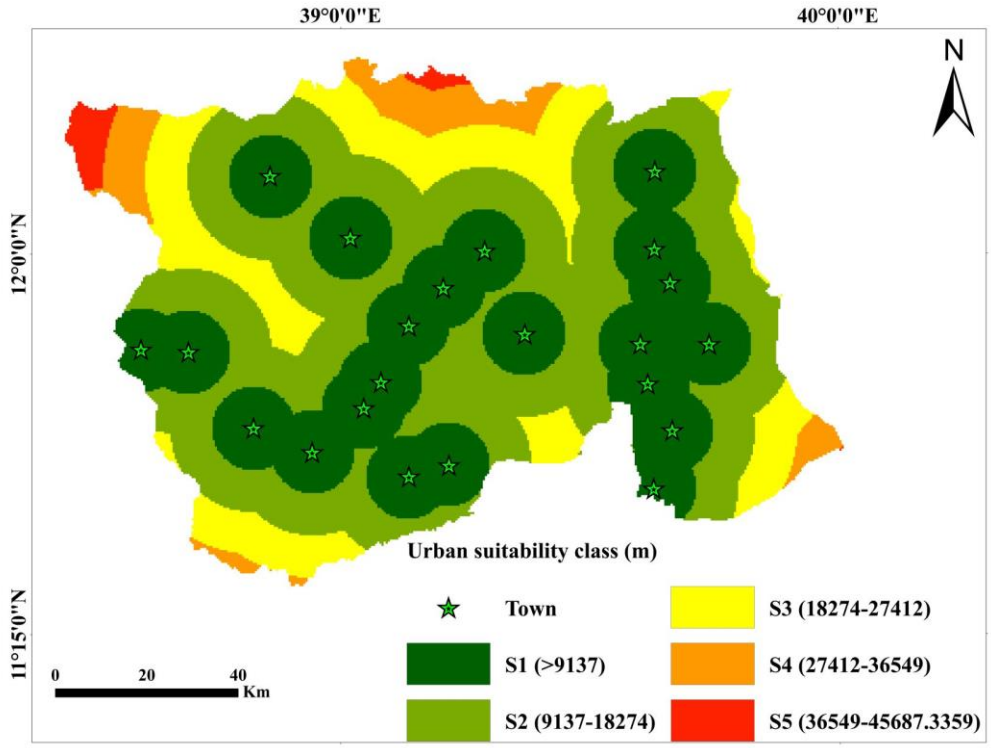
Table 10 urban suitability results

No_	Suitability classes range (m)	Area coverage (km^2)	% of Area coverage
1	S1 (>9137)	4590	36.16
2	S2 (9137-18274)	5139	40.49
3	S3 (18274-27412)	2103	16.57
4	S4 (27412-36549)	689	5.43
5	S5 (36549-45687.3359)	170	1.34

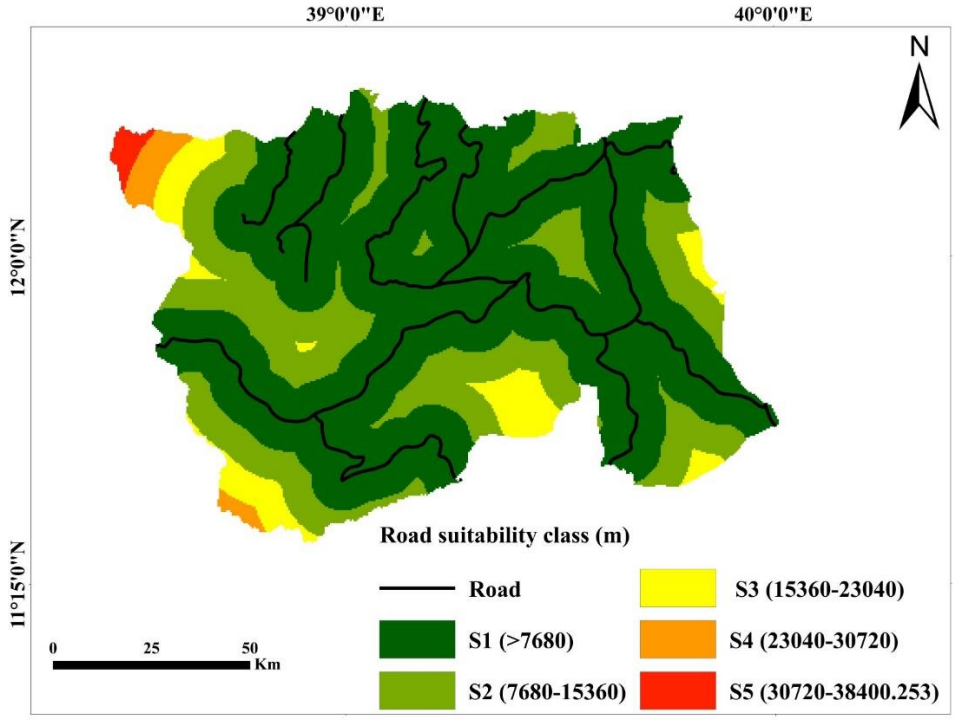
Table 11 Road suitability results

No_	Suitability classes range (m)	Area coverage (km^2)	% of Area coverage
1	S1 (>7680)	8465	66.79
2	S2 (7680-15360)	3129	24.69
3	S3 (15360-23040)	783	6.18
4	S4 (23040-30720)	215	1.69
5	S5 (30720-38400.253)	82	0.65

The urban suitability result (Table 10 and Figure 19 a) showed that 36.16% of the area is highly suitable and can get market access easily within a short distance and the irrigator easily distributes and sells their output to the users within 9 km. 40.49% of the area is found at a moderate distance from the city and classified under moderately suitable land and the user gets market access within a moderate distance of 18 km for their input need and output distribution. 16.57% of the area gets market access within a 27 km distance and is classified as marginally suitable land and 5.43% of the study area is found 36 km away from the city. The remaining 1.34% of the area was found far away from the city within 45 km and classified as a less suitable area for irrigation because it needs extra cost for transportation to get input and sell the output.



(a)



(b)

Figure 19 Suitability map of urban (a) and road (b) proximity

The result of road accessibility (Table 11 and Figure 19 b) showed that 66.79% of the study area is highly suitable for surface irrigation and can get road accessibility within a short distance of 7.6 km for their transport need. 24.7% of the area is found 15 km away from the road and classified under moderately suitable classes and access roads within a moderate distance and 6.18% of the study area is classified as marginally suitable area and gets road access within 23 km. 1.7% of the basin is accessed road between 23 km to 30 km whereas the reaming 0.65% of the area found far from roads and accessed road after 38 km and classified under not suitable for surface irrigation. The majority of the study areas are suitable for surface irrigation and can get market access easily according to urban and road suitability analysis.

4.1.5 Population density

Population density is the other potential factor to assess the market accessibility of the area. The area where the people live densely is suitable and easy for the farmer to sell their output without extra cost and in a sparse area, it is difficult to sell the output of the product. So, population density represents market access like urban and road centers. The population density ranges from 0 to 14,200 people per kilometer. The population density of the basin that is downloaded from the Global Gridded Population Database from the Center for International Earth Science Network (CIESIN) was reclassified into five suitability classes using geometric interval ranging technique due to high variability and skewed into one side. The geometric interval classification technique is adopted and best suited when the nature of the data is not normally distributed and is heavily skewed. The distribution is not normal and skewed in one direction (positive or negative skewed) the geometric interval classification technique is recommended (Kassie et al., 2022). This classification technique generates class breaks based on intervals with geometric series, the algorithm used created these intervals through square-sum minimization of element per class. In the study, area peoples are lived splay and the distribution is negatively skewed and classified into five suitable classes using geometric interval method. The area where the people live closely and highly dense is classified under highly suitable and categorized as (S1) and the density of the area is 14,200 persons per square kilometer, and people living splay and low dense are categorized under not suitable and classified as (S5) and the density is 0 person per kilometer or the people not living based on market availability (Figure 20).

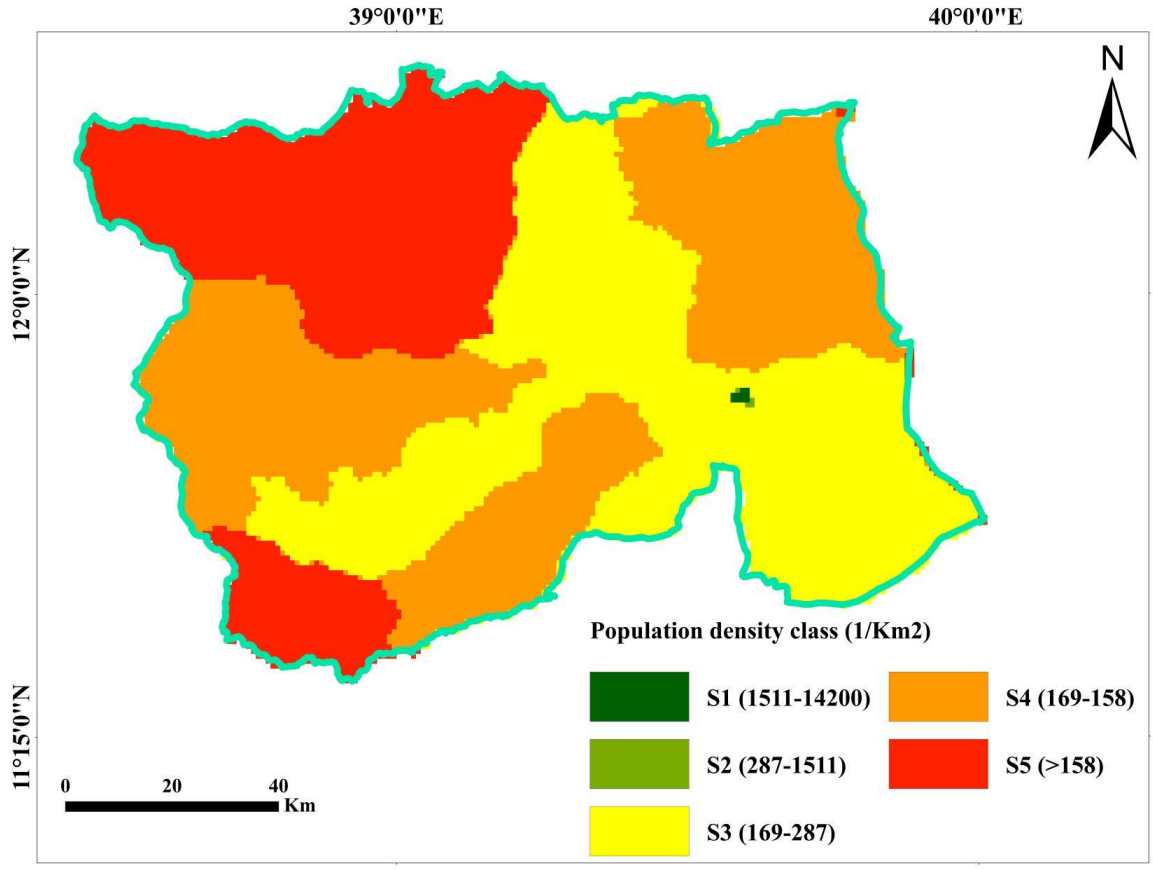


Figure 20 Population density suitability map

Table 12 Population density Suitability result

No_	Suitability classes range (population /km^2)	Area coverage (km^2)	% of Area coverage
1	S1 (1511-14200)	8	0.07
2	S2 (287-1511)	3	0.03
3	S3 (169-287)	4612	35.97
4	S4 (169-158)	4643	36.21
5	S5 (>158)	3554	27.72

The result (Table 12) showed that the people in the study area live splay and sparsely and are not suitable based on population density results. 0.07% of the basin is classified as a highly suitable area and the density is 1,511 to 14,200 persons per square kilometer. These showed that the area around the city and they are benefited from selling their output. In 0.03% of the basin, people live with a density of 287 to 1511 persons per kilometer and are classified under moderately suitable land. 36% of the basin is classified under marginally suitable class and community lives with a density of 169 to 287 persons per kilometer. In 36.21% of the basin,

people live with 169 to 158 people per kilometer, and the remaining 27.72% of the basin is classified as an unsuitable area for surface irrigation and people live sparsely below 158 people per kilometer.

4.1.6 Rainfall deficit

Irrigation is a practice designed to supplement rainfall deficit which means an imbalance between water supplied for the crop and evapotranspiration demand. During the rainy season available rainfall is high and there is no rain deficit for crop production in the dry season evaporation is high the amount of available rain is very low and empty and crops are stressed for water and supplied by irrigation water for their better growth and product. The suitability of the climate for irrigation is assessed by rainfall deficit by considering rainfall and evapotranspiration.

Monthly rainfall, temperature, wind speed, sunshine, and relative humidity of eighteen (18) stations in the study area obtained from the Ethiopian National Metrological Services Agency were used to calculate the rainfall deficit. Missed climatic data were estimated using a simple arithmetic average when the average annual rainfall of the nearest station and missed station difference within 10% and the difference above 10% normal mean ratio were used.

After all monthly rainfall data were aggregated annually to find the annual value for each station and interpolated using the IDW technique to find the whole basin rainfall data. The study area receives rainfall between 257 mm which is less amount and 1323 mm which is a high amount of rainfall. Some portion of Habru, Meket, Gubalafto, and Gidan receives a high amount of rainfall compared with others and some part of Gidan, Lasta, and Delanta woreda receives less amount of rainfall (Figure 21).

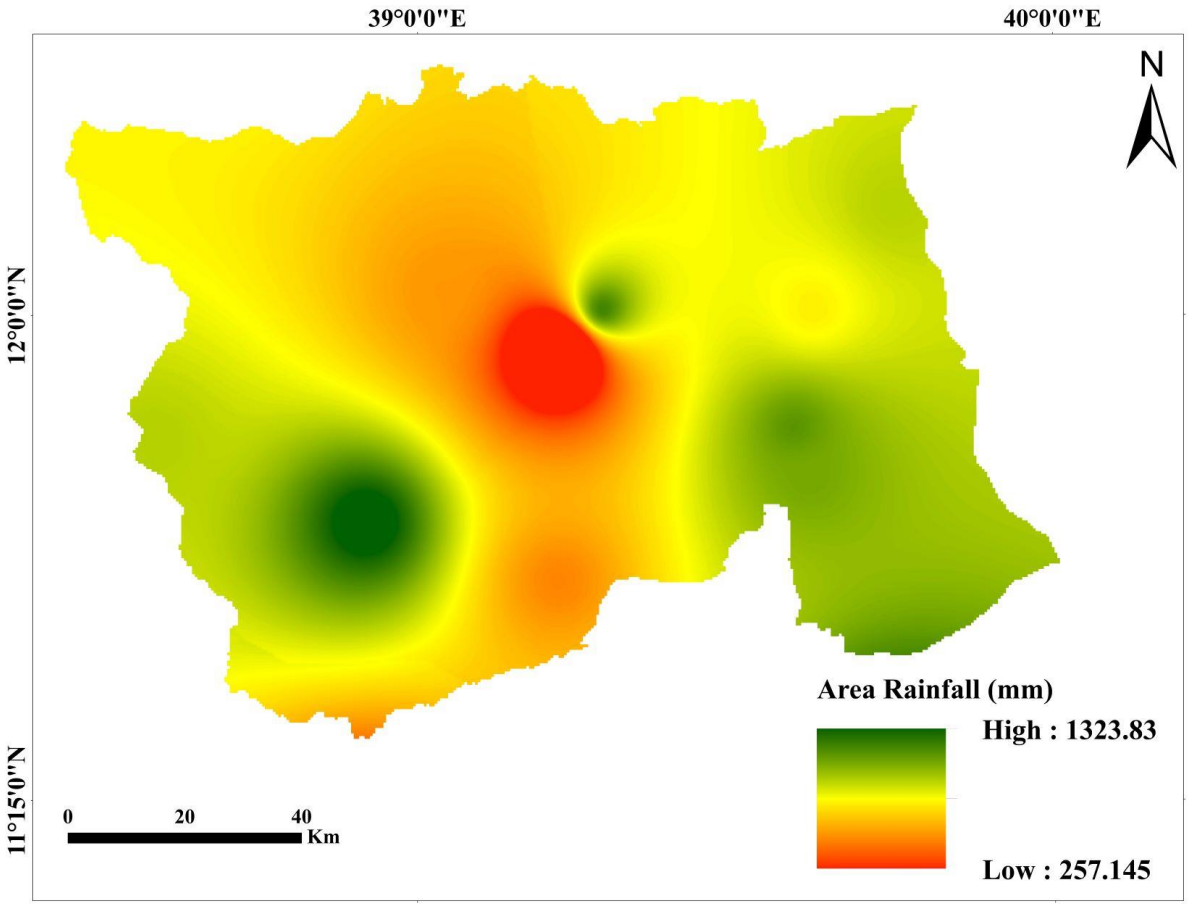


Figure 21 Rainfall of study area

Potential evapotranspiration was calculated using the FAO penman Monteith method and temperature-based method which are the station has not recorded all climatic parameters for the Penman-Monteith method and aggregated to annually and also interpolate using IDW like rainfall to find the whole study area evapotranspiration. The southern and ester part of the basin has a small amount of evapotranspiration and northern part and around cities the evapotranspiration is high. It ranges from 1352 mm to 1809 mm. Some areas of Kobo and Gubalafto are characterized by high evapotranspiration. Meket, Wadla, and Delanta have relatively less amount of evapotranspiration (Figure 22).

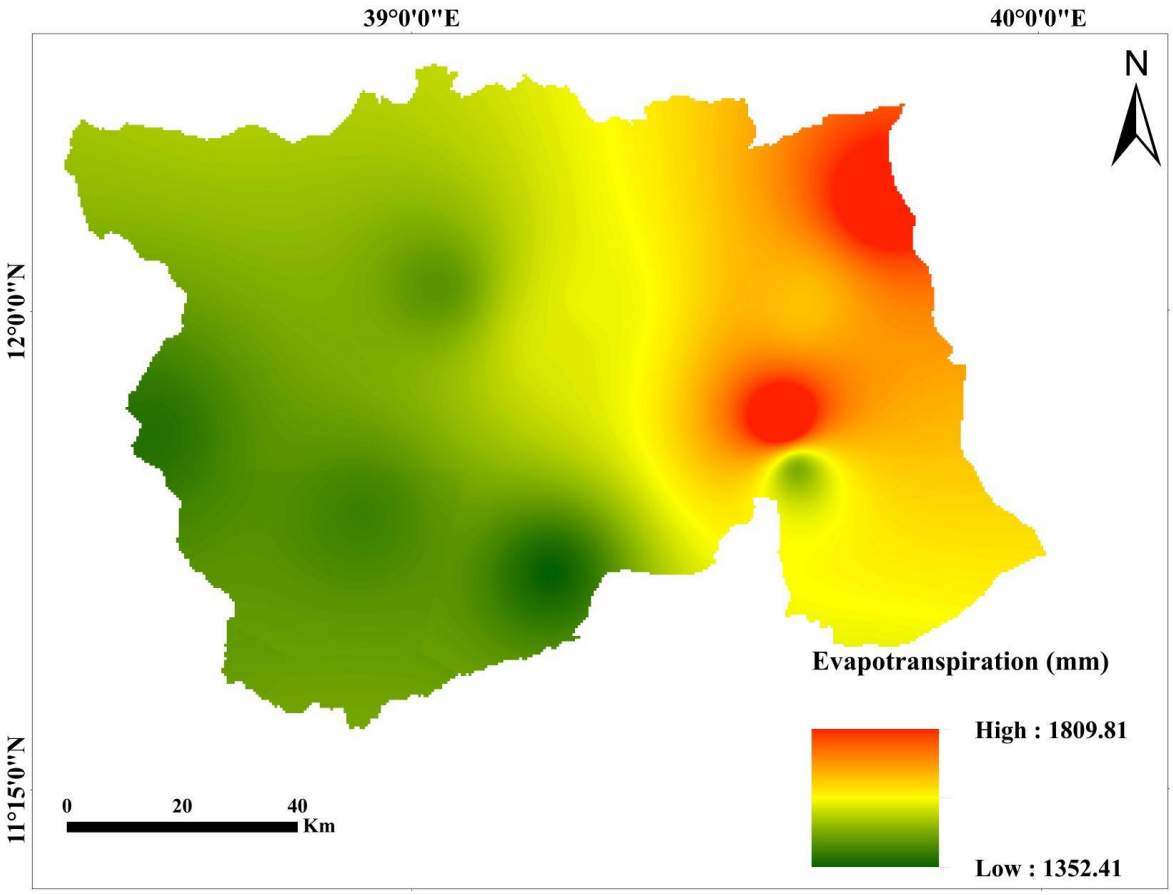


Figure 22 Evapotranspiration of the study area

By using the value of rainfall and evapotranspiration, the rainfall deficit was calculated by subtracting potential evapotranspiration from rainfall. A positive monthly rainfall deficit value indicates that the rainfall is higher than evapotranspiration and enough amount of water is available from rain and no irrigation requirement, while the negative values indicate that evapotranspiration is higher than rainfall and the crop needs additional irrigation water for their crop water requirement need; the higher the negative value means the higher irrigation requirement. In the study area, there is no positive value of rainfall deficit which means the evapotranspiration is higher than rainfall. The rainfall deficit of the study area is between -67 mm which indicates less rainfall shortage to -1249 mm which indicates that high rainfall shortage and needs more irrigation water. It indicates that Lasta, some parts of Gidan, and Kobo have high or negative rainfall deficit and require more irrigation water whereas Habru, Wadla, and Meket have a small amount of rainfall deficit or there is a small amount of rainfall deficit (Figure 23 a). These rainfall deficit data were classified by an equal interval approach into suitability classes for surface irrigation. The smaller negative value indicates that the area is

suitable for irrigation and classified as a highly suitable class (S1) and a higher negative value indicates that the area is less suitable for irrigation and classified under a less suitable class (S5)

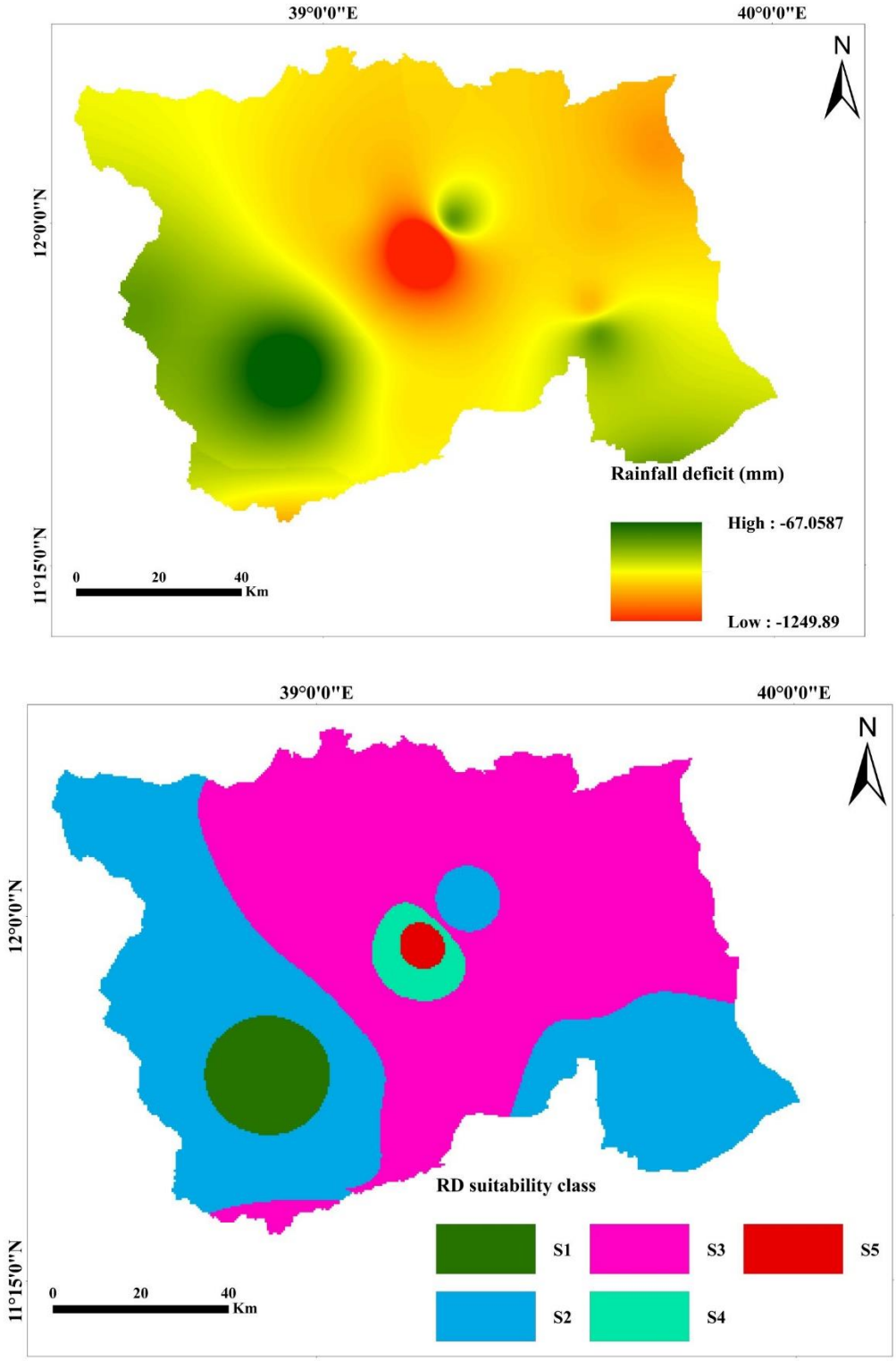


Figure 23 Rainfall deficit (a) suitability map (b

Table 13 *Rainfall deficit suitability result*

No_	Suitability class	Area coverage (Km^2)	% of the total area
1	S1	608	4.79
2	S2	5102	40.20
3	S3	6631	52.25
4	S4	264	2.08
5	S5	86	0.68

The rainfall deficit suitability result () showed that 5% of the study area is highly suitable (S1) and requires less amount of irrigation water to compensate for crop evapotranspiration needs and 40 % of the area is classified as moderately suitable area (S2) and requires a moderate amount of irrigation water for crop need and receives a reasonable amount of rainfall annually. 52% of the study area requires high irrigation water to composite their high evapotranspiration demand and is classified under marginally suitable classes (S3). 2% of the study area is less suitable according to rainfall deficit suitability result and it requires a high amount of irrigation water to fill the rainfall deficit and to meet crop water requirement whereas 0.68% of the area is not suitable for irrigation and it has high evaporation and less or no rainfall and needs total irrigation to grow crops in these areas.

4.1.7 River proximity

Surface water is an essential natural resource that plays a vital role in the irrigation and economic sector. An adequate supply of water is the main requirement for an irrigation system installation. Before installation of the irrigation system must find a source of water and determine the rate, quality, and quantities of the water. River proximity is the most important factor that decides and prioritizes the areas to be irrigated using surface irrigation by a surface water source. Agricultural land close to river networks can get water easily for crop production with short canals and small loss of water due to conveyance loss but the areas that are far away from a water source cannot access water easily and require high investment costs to construct irrigation canal to transport water and the loss of water due to conveyance, evaporation, and seepage are high.

The river network of the study was obtained from an online source of Hydro shed and also generated from the DEM of the study area downloaded from USGS. Euclidean distances were calculated for each major river in the study area and then an equal interval method was used for classification into five suitability lasses for suitability analysis due to high variability. The area close to the river or the nearest proximity is classified as highly suitable (S1) and the land that is found far away from the water source or furthest proximity is classified as not suitable (S5).

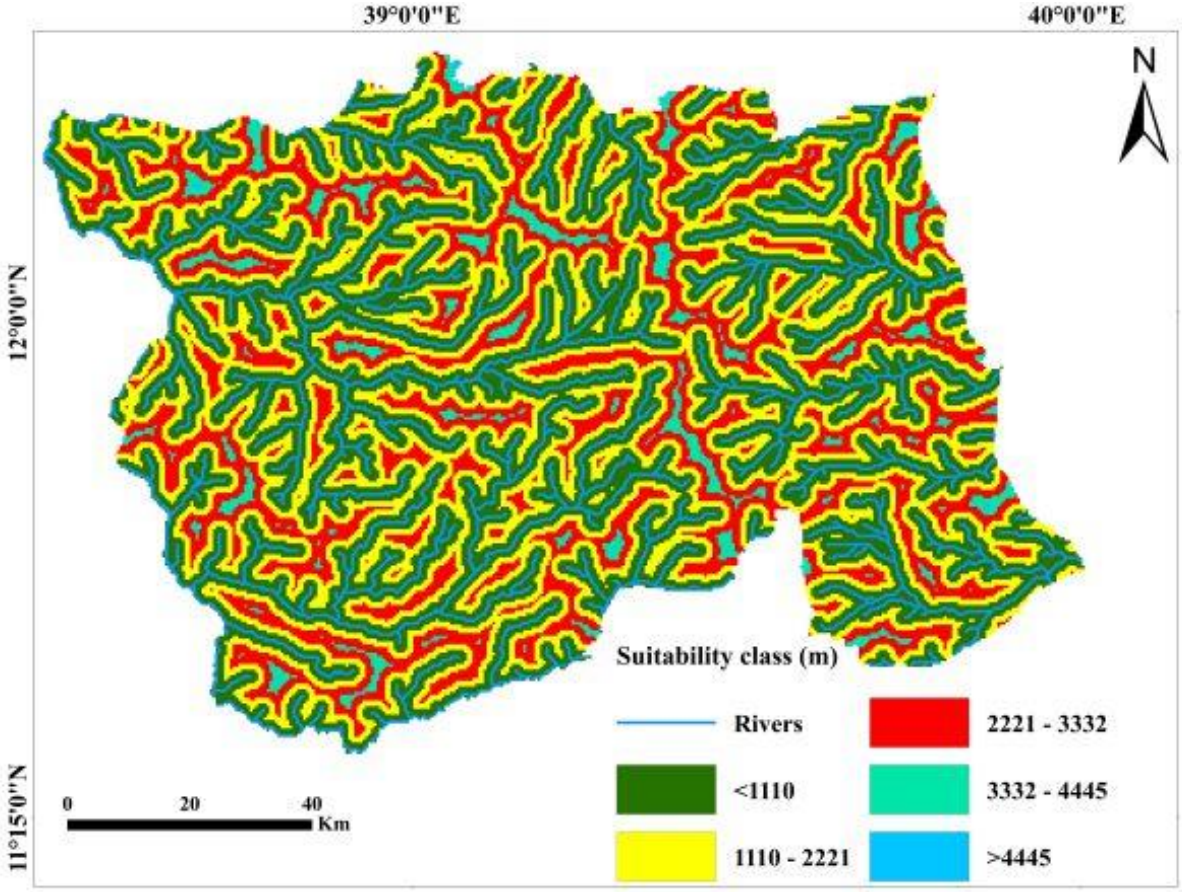


Figure 24 River proximity suitability map

Table 14 River proximity suitability result

No_	Suitability classes range (m)	Area coverage (km^2)	% of Area coverage
1	S1 (<1110)	5816.4	45.82
2	S2 (1110-2221)	3813.12	30.04
3	S3 (2221-3332)	2598.9	20.47
4	S4 (3332-4445)	454.54	3.58
5	S5 (<4445)	11.07	0.09

45.82% of the area coverage is found within the nearest proximity and near to the water source and can extract water easily from rivers for crop production within 11 km, these areas are

categorized under highly suitable area (S1), and 30% of the land is categorized under moderately suitable area (S2) and access irrigation water with a moderate distance between 11 to 22 km and 21% of the study area classified under marginally suitable class (S3) and get irrigation water with long distance between 22 to 33 km. 3.58% of the basin is found far away from the major river between 33 to 44 km and the irrigators suffering from water shortage whereas the remaining 0.05 of the area is classified as not suitable and can access water from major rivers after going above 45 km and the users are worrying to get water from a surface water source and it is not suitable for surface irrigation by a river (Table 14).

4.1.8 Groundwater depth, storage, and aquifer productivity

Groundwater is an important source of water where surface water is relatively scarce. Groundwater helps grow our foods and 64% of groundwater is used for irrigation to grow crops. Additionally, groundwater is a source of recharge for rivers, lakes, and wetlands. In some places, the use of groundwater is limited due to the presence of a high amount of dissolved salt and other contamination but it is less prone to pollution than surface water s (Eshete et al., 2024).

This study used Groundwater data such as groundwater depth and salinity to assess the suitability for surface irrigation using groundwater sources. Groundwater data of the basin were downloaded and extracted from the BGS of the African groundwater map. The groundwater depth map of the study area showed that 59.73% of the study area accessed groundwater with a very shallow groundwater depth up to 7 meters from the surface and 14.59% of the area gets within shallow groundwater accesses from 7-25 meters from the ground surface. The remaining portion of the area (25.68%) accesses water above 25 meters from the surface (Figure 15). Groundwater depth suitability assessment was done based on available water-lifting technology. The technologies considered included human, animal, diesel, or solar-powered pumps with a maximum operating depth of 50 m and pumping capacity of 0.15 l/s (Eshete et al., 2024) The majority of the study area has shallow groundwater below 25 m and is suitable for irrigation using groundwater sources favored for small-scale groundwater irrigation. According to Getahun et al. (2023) groundwater depths less than 30m are suitable for irrigation, so most of the study area 74.32% covered less than 25 m and is suitable for irrigation. According

to Worqlul et al. (2017), the depth of groundwater classified 0-7 m as S1, 7-25 m as S2, 25-50 m as S3, and above 50 m as S4. The basin has shallow groundwater (<25 m) accesses with a moderate borehole yield which makes the basin favorable for small-scale irrigation by groundwater source.

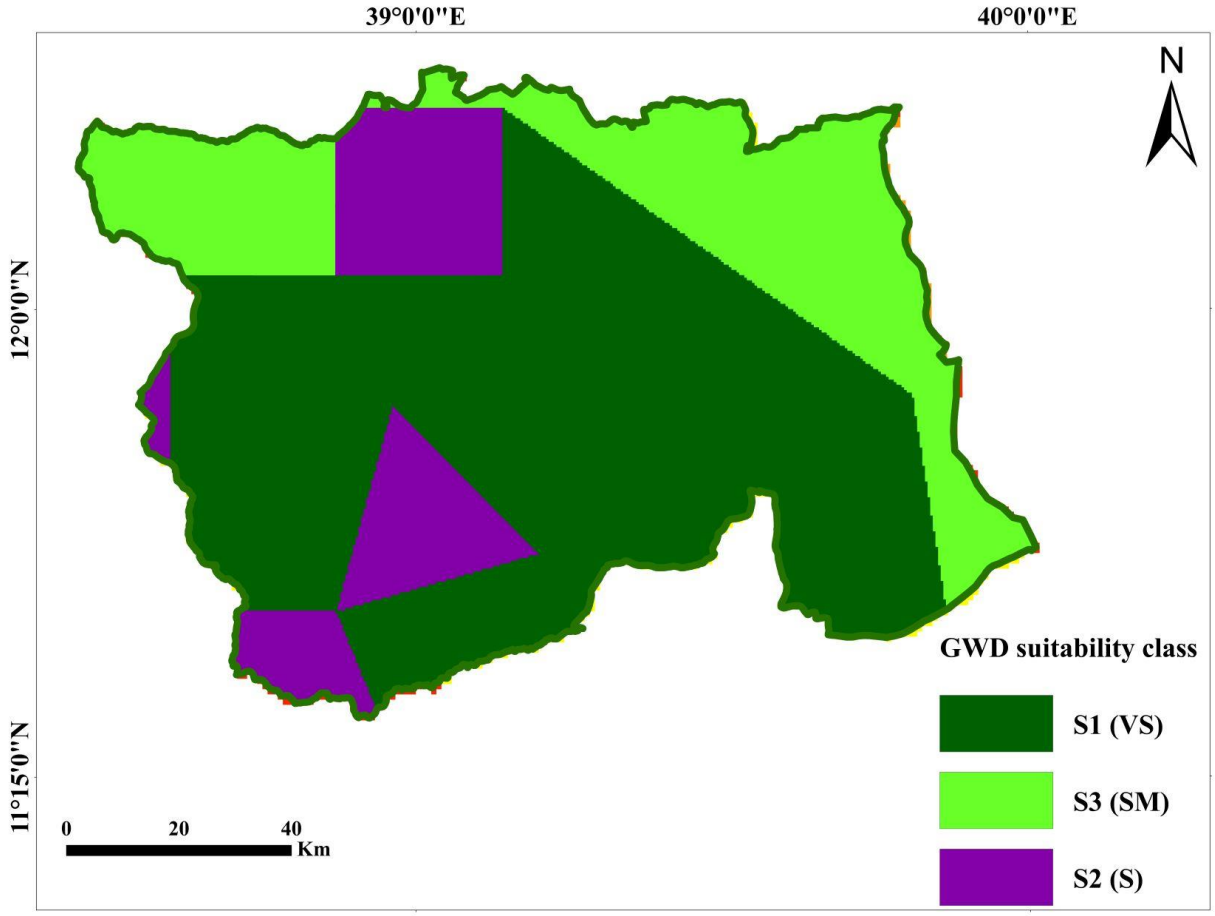


Figure 25 Suitability map of groundwater depth

Table 15Groundwater depth suitability results

No_	Suitability classes	Area coverage (km^2)	% of Area coverage
1	S1	7606	59.73
2	S2	1858	14.59
3	S3	3270	25.68

As the result (Table 15) showed 59.73% of the study area is categorized as highly suitable for irrigation using groundwater source access groundwater with very shallow depth. 14.59% of the basin gets groundwater with a shallow depth and is classified as moderately suitable (S2) whereas the rest 25.68% of the land is categorized under marginally suitable and accessed

groundwater between shallow to medium depth and classified as marginally suitable area (S3) by considering groundwater depth factors for irrigation using groundwater source. According to Worqlul et al. (2017), Aquifer productivity also classified 5-20 l/s as S1, 1-5 l/s as S2, 0.5-1 l/s as S3 and below 0.5 l/s as S4. As the result is shown (Table 16) below 0.05% of the area has aquifer with high productivity which is between 5-20l/s and classified as highly suitable (S1) area for groundwater source irrigation and almost all (99.95%) of the area have medium aquifer productivity which is between 1-5l/s and classified as moderately suitable area.

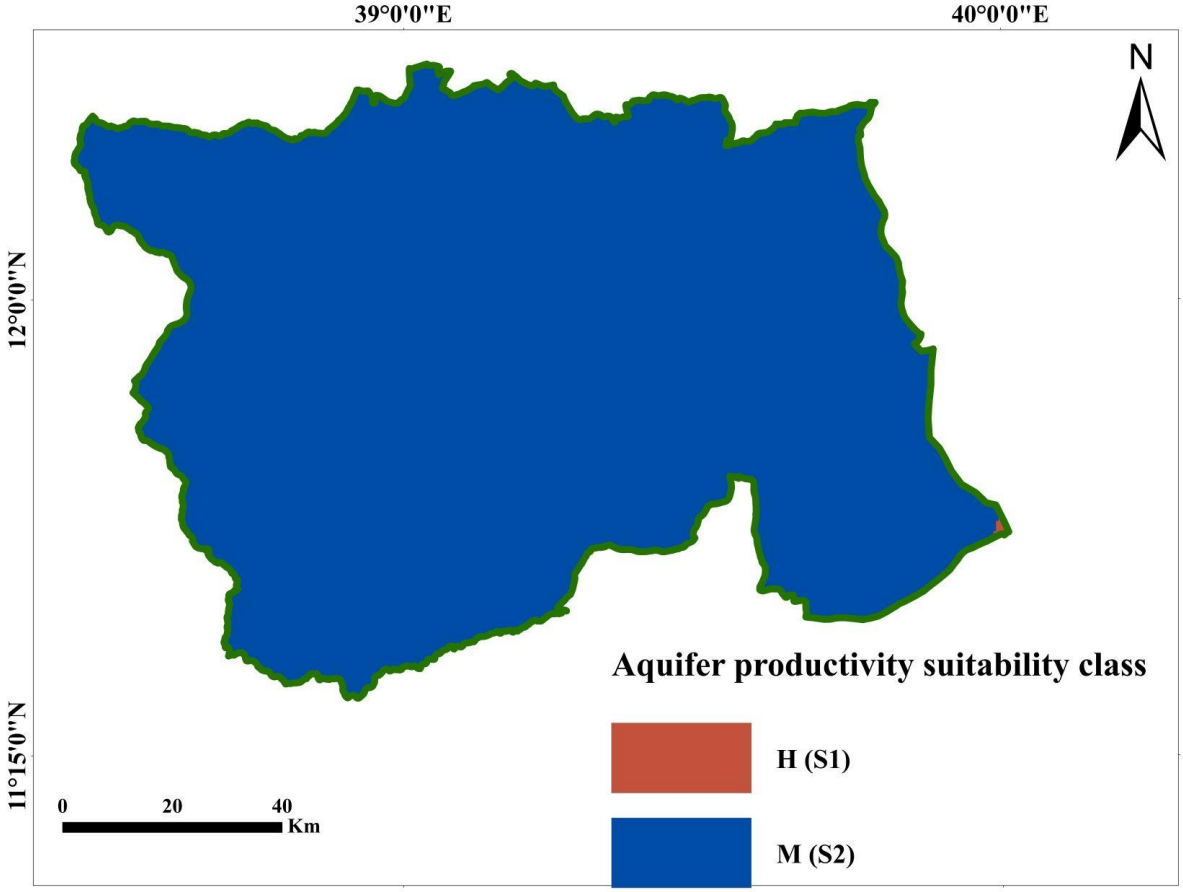


Figure 26 Suitability map of aquifer productivity

Table 16 Aquifer productivity suitability results

No_	Suitability classes	Area coverage (km^2)	% of Area coverage
1	S1	6	0.05
2	S2	12729	99.95

According to Worqlul et al. (2017), groundwater storage was classified into 100 million m^3/km^2 as S1, 10-100 million m3/km2 as S2, 1-10 million m^3/km^2 as S3, and below 1 million m3/km^2

as S4. The result showed in Table 15 that 0.45% of the area has water storage below 10Mm^3/km^2 and is classified as marginally suitable (S3) and the rest 99.55% of the area is classified under moderately suitable area and has storage between 10-100Mm^3/km^2.

Table 17 Ground storage water suitability results

No_	Suitability classes	Area coverage (km^2)	% of Area coverage
1	S3	58	0.45
2	S2	12677	99.55

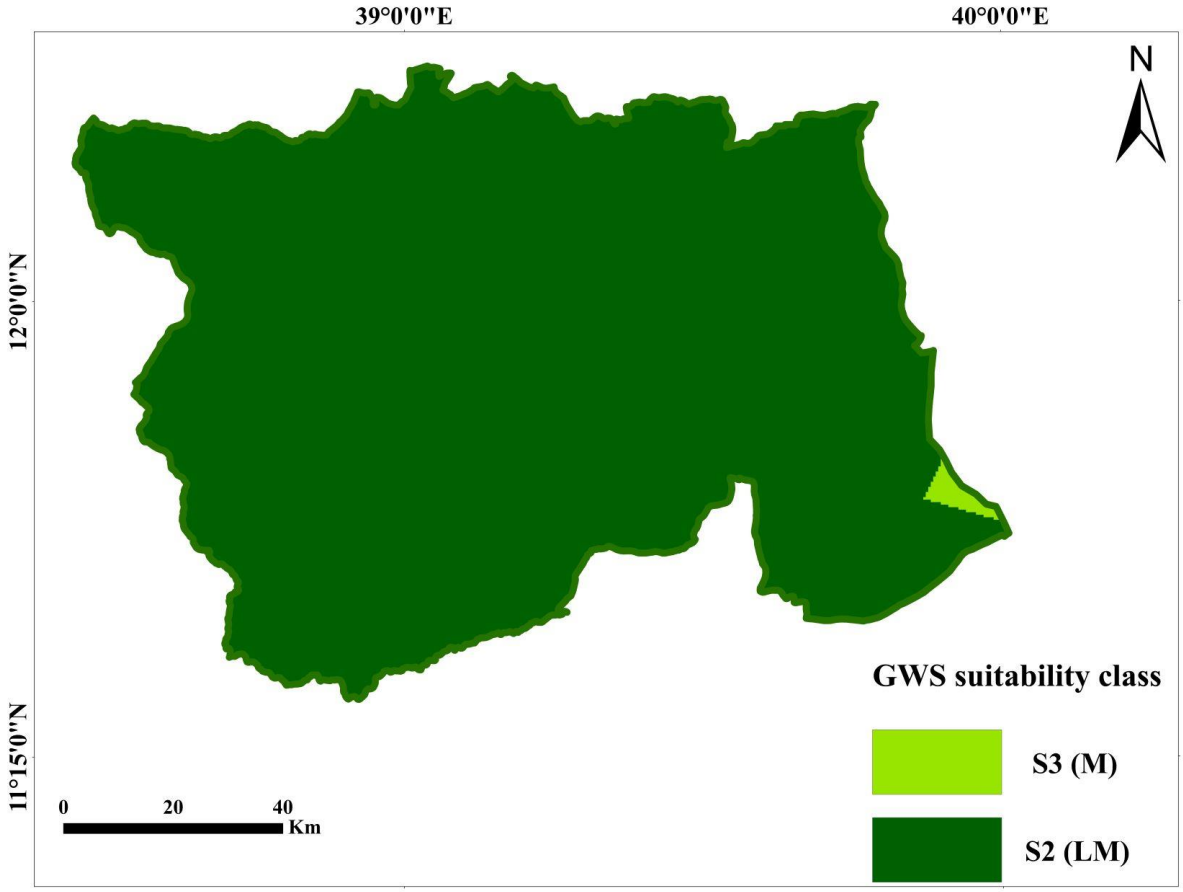


Figure 27 Suitability map of groundwater storage

4.1.9 Groundwater salinity

Groundwater is less susceptible to bacterial pollution than surface water because the soil and rocks through which groundwater flows screen out most of the bacteria. Groundwater may contain dissolved minerals and gases that give it the tangy taste enjoyed by many people. In some places, groundwater is contaminated and contains soluble salts that are not suitable for irrigation and crop production (Yohannes et al., 2017).

The quality of irrigation water for irrigation is described by salinity (EC) Sodium hazard (SAR), Residual sodium carbonate (RSC), and toxicity. The salt content of groundwater for irrigation purposes is measured by PH, electric conductivity, (EC) total dissolved solids (TDS), and others. Groundwater salinity is mostly measured by total dissolved solids (TDS) and the Britain Geological Survey (BGS) points out the salty area that has greater than 5 TDS but the study area is not included in these boundaries (Figure 28) so the salinity problem is not our issue because the irrigation water up to 275 TDS is excellent for irrigation (Tolera et al., 2023).

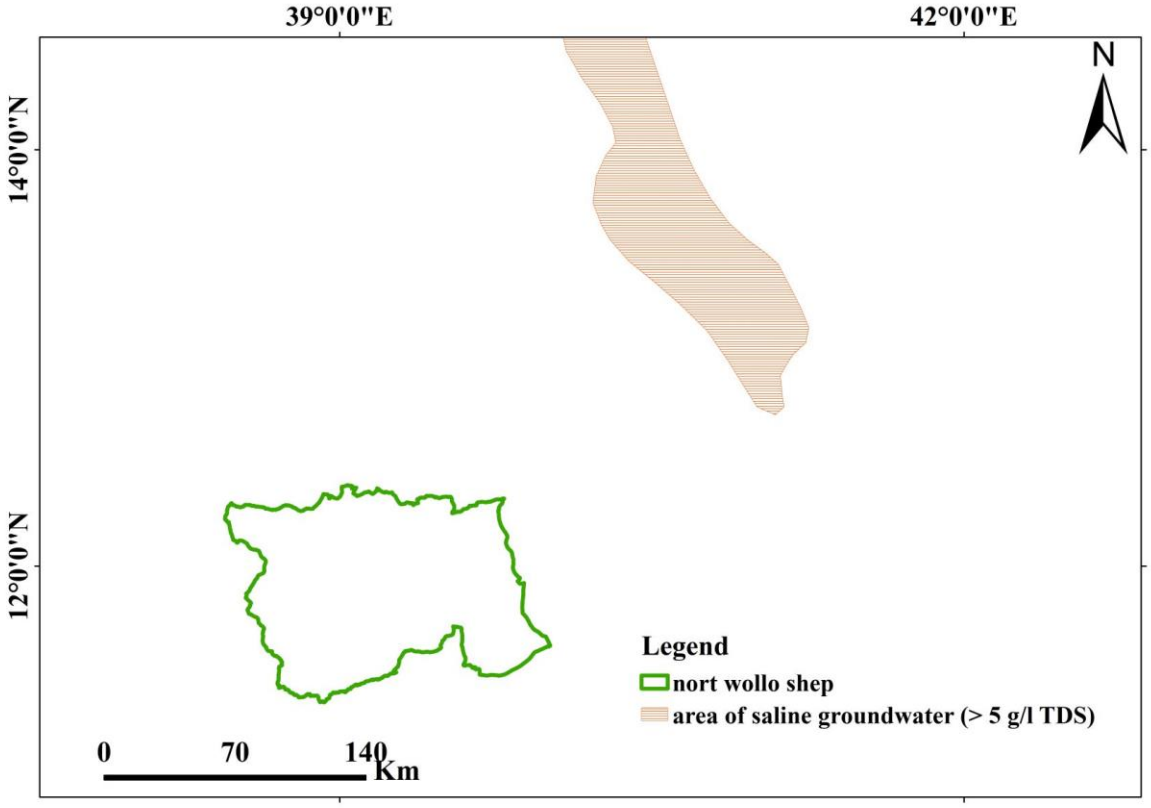


Figure 28 Area of saline groundwater (>5 g/l TDS) and study area

4.1.10 Constraints

A constraint serves to limit the alternatives under consideration. In many cases, constraints are areas excluded from the consideration that should be coded with a 0, and those open for consideration should be also coded with a 1. In this study, permanently unsuitable land (constraints) such as water bodies, major paved roads, urban/built-up areas, and protected areas were considered as constraints for physical land suitability for irrigation. A constraint map with

a value of zero and one was used to exclude the unsuitable areas from the preliminary suitable land.

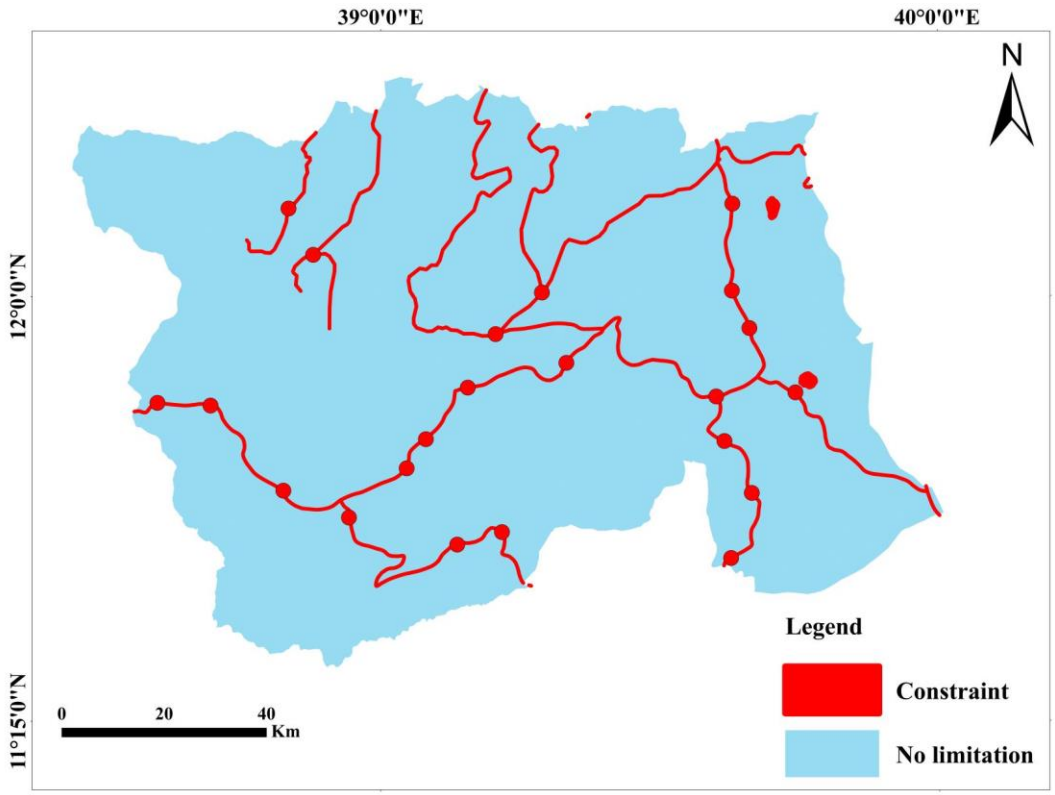


Figure 29 constraints

4.1.11 The weighting of factors for surface irrigation suitability mapping

4.1.11.1 Multi-Criteria Evaluation (MCE) Technique for the Assessment of Irrigable Land

The factors used in suitability assessment were tabulated and compared with each other means that column factors with the rows for their significance to surface irrigation, the highest value (9) corresponds to absolute importance, and the reciprocal of all scaled ratios were entered in the transpose position (i.e., 1/9 shows an absolute triviality using (Table 17), and then the pair-wise comparison matrices were filled and the weights of the factors were computed by normalizing the eigenvector by the cumulative vector. The eigenvector was calculated as the product of the row matrix. The weights are done for both surface and groundwater sources. The weight of factors was computed separately for rivers (Table 17) and groundwater sources (Table 18). Table 18 shows the comparison of each suitability factor and weights of suitability factor from river water sources and the consistency ratio of the pairwise matrix.

Table 18 *Suitability factor's scale and weight from the river*

Factors	River	Slope	SCI	Population	RD	UR	Road	Land use	weight	CR
River	1	2	3	3	4	3	2	5	26	
Slope		1	3	2	2	4	3	3	20	
SCI			1	3	5	4	3	4	18	
Population				1	2	1	2	3	10	
RD					1	1/3	1/3	3	6	
UR						1	1	3	9	
Road								2	8	
Land use								1	4	0.078

Note: SCI: - Soil Capability Index, RD: - Rainfall deficit, UR: - Urban center Source: (Nigussie et al., 2019; Worqlul et al., 2015, 2017)

Based on the results of the factors weight table above, river proximity was the most influential factor from the surface sources. Slope and soil capability index was found to be the second and the third influential factor from surface water. In Table 19, river proximity was replaced with groundwater depth, groundwater storage, and groundwater productivity were added when computing the weight for irrigation suitability from groundwater source while the remaining six parameters were the same and all are compared each other by scale in the table and the weight and consistency ratio were developed.

Table 19 *Suitability factor's scale and weight from groundwater*

Factors	GW	Slope	GWP	SCI	GWS	Pop	RD	UR	Road	Land use	weight	CR
GW	1	3	3	3	3	3	4	3	5	7	27	
Slope		1	3	3	3	3	4	3	3	3	17	
GWP			1	2	2	3	3	4	5	5	14	
SCI				1	2	3	5	4	4	5	13	
GWS					1	3	3	3	4	4	9	
Pop						1	2	1	2	3	4	
RD							1	2	2	2	4	
UR								1	½	3	4	
Road									1	2	5	
Land use										1	3	0.066

Note: GW: - groundwater depth, GWS: - groundwater storage, GWP: - groundwater productivity, Pop: - population. Source: (Assefa et al., 2018; Worqlul et al., 2015).

Based on the results of the factors weight table above, groundwater depth was the most influential factor from groundwater sources. Slope, GWP, and soil capability index were found to be the second, third, and fourth influential factors from a groundwater source. After all the consistency ratio was calculated using cumulative eigenvector and the weight module to check the consistency of the developed matrix, and the acceptable CR value is up to 0.1 based on (Saaty, 1977). The consistency of the pairwise matrix was checked, CR = 0.078 and 0.066, for surface and groundwater sources, respectively, and below the acceptable limit.

4.1.12 Weight overlay

After each suitability parameter was assessed, reclassified and the weight was developed separately the weights were distributed to individual factors of suitability classes based on an equal interval ranging technique, and the factors were combined using a weighted sum overlay to obtain the final suitability map of both surface and groundwater source.

The value of the suitability index ranges from 0 (permanently unsuitable land) to 100 (most suitable land). For surface water sources the suitability index map value (Figure 29) showed the range from 46% to 97%, where 46% of the suitability map value indicates that the area are least suitable land for irrigation and 97% of the suitability map value indicates highly suitable for irrigation production. As the percent of suitability increases from the least suitable range (46%) to the most or highly suitable range 97(%), the land suitable for crop production and irrigation practice is increased and becomes suitable above the 85% threshold value of suitability. Habru, Kobo, Wadla, Gubalafto, Delanta, and some parts of Gidan have more suitable areas than other Woreds in the study area. On the other hand, some parts of the Bugna, Dawnt, and north part of Lasta woreda are less suitable areas for irrigation from river sources (Figure 29).

For groundwater sources, the suitability map value (Figure 30) ranges from 63 to 95%, where 63% indicates the least suitable area for crop production and 95% value indicates that the area is highly suitable for irrigation by groundwater source. Irrigation from groundwater sources requires enough amount of groundwater at shallow depths which makes the area less suitable for irrigation by groundwater source than the surface water source. Habru, Wadla, Mekete, Kobo, and Gubalafto have a more suitable area from a groundwater source. On the other hand,

Bugna and some parts of Dawnt are low suitable for irrigation by ground water source (Figure 30).

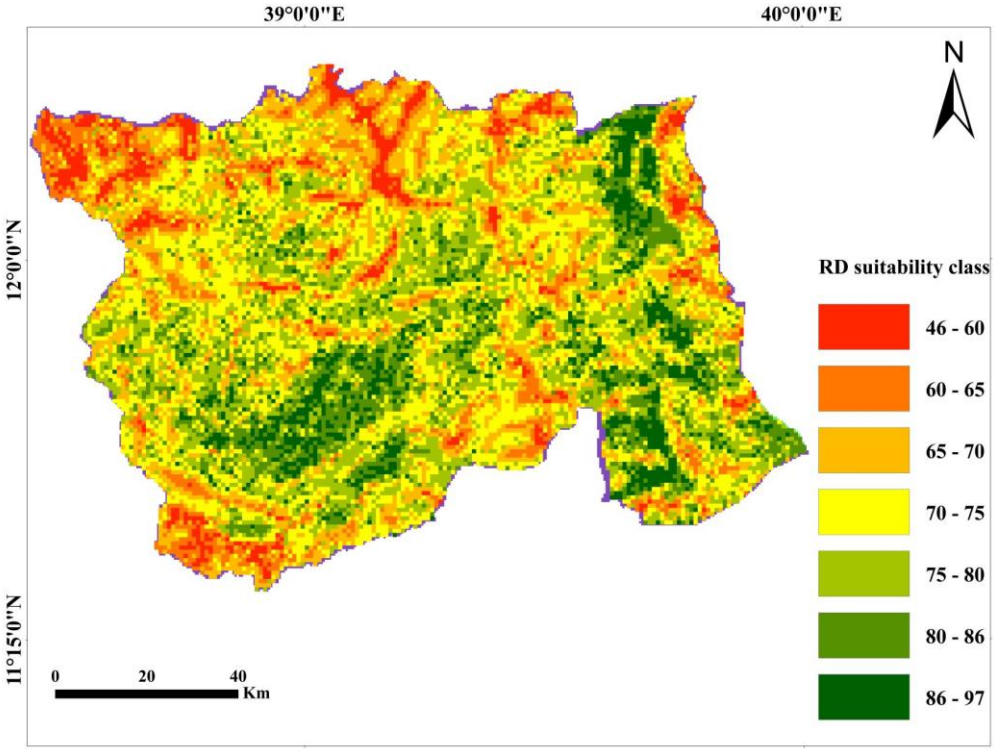


Figure 30 Suitable land from surface water source

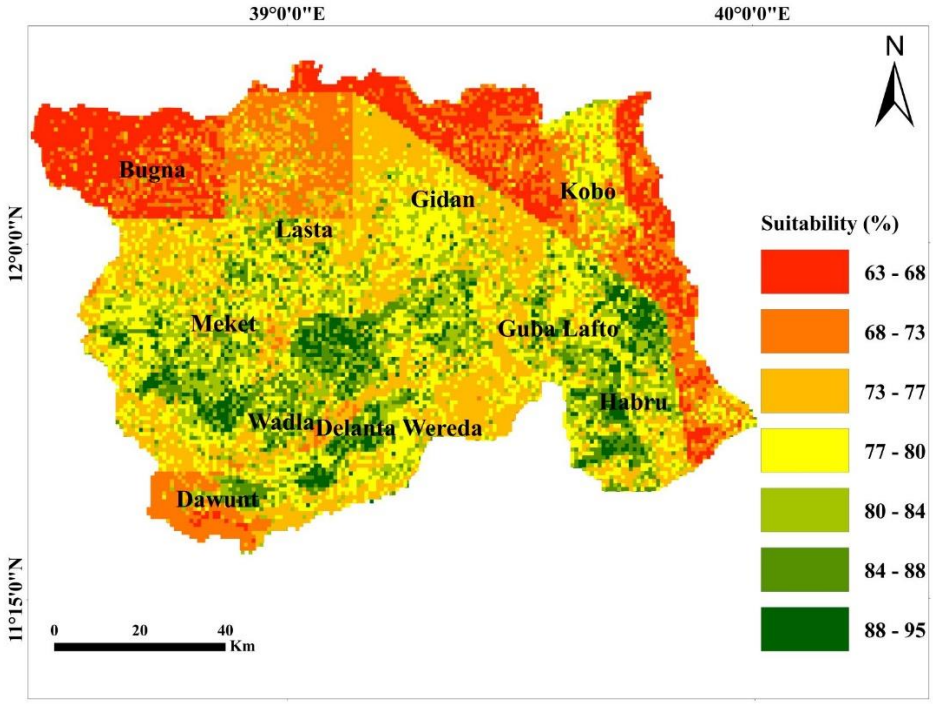


Figure 31 Suitable land from the ground water source

The suitability map of the study area from surface and groundwater sources (Figure 31) was further classified at 80 and 85% threshold values to know the suitable area for surface irrigation for Woreda in the study area. But these not to say that the area below 80% suitability value is not suitable for irrigation but this area requires high initial investment cost for land preparation, construction of a longer irrigation canal to supply water, drilling of a deep well for groundwater source and needs market access and road access to fit for irrigation. The suitability map from the surface water source indicates that at an 85% threshold level 18% or 2303 km^2 of the study area is suitable for surface irrigation and at an 80% threshold level 39% or 4857 km^2 of the land is suitable for irrigation and showed that the threshold level decreases the suitable area is increased but it needs high initial investment cost for land leveling and cleaning and the threshold value increased to 100% the area are very suitable and not need extra cost for land preparation. Additionally, the suitability map of groundwater source showed that at an 85% threshold level, 26% or 3326 km^2 of the basin was suitable for surface irrigation and at an 80% threshold level 53% or 6635 km^2 of the area was suitable for irrigation by groundwater source. At the 85% threshold level the suitability map was extracted by Woreda boundaries and the suitable area of each Woreda is calculated and tabulated below.

Table 20 Potential suitable land in Woreda of the study area from the river water source

Woreda	Total area coverage of Woreda (Km^2)	Potentially irrigable land in Woreda (km^2)	% of suitable area coverage from total area coverage
Bugna	1238	35	2.8
Kobo	1784	724	40.6
Gidan	1082	124	11.5
Meket	1893	371	19.6
Wadla	860	359	41.7
Delanta	1036	166	16.0
Habru	1193	405	33.9
Guba Lafto	977	191	19.5
Lasta	1127	88	7.8
Dawunt	600	27	4.5

Table 20 indicates the area of Woreda in the study area and their irrigation potential at an 85% threshold level for surface irrigation using a surface water source. The result showed Kobo Woreda has the largest area of suitable land for agricultural production, especially for irrigation which is approximately 724 km^2 of area coverage from the total area of 1784 km^2 which is 40% of the total coverage. Wadla has the largest percentage of suitable land for surface irrigation which is 42% of the total area followed by Kobo (41%) and Habru (34%). Bugna and Dawnt have the smallest area of suitable land which is 35 km^2 and 27 km^2 and have the smallest percentage of area coverage which are 2.8% and 4.5% of the total area of Woreda respectively.

Table 21 Potential suitable land in Woreda of the study area from the groundwater source

Woreda	Total area coverage of Woreda (Km^2)	Potentially irrigable land in Woreda (ha)	% of suitable area coverage from total area coverage
Bugna	1238	28	2.2
Kobo	1784	629	35.3
Gidan	1082	200	18.4
Meket	1893	783	41.5
Wadla	860	353	41.2
Delanta	1036	381	37.0
Habru	1193	548	45.4
Guba Lafto	977	341	35.3
Lasta	1127	228	20.2
Dawunt	600	111	18.7

Groundwater source suitability result (Table 21) showed the area of woreda in the study area and their irrigation potential at 85% threshold level for surface irrigation using groundwater source. The result showed that the Meket has the largest area of suitable land for irrigation which is approximately 783 km^2 of area coverage from the total area of 1893 km^2. And Habru has the largest percentage of suitable land for surface irrigation which is 45% of the total area. 98% of Bugna is not suitable for irrigation using groundwater sources. The suitable area of the Bugna is 28km^2 of land. Additionally, has the smallest percentage coverage of suitable land 2.2%.

4.2 Gross Irrigation Water Requirements of the Identified Command Areas

The amount of water required to compensate for the evapotranspiration from the cropped land is defined as crop water requirement. The crop water requirement depends on the prevailing climate condition, crop type, stage of crop growth, and soil properties. The dominant crops grown in the study area are wheat, maize, and sorghum from cereal crops. Root vegetables are also grown in the zone onion, potato and tomato are dominant. The crop coefficient and growing period of the dominant crop were extracted from the FAO–56 manual. According to this FAO manual, the listed cereal crops have a close crop coefficient and an average of 0.3, 1.15, and 0.4 for the initial, mid, and late-season stages respectively. The growing period of the dominant crop ranges between 130 and 140 days. Based on these data the crop requirement of the dominant crop was calculated using CROPWAT 8.0 software by inputting the parameter of crop, soil, and climate at 60% irrigation efficiencies to account for water losses due to conveyance and application. Net irrigation requirements were calculated by subtracting effective rainfall from crop water requirements. The maximum irrigation requirement in the basin is 426 mm and the minimum is 58 mm (Figure 32).

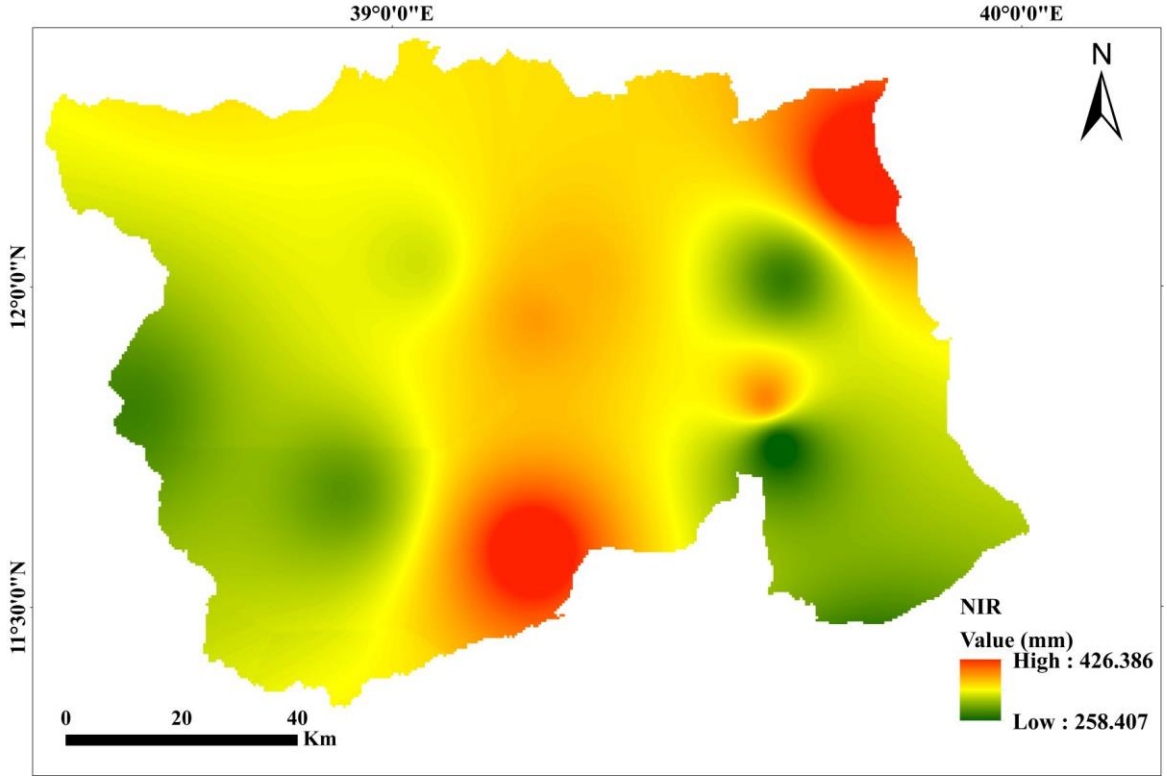


Figure 32 Irrigation water requirement of the study area

4.3 Surface water potential

Irrigation development requires assessment of the potential of the rivers and groundwater because assessing the suitability of land is critical to the development of productive and economically viable irrigation schemes (FOA, 2007). The potential of water resources is computed by comparing the irrigation water requirement of the dominant crop in the study area that is suitable for surface irrigation with available water. In the majority of the study area rainfall is sufficient for crop water requirement from June to September and it needs high irrigation water for the dry season from December to March. The Low-flow (Q90) potential of rivers was analyzed and compared with crop water requirement in the study area to know the irrigable area by water without constructing storage. The comparison was done in the case study by considering the gauged rivers of Merssa, Megenagna, Alawha, and Golina River Gauge station.

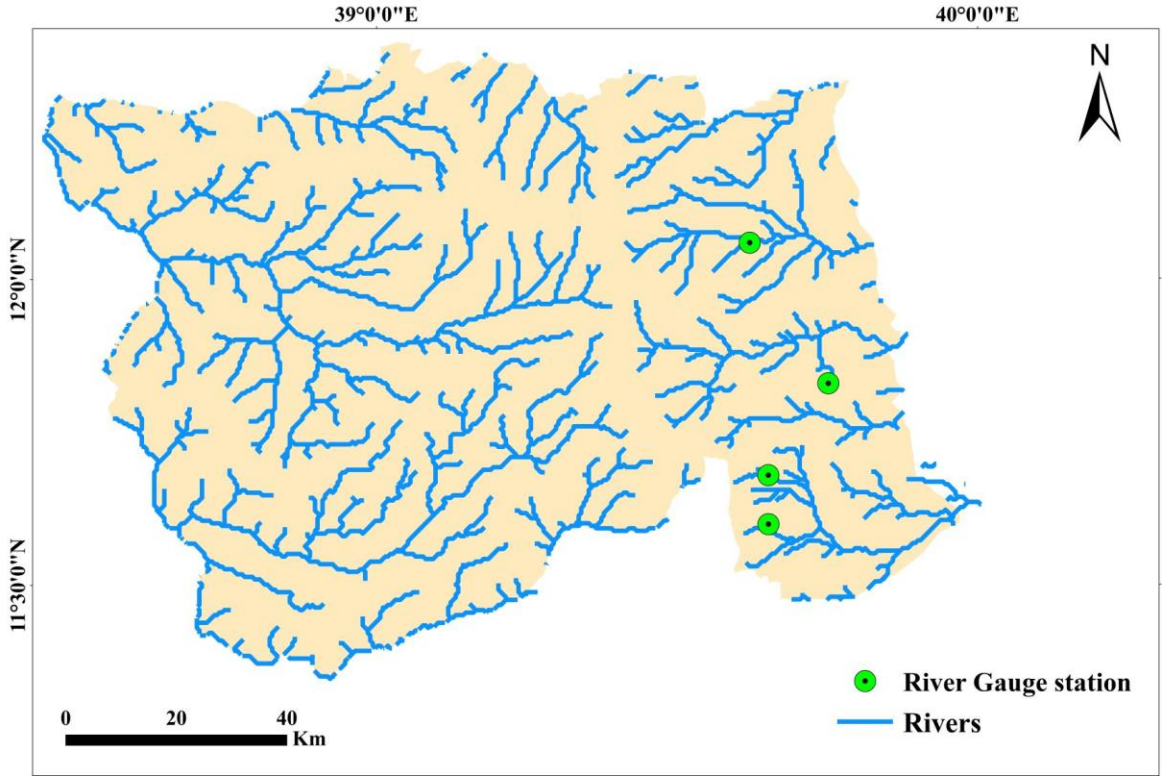


Figure 33 River gauge location

Low flow (Q90) analysis of the river is done by CumFreq model. The CumFreq model calculates the cumulative (non-exceedance) frequency distribution fitting a given data series (Hussien et al., 2019). So, the non-exceedance probability at 10% is used as a means to calculate

the exceedance probability of 90% to compare available water resources to irrigation requirements in a sustainable base and to avoid water scarcity. The input data of the model were the monthly river flow of Merssa, Megenagna, Alawha, and Golina. The missing value was done using the regression technique when the missed year was high and used average of adjacent year records when the missed year was small.

Table 22 River potential at 90% exceedance probability

	90% exceedance probability (Mm3)											
River name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Merssa	0.001	0.003	0.009	0.019	0.02	0.01	0.03	0.04	0.1	0.08	0.07	0.05
Megenagna	0.10	0.08	0.10	0.10	0.08	0.08	0.16	0.20	0.16	0.14	0.11	0.09
Alawha	5.2	4.5	4.5	1.4	2.1	1.8	1.8	1.3	1.0	1.1	2.2	1.7
Golina	1.0	0.7	0.8	0.7	1.3	1.6	1.3	1.3	0.4	0.4	0.5	0.4

The irrigation potential of the river is calculated by comparing the irrigation water requirement and river flow at a 90% exceedance probability. The potential of the river is tabulated below and it irrigates the last area without the need for storage.

Table 23 *Irrigable area by surface water source*

River name	IR (mm)	Q (@90%) (Mm^3)	River potential area	
			Km^2	Ha
Merssa	258.4	0.069	0.267	26.7
Megenagna	258.4	0.403	1.560	156
Alawha	389.1	16.366	42.06	4206
Golina	426.4	3.133	7.34	734

The result in the above table indicates that Alawha has the highest Q_{90} potential and high irrigation potential at 42 km^2 followed by Golina River which is a 7.34km^2 area of land. 51 km^2 of land can be irrigated at the gauge location of the river. The largest potential was obtained from the Alawha River 82% of the potential was covered by this river. This potential of rivers indicates the potential without the need for storage or construction of dams. According to Tadesse & Jothimani (2024), the study area generates the largest annual runoff, and most of the water potential is lost and drained so it needs a storage dam and water harvesting structures

during the rainy season for the use of the dry season to maximize the potential of the river. There are various challenges and opportunities to expand irrigation activities in our country from surface and groundwater sources. Inadequate awareness of irrigation water management as in irrigation scheduling, water-saving irrigation technologies, cost of operational, development, and irrigation equipment, adequate community involvement, scheme-based approach rather than area-based approach, poor economic background of the user to access irrigation technologies and agricultural input, shortage of technical knowledge on an irrigation pump, drip, sprinkler and inadequate baseline data on the development of water resource are the major challenges for irrigation development whereas abundant water resource, climate and land suitability, availability of inexpensive labor, and government strong political commitment to private and public sector involvement in irrigation are opportunities to expand irrigation activities in our country Ethiopia (Haile & Kasa, 2015).

4.4 Validation of result

4.4.1 Validation of result from surface source

The validation was done by comparing the result of suitable land from the river source and the location of two selected irrigation projects which are the Timtimat and Alawha irrigation projects in Wadla and Gubalafto woredas.

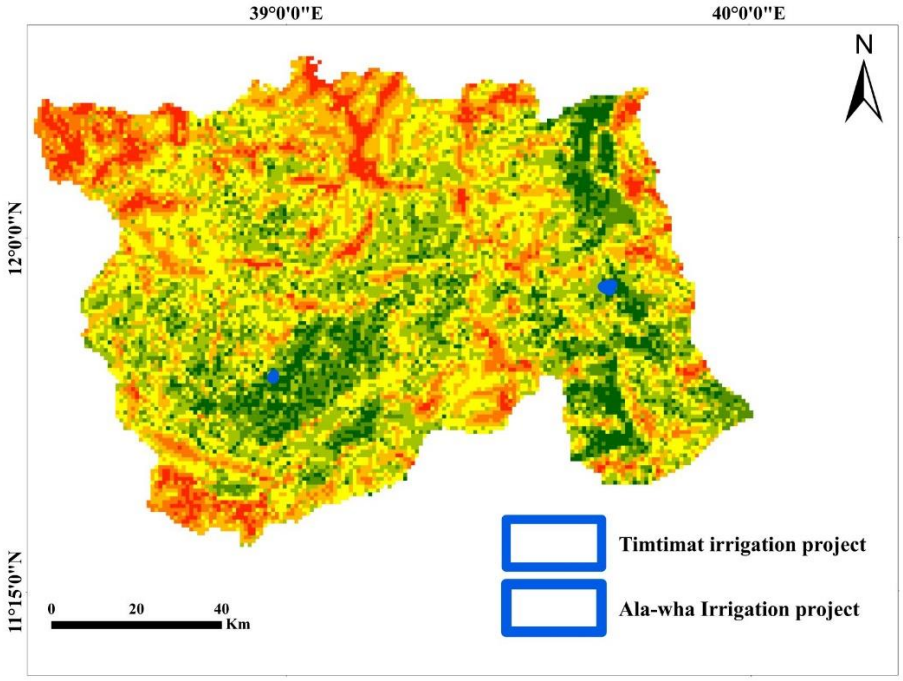


Figure 34 Study result and existing irrigation project for validation

The result of suitable land from the river and groundwater source of these studies showed that the area of the irrigation project of Timtimat and Alawha is found in the suitability map of these studies (Appendix Table III).

Figure 34 showed that, the comparison of results from the study and existing irrigation projects in the study area. As the map shows the suitable land from the river source is beastly fitted with existing irrigation projects. 100% of Alawha and Timtimat irrigation projects were found in the suitable area of the study at an 85% suitability threshold value.

4.4.2 Groundwater depth validation

Groundwater depth validation was done in the study area by connecting and comparing wells drilled in the zone with suitable areas from groundwater in the study. The comparison showed most of the wells in Figure 35 are found in the suitable area of the result except one well. Bilbala of Lasta is not found in the suitable area but found very near to the suitable area in the study this study considers not only groundwater but also different suitability factors based on these Bilbala wells are out of the suitable area and the well is constructed for drinking or domestic water use and near to the city as shown in Appendix Table V.

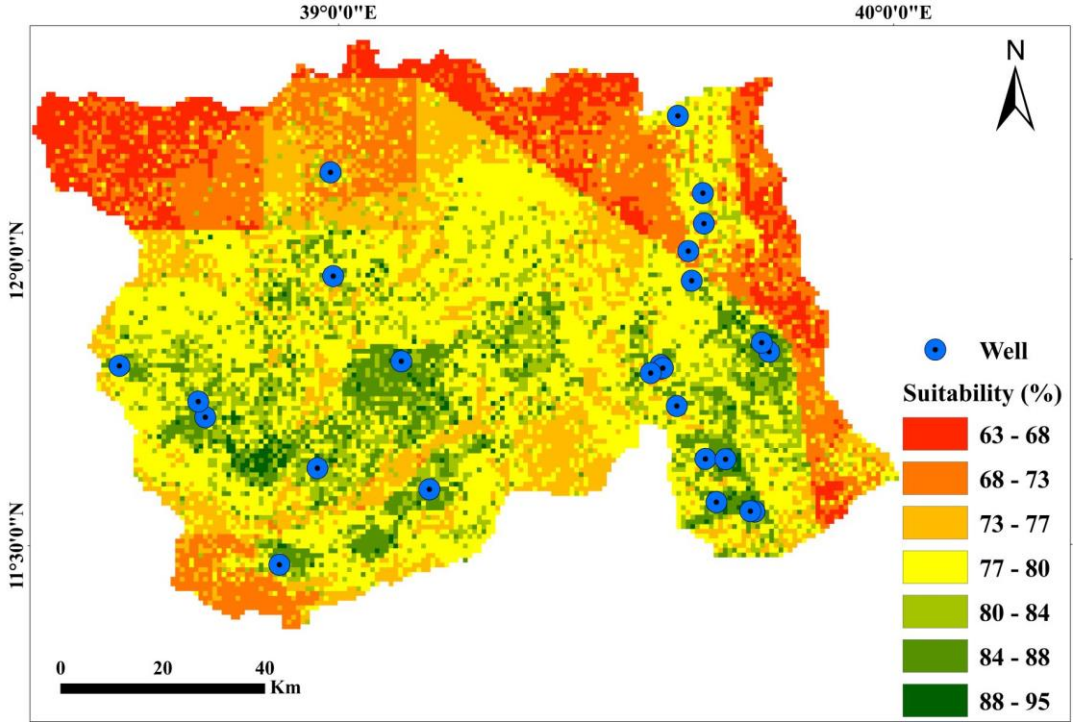


Figure 35 Suitable area from groundwater and well data

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Irrigation potential assessment is used for irrigation development and of the existing irrigation projects by providing full information. This study suitability evaluation for surface irrigation guides in cases of conflict between rural land use and urban or industrial expansion, by indicating which areas of land covers /uses are most suitable for irrigation and also use for decision-makers for future irrigation development.

Physical, climatic, and socio-economic factors were considered such as slope maps, land use land cover, soil data, rainfall deficit, road, and urban proximity. In addition to this river proximity was used for surface water sources and groundwater depth, storage, aquifer productivity, and salinity were considered for groundwater sources. These data were collected from online sources and governmental and non-governmental sources.

The result showed that 2.4% of the area is highly suitable by considering slope, and most of the land 75% in the study area characterized by a slope greater than 8% and unsuitable slope for surface irrigation and according to land use and land cover around 36% of the land are suitable and activate for irrigation. Soil suitability was evaluated by the Soil Capacity Index (SCI) and 90% of the study area is suitable for irrigation. This study try to assess the suitability of socio-economic factors from that 36% and 66% of the area are suitable by urban proximity and road proximity respectively. In 0.07% of the area, people live densely and in suitable areas by considering market access. Similarly, by considering the climatic factor (i.e., rain and evapotranspiration) 4.79% of the area is suitable for surface irrigation. In addition to these 45% of the area is found at a reasonable distance from river water sources and can get water easily for use and 59% of the area gets groundwater below 7 m groundwater depth. 0.45% of the area has high groundwater storage and 0.45% of the area is found in highly productive aquifer.

After all, the individual suitability factor was overlaid and suitability maps were developed for both surface and groundwater sources. The result showed that at an 85% threshold level 2303 km^2 which is 18% of the study area is suitable for surface irrigation from river water sources and 3326 km^2 which is 26% of the area is suitable for a groundwater source. Topography (slope) was the most limiting factor for irrigation for both surface and groundwater sources next to

river proximity and groundwater depth respectively. The validation result showed that suitable areas from river sources are beastly fitted (100%) with the selected existing irrigation projects in the study area and suitable areas from groundwater sources are validated using wells data (actual drilled well) constructed for domestic use in the study area and have good relation with the result.

The hydrological analysis was done to evaluate the potential of surface water by comparing the irrigation water requirement of crops grown in the study area with river potential the maximum irrigation requirement is 426 mm and the minimum is 258mm for cereal crops and the potential evaluation result showed that 51 km^2 of land can be irrigated by surface water at the gauge site of the river without the construction of the dam and other water harvesting technology to store water for irrigation simply needs diversion structures. However, the river can irrigate a greater amount or above the estimated value by constricting dams and conserving water during the rainy season.

5.2 Recommendations

There are so many challenges and bad things during the study. Data accessibility and political instability in some areas of the country to take actual data in the study area is challenging. Based on the result of the study the following points are recommended for future consideration.

- The suitable land is identified by considering physical and socio-economic suitability factors from those soil is the one factor and considering soil physical properties like texture, soil depth, and drainage to assess soil suitability of the basin. However, these physical factors only do not address the potential of the soil for irrigation. Chemical properties like soil salinity, PH, CaCO3, EC, and others of the soil are also very important for irrigation. Therefore, the research should be conducted by considering soil chemical properties.
- The suitability of the land for irrigation by considering updated physical, climate, socio-economic factors, and groundwater sources was assessed and identified in this study, and the groundwater data used for this evaluation were downloaded from the online source BGS. Further research should be done to improve the result by considering actual well data, groundwater quality, and groundwater potential used as an alternative irrigation water source.

- The environmental impact should be considered because irrigation development has some negative impacts on waterborne diseases, waterlogging, salinization, erosion, and pollution of ground and surface water.
- Due to rapid population growth, there are poverty and food insecurity problems and irrigation development have a great contribution to improving income and life quality of the population and economy of a country. Therefore, the government and other stakeholders should consider these suitable areas for irrigation development to improve the income of the population in the basin and to increase the county economy.

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7 APPENDICES

Appendix Table I: the rating of soil physical properties of soil capacity index (SCI) for irrigation

Soil textural class	Rating
Very fine sandy loam, fine sandy loam, loam, silt, silt loam	100
Loamy very fine sand, sandy loam, sandy clay loam, calcareous silty clay loam, clay loam	95
Coarse sandy loam, loamy fine sand, non-calcareous silty clay loam, clay loam	90
Clay	85
Loamy sand, very fine sand	80
Fine sand, loamy coarse sand, sandy clay,	65
Sand	60
Coarse sand	30

Soil depth(cm)	Rating
>100	100
80-100	90
50-80	80
20-50	60
<20	25

Drainage class	Rating
excessively drained and somewhat excessively drained	85
Well-drained	100
moderately well drained	90
imperfectly drained	70
somewhat poorly drained	70
poorly drained and very poorly drained	50

Capability index	Suitability classes	Definition
> 80	S1	highly suitable

60-80	S2	moderately suitable
45-60	S3	marginally suitable
30-45	S4	less suitable
< 30	S5	unsuitable

Appendix Table II Climate data

No.	Name of station	Rain	Tmin avg(◦c)	Tmax avg(◦c)	avg RH	avg WS	avg SH	ETO	NIR
1	Debre Zebit	1046.3	8.7	20.8	73	173	8.2	1371.3	282.5
2	Debre Zeit	555.9	9.1	21.90	72.0	173.0	9	1441.8	340.9
3	Gashena	1323.9	6.5	19.9	71	173	8.9	1390.9	291
4	Kulmesk	256.4	12.8	25.1	73	173	8.3	1507.0	361.7
5	Robet	940.0	14.1	26.8	73	173	8.6	1578.7	280.7
6	Woldia	1158.8	12.6	28.8	68	173	10.4	1809.9	389.1
7	Zobel	1041.7	9.7	26.7	67	173	10.8	1754.7	426.4
8	Amde Work	960.0	11.1	23.1	59.0	1.6	8.1	1483.56	345.6
9	Lalibela	804.6	13.5	25	58	1	7.3	1414.0	320.9
10	Wegel Tena	779.0	7	19.9	65	1.6	8	1352.39	412
11	Sirinka	1123	13.5	26.8	68	1.2	7.4	1443.69	258.4
12	Mariye	1333.2	9.9	23.4	71	173	9	1497.35	243.8
13	Muja	1194.7	13.5	25.4	74	173	8	1517.32	354.4
14	Wejed	1885.13	7.1	19.5	72	173	8.3	1342.95	234.8

Appendix Table III: ground truth data of command area for validation

Irrigation project name: Alawha **Woreda name: @ Gubalafto**

point No.	Easting	Northing
1	39.6829	11.8969
2	39.6861	11.8948
3	39.6879	11.8939
4	39.6886	11.8931
5	39.69	11.8926
6	39.6912	11.8924
7	39.6928	11.8926
8	39.6949	11.8921
9	39.6959	11.8905
10	39.6984	11.8897
11	39.6985	11.8914
12	39.6991	11.8925

13	39.7002	11.8951
14	39.7009	11.8986
15	39.7023	11.901
16	39.7029	11.9015
17	39.7029	11.9016
18	39.7019	11.9011
19	39.7012	11.9009
20	39.6991	11.9015
21	39.6973	11.9013
22	39.6952	11.8997
23	39.6935	11.9005
24	39.6915	11.9003
25	39.69	11.8986
26	39.6877	11.8972
27	39.6854	11.8976
28	39.6829	11.8975

Irrigation project name: Cheretie **Woreda name: @ Wadla**

Point No.	Easting	Northing
	Cheretie 1	
1	11.7796	39.7273
2	11.7792	39.7275
3	11.779	39.7284
4	11.7789	39.7292
5	11.779	39.7299
6	11.7793	39.7305
7	11.7797	39.7308
8	11.7801	39.7313
9	11.7805	39.7316
10	11.7811	39.7319
11	11.7809	39.7313
12	11.7805	39.731
13	11.7797	39.7303
14	11.7801	39.73
15	11.7796	39.7293
16	11.7795	39.7283
17	11.7797	39.7274
	Cheretie 2	
1	11.9013	39.7315
2	11.8997	39.732

3	11.9005	39.7326
4	11.9003	39.7334
5	11.8986	39.7346
6	11.8972	39.7351
7	11.8976	39.7343
8	11.8975	39.7341

Irrigation project name: Timtimat **Woreda name: @ Wadla**

Point No.	Easting	Northing
1	38.9697	11.7067
2	38.9682	11.7036
3	38.9718	11.7019
4	38.9731	11.7046
5	38.9736	11.7111
6	38.9739	11.7113
7	38.9742	11.712
8	38.9739	11.7127
9	38.9705	11.709
10	38.9707	11.7081
11	38.9687	11.7075
12	38.9693	11.7063

Irrigation project name: Wadla **Woreda name: @ Wadla**

Point No.	Easting	northing
1	39.0355	11.3632
2	39.0356	11.3637
3	39.0356	11.3642
4	39.0411	11.365
5	39.0413	11.3649
6	39.0407	11.3634
7	39.0356	11.3661
8	39.0401	11.3621
9	39.0406	11.3635
10	39.0424	11.3647
11	39.0425	11.3634
12	39.0431	11.3632
13	39.0404	11.3608

Irrigation project name: Delanta **Woreda name: @ Delanta**

Point No.	Easting	Northing
1	38.5557	11.351
2	38.5555	11.3509
4	38.5553	11.351
5	38.5553	11.3511
6	38.5554	11.3512
7	38.5555	11.3512
8	38.5557	11.3511
9	38.5544	11.3509
10	38.5543	11.3507
11	38.5537	11.3503
12	38.5535	11.3505
13	38.5532	11.3507
14	38.553	11.3504
15	38.5512	11.3514
16	38.552	11.3521
17	38.5527	11.3523
18	38.553467	11.352
19	38.554628	11.352108
20	38.554797	11.351756
21	38.5544	11.3506

Irrigation project name: Tabot Maderiya (Weir) **Woreda name: @ Gidan**

0	Plot number	X-coordinate (gcs or degree)		Y-coordinate (gcs or degree)	
1	PLOT 1	540376	12.16	1329707	39.22
2		540377	12.15	1329446	39.22
3		540231	12.14	1329283	39.22
4		540229	12.13	1329165	39.22
5		540142	12.01	1328973	39.22
6		540367	12.01	1329077	39.22
7		540403	12.14	1329253	39.22
8		540469	12.15	1329433	39.22
9		540469	12.16	1329582	39.22
10		540376	12.16	1329707	39.22
1	PLOT 2	540334	12.13	1329016	39.22
2		540138	12.12	1328941	39.22
3		539999	12.11	1328783	39.22
4		539956	12.1	1328570	39.22
5		539685	12.09	1328346	39.21
6		539252	12.03	1327311	39.21

7	539583	12.03	1327219	39.21
8	540106	12.09	1328295	39.22
9	540332	12.12	1328828	39.22
10	540334	12.13	1329016	39.22

Irrigation project name: Amid **Woreda name: @ Raya Kobo**

S.No.	x-coordinate (degree decimal)	y-coordinate (degree decimal)	x-coordinate (UTM)	y-coordinate (UTM)
1	11.987	39.647	570436.582	1325198.722
2	11.987	39.648	570545.452	1325198.977
3	11.992	39.656	571415.103	1325753.959
4	11.997	39.658	571631.521	1326307.401
5	11.998	39.659	571740.124	1326418.246
6	11.998	39.664	572284.457	1326419.553
7	11.999	39.666	572501.923	1326530.663
8	11.998	39.667	572611.057	1326420.341
9	11.994	39.665	572394.391	1325977.476
10	11.993	39.665	572394.657	1325866.891
11	11.992	39.663	572177.186	1325755.782
12	11.992	39.662	572068.317	1325755.52
13	11.992	39.66	571850.579	1325754.998
14	11.989	39.658	571633.633	1325422.724
15	11.989	39.656	571415.893	1325422.205
16	11.988	39.654	571198.415	1325311.103

Irrigation project name: Ademwuha (Intake) **Woreda name: @ Habru**

S. No.	x-coordinate (GCS)	y-coordinate (GCS)
1	114056	393794
2	114050	393799
3	114057	393801
4	114060	393810
5	114060	393814
6	114063	393818
7	114064	393820
8	114067	393825
9	114069	393834
10	114073	393837
11	114073	393841
12	114076	393849
13	114079	393859
14	114067	393874
15	114070	393877
16	114067	393882

Appendix Table IV Stream flow data used

Monthly Minimum flow of Mersa river (m3/sec)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	0.24	1.92	1.68	0.12	0.11	0.29	0.37	0.10	0.31	0.31	0.38	0.37
1997	0.38	0.37	0.36	0.07	0.06	0.08	0.09	0.10	0.13	0.19	0.28	0.38
1998	0.24	1.92	1.68	0.38	0.35	0.35	0.12	0.12	0.24	0.38	0.33	0.30
1999	0.27	0.00	0.00	0.01	0.02	0.01	0.03	0.11	0.12	0.17	0.23	0.26
2000	0.26	0.24	0.24	0.12	0.11	0.12	0.12	0.10	0.13	0.19	0.62	0.81
2001	0.81	0.71	1.68	0.23	0.29	0.16	0.16	0.12	0.10	0.38	0.41	0.77
2002	0.24	0.11	0.11	0.13	0.16	0.18	0.18	0.28	0.24	0.24	0.62	0.62
2003	0.24	1.92	1.68	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
2004	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2005	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.22	0.25	0.26
2006	0.20	0.18	0.18	0.16	0.11	0.12	0.12	0.10	0.13	0.19	0.28	0.38
2007	0.24	1.92	1.68	0.12	0.16	0.16	0.21	0.10	0.13	0.19	0.28	0.38
2008	0.22	0.20	0.22	0.22	0.22	0.22	0.22	0.27	0.22	0.24	0.22	0.38
2009	0.24	1.92	1.68	0.12	0.11	0.12	0.18	0.10	0.22	0.19	0.28	0.38
2010	0.24	0.18	0.24	0.24	0.11	0.12	0.12	0.10	0.13	0.19	0.28	0.38
2011	0.24	1.92	1.68	0.12	0.11	0.12	0.12	0.10	0.13	0.19	0.28	0.38
2012	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38
2013	0.24	21.11	17.11	0.12	0.11	0.12	0.12	0.10	0.13	0.19	0.28	0.38

Monthly Minimum flow of Megenagna river (m3/sec)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	0.17	0.18	0.12	0.11	0.13	0.13	0.06	0.09	0.06	0.13	0.11	0.15
1998	0.06	0.18	0.12	0.11	0.14	0.15	0.06	0.09	0.14	0.17	0.17	0.17
1999	0.13	0.13	0.13	0.10	0.11	0.11	0.06	0.09	0.08	0.13	0.27	0.27
2000	0.27	0.28	0.28	0.10	0.13	0.05	0.06	0.09	0.08	0.13	0.17	0.18
2001	0.34	0.35	0.12	0.25	0.13	0.11	0.06	0.09	0.08	0.32	0.32	0.30
2002	0.17	0.35	0.12	0.11	0.32	0.30	0.06	0.09	0.08	0.14	0.14	0.18
2003	0.17	0.18	0.12	0.11	0.13	0.13	0.06	0.09	0.08	0.13	0.29	0.32
2004	0.17	0.18	0.12	0.11	0.13	0.35	0.06	0.09	0.08	0.13	0.17	0.18
2005	0.17	0.18	0.12	0.11	0.13	0.13	0.06	0.09	0.08	0.13	0.17	0.35
2006	0.34	0.37	0.12	0.11	0.13	0.13	0.06	0.09	0.08	0.13	0.17	0.18
2007	0.17	0.18	0.12	0.11	0.13	0.13	0.06	0.09	0.08	0.12	0.12	0.11
2008	0.11	0.12	0.12	0.12	0.11	0.11	0.06	0.09	0.08	0.13	0.17	0.11
2009	0.17	0.18	0.12	0.11	0.13	0.08	0.08	0.09	0.06	0.05	0.05	0.04
2010	0.05	0.05	0.06	0.12	0.13	0.13	0.06	0.09	0.08	0.13	0.17	0.18
2011	0.17	0.06	0.05	0.05	0.13	0.05	0.06	0.09	0.05	0.04	0.17	0.06
2012	0.05	0.05	0.12	0.11	0.07	0.08	0.06	0.09	0.09	0.07	0.08	0.05
2013	0.17	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.08	0.13	0.17	0.18
2014	0.17	0.18	0.12	0.11	0.13	0.13	0.06	0.09	0.08	0.13	0.17	0.18

Monthly Minimum flow of Allawoha river (m3/sec)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	2.31	1.7	0.7	1.421	1.421	1.396	1.724	1.582	1.295	1.295	1.345	2.193
1998	0.91	0.86	1.5	2.094	2.029	2.094	1.153	1.842	1.783	2.806	2.159	1.966
1999	2.31	0.78	2.13	1.783	1.638	1.666	2.061	1.724	1.638	1.295	0.957	0.916
2000	1.34	0.87	0.89	0.896	1.345	1.13	1.783	0.936	2.399	2.029	1.997	1.966
2001	2.31	2.12	0.78	1.903	1.555	1.527	1.783	1.199	0.998	0.957	0.936	0.916
2002	1.32	1.7	0.49	1.063	0.936	1.6528	1.107	0.936	1.842	1.638	1.555	1.61
2003	2.31	2.12	2.13	3.167	1.223	1.13	1.753	3.599	2.8215	4.51	2.9957	4.717
2004	2.31	2.12	2.13	2.6292	1.724	2.159	2.029	1.695	1.753	3.5042	1.783	1.783
2005	2.31	2.12	0.6	9.506	1.939	1.6528	1.6141	1.918	15.123	19.511	18.724	31.277
2006	0.98	2.12	2.13	5.897	5.837	1.6528	1.6141	1.918	2.8215	3.5042	2.9957	4.2554
2007	2.31	2.12	2.4	2.6292	1.939	1.6528	1.6141	1.918	2.8215	3.5042	2.029	1.345
2008	0.6	0.8	2.13	1.783	1.842	1.6528	1.6141	1.918	2.8215	3.5042	2.9957	4.2554
2009	2.31	2.12	2.13	2.6292	1.939	1.6528	1.063	1.5	1.107	1.063	1.107	1.13
2010	0.78	2.12	1.03	1.13	1.939	1.474	1.474	1.783	2.329	3.5042	2.9957	4.2554
2011	2.01	0.97	1.3	1.695	2.295	2.729	2.193	3.92	2.506	2.506	2.399	1.246
2012	0.97	1.3	2.13	1.842	1.421	1.223	1.246	2.295	1.085	0.936	0.957	4.2554
2013	2.31	1.5	1.79	2.6292	1.939	1.6528	1.6141	1.918	2.8215	3.5042	2.9957	4.2554

Appendix Table V Well data for Groundwater source validation

NO.	Locality	X_UTM	Y_UTM	Elevation	Yield
1	Robit/Kobo, N/Wello	568484	1328445	1594	5.16
2	Aradom/Kobo, N/Wello	567978	1334918	1492	3
3	Bilbala, Lasta, North Wollo	498419	1343722	2125	12.5
4	Ayub/Kobo, North Wello	566437	1354670	1455	8
5	Haramat/Kobo, North	568711	1339685	1472	38
6	Beteyohanes,02/Wadla, N/Wollo/Amhara	495860	1286350	2911	12
7	Shumsha,023/Lasta, N/Wollo/Amhara	498954	1323591	1981	5.1

Appendix Table VI Confusion matrix of classification accuracies

Confusion matrix of classification accuracies for N/Wello

	Reference Data									
Classified data	Bare land	Forest	Grassland	Build Up	Shrub	water	Flooded Vegetable	Crop land	Total	User accuracy (%)
Bare land	**207**	0	1	3	1	0	0	6	218	94.9
Forest	0	**6**	0	0	0	0	1	0	6	100
Grassland	0	0	**3**	0	0	0	0	0	3	100
Build Up	0	0	0	**7**	0	1	0	0	8	87.5
shrub	1	3	1	0	**61**	0	1	14	80	76.2
water	1	0	0	0	0	**2**	0	0	3	66.6
Flooded Vegetable	0	1	0	0	1	0	4	0	6	66.67
Crop land	12	0	0	2	2	0	0	**561**	577	97.2
Total	221	9	5	12	64	3	6	581	**851**	
Producer accuracy (%)	93.67	66.6	60.00	58.33	95	66.7	66.7	96.56	**917**	

0ver all accuracy = 92.81, Overall Kappa Statistics = 0.87