Research Article
Volume 9:2, 2020
DOI: 10.37421/idse.2020.9.245

Irrigation and Drainage Systems Engineering

ISSN: 2168-9768 Open Access

Land Suitability Evaluation for Surface Irrigation Using Spatial Information Technology in Omo-Gibe River Basin, Southern Ethiopia

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Abstract

Irrigation would provide farmers with sustained livelihoods and improve their general well-being. The aim of this study was to evaluate the suitability of the land for surface irrigation using GIS based weighted overlay analysis of individual parameters for better utilization of land resources. Factors considered included physical land features (land use/land cover, soil and slope), and proximity to water sources. Based on soil depth, 82.4% of the study area is potential suitable for the intended uses; the drainage class scores 70% suitability; 80% the soil texture was clay dominant hence it was moderately suitable for surface irrigation. Considering the terrain, 11.75% of the basin is suited for irrigation practice. The LULC classification revealed that, 54.42% was found to be highly suitable and 16.7% is found to be unsuitable. In reference to river proximity, around 81% of the area could be highly recommended for the intended use. Excluding the national parks, 71% (7% is S1 and 64% is S2) is suitable for the intended use. Hence, future surface irrigation development is feasible. Based on the findings, to increase the land area to be irrigated; an appropriate drainage provision and cost wise land leveling should be taken into consideration, further land suitability analysis for other types of irrigation and water source should be carried out. The study result could assist policy makers for better decisions during the development of irrigation projects in Omo-Gibe river basin.

Keywords: Land suitability • Surface irrigation • Weighted overlay • ArcGIS • Pair-wise comparison

Introduction

Agriculture is a mainstay of Ethiopian economy. The country is endowed with ample water resources with 12 river basins. Irrigation in Ethiopia is considered as a basic strategy to alleviate poverty and hence to achieve food security and improve the economy of the farming community through generating additional income during the dry season. It is useful to transform the rain-fed agricultural system which depends on rainfall into the combined rain-fed and irrigation agricultural system. This is believed to be the most prominent way of sustainable development in the country [1-4]. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses [5]. Proper use of land depends on the suitability or capability of land and water resources for the development of irrigation facilities could lead to substantial increase in food production [6].

For land suitability analysis of surface irrigation, particular attention is given to the physical properties of the soil, distance from available water sources and terrain conditions in relation to methods of irrigation considered [7]. In addition, land cover/land use types are considered as limiting factors in evaluating suitability of land for irrigation [8]. Irrigation suitability land classification investigations are an integral part of multi objective planning for the development and operation of water resource projects with an irrigation component. They support planning and management by identifying land resource potentials or problems through the collection, evaluation, and presentation of land resources data [9]. Availability of irrigation leads to land use change as well as intensive cropping system. Improper use of irrigation water has resulted in environmental degradation of natural resources that leads to decline in the productivity of land resources and deterioration of land quality for its future use [10].

Irrigation would provide farmers with sustained livelihoods and improve their general well-being. Thus, to bring food security in the national as well as in house hold level, improvement and expansion of irrigated agriculture must be enhanced as noted by Negash [11]. Soil, terrain feature (DEM and its derivatives), water potential and land use classification criteria are the basis used to define the suitability. With this respect, the Geographic Information System (GIS) facilities will be extensively used. To ensure adequate management and design of a particular irrigation system, a well-developed and suitable database is quite important. Thus, it should be able to deal with spatially and temporally varying factors affecting the system.

Being Ethiopia's second largest river system, the Omo-Gibe basin contributes 90% of the runoff to Lake Turkana (located downstream in Kenya) and accounts for 14% of the country's annual runoff, second only to the Blue Nile in runoff volume [12]. According to Woodroofe et al. [13], it is considered as a very significant resource within Ethiopia. Appropriate management and selection of applicable irrigation method is a prerequisite for better utilization of land resources which help to optimize and sustain the productivity of these land resources [10]. Therefore, the objective of this study is to spatially evaluate and map suitable parcel of land for surface irrigation in the Omo-Gibe river basin using weighted overlay analysis in ArcGIS environment though the characterization of biophysical suitability factors aimed to assist in land use policy decisions.

Materials and Methods

Description of the study area

Omo-Gibe River Basin is situated in the South-West part of Ethiopia, between 4°30' and 9°30' N latitude, and between 35° and 38° E longitude

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Received 20 August 2019; **Accepted** 10 June 2020; **Published** 17 June 2020

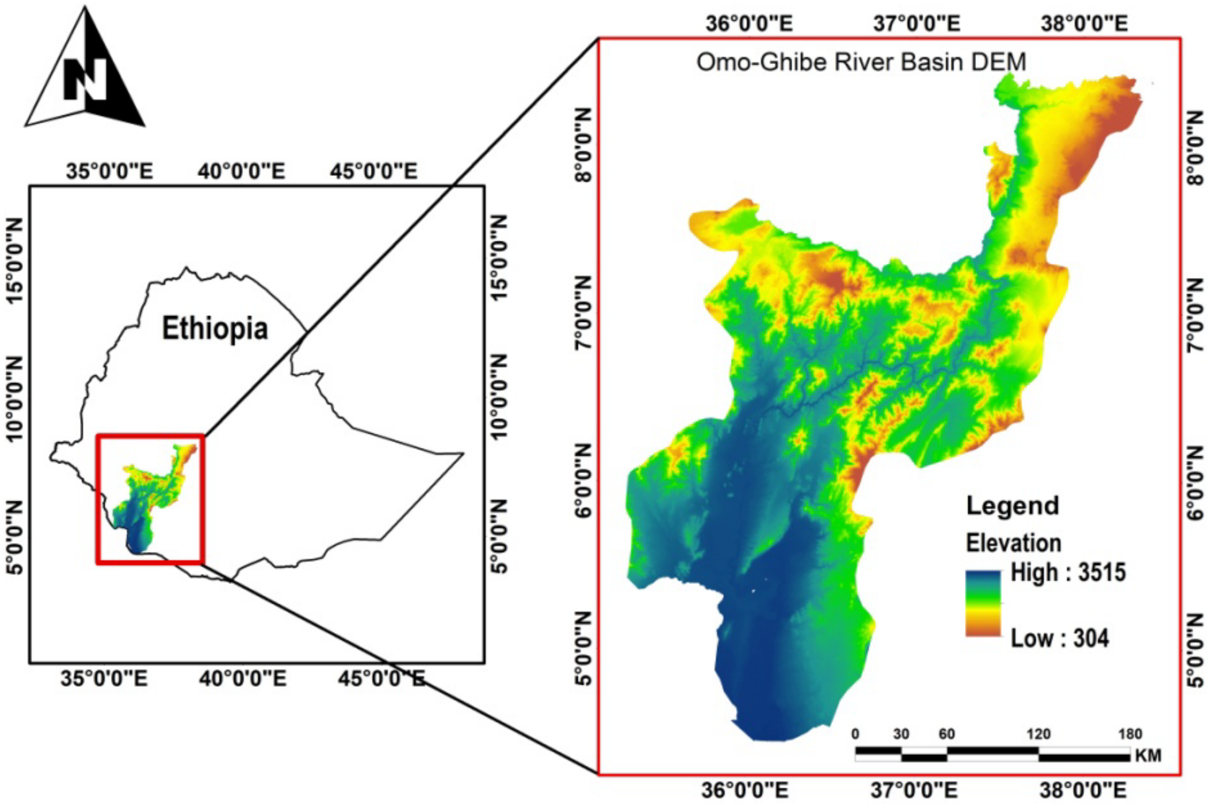


Figure 1. Location map of the study area.

(Figure 1). It encompasses parts of two National Regional States; Oromia which occupies the north-eastern part of the basin and the rest of the basin, this study focused, is situated in the Southern People's Regional States (SNNPRS). It is drained by two major rivers from the highlands, the Gibe River flowing southwards and Gojeb River flowing eastwards. The Gibe River is called the Omo River in its lower valley south and south westwards from its confluence with the Gojeb River. The northern part of the basin has a number of tributaries from the northeast of which the largest are the Walga and Wabe rivers. The Tuljo and Gilgel Gibe rivers are important rivers that drain to the Gibe [14].

Factors used to assess land suitability for irrigation

The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses [5]. This kind of test "land suitability analysis" is an essential starting point for the development. Where, it provides the necessary information about the deferent limitations and the possible opportunities for the land use under investigation based on the land capabilities. The factors were identified from different relevant sources and data availability. For this study, factors considered included physical land features (land use/land cover, soil and slope), and proximity to water sources. To achieve this, characterization and geo-referencing the biophysical database is required, hence the following datasets were collected and reclassified in to different suitability classes.

Soil database: Soil is a key factor in determining the suitability of an area for agriculture in general and irrigation in particular. The soil data (physical property; texture, drainage class and soil depth) covering the study area was accessed from the FAO website Harmonized World Soil Database, in Environmental System Research Institute (ESRI) shape file format (version 1.21) [15].

Terrain feature: The slope gradient of the land has great influence on selection of the irrigation methods. According to FAO standard guidelines for the evaluation of slope gradient, slopes which are less than 2%, are very suitable for surface irrigation. But slopes, which are greater than 8%, are not generally recommended [16]. The slope of the study area was reclassed in ArcGIS environment using 30m resolution Digital Elevation Model (DEM) data from freely available Shuttle Radar Topography Mission (SRTM) and the percentage slope was determined.

Distance to water sources: It is important to make sure that there will be no lack of irrigation water. If water is in short supply during some part of the irrigation season, crop production will suffer, returns will decline and part of the scheme's investment will lay idle [7]. The suitability class of a land parcel with respect to river proximity is determined by its distance in relation to the perennial rivers. Distance to the existing river was calculated in ArcGIS tool by projecting the locations to a Mercator (UTM) Zone 37N. After categorizing the distance map of the river in to four different classes, the farthest distances were assigned as not suitable and closer distances was classified as highly suitable. In addition to river proximity, electrical conductivity (EC) of the river water was included as an information.

Land use/Land cover (LULC): The 2018 LULC of the Omo-Gibe river basin was assessed and mapped using Landsat-8 satellite images. Prior to image classification, detailed image pre-processing including radiometric and geometric correction were performed to correct the surface feature reflectance characteristics. Image classification was processed using supervised image classification technique according to the desired decision rule of maximum likelihood algorithm for the respective years by using ERDAS IMAGINE. To improve classification accuracy and reduction of misclassifications, post-classification refinement was therefore used for simplicity and effectiveness of the method [17-20]. Visual interpretation of satellite images was made by using ERDAS IMAGINE and ArcGIS software package for satellite image processing and LU/LC analysis. Agricultural land use is considered as highly suitable, grass land is moderately suited, shrub land and forest areas assigned as marginally and not suitable for irrigation respectively.

Framework of land suitability evaluation

The FAO approach (Table 1) defines land suitability as aptitude of a given type of land to support a defined use [5]. After all the required data were collected from different data sources, further analysis was carried out for each biophysical factor for a better understanding of their contribution in assessment of land suitability potential for irrigation.

Classification of individual factors: According to FAO [5], each factor determining the suitability of the land for irrigation was classified into four classes such as highly suitable (Class S1), moderately suitable (Class S2), marginally suitable (Class S3), currently not suitable (Class N) (Table 2 and Figure 2) and data layers were prepared for further overlay [21,22].

Overall land suitability/weighted overlay: Potential irrigable land was obtained by creating irrigation suitability model analysis which involves weighting of values of all individual data sets. The purpose of weighting in land suitability analysis is to determine the importance of each factor relative to other factors. Analytical Hierarchy Process (AHP) (Figure 3), a well-known Multi-Criteria Decision Analysis method developed by Saaty [23] was used to express the relative importance of each suitability factors.

The pair-wise comparison matrix is a rating of the relative importance of the two factors regarding the suitability of the land. A scale of importance is broken down from a value of 1 to 9 (Table 3). The intensity of importance and their explanation is given in Table 3. Despite there are various scales to rate the related stakeholders' judgments, the 1-9 point scale has strongly been recommended to be used as an acceptable scale in the AHP and it was implemented in this study too. The 1-9 point scale is simple, straightforward, and easy to use [20-21].

If factor X is exactly as important as Y, this pair receives an index of 1. If X is much more important than Y, the index is 9. All gradations are possible in between. For a "less important" relationship, the fractions 1/1 to 1/9 are available: if X is much less important than Y, the rating is 1/9. The values are entered row by row into a cross-matrix. The diagonal of the matrix contains only values of 1. If X to Y was rated with the relative importance of n, Y to X has to be rated with 1/n. Then to calculate the weight, a normalized comparison matrix was created: each value in the matrix was divided by the sum of its column. To get the weights of the individual criteria, the mean of each row of this second matrix was determined. These weights are already normalized; their sum is equal to 1.

In the application of the AHP method it is important that the weights derived from a pairwise comparison matrix are consistent. It should be noted that for preventing bias thought criteria weighting the Consistency Ratio was used (CR). Consistency for a comparison matrix was measured by calculating the consistency index (CI) (eqn. 1).

$$CI = \frac{\lambda \max - n}{n-1} \qquad (1)$$

The consistency ratio (eqn. 2) is defined as

$$CR = \frac{CI}{RI} \qquad (2)$$

Where, n is the number of criteria or sub-criteria in each pairwise comparison matrix and λmax is the maximum eigenvalue of the comparison

Table 1. Land suitability classification [5].

Class	Suitability	Description
Class S1	Highly suitable	Land without any significant limitations
Class S2	Moderately suitable	Moderately severe limitations which reduce productivity or benefits or increase required inputs.
Class S3	Marginally suitable	Overall severe limitations; given land use is only marginally justifiable
N	Not suitable	Limitations not currently overcome with existing knowledge within acceptable cost limits

Table 2. Suitability criteria set for studied parameters.

Soil suitability			Land use/ land cover	Slope (%)	Suitability class
depth (cm)	texture class	drainage class			
>100	Loam/loamy sand/Sandy loam	Well	Cultivated land	0-2	S1
75-100	clay loam/ sandy clay loam/clay (light)/silty clay loam	Moderately Well	Grass land	2-5	S2
50-75	Sand	Imperfect	Barren & shrub land	5-8	S3
<50	Silty clay	Poor/very poor	Constraints (Forest, built-up, water, wetland)	>8	N

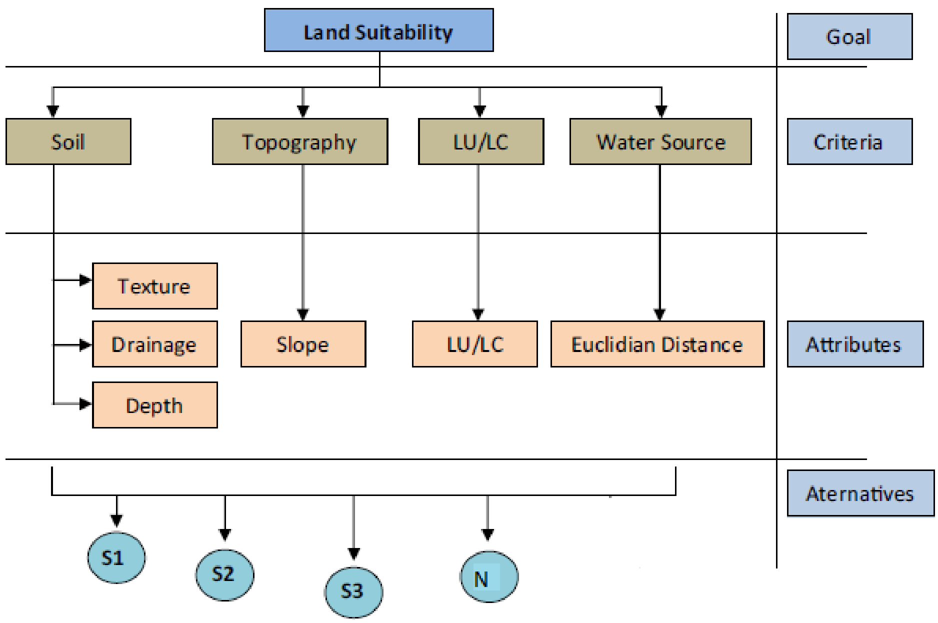


Figure 2. Hierarchical organization of individual criteria [18].

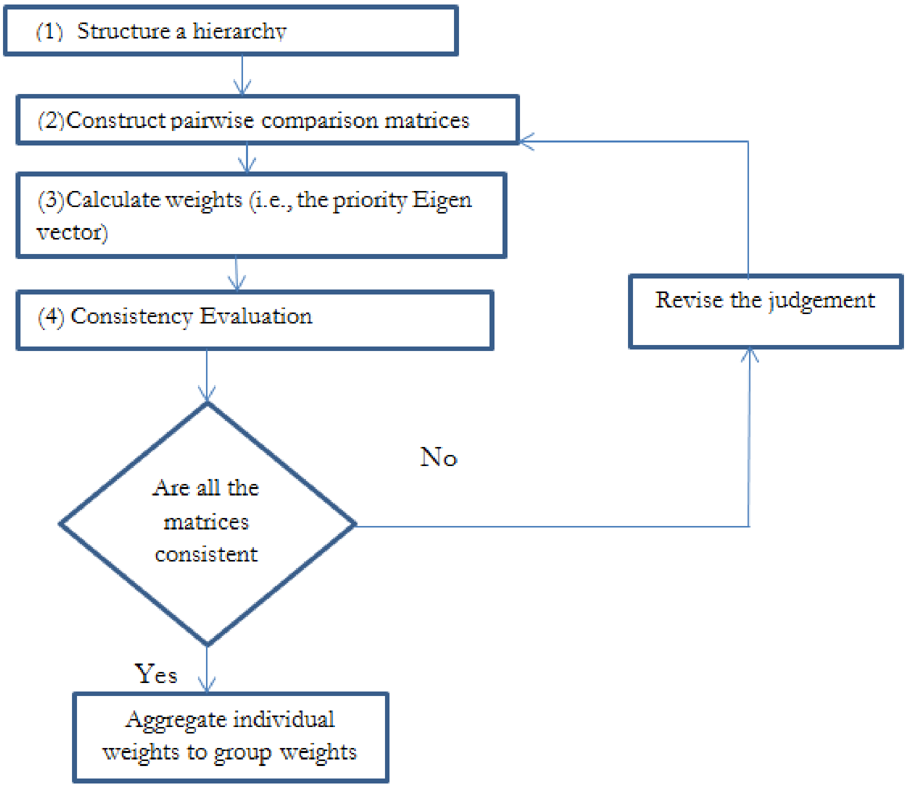


Figure 3. Steps used in the AHP method to establish weights as a flow chart [19].

Table 3. The AHP Pair-wise comparison scale and definition [20].

Definition	Index	Definition	Index
Equally important	1	Equally important	1/1
Equally or slightly more important	2	Equally or slightly less important	1/2
Moderately/Slightly more important	3	Moderately/Slightly less important/ Experience and judgment slightly favor one over the other.	1/3
Slightly to much more important	4	Slightly to way less important	1/4
Strongly more important / Much more important	5	Way less important/ Experience and judgment strongly favor one over the other.	1/5
Much to far more important	6	Way to far less important	1/6
Very much more important/Far more important	7	Far less important/ Experience and judgment very strongly favor one over the other.	1/7
Far more important to extremely more important	8	Far less important to extremely far less important	1/8
Absolutely more important / Extremely more important	9	Extremely less important/ The evidence favoring one over the other is of the highest possible validity.	1/9

matrix (the average of consistency vector). This consistency index was then compared to a random index (RI). The RI is the average CI of randomly generated reciprocal matrices using the scale 1/9, 1/8. . . 8, 9. For different dimension of the matrix (n), Saaty [22] generated random matrices and calculated their mean CI value. The random consistency index for different dimensions n is given in Table 4 [22]. Thus, for n=3 and n=4, conventionally it is required that CR≤0.05 and 0.08, respectively to be acceptable. For n≥5, a consistency ratio of 0.10 or less is acceptable. A consistency ratio (CR) of 0.10 or less indicates a reasonable level of consistency [23]. If the CR is >0.1, the comparison matrix should be revised again.

Using the ArcGIS weighted overlay analysis tool (Figure 4), overall land suitability was assessed spatially and suitability map was generated by aggregating the output from AHP.

Results and Discussion

Classification of land suitability for sustainable use requires an understanding of controlling land characteristics and qualities in the study area. The main biophysical factors which could influence land suitability evaluation have been defined, analyzed and thematic map/layer have been produced for further analysis.

Suitability of individual factors

Soil database: The area (4633518.25ha) is dominated by fine textured clay soil which is assigned as moderately suitable (79.95%) for irrigation and 18.72% (loam/sandy loam) of the study area is found under highly suitable class whereas sand texture covering 0.58% of the study area is accounted for marginal suitable class. The remaining part, which water body (0.75%) is classed under not suitable (Figure 5).

Considering soil drainage class (Figure 6), moderately well drained condition does have the largest coverage around 69.83% hence majority of the study area (4047072.92ha) is moderately suited for surface irrigation application. Marginally suitable accounts for 17.48% (Imperfectly drained), only 0.16% is well drained soil and highly suitable whereas 12.53% of the basin is not recommended for surface irrigation practice at the present condition because such soils area characterized by very low hydraulic conductivity, and the water available pores are very low.

Majority of the basin (Figure 7) was dominated by deeper depth

Table 4. Random Consistency Index [22].

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49	1.51	1.54	1.56	1.57	1.58

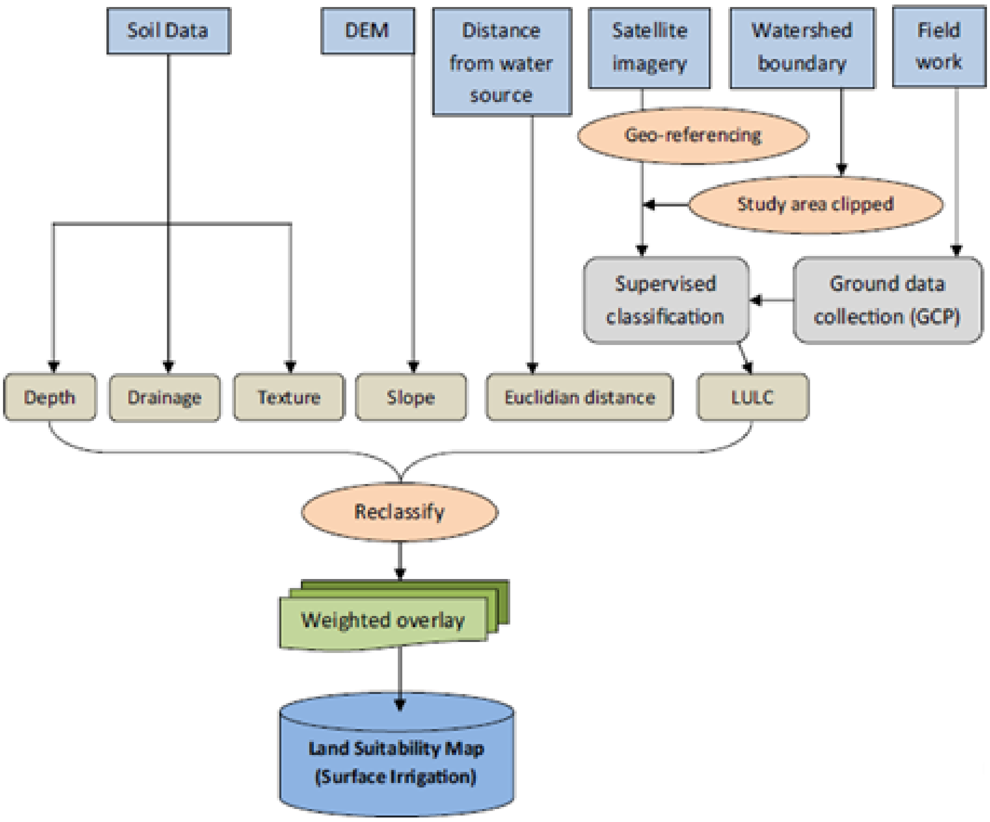


Figure 4. General Flowchart of the methodology [18].

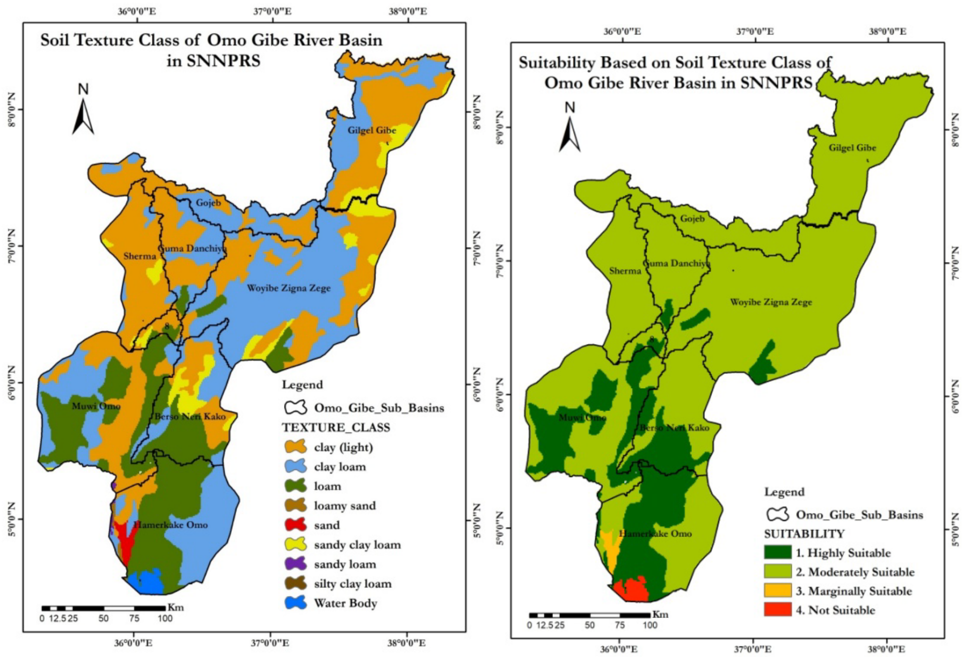
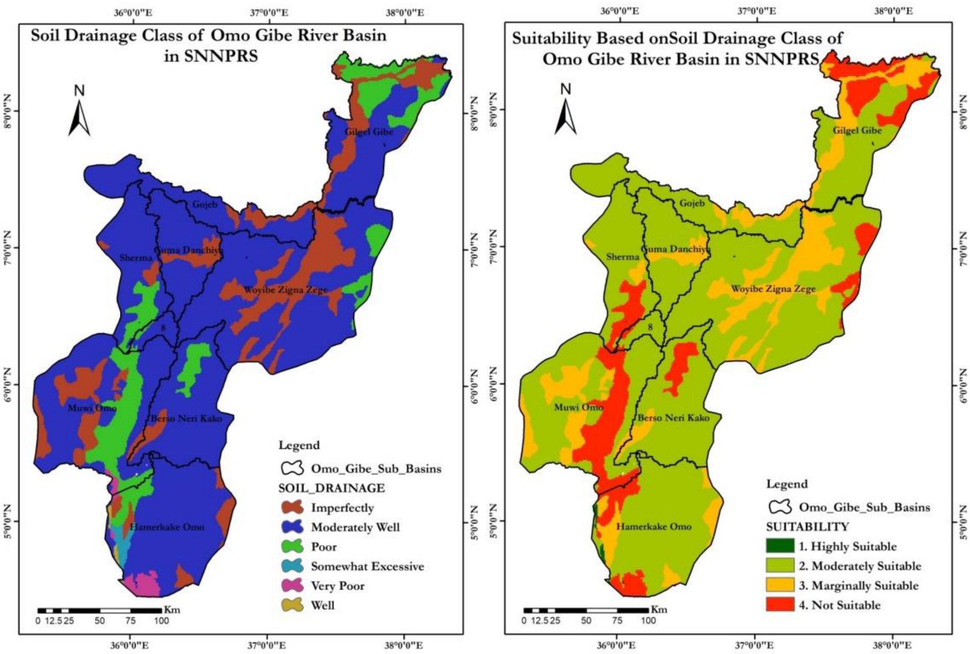


Figure 5. (a) Soil textural class and (b) its suitability map.

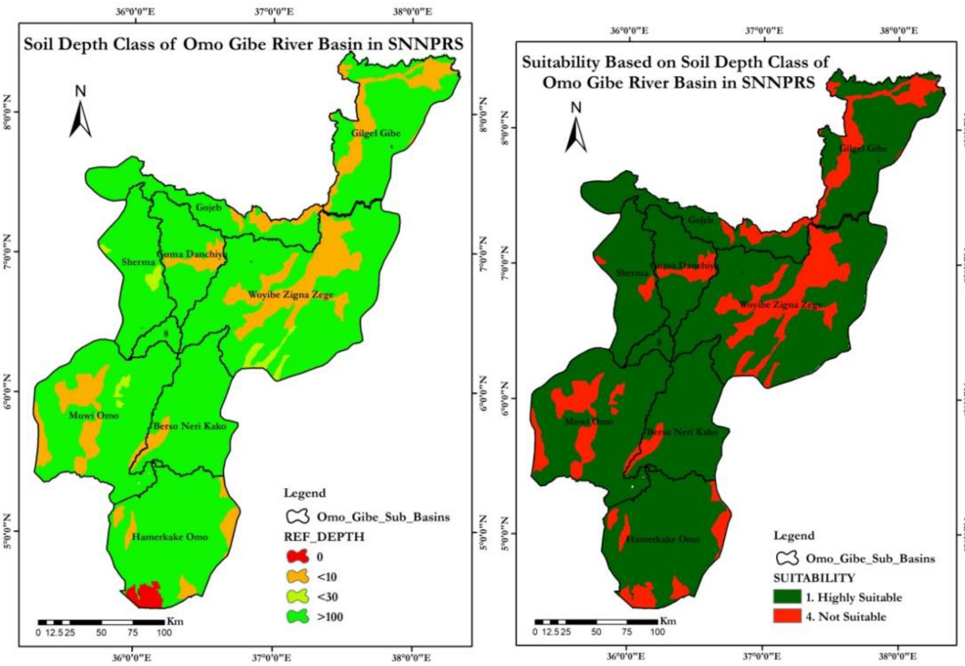
(4773785ha or 82.37%) assigned with high suitability class and (1021563.8ha) 17.63% is categorized under shallow soil which is not suitable for surface irrigation system.

Slope classification: The reclassified slope analysis (Figure 8) indicated that 2.19% is below 2%; 9.56% is ranging between 2-5% slope and 12.09% laying between 5-8% slope range. In the current condition, majority of the study area (76.16%; steep slope) is not recommended for the implementation of surface irrigation based on slope parameter.



(a) (b)

Figure 6. (a) Soil drainage class and (b) its suitability map.

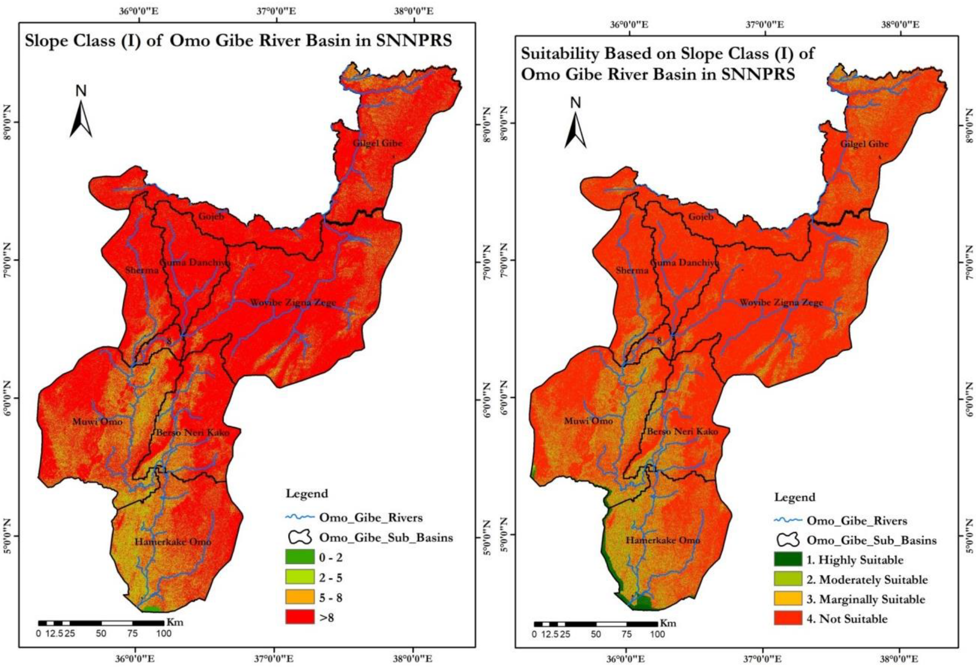


(a) (b)

Figure 7. (a) Soil depth and (b) its suitability map.

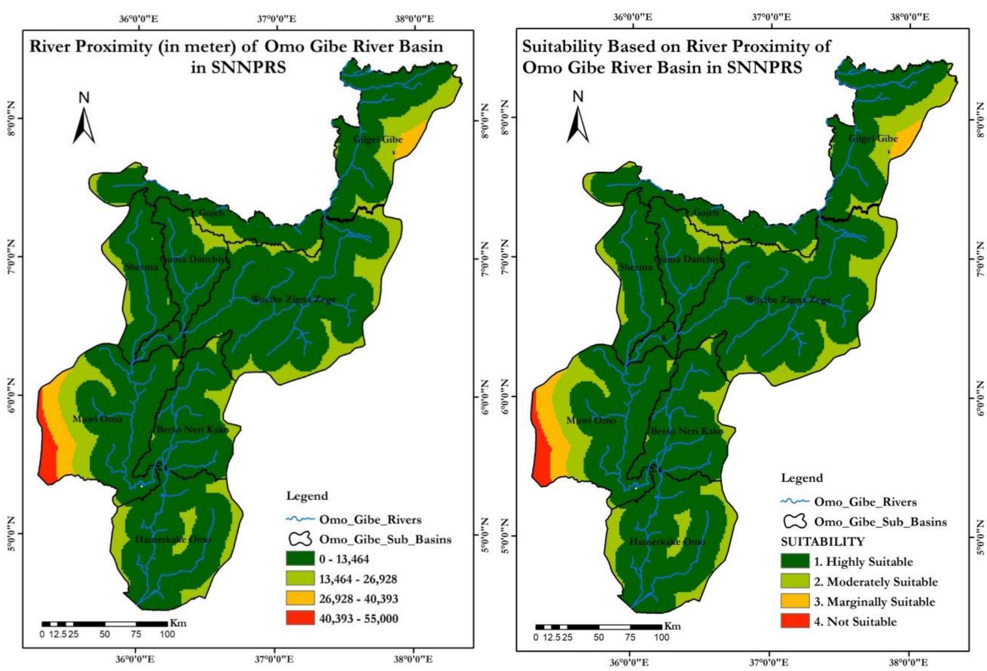
Euclidean distance: From Figure 9a, it is identified that nearly 80.85% (4687097.32ha) of the area is most suitable in terms of nearness to water supply and hence is considered as S1. Nearly 15.43% (894435.97ha) and 2.6% (151113.85ha) land of the area are found to be moderately (S2) and marginally (S3) suitable for irrigation water supply respectively (Figure 9). Whereas, (64593.76ha) 1.11% is not recommended (N) for the implementation of surface irrigation practice in the present situation. In calling EC value (Figure 9b), the water quality of Omo-Gibe River Basin is suitable for the intended purpose as it ranges between no to moderate degree of restriction.

LULC of Omo-Gibe river basin: The study area was defined to have seven LULC categories: water body, pastureland, forest-evergreen, agriculture land, shrub land, residential area and Bare land (Figure 10). The analysis indicated that the basin is dominated by crop land/vegetation (54.42% and highly suitable for surface irrigation), based on the suitability class 16.7% of the study area (forest, water and built up area) is not suitable on the current status. The shrub and bare land, together covering an area of 14.01% is classed under marginal suitable whereas the remaining 14.83% that is covered by grass is assigned with moderately suitable for the intended use.



(a) (b)

Figure 8. (a)Reclassified slope and (b) siutability class map.



(a1) **(a2)**

Figure 9(a). Nearness to river and its suitability class.

Overall suitability/Weighted analysis

Weighting of factors using AHP: The pair-wise comparison matrix and overall weights of the factors selected for the study area was shown in tables below. The six factors are listed in columns and rows; hence the row factors were compared with the factors in the columns for their significance to irrigation, and then using the scoring of Saaty [23] in Table 4, the pair-wise matrix Table 5 was prepared.

The results in Table 5 show that the factor "river proximity" is the most important factor since all its values are greater than 1 in its row followed by "soil depth" that only has one value less than 1. Based on pair wise calculated value of criteria weight river proximity is the most important factor followed by the soil depth of the land. The least important factor in considering irrigation suitability is "land use "with all its row values less than 1. Next, the weights of the factors are computed by normalizing the respective eigenvector by the cumulative eigenvector. Eigen value vector is the nth root of the product of rows [24]. The weights of each factor calculated by using pair-wise technique is listed in the last columns of Table 6, where the greater the value, the more important the factor. The sum of the last columns is 100. The consistency ratio (CR) is 0.051 which indicates that the comparisons of land characteristics were consistent and that the relative weights were appropriately chosen (Table 6).

Overall suitability class: The overall spatial suitability assessment for irrigation based on the overlaid individual layers indicated that (Figure 11) about 77% of the study area were potentially suitable for irrigation. Of the

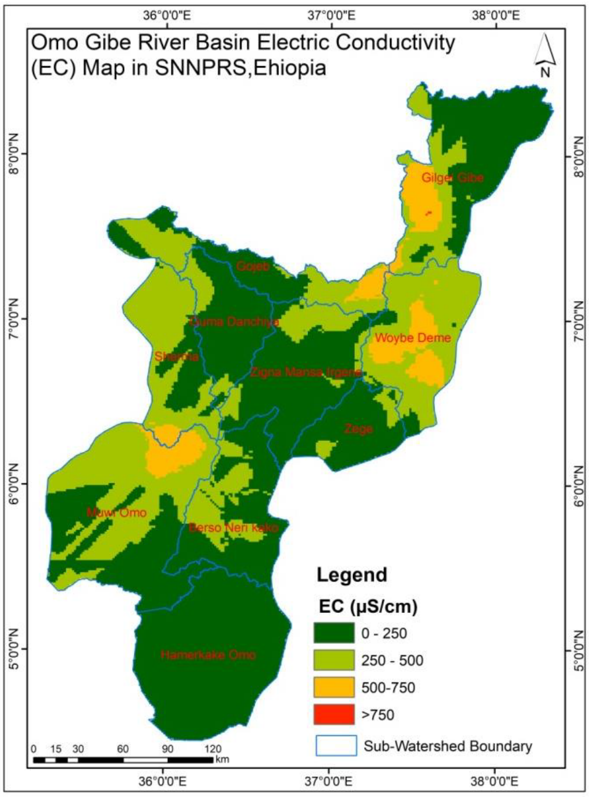


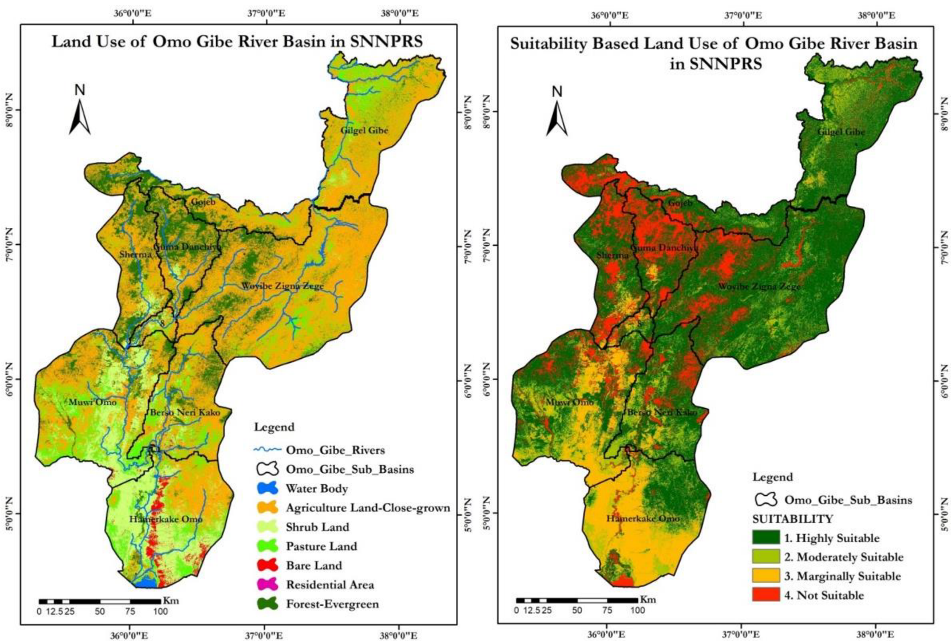
Figure 9(b). Nearness to river and its suitability class.

potential suitable land, 8.1% was highly suitable, 68.9% was moderately suitable, whereas 5.9% of the basin is accounted for marginal suitability. Whereas 0.5% was not suited for irrigation and 16.6% is considered as constrained area (Table 7).

Conclusion

The suitability analysis indicated that, 11.75% and 82.4% of the study area based on slope and soil depth respectively is suited for surface irrigation. In reference to soil drainage class 70% of Omo-Gibe river basin is accounted for suitable class (S1 and S2) at present condition and 17.5% is classed under marginal suitability class. Based on the LULC, 54.42% is highly suited for surface irrigation. In regard to water resource proximity, majority of the study area (80.85%) is currently suitable (S1). In overall, most of the study area is suitable for irrigation (71% excluding the national parks; 7% is S1 and 64% is S2) whereas the remaining 29% is not recommended for surface irrigation. Hence, future surface irrigation development is feasible based the land features and river proximity.

Based on the finding of this study, for the area which have slope above 8% (76.16% of the total area), land leveling operation and/or soil conservation work have to be incorporated to break surface slope and to make it suitable for surface irrigation. The result obtained reveled that, 12.5% of the study area has poor drainage condition. These soils could be made more suitable by adopting improved drainage system, soil and crop management practices. Hence an appropriate drainage provision should be taken into consideration in further development. In consideration to river proximity, almost 4% of the river basin is not suited for surface irrigation therefore looking for other sources of water in the nearby is recommended.



(a) (b)

Figure 10. LULC (2018) and its suitability class with 30m resolution.

Table 5. Pairwise comparison matrix of the selected criteria's.

Factors	Soil depth	Soil texture	Soil drainage	Land use	River proximity	Slope
Soil depth	1	2	2	7	1/2	2
Soil texture	1/2	1	2	5	1/3	1
Soil drainage	1/2	1/2	1	5	1/3	1
Land use	1/7	1/5	1/5	1	1/7	1/5
River prox.	2	3	3	7	1	3
Slope	1/2	1	1	5	1/2	1

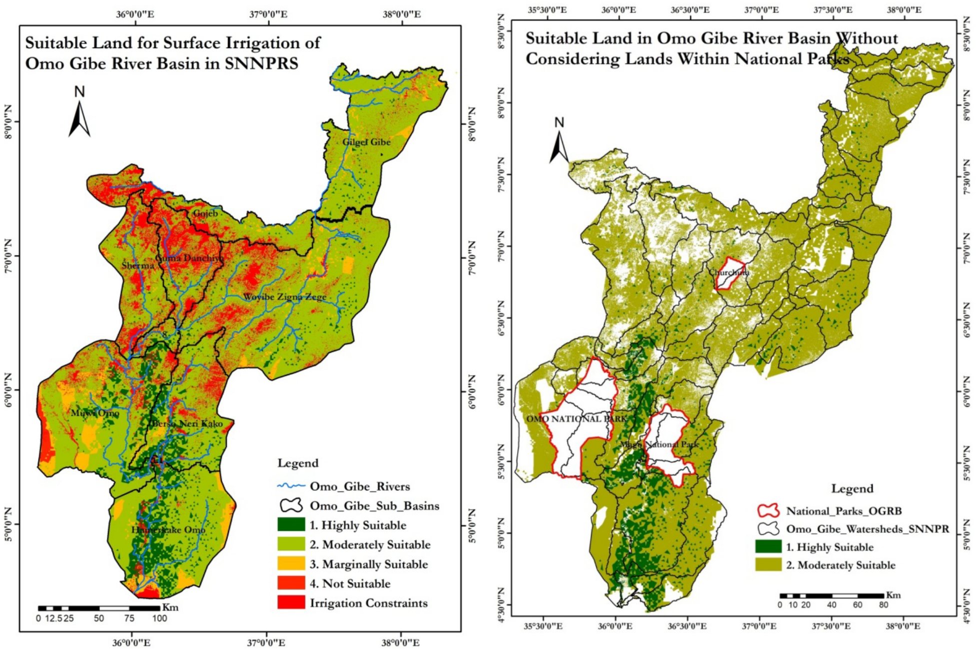
Table 6. Normalized pairwise comparison matrix and computation of criterion weights.

Factors	Soil depth	Soil texture	Soil drainage	Land use	River proximity	Slope	Criteria Weight (%)
Soil depth	0.2154	0.2597	0.2174	0.2333	0.1780	0.2439	22
Soil texture	0.1077	0.1299	0.2174	0.1667	0.1186	0.1220	14
Soil drainage	0.1077	0.0649	0.1087	0.1667	0.1186	0.1220	11
Land use	0.0308	0.0260	0.0217	0.0333	0.0508	0.0244	3
River prox.	0.4308	0.3896	0.3261	0.2333	0.3559	0.3659	35
Slope	0.1077	0.1299	0.1087	0.1667	0.1780	0.1220	15
CR=0.051	Lambda (λ_{max}) which is the Maximum Eigen Value = 6.32						100

Table 7. Overall suitability class for Omo-Gibe River basin.

[a]Area (ha)	Suitability	Description	Percentage (%)	[b]Excluded areas (ha)
465822	S1	1.Highly Suitable	8.1	71590
3978221	S2	2.Moderately Suitable	68.9	276441
340644	S3	3.Marginally Suitable	5.9	
29622	N	4. Not suitable	0.5	
960392	Constraints	Irrigation Constraints	16.6	

[a]total area of land under each suitability class
[b]total area of land not counted as S1 & S2 (which was demarcated as national parks)



(a) (b)

Figure 11. Overall irrigation suitability class in Omo-Gibe River Basin with (a) and excluding the national parks (b) in the River Basin.

Groundwater is a viable option for supplementing surface water resources for irrigation in several basins in the country. Further land suitability analysis for sprinkler and drip irrigation should be carried out to increase the land area to be irrigated.

Conflict of Interests

The authors confirm and declared that there is no conflict of interest in this paper.

Acknowledgements

We would like to acknowledge the unreserved support of Southern Nation Nationalities People Regional State Water and Irrigation Development Bureau Irrigation Construction and Scheme Administration Agency. Our deepest thanks go to the staff members of Hawassa University, Institute of Technology, Faculty of Biosystems and Water Resource Engineering for their valuable comments and expert's suggestion.

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How to cite this article: Rediet Girma, Eshetu Gebre and Teshale Tadesse. "Land Suitability Evaluation for Surface Irrigation Using Spatial Information Technology in Omo-Gibe River Basin, Southern Ethiopia." *Irrigat Drainage Sys Eng* 9(2020): 245 doi: 10.37421/IDSE.2020.9.245