Land Suitability Assessment for Surface Irrigation Using Geospatial Techniques, Shinfa River Basin, Ethiopia

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Abstract

Assessment of potential lands suitable for surface irrigation techniques is vital for Ethiopia, where sustainable development is a desire of its people while the country has sufficient water resources and potentially suitable lands. This study aims to identify suitable land for surface irrigation in the Shinfa River basin, and Metema-Quara districts. The study used a combination of Geographic Information System (GIS), and Analytical Hierarchy Process (AHP) techniques to identify surface irrigation-suitability lands. Distance proximity (river, town, and road) and land features (LULC, major soils, soil characteristics, and slope) were the suitability factors. The results show that 1.64% (8,991.5 ha) of land is highly suitable and 69% (377,431.5 ha) of land is moderately suitable in the basin having a total of 5,467.3 km^2 basin area. In the middle downstream of the basin, an 85,480-ha large-scale irrigation project was designed by Amhara Design and Supervision Works Enterprise (ADSWE) by providing storage at Gubay Jejebit Kebele. Referencing the proposed dam site, the downstream Metema-Quara district had 105,042 ha of suitable irrigation potential within the basin. However, only 38% of suitable land was proposed and designed for surface irrigation development. Therefore, to increase the irrigable land in the district, design extensions and other water source alternatives (diversion, groundwater, and rainwater harvesting) should be considered, and having large-scale suitable irrigation potential requires the implementation of irrigation projects for the better development of the country.

Keywords: Irrigation potential, Surface irrigation, Shinfa Basin, Land suitability Factors

1. Introduction

Agriculture contributes significantly to Ethiopia's economy, accounting for 40% of GDP, 45% of export revenue, and 75% of jobs created for the country's labor force (Kassie, 2020; Teshome M, 2014). Utilizing subterranean water or redirecting river water for agricultural purposes is referred to as irrigation (FDRE, 2010). Improved management of limited freshwater and land resources results from the increasing global demand for water and the growing need for irrigation in agriculture (Pimentel *et al.*, 2004).

In Ethiopia, irrigation is seen as a vital strategy to improve food security and reduce poverty (Ahmed, 2019; Haile, 2015b). Hence, transitioning from rainfall-dependent farming to an irrigation and rain-fed farming system is crucial (Jaramillo, Graterol, & Pulver, 2020) and, it should be the main strategy for sustainable development, maximizing the use of the country's water and land resources while primarily concentrating on agricultural production. Despite substantial investments, strong public backing, and supportive government policies, irrigated agriculture in Ethiopia is currently illogical. Ethiopia's current progress in irrigation falls far short of the nation's irrigation capacity. Therefore, until now, irrigation has not been a significant factor in lowering food insecurity and, consequently, poverty (Mekonen, Gelagle, & Moges, 2022). Irrigation can be a beneficial tool to enhance agricultural productivity per unit of land, meeting food demands while reducing greenhouse gas emissions (Yimere & Assefa, 2021). Moreover, it has been identified as an important tool for sustainable development and is considered a foundation of food security and poverty reduction in Ethiopia (Nigussie, Moges, Moges, & Steenhuis, 2019). Reducing recurrent drought effects and easing food shortages in Northern Ethiopia necessitates efficient and appropriate irrigation utilization (Awulachew et al., 2005).

Out of Ethiopia's estimated 2.5 million hectares of potentially irrigable land, the Abbay River basin comprises 21.04% (or 526,000 ha) (Howell, 2003). Of the total 526,000 hectares, 28% are located in the Beles sub-basin, 23% in Lake Tana, 13% in Didessa, 11% in the Northwest (where this study was conducted), and the remaining 25% in other regions (Atlas, 2018). Scientific research has been focusing on the evaluation of irrigation practices in this basin across various scales (small, medium, or large) and types (diversion, storage, gravity, or pumped) (Robel, 2005).

It's clear that for achieving sustainable production utilizing this method, research must focus on optimizing vital resources in irrigated agriculture, like water and land capacity (Velasco-Muñoz, Aznar-Sánchey, Batlles-delaFuent, & Fidelibus, 2019). An in-depth assessment of the available irrigable land

and accessible water resources is crucial for conducting studies, designing, and planning to facilitate decision-making regarding new irrigation projects (Nigussie et al., 2019). For developing adaptation and mitigation strategies for constructing irrigation infrastructure, policymakers, researchers, and planners heavily depend on scientific studies regarding irrigation suitability (Shitu & Berhanu, 2020).

The lack of a reliable, consistent inventory and well-documented, well-researched issues on potential irrigation and water-related matters in the Ethiopian environment indicate a scarcity of thorough research in the area (Haile, 2015b). However, there are some irrigation potential studies previously conducted in the upper Abbay basin (FAO, 2000; Haile, 2015a; Yimere & Assefa, 2021, 2022) and the Lake Tana basin (A. Abera, Verhoest, Tilahun, Inyang, & Nyssen, 2021; M. Abera, 2017; Esa, 2021; Wale, Collick, Rossiter, Langan, & Steenhuis, 2013; Worqlul, Collick, Rossiter, Langan, & Steenhuis, 2015). For this, the assessment of irrigation potential is very significant for the development of future irrigation schemes. especially, this study districts with no studies had been exercised previously except general information driven from Abbay Basin Atlas (Atlas, 2018). Therefore, the main objective of this study is to assess the irrigation land potential of Shinfa river basin and Metema-Quara Districts in the Northwest Ethiopia.

2. Material and Method

2.1 Description of Study Area

The Shinfa basin is one of the tributaries of the Abbay Basin and is located in the North-Western part of Ethiopia. During the summer season, there is high water fluctuations and full bank flows that ranges from 1000mm to 1500mm across the top of the western plateau with nearly 80% of the rainfall records from June to September, and about 50% of annual total falling from July and August. The rainfall in lowlands at elevations from 500m to 1000m is also highly seasonal (Kappelman et al., 2014). But, in the dry seasons little and no flows occur depending on the river sand deposition and climatic conditions (Lani, Neil, John, & Lawrence, 2017). The Shinfa (Rahad), Gelegu, and Ayima (Dinder) rivers are the main tributaries of Abbay that run from north to south across the Northwestern Plateau and into Sudan; some of these rivers go by various names in Sudan (Kappelman et al., 2014). Different community (Amhara, Agew, and Gumiz) use the river as fish source in the Metema and Quara districts (Kappelman *et al.*, 2014).

This study was conducted in the 5467.3 km^2 basin area that is located in the middle downstream side of the basin (i.e., Metema and Quara districts) as it has fertile soil and cash crops like cotton and sesame crops were highly cultivated and gets attention for this study. Determining the exact suitable irrigation land value is very critical for decision-makers in the area of irrigation development sectors. Therefore, this study aims to assess the suitable irrigation area in the basin and in the Metema-Quara districts.

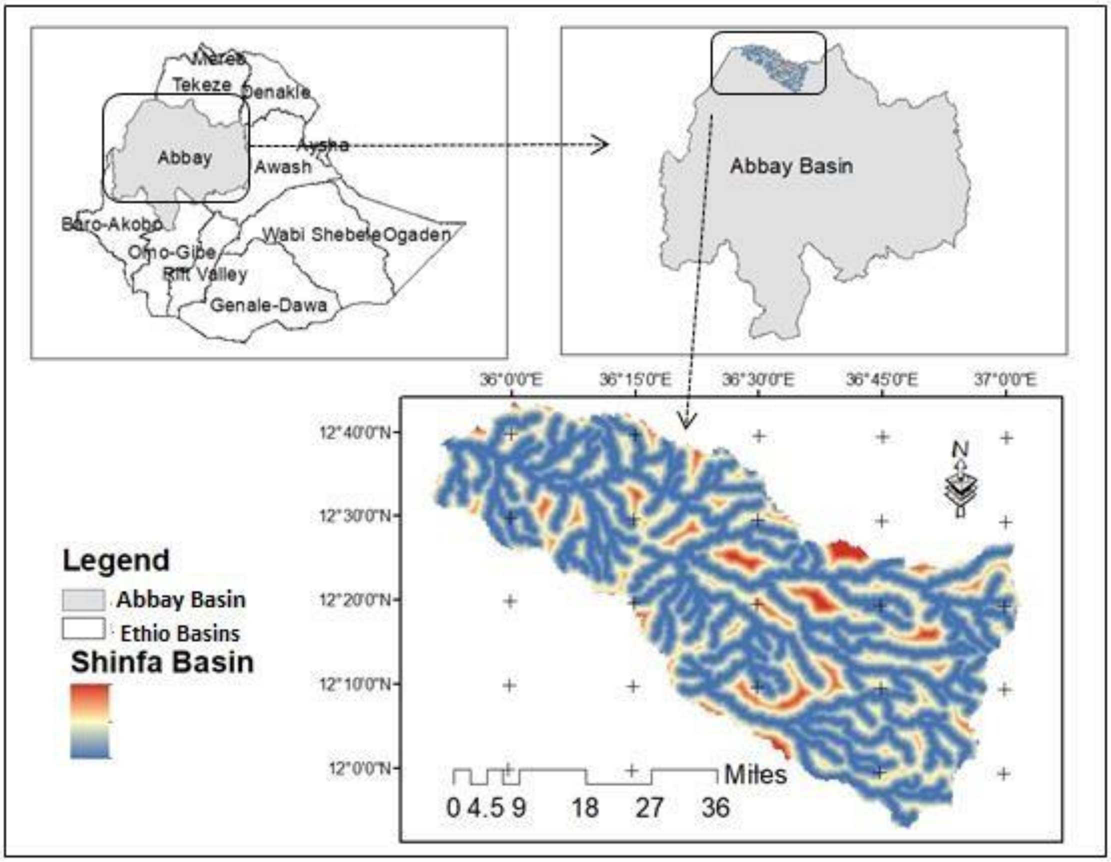


Figure 1.Location of the study area

2.2 Spatial data

The spatial data about the land use land cover were collected from the Ethiopian National Map Agency (ENMA). A 30-m by 30m resolution Global Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was downloaded from the USGS website and used to derive the slope map which helps to analyze the suitability of irrigable land by using GIS-based Multi-Criteria Evaluation (MCE) techniques.

Soil Data

Soil characteristics (soil type, texture, stoniness, and soil depth), major soils, and distance proximity (river, town, and road) were clipped from regional soil shape files.

2.3 Methods of Analysis

Geographic Information System (GIS) with Multi-Criteria Evaluation methods (MCE) and Analytical Hierarchy Process (AHP) techniques were used to identify surface irrigation suitability lands. (Saaty, 1987; Saaty, 1980; Saaty, 2008). The ten parameters (land use land cover, drainage density, slope, soil type, texture, stoniness, soil depth, river proximity, town proximity, and road proximity) were first identified using Food and Agricultural Organization suitability classes (FAO, 1976, 1979, 1985, 1991, 1997). Then, by applying the ranking technique the pairwise comparison matrix was developed. Finally, the weighted value of the suitable irrigation area was estimated (Birhanu, Pingale, Soundharajan, & Singh, 2019). According to (Chen, 2006), pairwise comparison analysis has three main objectives: (i) developing a comparison matrix (ii) computing the relative weights and (iii) estimating the consistency ratio to check the consistency of judgment. In GIS, multi-criteria evaluation (MCE) is arguably the most basic decision support procedure (Jiang & Eastman, 2000). AHP integrates different parameters in a single overall value for ranking decision alternatives (Rahman & Saha, 2007). Obtaining solutions in the AHP is not a statistical procedure, because it can help either a single decision maker or a decision group to solve multi-criteria decision problems (Chen, 2006).

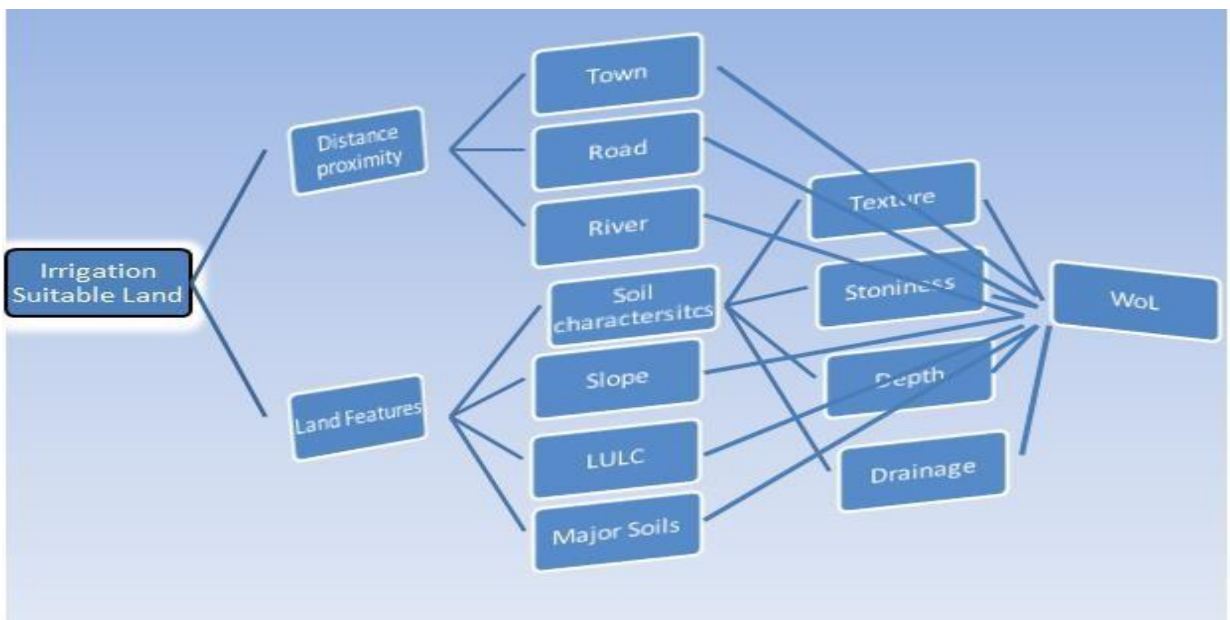


Figure 2.The input data and conceptual framework of the study

2.4.1 Soil Type classification

It is important to know soil formation and management because it influences runoff, drainage, erosion, and the selection of methods of irrigation. To assess soil suitability for irrigation, soils in the study area were classified from the revised FAO/UNESCO soil map of East Africa classification system. The major soil group of the basin is shown in the Figure 3 a.

Table 1.Soil suitability classification

Legend	Major Soils	Factor rating
1	Luvisols, Nitisols (very productive soils)	S1 (Highly Suitable)
2	Vertisols, Fluvisols, Cambisols (good natural fertility)	S2 (Moderately Suitable)
3	Regosols, Alisols (low moisture holding capacity)	S3 (Marginally Suitable)
4	Leptosols (gravely and stony)	N (Not Suitable)

Source: (FAO, 2014)

2.4.2 Slope

To derive a slope suitability map of the study area, a digital elevation model of the area was clipped from the SRTM of a NASA satellite with 30-meter spatial resolution. The slope derived from the DEM was classified based on the classification system using the "Reclassification" tool, which is an attribute generalization technique in the Arc-GIS tool. The four suitability ranges (S1, S2, S3, and N) were classified for surface irrigation as shown in Table 2: and the basin slope was as shown in Figure 3 b.

Table 2: Slope suitability classification for surface irrigation

Legend	Slope (%)	Factor rating
1	0-2	S1 (Highly Suitable)
2	2-5	S2 (Moderately Suitable)
3	5-8	S3 (Marginally Suitable)
4	>8	N (Not Suitable)

Source: (FAO, 1999)

2.4.3 Land Use Land Cover

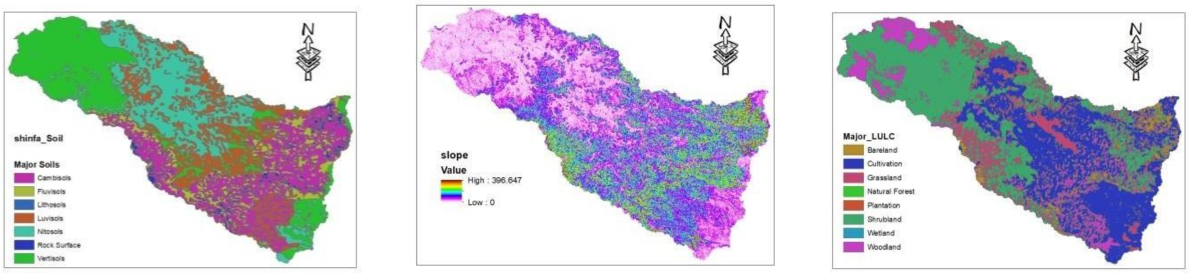
A land-use land-cover map of the study area was extracted from the land-use/land-cover map developed by the Ethiopian Mapping Agency. Land use land cover types of the study area were ranked based on their suitability for irrigation potential, working efficiency, costs to land clearing or land preparing for cultivation, and environmental impacts and depicted at Figure 3 c.

Table 3. Land use land covers suitability classification

S-No	Irrigation Suitability	Land use land cover
1	S1 (Highly suitable)	Farm Village/intensively cultivated land/moderately cultivated land and separately cultivated land
2	S2 (moderate suitable)	Open grass land and shrub grass land
3	S3 (marginal suitable)	Degraded wooded/dense/open shrub land /Seasonal wetland

4	S4 (unsuitable)	Towns/dense natural forest/plantation forest/ponds and dams/rivers/ sub-afro-alpine vegetation

Source: (FAO, 1976)



a, major soil group b, slope c, land use land cover

Figure 3. The major soil group, slope, and land use/cover of the basin

2.4.4 Soil characteristics

The dominant physical properties of soil that affect the suitability of land for irrigation are soil depth, soil drainage, stoniness, and soil texture.

Table 4.Soil suitability factor rating

Factor	**Factor rating**			
	S1 (highly Suitable)	**S2 (moderately suitable)**	**S3(marginally suitable)**	**N (None Suitable)**
Drainage	Well	Imperfect	Poor	Very poor
Soil depth(cm)	>100	80-100	50-80	<50
Soil texture	L-SiCL, C	SL	-	-
Soil stoniness	None	Few	Common	Abundant & many, Common to many

Source: guideline for land evaluation (FAO, 1976, 1981, 1985)

Soil drainage determines which types of plants grow best in an area. Many agricultural soils need good drainage to improve or sustain production or to manage water supplies. Poor drainage (causing water-logged areas) can often be identified by examining the soil conditions.

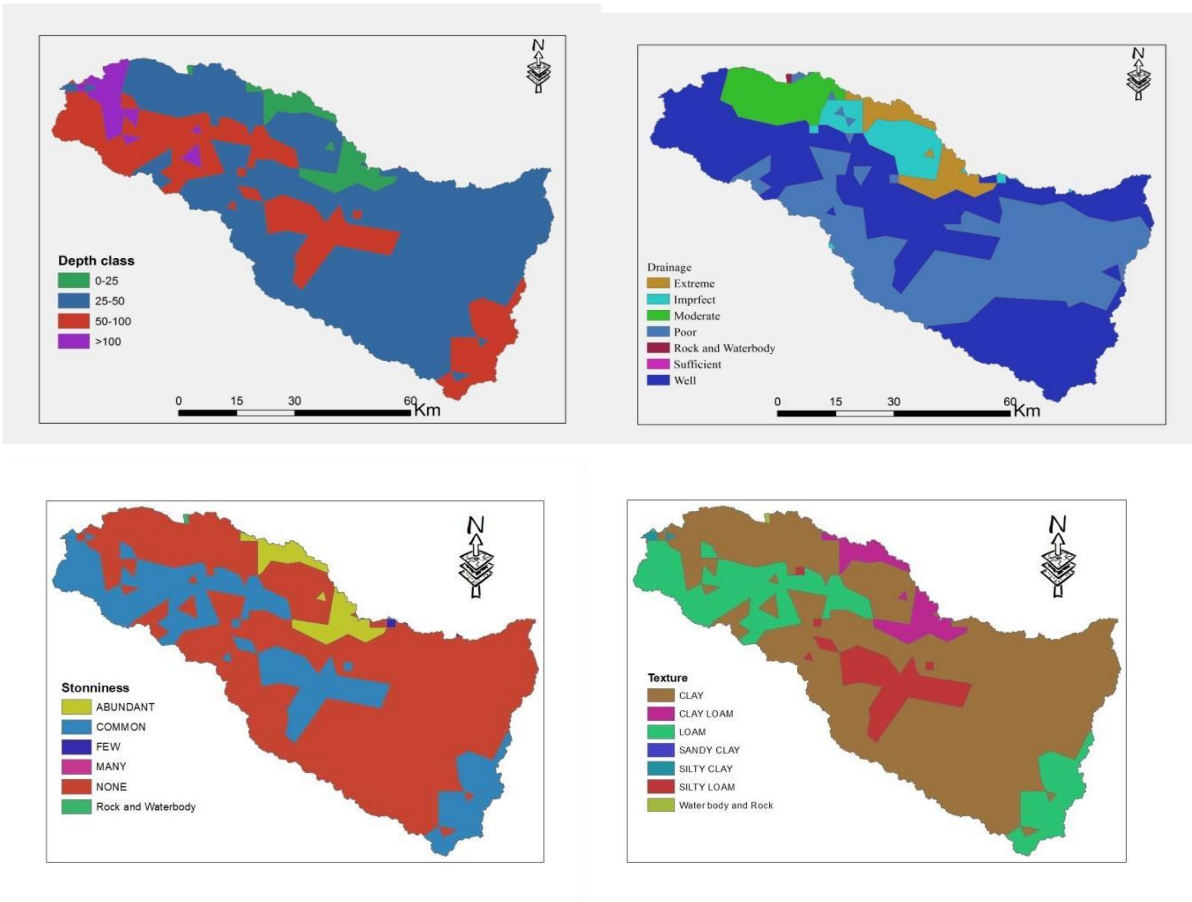


Figure 4. The soil characteristics of the basin

2.4.5 Town, Road, and River proximity

From the DEM, the Euclidean distance map was developed and data layers were prepared for weighting overlay analysis.

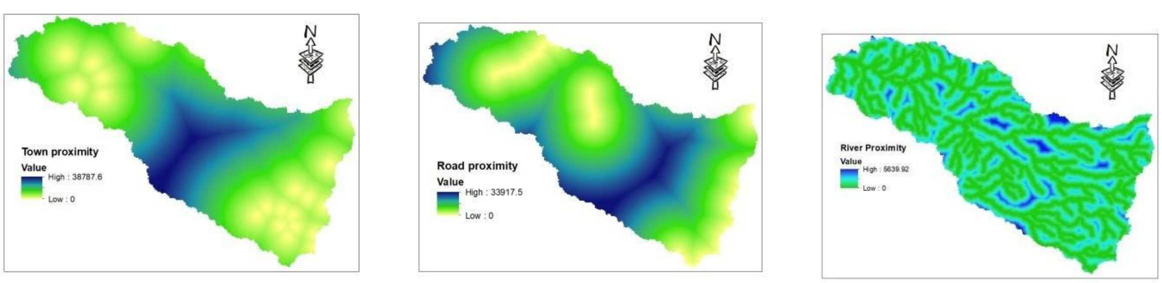


Figure 5. Distance proximity of the basin

2.5 Lighting of irrigation suitability of the basin and Metema-Quara districts

After the irrigation suitability of each parameter was assessed and the suitability map layer of each criterion was developed, the weighted value of an overlay analysis was done to generate one suitability map of the river basin using "model builder" in the Arc tools box of spatial analysis toolsets. To do this pair-wise comparison techniques between parameters were applied (Saaty, 1987; Saaty, 1980; Saaty, 2008). Finally, four irrigation suitability classes were determined.

Table 5. Pair-wise comparison scale and definition

importance	**Definition**	**explanation**
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favor one over the other
5	Much more important	Experience and judgment strongly favor one over the other
7	Very much more important	Experience and judgment very strongly favor one over the other. its importance is demonstrated in practice
9	Absolutely	The evidence favoring one the other is of the highest possible validity
2,4,6,8	Intermediate value	When compromise is needed

Source: (R. W. Saaty, 1977, 1987; Satty & Kearns, 1985)

In AHP (T. Saaty, 1980) explanation about the acceptable comparison values using consistency ratio (CR).

$$CR = \frac{CI}{RI}$$

Where; RI is the random consistency index obtained from a randomly generated pairwise

Comparison matrix for N = 10, RI = 1.49.

CI is the consistency index, which can be calculated by; CI = $\frac{\lambda max - n}{n-1}$ where, λmax is the biggest consistency measure value of the pairwise comparison matrix and n is the total number of factors.

Table 6. Random inconsistency indices (RI) for N=10

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

Source: (T. Saaty, 1980)

Table 7. Classification of land suitability for surface irrigation

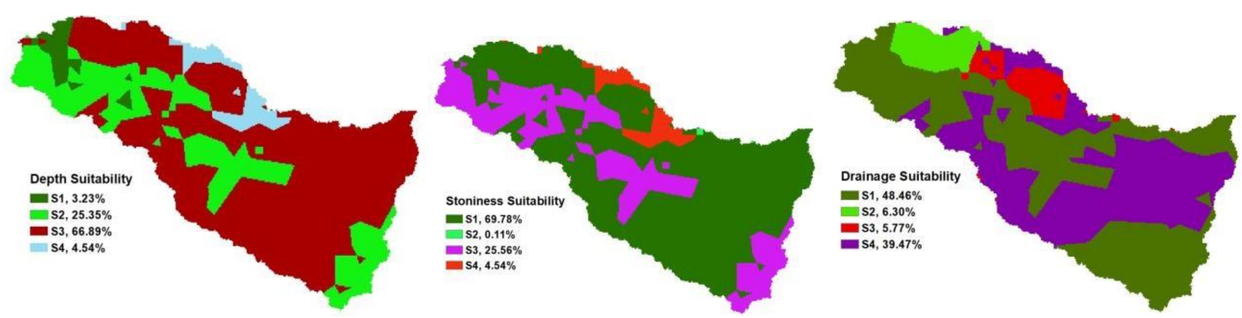
Classes	Description
S1 highly suitable	Without significant limitations this land is the best possible and does not reduce productivity or require increased inputs.
S2 moderately suitable	Land that is suitable but has limitations that either reduce productivity or require an increase of inputs to sustain productivity compared with those needed on S1 land
S3 marginally suitable	Land 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 that cannot support the particular land use on a sustained or land on which benefits do not justify inputs

Source: (FAO, 1976)

3 Results and Discussions

3.1 Surface irrigation suitability

The suitability of surface irrigation land was estimated after each parameter's surface irrigation suitability, was determined based on FAO guidelines. The major soils, the soil texture, river, and the having 97.24, 92.66, 76.91, and 70 percent of the total area coverage are suitable for surface irrigation development respectively. The soil depth and slope having only 28.57 and 23.31 percent respectively were the least suitable parameters. Figure 6; revealed that from the soil characteristics of the basin soil depth, soil stoniness, soil drainage, and soil texture had 3.23, 69.78, 48.46 and 70 percent are highly suitable, and 25.35, 0.11, 6.30, and 22.76 percent are moderately suitable respectively. The LULC, Slope, and Major Soils, 36.4, 5.67, and 62.96 percent are highly suitable, and 10.61, 17.64, and 34.28 percent are moderately suitable respectively.



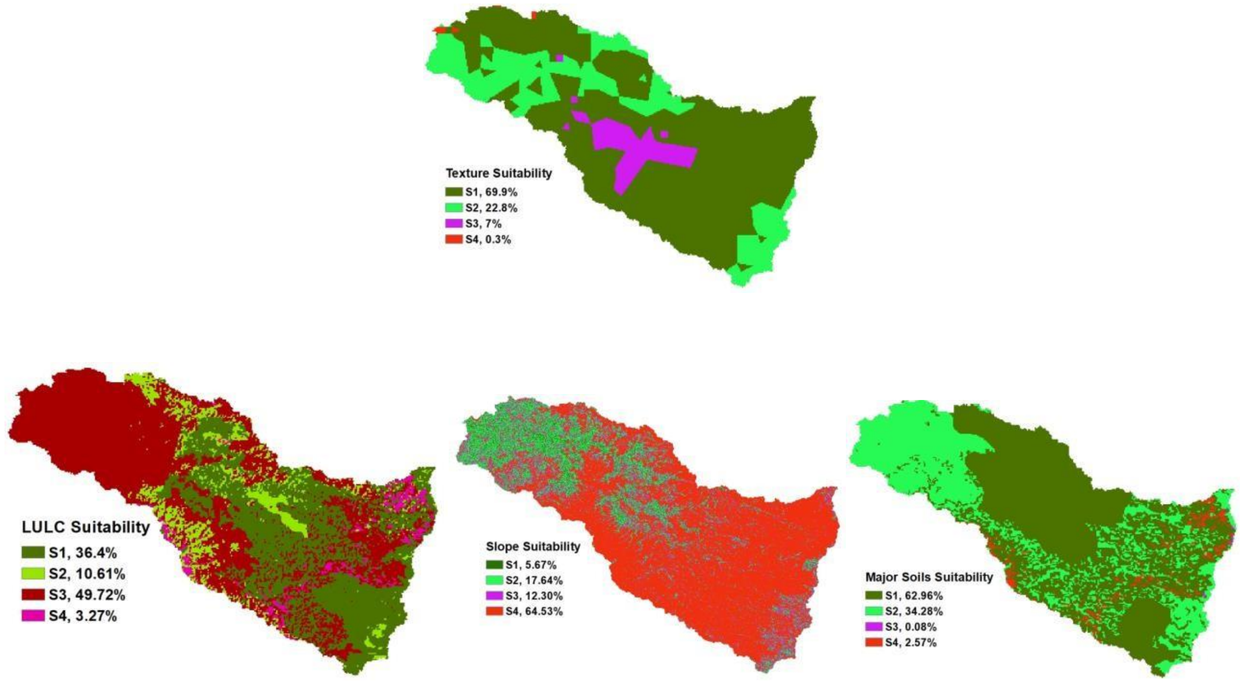


Figure 6. Reclassified land feature

The distance proximity of river, road, and town analysis showed that 36.08, 24.68, and 33.87% of the area was highly suitable, and 40.83, 30.22 and 27.98% moderately suitable.

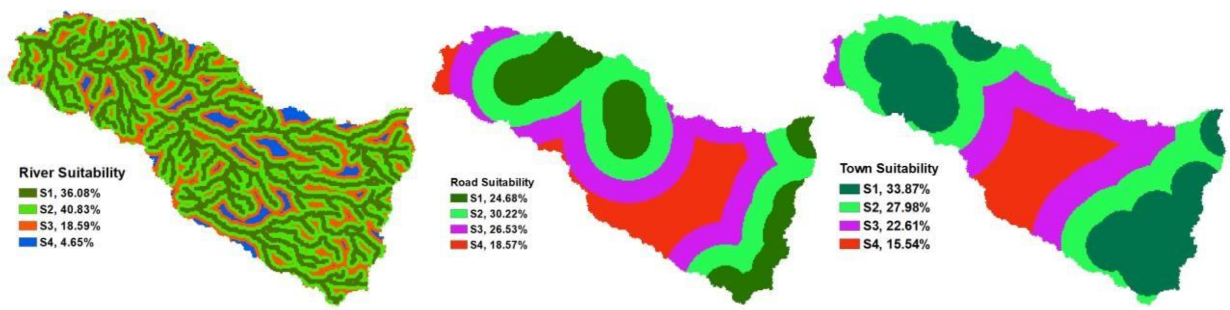


Figure 7: Reclassified distance proximity

3.2 Weighted factors and suitable areas of the basin

The pair-wise comparison matrix using Table 5 was constructed first. The ten factors are listed in the first ten columns and the first ten rows in Table 8. The column factors were compared with the factors in the rows for their significance to surface irrigation, then using the scoring of pair-wise comparison techniques (Saaty, 1977). Using Tables 5, 6, and 7 completing the pair-wise comparison matrix Table 8, the weights of the factors are computed by normalizing the respective eigenvector by the cumulative eigenvector. the vector is the root of the product of rows (Podvezko, 2009).

Table 8. pair-wise comparison matrix

Factors	Slope	Depth	Drainage	Stoniness	Texture	Type	River	LULC	Road	Town	Weight (%)
Slope	**1**	3	7	5	3	3	9	3	9	9	**22**
Depth	1/3	**1**	3	2	2	2	1/3	1/5	3	5	**9**
Drainage	1/7	1/3	**1**	1/3	1/3	1/3	1/3	1/5	3	5	**4**
Stoniness	1/5	1/2	3	**1**	1/3	1/3	1/3	1/5	3	3	**5**
Texture	1/3	1/2	3	3	**1**	1/3	1/3	1/3	3	5	**8**
Type	1/3	1/2	3	3	3	**1**	1/3	1/3	5	9	**10**
River	1/9	3	3	3	3	3	**1**	2	7	9	**21**
LULC	1/3	5	5	5	3	3	1/2	**1**	7	9	**16**
Road	1/9	1/3	1/3	1/3	1/3	1/5	1/7	1/7	**1**	3	**3**
Town	1/9	1/5	1/5	1/3	1/5	1/9	1/9	1/9	1/3	**1**	**2**

The consistency index CI is the summation of $\frac{(\lambda \max - n)}{n-1}$ which is 0.12737 and the Random inconsistency indices (RI) for N=7 is 1.49

Therefore, the Consistency Ratio, $CR = \frac{CI}{RI}$ $\frac{0.12737}{1.49}$ = 8.5 % which is less than 10 % and acceptable.

The weights of the factors were distributed to the different levels of suitability classes by an equal (S1, S2, S3, and S4) interval-ranging technique. The preliminary land suitable area was computed using the Weighted Overlay analysis tool of the Arc-GIS Spatial Analyst tool (Figures 6, 7, and 8). The pair-wise comparison matrix was used to weight the factors. Ten of the major factors were compared one-to-one and scored using a scale from (Saaty, 1977) see Table 8.

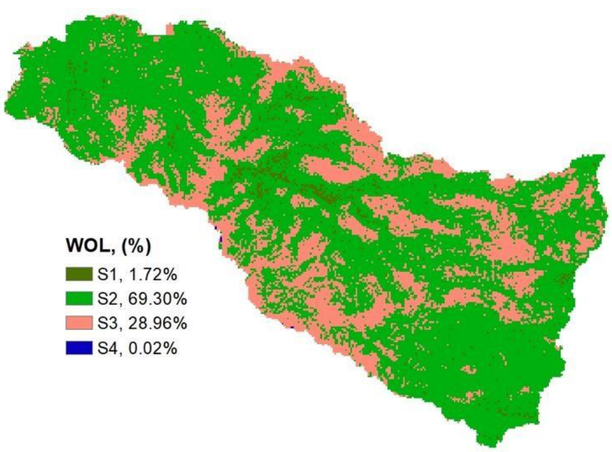


Figure 8. the weighted overlay

The results in Table 8 show that factor value judgment is subjective, the weighting of decision factors is determined based on the importance of each factor. This is conducted based on the knowledge of those familiar with irrigation in the area and watershed characteristics. The calculated weights the greater the value, the more important the factor. For this basin slope and river were the most important factors followed by land use land cover for determining the suitability of an area for irrigation. Town and road proximity were listed as less important. The credibility of the pair-wise matrix consistency was evaluated using the consistency ratio. The value of the consistency ratio is 0.08 which is within an acceptable range.

From the weighted overlay analyses result table 9: shows that 8991.50 ha of land is highly suitable. 377,431.50 ha is moderately suitable. This means a total of 70.64% (3864.23 km^2 or 386,423 ha) of the basin area is suitable for irrigation development.

Table 9. weighted overlay irrigation suitability result

Value or Class	Area (Km^2)	Area (Ha)	Remark
S1	89.915	8991.50	Highly Suitable
S2	3774.315	377,431.50	Moderately Suitable
S3	1602.07	160,207.00	Marginally Suitable
S4 (N1)	0.989	98.90	Not Suitable

3.3 Weighted factors and suitable areas of Metema-Quara districts

Soil characteristics (i.e. soil type, texture, stoniness, and depth), major soils, land use land cover, and slope were the selected factors for irrigation suitability. Even though, the factors of road, and river proximity were judged as very important because they are associated with a large initial investment (Worqlul et al., 2015) the distance proximities (town, road, and river) were not considered for this study. The dam site and irrigation infrastructure (conveyance system) design work were already designed by ADSWE and because of topography suitability getting access road along and within the district. Therefore, the man-made or economic interruptions for irrigation development were not selected as suitability parameter factors for this district.

Table 10. Pair-wise comparison matrix

Factors	Slope	Depth	Drainage	Stoniness	Texture	Type	LULC	Weight
Slope	1.00	2.00	3.00	3.00	3.00	2.00	2.00	27
Depth	0.50	1.00	3.00	3.00	3.00	2.00	0.33	17
Drainage	0.33	0.33	1.00	2.00	2.00	2.00	0.33	11
Stoniness	0.33	0.33	0.50	1.00	2.00	0.33	0.33	7
Texture	0.33	0.33	0.50	0.50	1.00	0.33	0.33	6
Type	0.50	0.50	0.50	3.03	3.03	1.00	0.33	12
LULC	0.50	1.00	3.03	3.03	3.03	3.03	1.00	21
Sum	**3.50**	**5.50**	**11.53**	**15.56**	**17.06**	**10.69**	**4.65**	**100**

The consistency index CI is found to be 0.104 and the Random inconsistency indices (RI) for N=7 was 1.32. Therefore, the Consistency Ratio, CR is 7.8 % which is less than 10% and acceptable. The results show that 56 ha of land is highly suitable and 104,985.80 ha of land is moderately suitable for surface irrigation from the total area of 150,424 ha of land in the district. The proposed dam was designed to irrigate about 85,480 ha of command area on both Metema and Quara districts by using surface irrigation application technology. The design report shows that from the total 85,480 ha of designed irrigable land, only 40,000 ha of land were within the Shinfa sub-basin. The rest is out of this catchment and Gelego watershed, only Quara district. Even though, surface irrigation was conducted using a gravity system and the topography may trouble the area, the potential of the designed irrigation project area within the Shinfa basin particularly the Metema Quara district should be advanced for better utilization of land and water resources. In different irrigation scales (large, medium, and small) governmental, private, and farmer-oriented irrigators should find out the different irrigation water source (diversion, rainwater harvesting, and groundwater) alternatives to increase the irrigation potential of this area.

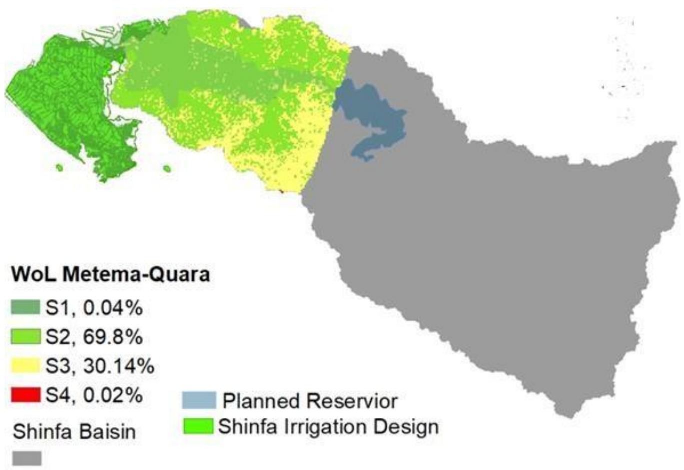


Figure 9. Metema and Quara district irrigable area

4. Conclusions

The irrigable land of the whole basin and Metema-Quara Districts were identified and mapped based on the factors that affect the suitability of land for surface irrigation. The land features of the basin i.e. land use land cover, major soils, soil characteristics, and distance proximity for the basin only (i.e. river, town, and road), and slope were the selected parameters for this study. Based on the overlay analysis about 70.64% (386,423 ha) of land is suitable for irrigation having a total of 5467 km^2 area in the Abbay sub-basin.

In the Metema and Quara districts, 105,042 ha is suitable for irrigation development. But, from the designed or planned irrigable area of 85,480 ha, only 47% is available within the Shinfa basin, and this proposed irrigable land covers only 38% of suitable land in the district. Therefore, to increase the irrigation land particularly, in the Metema-Quara district, design extension, and other irrigation water source alternatives should be investigated. Finally, this study concluded that it will be very essential if the designed project is implemented in the proposed area and project extension would be done for better agricultural development.

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