ORIGINAL ARTICLE

Evaluating Surface Water Irrigation Potential of Gumara-Maksegnit Catchment using Spatial Modeling, North-East Lake Tana Basin, Ethiopia

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Abstract

Despite large potential for surface irrigation development, only few percentages of suitable area have been utilized in Ethiopia. This study evaluated the physical land suitability of surface water irrigation for small-scale irrigation development (<200 ha) in the study area. The potential was examined by considering various interacting physical factors, such as river proximity, nature of soil type, land use/ cover, and slope gradient factors with a spatial modelling-based multi-criteria evaluation (MCE). The relative importance of each factors in an overall suitability process were determined based on relevant literatures and expert's estimation to produce the resultant suitability maps of the study area. The results of this study indicated that nearly 2254 ha (6%) of the study area were classified as suitable for surface water irrigation. The findings also revealed that about the largest percentage, i.e., 21737ha (58%) of the study area were classified as moderately suitable. This was largely due to physical limitations such as existing topography and spatial proximity in surface water source. On the other hand, irrigation activities practiced in the study area are largely characterized by traditional water diversion structures, which are often traditional, prone to water wastage and less efficient schemes of lower productivity and poor market linkage. Therefore, the irrigation potential in the study area can only be met by increasing dry season flows (following watershed management in the upstream), increasing water use efficiency thereby decreasing water use wastage, and provision of adequate extension service for small scale irrigation scheme holders.

Keywords: *surface water irrigation, Spatial modelling, MCE, Small-scale irrigation scheme, Water use efficiency, Extension service*

1. Introduction

Ethiopian highlands are comprised of land resources that are potentially suitable for irrigation to provide farmers with sustained livelihoods to improve their general well-being (Abeyou et al., 2018). However, only 5% of potentially available, 30 to 70 million hectares (ha) has been utilized in the country (Awulachew, 2019). Moreover, estimates of irrigable land in Ethiopia vary between 1.5 and 4.3 million, i.e., by far too low compared to the total area currently under cultivation (Gebremedhin and Asfaw, 2015).

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The ever-increasing demands for food caused by rapid population growth can be obtained either by intensification or expansion of farmlands at the expenses of other life support systems. However, further expansions of cultivation land are very limited.

Irrigation in Ethiopia is considered as a basic strategy to alleviate poverty by ensuring food security (Gebremedhin and Asfaw, 2015). It is useful to transform the rain-fed agricultural system into the combined rain-fed and irrigation agricultural system. This is believed to be the most prominent way of sustainable food production. Therefore, increasing agricultural production using irrigation is one of the major crop production sector to end food insecurity caused by insufficient outputs of rainfed systems and population pressure (Abeyou et al., 2018).

Subsistence dominated smallholder farmers' economy can be improved through the use of irrigation in the Ethiopian agriculture (FAO, 2005). Similarly, making use of irrigation agriculture is going to be a means for increased agricultural production to meet the growing food demands of rapid population growth. As a result, irrigation infrastructures are increasing year after year, which show countrywide positive development implications and experiences in small- and large-scale irrigation schemes. However, individual land holdings per households are too small to feed the household. With these limited landholdings, increasing food demands of the population depends on either one or a combination of increasing agricultural yield, increasing the area of arable land, and increasing cropping intensity by growing two or three crops per year using irrigation (Gebremedhin and Asfaw, 2015).

One of the challenges in Ethiopia is the ineffective water resources development for irrigation that has been the lack of hydrological data, because only few rivers have been gauged (Getenet et al., 2019). Growing population pressure in the highland areas and rainfed agriculture on a rapidly declining natural resource base has made irrigated agriculture as a prominent position on the country's development agenda (Getenet et al., 2019). However, there are constraints in smallholder, medium-scale and large-scale irrigation such as lack of institutional capacity, private sector involvement and markets (FAO, 2005). Thus, increased utilization of water resources for irrigated agriculture to overcome existing food shortage and poverty by growing food crops during the dry phase on agricultural land is still limited (Awulachew, 2019).

Maintaining the productivity of land is a determinant factor to obtain sustainable services and goods from land (Ebrahim and Mohamed, 2017). Proper use of land depends on the suitability or capability of land and water resources for the kind of land uses, surface water irrigation in this case, that could lead to substantial increase in food production (FAO, 1976). Nevertheless, agricultural land use is often conducted without a correct pre-assessment of its potential and leading challenges have caused widespread degradation and significant decline in soil productivity in Ethiopia (Asmamaw et al., 2015). Irrigation planning process requires integrating important physical factors the physical suitability of the land, climatic conditions and surface water availability (FAO, 1997). The physical and chemical land qualities that have great contribution to land suitability evaluation of specific use must also be evaluated on condition that water can be supplied to it (Meseret et al., 2020). Studies by Tesfay and Shoeb, (2017); Meseret et al., (2020); Ebrahim and Moahammed (2017) revealed that most of surface water irrigation schemes in the country did not consider the existing constraints and potentials of land interms of dignostic land characteristics to ensure sustanable production. Therefore, evaluations of the land quality with respect to its potential and constraints is related to the selection of suitable land for irrigation and provide management alternatives that are physically practicable and economically viable (FAO, 1985).

About a total of 815,581 hectares of potential irrigable land in Abay Basin is estimated, out of which 45,856 ha are for small-scale, 130,395 hectares for medium-scale and 639,330 hectares for large-scale development (Awulachew et al., 2007; Awulachew, 2019). This shows that little has been utilized from the existing potential. On the other hand, a study by Wale et al., (2013) indicated that nearly 11% of the Lake Tana Basin is suitable for surface irrigation while less than 3% of the potential irrigable area could be irrigated consistently by run-of-the river-systems. Studies by Erkie (2017); Teshome and Halefom (2020); and Balew et al. (2021) also assesed the surface water irrigation potential of Gilgel Abay, Gumara and Rib-Gumara watersheds in Lake Tana Basin. Lack of detailed studies of surface water irrigation potential in the Lake Tana Basin, motivated this research to evaluate the physical suitability of the land for small-scale irrigation schemes. This could provide an input to decision making process for local and regional administrators in the area of small-scale irrigation practices prior to the actual commencements of projects.

Groundwater potential in the study area has not yet been considered for irrigation development, mainly due to high investment and running costs, but smallholder farmers are often under competition over surface water resources of rivers during the dry season. In addition, field observation on the lower course of the catchment shown that over exploitation of surface water from Gumara-Maksegit river sometimes caused to dry-up the streams, and source of local conflicts among users. The major contributing factors for excessive use of surface water in these areas are largely attributed to lack of proper irrigation technology that efficiently utilizes water resources. This investigation focused on Gumara-maksegnit catchment situated in the eastern Lake Tana Basin, which has been designated as one of the growth development corridors for economic development by the government of Ethiopia to end poverty. This study is, therefore, important to understand the extent of surface water irrigation potential of the study area. suggesting possible way forward to sustainably utilize the surface water resources while ensuring food security and improved livelihood.

2. OBJECTIVE OF THE STUDY

The objective of this study is to evaluate the physical land suitability of agricultural catchment for surface water irrigation purpose using a GIS-based multi-criteria evaluation (MCE), which considers the interaction of various factors in spatial modeling technique.

3. MATERIALS AND METHODS

3.1. Location description

Gumara-Maksegnit watershed is part of the Lake Tana Basin situated in the Northeastern side of the lake crossing Gondar Zuriya and East Dembya Woreda. It lies between 12017’06” to 12030’53” Latitude and 37025’07” to 37041’54” Longitude an area of 37,051 ha. The altitude ranges between 1785 m Lake Tana (outlet) and 2848 m a.s.l. at headwaters in the western escarpment of Gondar Zurya Woreda (Figure 1). The river originates from the high plateau of the east, which is characterized by mountainous, highly rugged and dissected topography. It drains into the plain in the west with flat to gentle slopes (Ayenew, 2008). Lower course of this river is one of the major flooding hazard prone areas of East Dembya Woreda due to overflow of river water from river banks and backflow to Lake Tana during intense rainy seasons. The dominant irrigated crops commonly grown in the study area are usually of high value, which include Khat (a mild narcotic leaf),

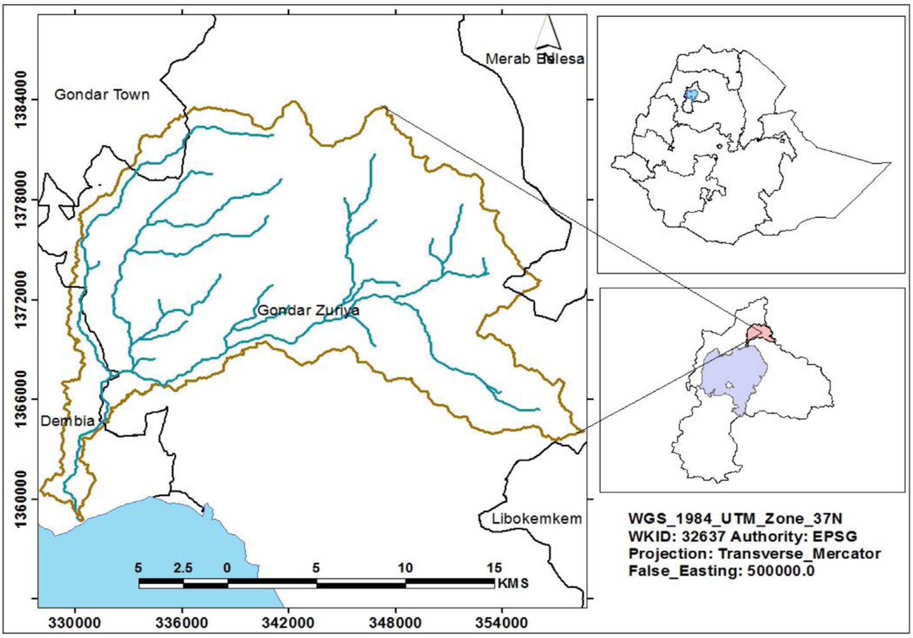
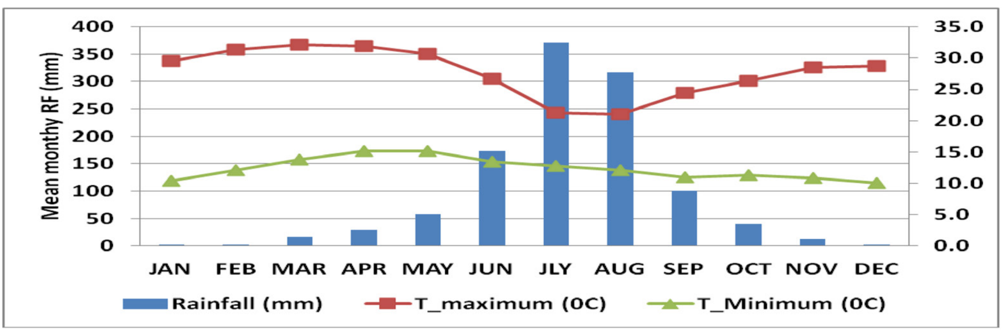


Figure 2.1. Location map of the study area (Krauer et al., 2014)

Local climate and Agroecology

The agro-climatic zone of Gumara-Maksegnit watershed varies from Low-altitude Sub-Tropical (Woyna Dega) from 1785-2300 m.a.s.l and mid-altitude Temperate (Dega) from 2300-2848 m.a.sl. Among these Agro-ecological zones, woina Dega covers highest percentage (79.8%) that is moderately suitable for settlement and crop production while Temperate (Dega) agro ecological zones cover about 10.2% of the watershed (Hurni, 1998). The meteorological station data obtained from NMSA Bahir Dar branch for Maksegnit Station indicated that the mean annual rainfall of the watershed varies from 792.1mm to 1129.4 mm per year. High rainfall season in the watershed starts during summer in June and ends in September, while short rainy season are recorded in autumn. Figure 2.2 shows that the long-term mean monthly minimum temperature is less than 12.3°C, while the maximum mean temperature is 27.7 °C.

Figure 2.2. Mean monthly rainfall and temperature (2008-2018) characteristics of the stations in the Gumara watershed. Source: National Meteorological service Agency (NMSA) 2018/2019



onions, potatoes and vegetable crops (Abeyou et al., 2015) through both surface water irrigation and groundwater use.

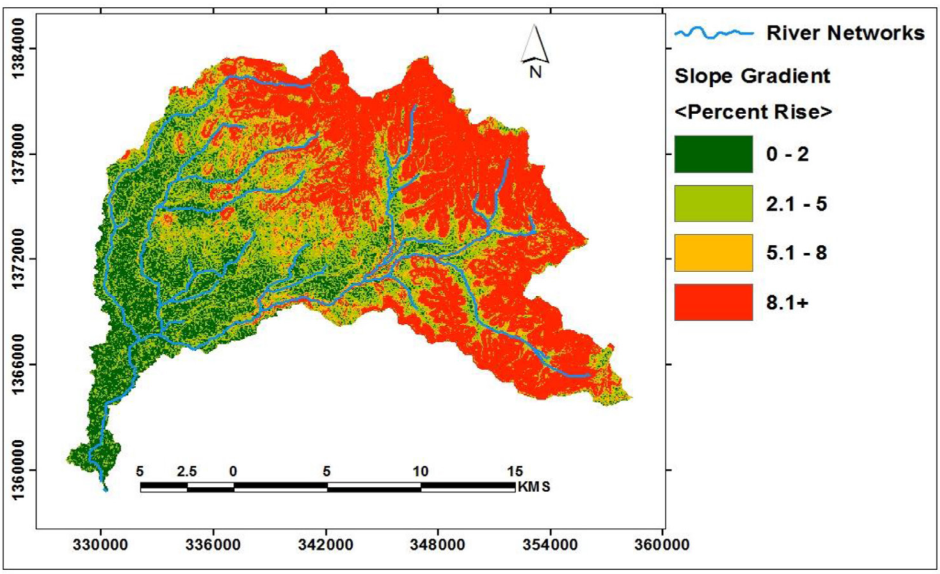
3.2. Methodology

This study focused on the physical land suitability evaluation for surface irrigation potential using spatial modeling technique where socio-economic aspects were exempted from the analysis. The surface water availability and land potentially suitable for irrigation development were considered. The spatial modeling analysis based on MCE of factor layers was employed to evaluate the overall physical suitability of the study area to a specified kind of land use (surface water irrigation) potential. Land suitable area for surface irrigation considered the interaction of various factors such as river proximity, soil type, land cover, and topography/slope. Land suitability was determined by assigning weights (or ranks) to the factors that likely affect the irrigation potential of a certain land area. Weights are assigned based on the relative importance of each factor in an overall suitability evaluation.

3.2.1. Sources and Types of data used

In this study, different sources of data were used to identify potential land areas suitable for Surface water irrigation using a spatial modeling based Multi-Criteria Evaluation (MCE) technique. To achieve this, the following datasets for the study area were employed. Topographic data: SRTM (Shuttle Radar Topographic Mission) with 30m-by-30m spatial resolution DEM data was obtained from USGS database (www.earthexplorer.usgs.gov). It was used to generate slope gradient factor layer map in percentages. Slopes ranges from flat and gentle slopes (0-10%) are largely extended towards the lower course while steep slopes (30% and above) are located around the upper course of the catchment (Figure 2.3).

Figure 2.3. Slope gradient map of the study area



Land use/cover data: In this study, Arcmap shapefile showing the 2014 land use/cover class map of Lake Tana Basin by Amhara Water Works Design and Supervision Enterprise (AWWDSE) is considered as an input layer in irrigation suitability evaluation. Thus, about 14 land use/cover subclasses of the 2014 reference year were employed in surface water potential evaluation assessment (AWWDSE, 2015). The dominant land use/cover sub classes identified in the study area for the reference period were Intensively cultivated land, Open shrub land, Open grass land, Moderately cultivated land and Farm Village with about 18477.5 ha (49.88%), 5635.9 ha (15.21%).4868.8 ha (13.14%), 2702.8 ha (7.30%), and 2519.5 ha (6.80%) of the study area (Figure 2.4 and Table 2.1).

Table 2.1. The 2014 land use/cover class coverage of the study area (AWWDS, 2015)

Land use/cover classes	Ha	%
Town	282.8	0.76
Dense natural forest,	815.6	2.20
Dense shrub land	288.7	0.78
Farm village	2702.8	7.30
Intensively cultivated land	18477.5	49.88
Moderately cultivated land	2519.5	6.80
Open grass land	4868.8	13.14
Open shrub land	5635.9	15.21
Permanent wetland	8.7	0.02
Plantation forest	432.9	1.17
Seasonal wetland	145.3	0.39
Shrub grass land	11.9	0.03
Sparsely cultivated land	855.4	2.31

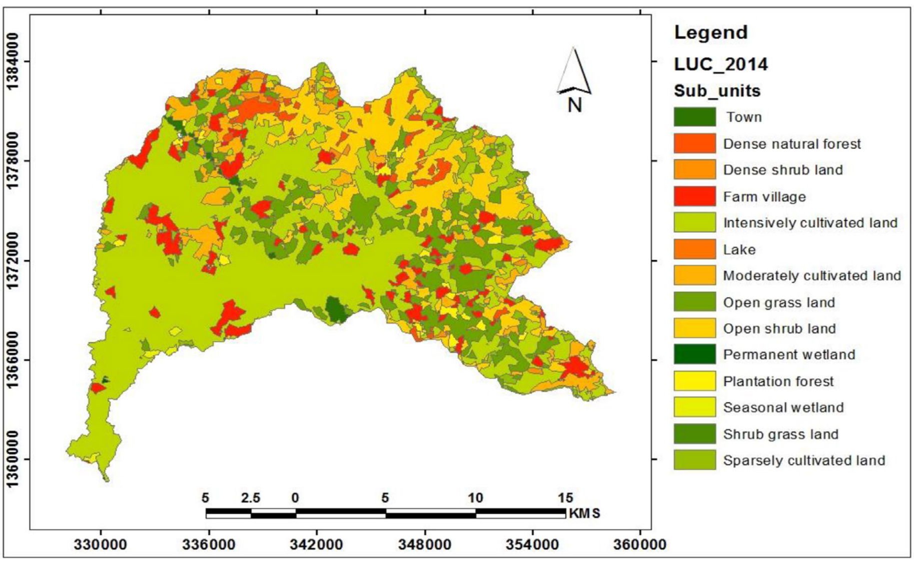


Figure 2.4. The 2014 land use/cover map of the study area (AWWDSE, 2015)

Soil data: Soil type map of the study area was generated from FAO (1997) map of Ethiopia with their diagnostic properties. The dominant soil groups according to FAO soil classification (FAO, 1997; 2006) in the study area are eutric cambisols (47.6%), chromic vertisols (22.6%), eutric regosols (17.4%) and calcic xerosols (9.3%) as shown in figure 2.5 and table 2.2.

Table 2.2. Spatial coverage of major soil types (FAO, 1997)

No	Soil type	Area Coverage	
		Ha	%
1	calcic xerosols	3443.3	9.3
2	chromic vertisols	8355	22.6
3	dystric nitisols	1034	2.8
4	eutric cambisols	17633.6	47.6
5	eutric regosols	6434	17.4
6	leptosols	150.3	0.4

Figure 2.5. Soil type coverage map of the study area (FAO, 1997)

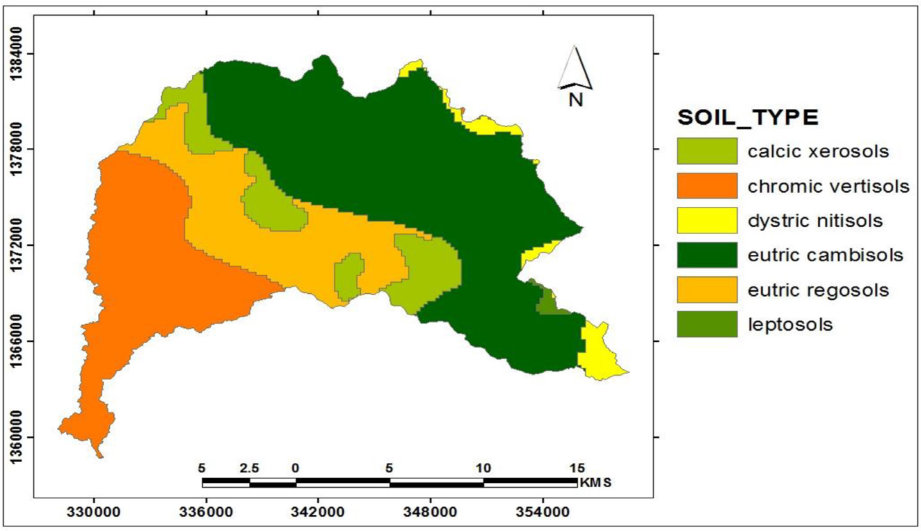


Figure 2.5. Soil type coverage map of the study area (FAO, 1997)

Stream network data: river network of the study area was generated from SRTM with 30m-by-30m spatial resolution data, which was obtained from USGS database (www.earthexplorer.usgs.gov). River networks are indicators for surface water availability, which determines the spatial proximity/access to surface water sources. In this study, distance from the main stream cannel was considered for physical land evaluation of surface irrigation potential (Figure 2.6).

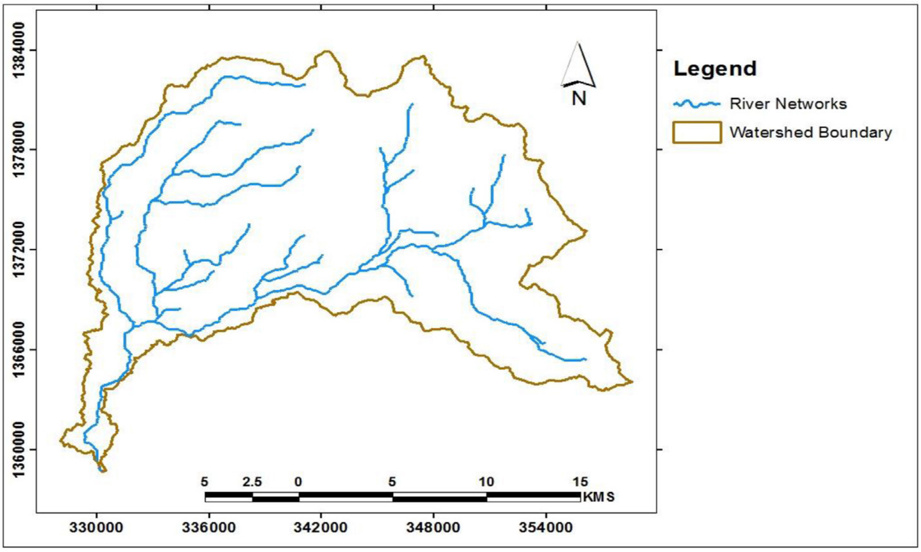
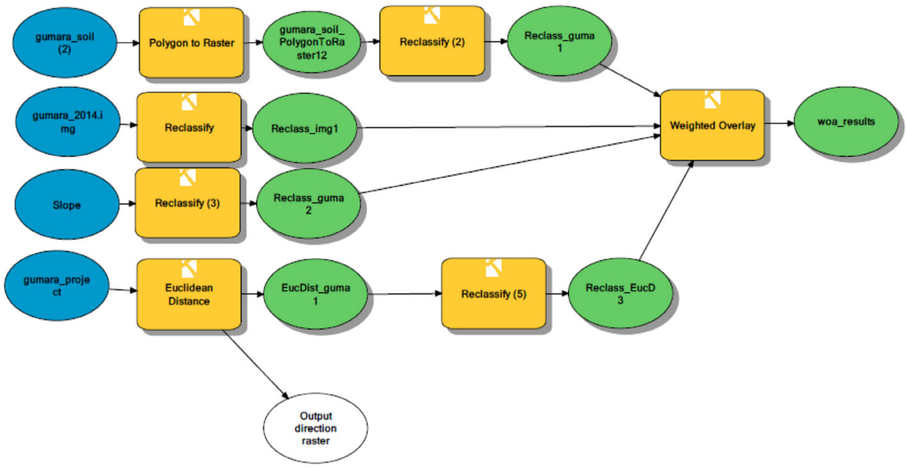


Figure 2.6. Stream network map of Gumara-maksegnit watershed

3.2.2. Weighted overlay analysis

The physical land suitability involving the classification of land quality layers such as soil types, land use/cover types, topography/slope gradients and stream networks against the requirements for surface water irrigation, i.e., land use is considered (FAO, 1985; 2007). Each land quality layers are classified into four levels of suitability such as S1= suitable, S2=moderately suitable, S3=marginally suitable, and N=Not suitable classes using ad-hoc combination of land quality ratings.

Land suitability assessment is inherently a multi□criteria approach where multiple factors are analyzed by GIS for spatial MCE process based on FAO (1985) guidelines for irrigation agriculture. The criteria are measurable based on which decisions about land quality and its suitability for a specified use can be made (Sarkar et al., 2014). Once individual factor layers are classified into single factor rating values, combination of each layer was done using weighted overlay analysis of ArcGIS 10x. Weights to individual layers were given based on the relative significances of each layer in an overall physical suitability evaluation (Saaty, 1990). The derivation of weights is a central step in defining the decision maker's preferences as an indicative of its importance relative to other criteria under consideration (Odu, 2019). Finally, the weighted factor maps are overlain and surface irrigation area suitability map is computed using spatial modeling tool in ArcGIS spatial toolbox (Figure 2.7).



4. RESULTS AND DISCUSSION

4.1. Single factor rating values

Slope steepness factor: The results of slope factor layer showed that about 719.2 ha (19.6%) of 0-2% slope category is highly suitable, 10171 ha (27.7%) of 2-5% slope category is moderately suitable and 4501.2 ha (12%) of 5-8% slope category is marginally suitable for surface irrigation system as shown in table 4.1 and figure 2.3 (FAO, 1985; FAO, 1996; Girma and Tasisa, 2020). The remaining 14817.3 (40.4%) of the area of watershed is not suitable for surface irrigation for physical reasons (FAO, 1976). Most of the area of the watershed falls below 8%, which is suitable at different range of suitability with miner modification to negotiate the natural slope in the form of constructing channel support walls and micro dams or diesel/benzene powered portable pumps.

Table 4.1. Slope suitability classification for surface irrigation (FAO, 1996)

No	Slope gradient classes (%)	Coverage		Suitability class
		Ha	%	
1	0-2	7199.2	19.6	S1
2	2-5	10171.0	27.7	S2
3	5-8	4501.2	12.3	S3
4	>8	14817.3	40.4	N

Land use/cover factor: Land use/cover sub-classes such as intensively and moderately cultivated land, open grassland, and open shrub land were classified as highly suitable (S1) for irrigation with the assumption that these land cover classes can be irrigated without limitations. Open grasslands are considered for weighting assuming that cut and carry livestock forage system and other improved cattle feed options could be introduced for areas of livestock-based agriculture. In addition, crop residue during harvesting could also be other options of animal fodder. They have contributed about 31501 ha (85%) of the study area. Sparsely cultivated land, seasonal wetlands, shrub-grasslands, which contributed about 1012.6 ha (2.7%) are classified as moderately suitable (S2) for surface water irrigation possibly due to topographic problems as a limiting factor (Table 4.2 and Figure 4.1). Other land use/cover units such as dense shrub land, plantation and natural forests were classified as lands not suitable (N) for irrigation, 1537.2 ha (4.1%) of the study area. According to the local land use system, they cannot be put under cultivation possibly for conservation reasons. However, restrictions on land use/cover sub classes such as water body, settlements (farm village and town) and permanent wetlands were based on the fact that they are exempted from surface water potential use analysis and covers about 2994.6 ha (8.1%) of the study area (FAO. 1985; Getnet et al., 2019; Girma and Tasisa, 2020).

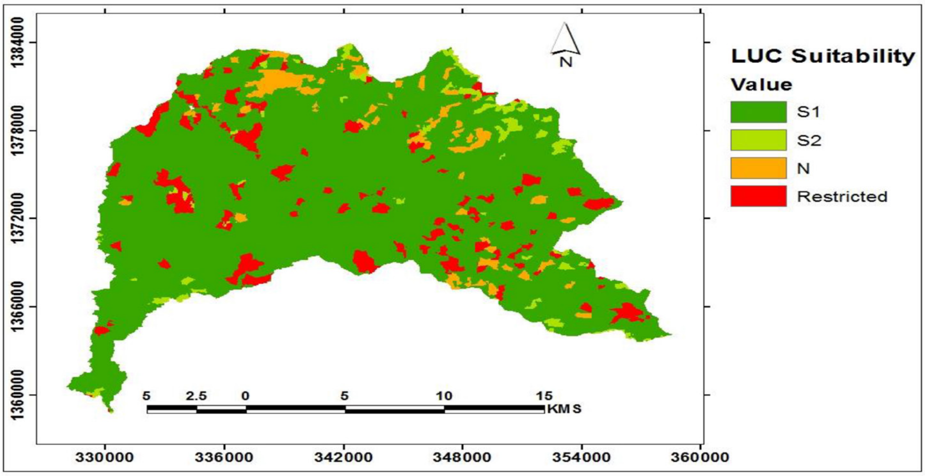


Table 4.2. Land use/cover factor suitability status of the study area (FAO. 1985; Getnet et al., 2019; Girma and Tasisa, 2020)

No	Land use/cover Subunits of the study area	Area coverage		
		Ha	%	Suitability status
1	Intensively and moderately cultivated land, open grassland, and open shrub land	31501	85	S1
2	Sparsely cultivated land, seasonal wetlands, shrub-grasslands	1012.6	2.7	S2
3	Dense shrub land, plantation and natural forests	1537.2	4.1	N
4	Water body, settlements (farm village and town) and permanent wetlands	2994.6	8.1	Restricted

Soil factor layer: Soil map of the study area are reclassified into four different ranges of suitability classes based on their inherent fertility and drainage conditions as a basis for determining the suitability status to a wide range of agricultural uses. It is produced after the vector soil map of the study area is converted into raster soil layer where individual soil type is reclassified into the corresponding assigned suitability classes. In this study, eutric cambisols and leptosol are classified as suitable (S1), eutric regosols and dystric nitisol are classified as moderately (S2), chromic vertisols are classified as marginally suitable (S3) while calcic xerosols is classified as not suitable (N) with about 48%, 20%, 23% and 9% area of the study area (Table 4.3 and Figure 4.2).

Figure 4.2. Soil suitability layer map of the study area

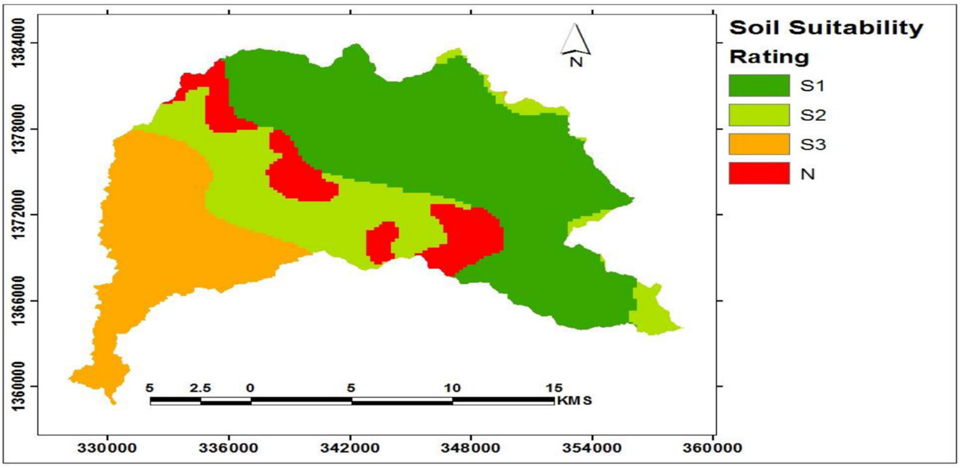


Table 4.3. Soil suitability classification result for surface irrigation (FAO, 1985; 197; 2006; Tesfay and Shoeb, 2017; Getenet et al., 2019; Girma Tasisa, 2020)

No	Soil Types	Area coverage		Suitability status
		Ha	%	
1	eutric cambisol, Leptosol	17789	48	S1
2	eutric regosol, dystric nitisol	7472	20	S2
3	Chromic vertisol	8352	23	S3
4	Calcic xerosol	3437	9	N

River Proximity factor layer: Stream network distance analysis from the main stream lines (nearest water source) indicated that distance for each cell, the Euclidean distance to the closest source, i.e., river networks are calculated. In this study, surface water irrigation using drainage channel constructed locally based on gravity rules were considered in the analysis. The spatial proximity factor rating values, i.e., distance from the main stream channel was estimated based on the field observation in the study area and literatures (Getenet et al., 2019; Girma and Tasisa, 2020). Therefore, distances from the closest source such as ≤100m, 100-500m, 500-1000m and >1000m have contributed about 9%, 31%, 29% and 31% area of the study area; which intern classified as S1, S2, S3 and N, respectively (Figure 4.3).

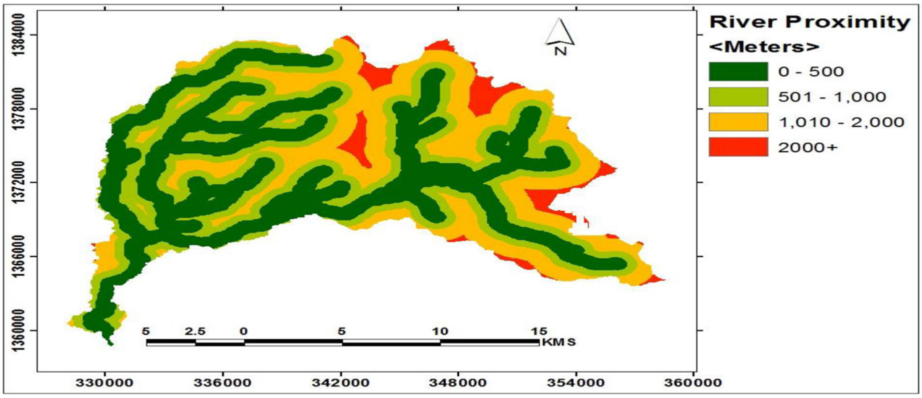


Figure 4.3. Euclidean distance of irrigation area from potential diversion point (Getnet et al., 2019)

4.2. Surface water irrigation potential assessment

In this study, the weighting process combined the literatures and expert's estimation to produce the resultant suitability maps of the study area. Therefore, the percentage values of the relative importance of each factor layers such as soil type, land use/cover, river proximity and slope gradient were 28%, 10%, 23.4% and 38.6%, respectively (Table 4.4).

Table 4.4. The relative importance's of each factor layers in MCE process, modified after Abeyou et al., 2013; Wale et al., 2013; Erkie, 2017; Getenet et al., 2019; Teshome and Halefom, 2020; and Balew et al., 2021

No	Factor layers	Weights	
		proportion	%
1	soil type	0.28	28
2	land use/cover	0.1	10
3	River proximity	0.234	23.4
4	Slope gradient	0.386	38.6
Total		1.00	100

The MCE result revealed that about 2254 ha (6%), 21737ha (58%), and 9566 ha (25%) of the study area are classified as S1, S2 and S3, respectively (Table 4.5 and Figure 4.4 left). However, about 1782 ha (4%) of the study area are classified as N for physical reasons. On the other hand, land use/cover subclasses restricted/exempted from physical suitability classification contributed about 2950 ha (8%) of the study area as not suitable for socio economic reasons (Figure 4.4 right). This reflected that only small percentage is conducive with no limitation while the largest proportion of the study area is moderately conducive for surface water irrigation limited largely by topography.

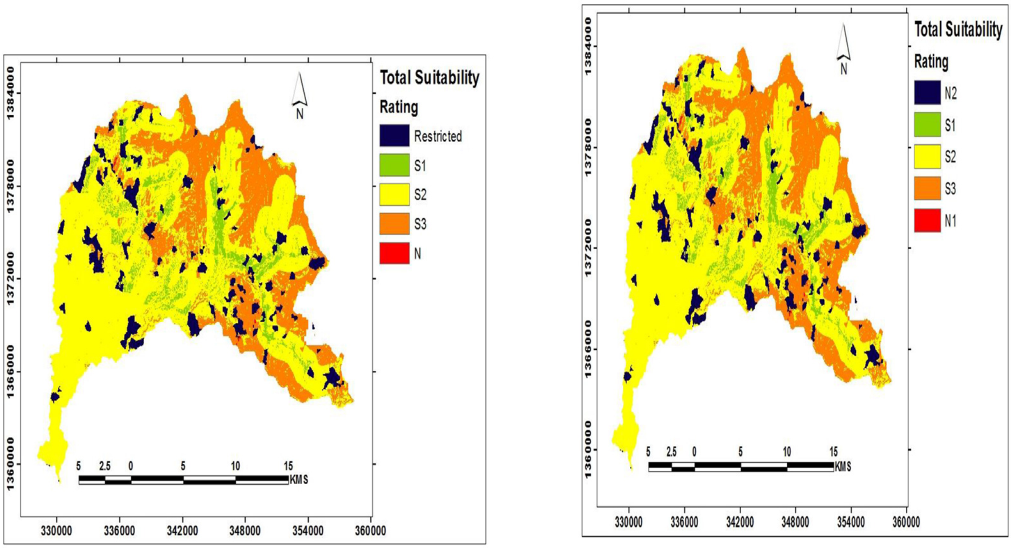


Figure 4.4. Physical (left) and socio-economic (right) land suitability map of surface water irrigation for stallholder farmers in the study area

Table 4.5. Surface water irrigation physical land suitability classes for stallholder farmers in the study area

Suitability class	Area (ha)	%
S1 (Suitable)	2254	6
S2 (Moderately Suitable)	21737	57
S3 (Marginally Suitable)	9566	25
N (Physically Not suitable)	1782	4
R/N2 (Restricted/ economically unsuitable)	2950	8

Studies by Kassaye and Shimellis (2020); Wale et al., (2013) indicated that about 16% and 11% of Borkena watershed and Lake Tana Basin are suitable for surface irrigation. A study by Banchiamlak (2017) at Abagerima watershed showed, about 20% of the watershed can potentially be suitable for surface irrigation. In similar studies by Erkie (2017); Teshome and Halefom (2020); and Balew et al. (2021) about 14%, 20% and 27.5% of Gilgel Abay, Gumara, Rib-Gumara watersheds are potentially suitable for surface water irrigation purposes in the Lake Tana Basin, respectively. However, extremely low percentages of the potential irrigable areas could actually be irrigated consistently with runoff from the river discharge. It is because the river often dried up during the excessive dry season driven largely by land use/cover changes, climate variability and excessive uptake of water for traditional small-holder irrigation schemes.

Out of the total 15000 hectares area for devoted to small-scale irrigation in Gondar Zurya Woreda, only about 5000 hectares of land were attributed to Gumara-Maksegnit catchment (GZWARD, 2021). This means, about 20.8% of the total area suitable and moderately suitable areas of the catchment for irrigation were covered with small-scale irrigation practices at a household level. These could possibly benefit about 10000 households if the associated physical and socioeconomic barriers were resolved for farming households.

The traditional forms of irrigation practiced in the study area were generally characterized by diversion structures constructed by peasants from mud, rocks, twigs or other mixtures. The structures are generally washed away by floods during the main rainy seasons and they require maintenance or reconstruction at the end of each maximum river discharge seasons. In addition, these structures usually facilitated loss of river water to the evaporation and ground water system. As a result, the efficiency of water use by traditional schemes is low as surface irrigation without land leveling is used for distributing water.

On the other hand, productivity of land in traditional irrigation schemes often characterized by lower productivity and poor market linkage (Erkie, 2017). As a result, the impacts on visible livelihood improvement among farming households often limited. The major constraints limiting the productivity of traditional irrigation schemes are inadequate extension service shortages of extension agents with relevant skills, agricultural inputs (fertilizers, pesticides and improved seeds), technological inputs to improve water use efficiency, and poor market linkage. Therefore, the overall performances of traditional schemes were generally low although considerable opportunities for improvement are still existed.

5. CONCLUSION

In this study, the surface water irrigation potential of the study area was mapped based on factors, which affect the physical suitability of land for surface irrigation, such as proximity to river, slope gradient, land use and nature of soil. The findings of this research indicated that only small percentage, i.e., 6% of the study area are physically suitable for surface water irrigation compared with Gilgel Abay, Gumara, Rib-Gumara watershed in the Lake Tana Basin largely caused by physical limitations. The major physical limitations identified in the study area were the nature of topography (slope gradients), spatial proximity to surface water, and seasonal variability of stream flow. In addition, the excessive abstraction of water in traditional irrigation practices are largely drying up the mainstream early in the dry season causing conflicts among users in the catchment. Therefore, the irrigation potential in the study area can only be met by increasing dry season flows (following watershed management in the upstream), increasing water use efficiency thereby decreasing water use wastage, and provision of adequate extension service for small scale irrigation scheme holders.

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