Geospatial analyses to identify suitable land and development potential options for irrigation and rainfed agriculture scenarios, Ethiopia

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Highlights

- About 34% and 1.3% of the land are the highest suitable land for irrigation and rainfed agriculture.
- About 71317 sq.km (6.8%) & 347435 sq.km (33.3%) of area were found for the highest & high irrigation development options, respectively.
- For rainfed agriculture, ca. 33,821 (3.2%) sq.km & 105,013 (10%) sq.km of land are found to be the highest & high potential, respectively.

Abstract

Agriculture is the leading sector in the Ethiopian economy, which contributes about 44 percent of the total GDP as compared to 14 percent from industry and 42 percent from services. Although it is still the dominant sector, most of Ethiopia's cultivated land is under rainfed agriculture, and only 7.5 percent of irrigable areas are under irrigation schemes. The objectives of this study were to: (1) identify where and quantify highly suitable areas for irrigation schemes and rainfed and analyze the gaps with the existing areas for irrigation and rainfed, (2) identify development potentials for both irrigation and rainfed scenarios by using determining factors affecting their potential, (3) draw the attention and provide a better guide for investment decisions that would enhance national and regional development potential in boosting agricultural production and productivity in Ethiopia. Regarding land suitability, different input datasets were analyzed and suitable areas were identified for irrigation and rainfed agriculture. Some common variables were used to identify land suitability of both scenarios (irrigation and rainfed), which include agroecology, slope classes, land use land cover types, road networks, soil types, and woreda and town populations. Whereas rainfall and rainfall variability were additional inputs for rainfed agriculture but the river and river flow rates were used as additional inputs for land suitability for irrigable areas. Furthermore, five major factors were identified to model development potential options for rainfed and irrigations scenarios, which are (1) land suitability, (2) agroecology, (3) population density, (4) market access, and (5) length of growing periods. These factors were modelled the using Geographically Weighted Regression (GWR) approach to identify potential levels from the highest to middle for both scenarios (irrigation and rainfed). Moreover, a multi-criteria decision support method was used to test the sensitivity analyses of explanatory variables for each scenario. The results of these analyses indicate that is about 359,360 sq.km of land (34.1%) is highly suitable for irrigation agriculture whereas about 13,802 sq. km (1.3%) of the landmass was found for rainfed agriculture. Nationally, about 1.6% of areas are highly suitable and 54% are moderately suitable areas for rainfed agriculture, indicating that we traditionally depend on the moderately suitable areas without knowing their status as about 12% of the landmass is currently cultivated, which is putting aside the highest suitable areas for irrigation. Development options for irrigable areas are found to be about 71,317 sq. km (6.8%) and 347,435 sq. km (33.3%) of areas for the highest and high potential options, respectively. On the other hand, for rainfed agriculture, about 33,821 (3.2%) sq.km and 105,013 (10%) sq.km of land are found to be the highest and high potential, respectively. Both irrigation and rainfed potential options indicate that the country has untapped potential for agricultural development options.

Keywords: geographically weighted regression, geospatial analyses, irrigable areas, land suitability, rainfed areas, spatial analyses.

Introduction

Agriculture is the leading sector in the Ethiopian economy, which contributes about 44 percent of the total GDP as compared to 14 percent from industry and 42 percent from services (AfDB, 2010). Although it is still the dominant sector, most of Ethiopia's cultivated land is under rainfed agriculture. On the other hand, Ethiopia has 12 river basins with an annual runoff of about 122 billion m^3 of water and an estimated 2.6-6.5 billion m^3 of groundwater potential, which are large volumes (Awulachew et al., 2007). However, due to a lack of water harvest on hand, and large spatial and temporal variations in rainfall on the other, there is not enough water for most farmers to produce more than one crop per year. Hence, frequent droughts, and dependent on rainfed agriculture exacerbate the incidence of crop failures and result in food insecurity and poverty (Awulachew et al., 2007; Shiferaw et al., 2022). The problem is further complicated by frequent crop failures due to extended dry spells and droughts (WWSE, 2009). Some of the main challenges, according to WWSE (2009) are: long dry or rainless spells, water resources suffering from spatial and temporal variation underutilization due to lack of required infrastructure, lack of supporting institutions, transboundary nature reverse-stagnation to augment crop production and productivity using water resources, and lack of water use rights and management to take their maximum advantage although fragmented irrigation schemes/projects are in progress in the country.

Moreover, among the more specific causes of rural poverty in Ethiopia are (URL1): wide fluctuations in agricultural production as a result of traditional systems, an ineffective and inefficient agricultural marketing system, underdeveloped transport and communication networks, and underdeveloped production technologies. However, according to Mellor and Dorosh (2010), there is substantial evidence that raising agricultural productivity is possible and that agricultural growth plays a key role in economic growth, particularly in low-income countries. The Government of Ethiopia is committed to the rapid growth of agriculture as a means of accelerating the economic transformation and reducing poverty. Ethiopia is now increasingly investing in this sector to achieve a ten years' development plan and its goals so that the country will be transformed into an industrialized economy. However, there is a need to have clear and concrete information where are the potential areas to achieve these goals from agricultural productivity perspectives.

Of the total 1.13 million km^2 land area of the country, the cultivated land is about 12.98 million ha, or ~12 % of the total land area except for dry season irrigation areas (CSA, 2020). Again the total irrigated area is 7.5 % (CSA, 2020). Small-scale farmers occupy 96 % of the cropped area, while the remaining 4 % is cropped by State Farms and Producers Cooperatives (FAO, 2001). In Ethiopia, irrigable areas are categorized into three: large scale (>3000 ha); medium scale (200-3000 ha), and small scale (<200 ha) WWSE (2009). Given the amount of water available even for the semi-arid, arid, and desert areas, it is evident that the promotion of irrigation at small and large scales provides an opportunity to improve the productivity of land and labor and increase production volumes (Awulachew et al., 2007). Moreover, identifying irrigation and rainfed agriculture potential areas, which have reliable moisture contents for agricultural production is very imperative. Combining these two approaches-either for irrigation or rainfed or both depending on the suitability of the areas, which have a high potential for growth and development through agricultural production. This enhances the government strategies of the climate resilient green economy of the country. Hence, there is a need to have clear information on where to design what kinds of schemes are based on land suitability so as to design the best development potential.

Land suitability helps to design the irrigation schemes and reliable rainfed programs accordingly. On the other hand, land suitability (for agriculture potential), market access, population density (pressure), and length of growing periods will enhance development potential. Therefore, this work will focus on: 1) identifying where best suitable areas are found for irrigation, and 2) identifying where best suitable areas are found for reliable rainfed agriculture; and 3) indicating where are different agricultural development potential can be achieved by analyzing spatial and infrastructure factors across the country. These analyses will be carried out across different agro-ecological gradients for lowland, mid-lowland, mid-highland, and highland areas in the country. These four agro-ecological gradients are the possible distinct agricultural production systems of the country from lowland (which mixed root crops and maize production including pastoralist and agro-pastoralist areas) to highland areas (for barley, wheat, oilseeds, and pulses production or most cereal production areas).

The specific objectives of this study are to: (1) identify land suitability for irrigation and rainfed areas for agricultural productions in the country; and by different agroecology; (2) gap analysis by comparing existing irrigated with irrigable areas; and existing rainfed with reliable potential rainfed areas; (3)

identify development potentials for two scenarios (irrigation and rainfed areas); and (4) draw the attention and provide a better guide for investment decisions that would enhance national and regional development potential in boosting agricultural productions and productivity in Ethiopia. Whereas specific research questions to be addressed in this study are: (1) how many areas are suitable for irrigation and rainfed agriculture at different agroecology levels (lowland, mid-lowland, mid-highland, and highlands)? (2) how much percent of best (highly) suitable areas are available for both irrigation and rainfed agriculture in the country and at different agroecology? (3) how much water capacity of the permanent rivers can have for irrigation potentials (irrigable service areas from existing river flows) that can be used within a limited buffer distances to each station measured in those rivers? (4) where are irrigable agriculture development potential areas found in the country by agroecology? (5) where are rainfed agriculture development potential areas found in the country by agroecology? and (6) is there any gap between the existing (irrigated) and irrigable area; and existing rainfed and potential rainfed areas?

2. Materials and methods

2.1. Materials (datasets)

Different sets of input data are used for this analysis: spatial (biophysical and infrastructure), climate, population, services (market access), and water access. Input datasets are different for different stages of analyses. For example, datasets for suitability analyses in both scenarios are different from that of development potential options. Input datasets for suitability analyses are: (1) agroecology or elevation changes disaggregated into Lowland Mid-Lowland, Mid-highland, and Highland; (2) slope classified into different classes; (3) Land cover/land use excluding built-up areas, water bodies, and forest & parks; (4) Rivers (permanent rivers) and flow measures; (5) Roads; (6) Soil types; (7) Rainfall, and rainfall variability; and (8) Amount (capacity) of permanent rivers. Datasets used for development potential analyses are different from the land suitability analyses. For example, (1) agroecology, (2) population density, and (3) market access were common inputs for both scenarios while (4) irrigable area suitability for irrigable areas or (5) rainfed agriculture suitability and length of growing periods for rainfed.

Based on the output from the above datasets, land suitability (agricultural potential) areas are identified according to FAO classification of degrees of land suitability: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and unsuitable (N). And finally, the following five factors (land suitability, agroecology, length of growing period, population density, and travel time) were used to evaluate whether the given area has a good potential for agricultural growth and development potential or not.

The rationale of the datasets

Many factors combine to determine comparative advantage and the appropriate response to different agricultural growth and development potential. We will focus on five factors that we believe are critical: land suitability areas (agricultural potential for irrigation and rainfed scenarios), access to markets, population pressure, and length of growing periods (esp. for rainfed agriculture).

Land suitability: the suitability of a given piece of land is its natural ability to support a specific purpose (FAO, 1976). According to the FAO methodology, this is strongly related to the "land qualities" such as erosion resistance, water availability, and flood hazard that are not measurable. However, as these land qualities are derived from the "land characteristics", such as slope angle, soil texture, rainfall, and length, which are measurable, and it is advantageous to use these land characteristic values to study the degree of land suitability.

Market access: the term 'accessibility' refers to the distance to a location of interest and the ease with which each destination is reached; more recently, it has been defined as the ability to interact or contact sites of economic or social opportunity (Deichmann, 1997). Travel time to reach the destination are crucial to understand accessibility, i.e., the less time required to reach to destination, and the more varied destinations are, the highest the level of accessibility (Handy and Niemeier, 1997).

Agroecology (elevation change): is an important determinant of climate, having a strong influence on temperature and rainfall. As such, elevation is a fundamental dimension of the geographical context in Ethiopia in which agriculture and other rural activities take place (ERE-A, 2006). Because of Ethiopia's location near the Equator, elevation has a very strong influence on temperature and, to a lesser extent, on rainfall (ERE-A, 2006). The most basic understanding of Ethiopian land use and agricultural practices is defined by a distinction between highlands and lowlands (Hurni, 1998). Rainfall decreases considerably with a loss of elevation, especially toward the eastern part of the country. Most of the eastern lowlands are too dry for crop production for rainfed agriculture (NMA, 2010; Census Atlas, 2010).

The length of growing period (LGP): generally, it refers to the cumulative time in a normal year when moisture conditions are adequate for plant growth. LGP comprises many factors (potential evapotranspiration, rainfall, and soil moisture storage properties) that together define the most important dimensions of agricultural potentials. Thus, a longer LGP indicates higher agricultural potential (ERE-A, 2006).

Population density: is also expected to influence the labor intensity on one hand and having free land for agricultural production on the other, including the choice of commodities and production technologies and land management practices, by affecting the land-labor ratio (Pender et al, 1999; Jordan *et al.*, 2006). However, in the Ethiopian case, population density (pressure) is more of a negative impact that affects the agricultural production of a given area. That is, very high populated areas (e.g. $>=$ 150 people per square kilometer) are not suitable for agriculture but rather it is considered/assumed as settlement areas. Population density of 100 or more persons per square kilometer is defined as high-density areas (Steven *et al.*, 2006), and so forth

2.2. Methodology

Land suitability for rainfed and irrigation potential was identified using features like spatial, biophysical, and infrastructure variables: distance to the permanent river and flow amount, slope, land cover, soil for suitable irrigable agriculture; while rainfed suitable areas are identified using slope, soil, land cover and access to rainfall & rainfall variability.

2.2.1. Modelling land suitability

Land suitability was generated using the model developed after testing the sensitivities of factors by varying the weights assigned to them. Both irrigable and rainfed land suitability were identified. Irrigable suitable land was identified using four main indicators, which were believed to be the main determining factors for this agriculture. We used the following four indicators to the model inputs that help identify irrigable areas: 1) distance to the closest main (permanent) rivers from anywhere, 2) slope of the area given in percent, 3) soil types of the areas and 4) land cover/use types of a given area, excluding parks/natural forests, water-bodies/wetlands/lakes, built-up areas/settlements. Rainfed suitable land was identified using four main indicators: 1) rainfall access (combined rainfall availability and rainfall variability) 2) slope, 3) soil types, and 4) land cover/use types. Table 1 shows factors used for the models in land suitability identification for irrigation and rainfed area analyses. The detailed methodology for suitability analyses is given in Annex 1. Each of the input datasets is represented as one km^2 grid size.

Table 1. Summary of datasets used for both models (irrigation & rainfed) and their categories

Factors	Explanation of categories of
Permanent river & distance from each riverbank	Annual river flow (in million m^3
Slope: it is an input for both models	Slope affects the agricultural su
Population density grid for both irrigable & rainfed area	(Woreda Population density as
Traditional agroecology grid for both irrigable & rainfed	(Lowland is hot lowlands of less
Soil types: it is an input for both models	Best soil (physical and chemical
Land cover: it is an input for both models	Land cover types got different r
Market access grid for both irrigable and rainfed	Market access into two classes:
Annual Rainfall access & its variability: were inputs for rainfed agriculture	Rainfall is essential for the non-
Length of growing period (LGP) grid for rainfed	

These factors were assessed using Geographically Weighted Regression (GWR) method according to their importance and assigned with weights using the following formula in Equations 1 & 2 using an open spatial analyst software QGIS3.8:

$S=DRv*Wt_1+SL*Wt_2+So*Wt_3+ LC*Wt_4$ ------------------------- *1*

While for the rainfed model, we replace DRv with rainfall availability and variability (called rainfall access- *RfAcc*), which has Wt_1 amount of weight (importance) among other factors.

Thus, it becomes:

$S= RfAcc*Wt_1+SL*Wt_2+So *Wt_3+ LC*Wt_4$----------------------- *2*

Where: *S = Suitability; DRv = Distance to Riverbanks;*

SL = Slope; So = Soil type; LC = Land cover. RfAcc= rainfall access (weighted rainfall availability and rainfall variability); Wt_1*= the weight assigned to the first factor and determined after sensitivity analysis;* Wt_2*= the weight assigned to the second factor and determined after sensitivity analysis;* Wt_3*= the weight assigned to the third factor and determined after sensitivity analysis;* Wt_4*= the weight assigned to the fourth factor and determined after sensitivity analysis.*

Sensitivity analysis (SA): is a prerequisite for model building since it determines the reliability of the model through the assessment of uncertainties in the simulation results. With growing interest in extending geographic information systems (GIS) to support multi-criteria decision-making (MCDM) methods, enhancing GIS-based MCDM with sensitivity analysis procedures is crucial (Franklin *et al*, 2002; Feick & Hall, 2004; Chen *et al*, 2009). SA should be involved in GIS-MCDM model evaluation that tests the robustness of a model and the extent of output variation when parameters are systematically varied over a range of interests (Jacek, 1999). The most common approach is based on varying criteria or their weights which represent input parameters in order to understand the model behavior and its limitations (Jacek, 1999; Chen *et al*, 2009). It is used to explore the dependency of model output from the input parameters, identify indicators that are especially sensitive to weight changes, and show the impacts of changing criteria weights on the model outcomes in the spatial dimension. The result is a series of model outputs that can be summarized by identifying factors that most strongly contribute to output variability and figuring out minimally contributing factors from the model. A model is developed in an QGIS environment to perform simulations where the decision weights associated with all criteria used for suitability modelling were varied to investigate their relative impacts on the final results of the evaluation for both scenarios. Those four input factors multiplied by Wt_1, Wt_2, Wt_3, and Wt_4 factors (weight of importance given in equations 1 & 2 above) are represented by the optimized weight of importance multiplied by (10-40%) for both scenarios. Finally, the percent of importance was decided to use $Wt_1=0.4$; $Wt_2=0.3$; $Wt_3=0.2$, and $Wt_4=0.1$ after sensitivity analysis and weight determination for distance to rivers, slope, soil, and land use/cover, respectively (Annex 2). Hence, weights were assigned and assessed according to their importance and assigned using the following formula:

$S= DRv*0.4 + SL*0.3 + So*0.2 + LC*0.1;$

where for the rainfed model, we replace DRv with rainfall availability and variability (called rainfall access- RfAcc), which has a 40% weight of importance similar to distance to the rivers.

*And it becomes: S = RfAcc*0.4 + SL*0.3 + So*0.2 + LC*0.1.*

The suitability of an area is assessed using ranking methods of the given criteria (Jacek, 1999). We used the most popular ranking sum approaches using the Weighted Overlay analysis tool in Equation 3:

$$wi = \frac{(n-rj+1)}{\sum(n-rk+1)} \text{---}3$$

Where wi is the normalized weight for the jth criterion; n is the number of criteria under consideration (k= 1, 2, …, … n), and r is the rank position of the criterion. Each criterion is weighted (n-ri+1) and then normalized by the sum of all weights, that is Σ(n-rk+1).

According to FAO classifications, five types of land suitability indexes are reported and represented by symbols (S1, S2, S3, N1, and N2) are considered in this study. S1 represents highly suitable land for specific uses, which accounts for more than 80% of the suitability index. S2 represents 60-80% and it is a moderately suitable area and S3 represents 45-60% of the suitability index that is marginally suitable areas. N1 represents 30-45% of the suitability index and it means the area is not suitable currently, whereas the suitability index of less than 30% is represented by N2 and this area is permanently not suitable (FAO, 1976), however, it may suitable for other purposes. Finally, four types of suitable land are identified for irrigation and rainfed agricultures based on the four elevation levels (agro-ecological zones), Lowland, Mid-lowland, Mid-highland, and Highland areas (Annex 3).

Annual rivers flows were collected from the Ministry of Water and Energy (MWE, 2016) those were recorded from 1967 to 2012 for some places. Although these records are not covered the whole country and every river, it indicates most potential uses of these permanent rivers' annual flows. The youngest is 3 years and the oldest is 59 years of station records. The river flow was recorded in cubic meters per second. This was converted into minutes, day, and month records using the flowing formula in Equation 4:

X= (Y*Sec*Mnt*H*Z*M) --------------------------------------- *4*

That is, X amount of water in a year is the sum of the amount of flow (Y) in m^3/second * 60 seconds*60 minutes*24 hours* Z number of days/month * 12 months in a year.

Where X= amount of average from per year; Y= amount of flow in cubic meters per second; Sec= 60 Seconds; Mnt= 60 minutes; H= number of hours per day; and Z= number of days per month; and M= number of months per year (12 months).

2.2.2. The model for development potential scenarios

Irrigable area scenario: There are three main factors, which are believed in to determine the development potential of agricultural production for irrigable areas. These are: 1) travel time or market access to a city having at least 10,000 people (it is categorized into two subclasses of remote (>5 hours travel time) and non-remote (<=5 hours travel time), 2) woreda population density- density above 150 people per square kilometer is assumed to be settlement or built-up areas and which is not suitable for production but density below 150 is taken into account for production within different levels of density, and 3) land suitability generated from other datasets. These potentials are summarized (Table 3). The development potentials for irrigable areas were, therefore, derived from the analysis of the following factors: land suitability, market access, and population density. Table 3 shows the general approaches for growth and development potentials of the two scenarios (irrigation and rainfed) at four different agro-ecological levels.

Rainfed area scenario: Rainfed production areas were identified using the following four main factors which affect agricultural production: (1) length of growing period (if an area has more than 5 months of length of the growing period, it is assumed that it has better soil moisture for agricultural production), (2) Market access, (3) Woreda population density, and (4) Land suitability for rainfed. Agricultural development potentials were derived from this analysis to identify which levels of development potentials are more applicable and where. Both Rainfed and irrigation potential areas were evaluated against each criterion (feature) formulated in the Table 3 (i.e., land suitability, travel time or market access, population density, both for rainfed or irrigation, and LGP for rainfed). This helped to develop four agroecology zones (Lowland, Mid-lowland, Mid-highland, and Highland zones) and categorized them into irrigation and rainfed.

2.2.2.1. Inputs for development potential options

Land suitability: After testing the robustness of the model, suitable areas were identified for both irrigable and rainfed scenarios. Suitable areas were categorized into four levels of suitability according to FAO classification: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and currently not suitable (N) per different agroecology gradients. The outputs of these models were used as one of the inputs for the development potential area identifications for both scenarios.

Population density: Woreda population density from 2007 population and housing census and projected 2020 (CSA, 2007, 2020), was calculated to evaluate whether the area is densely populated or not. Population density is defined as the number of people per square kilometer of an area. Hence, in this study, the woreda population is divided by the woreda area (sq. Km), and densely populated woreda is considered less important for agriculture than less populated woreda. Accordingly, if population density is less than 50 people per sq. km, it is represented as “low population density” and considered as the “best site” for agriculture, population density from 50-100 is represented as “middle population density” and assigned as “better site” for agriculture development.

Population density of 100-150 is represented as “high population density” and these sites are “less important” for agriculture development. If areas have 150 or more population density, we considered it a “very high population density”, and these areas might be settlement areas (or even maybe built-up areas) and are “not important” to take into account these areas for the same purposes.

Central highland areas of the country are highly populated (overpopulated), which is the case depends on factors like access to services, infrastructure, and access to resources. These high and very high population density woredas are found on the north-south axis of the country: central Oromia, northern and central Amhara, northeast SNNP and southeast of Tigray woredas. Hence, highly populated areas are not suitable areas for agricultural investments in both scenarios. Considered as settlement areas, in this analysis, is one of the bottlenecks for agricultural development; but less populated areas were preferred areas that would support development without looking for displacement (resettlement) of people to carrying out agricultural practices.

Comparing country-level population density by woreda, about 63.4 % of the area is less populated, and only 11.1 % of the area is overpopulated (>150 people per sq. km). Generally, about 75.7 % of the area of the country has a dispersedly distributed population; whereas about 24.3 % of the area of the country is densely populated (>100 people per sq. km). Considering population density, the country has large areas for agricultural investment potential since 63.4 % of the country has a low population density (Annex 3).

Market access: Towns with a population of 10,000 or more were considered as these towns at least satisfied with agricultural service quarters (e. g, farmer training centers, development agents offices, etc), other basic services (health, education, hygiene, and sanitation, etc), market information flow and infrastructure access, and other market services to buy and sell agricultural inputs and outputs. Hence, travel time to those towns (most of them are woreda towns) was taken into account as one of the factors affecting agricultural development potential. Those areas that took more than 5 hours to reach these towns are considered remote areas while those that take less than or equal to 5 hours are considered non-remote areas.

We have about 644,729 sq. km (56.6 %) and 494,004 sq. km (43.4 %) areas of the country that are remote and non-remote, respectively. Of the non-remote areas, about 77,432 sq. km of the area (15 %) is reached in less than one hour to these market places. Central and highland areas of the country are more connected (non-remote) whereas the lowlands areas of the country (esp. Somali, Afar, Gambella, Benshangul Gumuz, and south of SNNP areas) are distant (remote) areas. Among the remote areas, 52.4 % of areas are reached by more than 10 hours of travel to their market places.

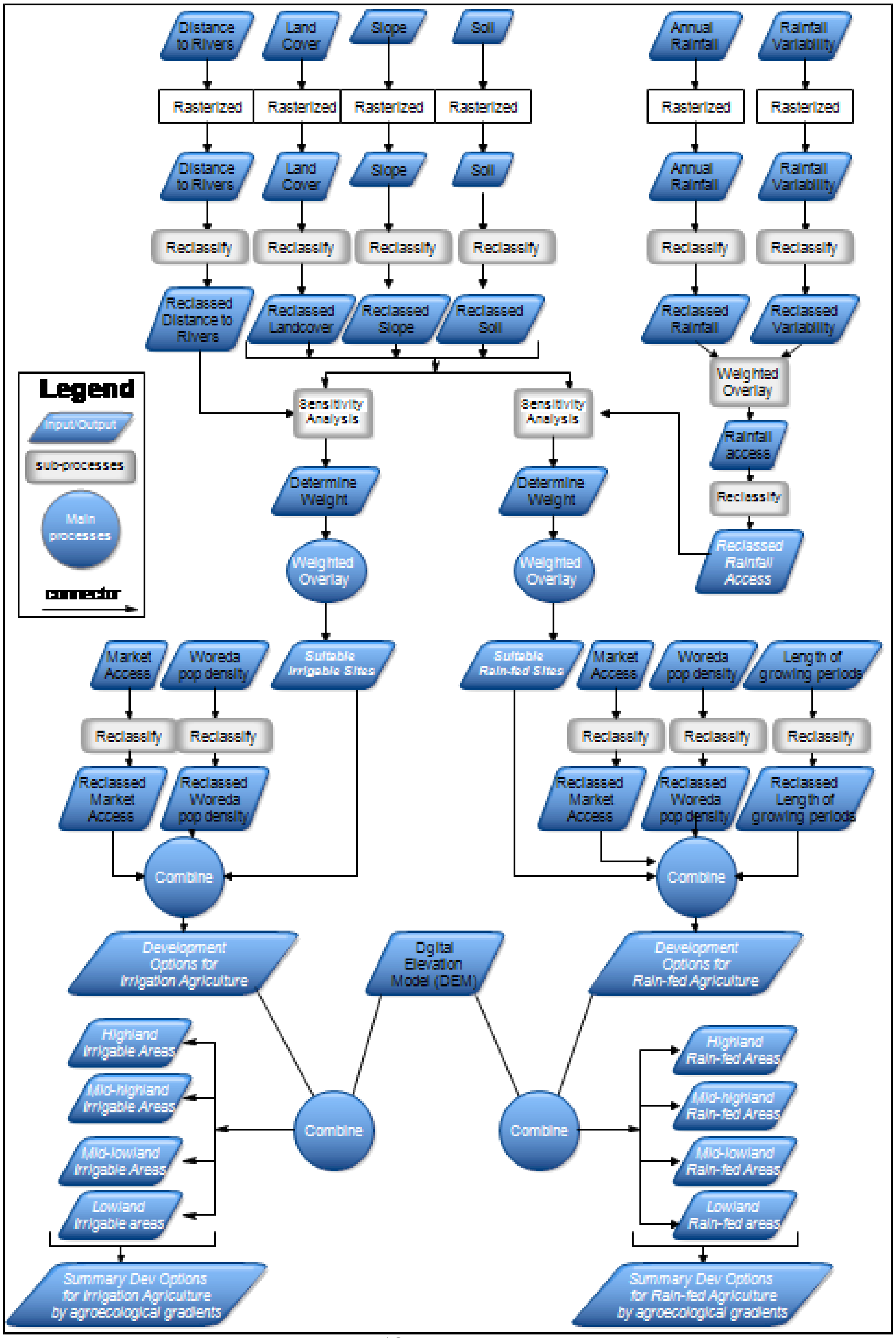
The length of growing period (LGP): The Food and Agriculture Organization of the United Nations (FAO) defines LGP as the number of days in a year when sufficient water is available in the soil profile to support the growth of plant. Here, LGP is defined as the number of days with a mean daily temperature above 5°C, and with available water ranged from precipitation or stored soil moisture that exceeding half the potential of evapotranspiration. LGP captures multiple factors (rainfall, potential evapotranspiration, and soil moisture storage properties) that together define one of the most important dimensions of agricultural potential. Thus, a longer LGP generally indicates higher agricultural potential (ERE-A, 2006). LGP and its variability were considered in the analysis, particularly for rainfed agriculture. The results were assigned into 5 groups (Best, Better, Good, Not-bad, and Worse) according to the number of moisture available days per year. Those sites considered as "best sites" have moisture for 10 months and more. If areas have 8 and more months of moisture, it is assigned as "better sites" for rainfed agriculture. If areas have 6 and more months of moisture, it is assigned as "good sites" for rainfed agriculture. If areas have 5 and more months of moisture, it is assigned as "not-bad" sites for rainfed agriculture whereas if areas have less than 5 months of moisture, it is assigned as "worse sites" for rainfed agriculture. Areas having LGP between two and five months were classified as being of low agricultural potential, and those of less than two months were classified as not suitable (Steven et al., 2006). That is, if an area has five months or longer was classified as being of high water availability, otherwise low water availability and short LGP (unsuitable for rainfed).

It is important to note that the potential for rainfed agriculture is reflected by LGP. Western mid-highland and highland areas of the country have the longest LGP that could reflect the potential of rainfed agriculture areas. About 40 % of the country has got more than 300 days (10 months and more moisture availability per year), which has a relatively higher potential for rainfed agriculture. On the other hand, the eastern lowlands of Afar and Somali regions have the shortest LGP and are unsuitable for rainfed agriculture. LGP of five months or longer was classified as being of high water availability.

2.2.2.2. The development potential options

Considering these four major factors, agriculture growth and development areas are identified for both scenarios (rainfed and irrigation) for different agroecological gradients of the country. Then after, development potentials/options were drawn from these models and five kinds of agricultural development potentials were generated using the "combine" tool in QGIS. Development potentials were sorted according to crop-specific areas (agroecological requirements). These potentials include the highest, high, middle, lower, and lowest potential for both irrigation and rainfed agricultural productions scenarios across four agroecology gradients (Lowland, Mid-lowland, Mid-highland, and Highland areas). Therefore, we have four land suitability types and five agricultural growth and development potentials (from highest to lowest) across four agroecology gradients depending on the crop elevation requirements. Hence, the methodology is categorized into two agricultural activity scenarios: irrigation and rainfed agriculture. The models for scenarios are following the same approach, except for some input dataset differences. For example, in the rainfed model, we used the length of growing periods in addition to other datasets used for irrigation. The general approaches for development potentials of the two scenarios (irrigation and rainfed) is presented for four different agro-ecological levels (Annex 3). A schematic representation of general methodology (procedures) in GIS modeling is given in figure 1.

Using the "combine" tool in QGIS, we generated a summary of the main factors for different development potentials. These development potentials were grouped into five main types of development options (the highest option, high option, middle option, lower option, and lowest option) if a given area is satisfied the criteria used to be assigned to one of the categories. For example, if an area is highly suitable for rainfed, has low population density, is non-remote, and is best in moisture availability, we assigned this pixel as the highest development option for rainfed agriculture.


Distance to Rivers
Land Cover
Slope
Soil
Annual Rainfall
Rainfall Variability
Rasterized
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Distance to Rivers
Land Cover
Slope
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Annual Rainfall
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Reclassed Distance to Rivers
Reclassed Landcover
Reclassed Slope
Reclassed Soil
Reclassed Rainfall
Reclassed Variability
Legend
Input/Output
sub-processes
Main processes
connector
Weighted Overlay
Sensitivity Analysis
Sensitivity Analysis
Rainfall access
Determine Weight
Determine Weight
Reclassify
Weighted Overlay
Weighted Overlay
Reclassed Rainfall Access
Market Access
Woreda pop density
Suitable Irrigable Sites
Suitable Rain-fed Sites
Market Access
Woreda pop density
Length of growing periods
Reclassify
Reclassify
Reclassify
Reclassify
Reclassify
Reclassed Market Access
Reclassed Woreda pop density
Reclassed Market Access
Reclassed Woreda pop density
Reclassed Length of growing periods
Combine
Combine
Development Options for Irrigation Agriculture
Digital Elevation Model (DEM)
Development Options for Rain-fed Agriculture
Highland Irrigable Areas
Mid-highland Irrigable Areas
Mid-lowland Irrigable Areas
Lowland Irrigable areas
Combine
Combine
Highland Rain-fed Areas
Mid-highland Rain-fed Areas
Mid-lowland Rain-fed Areas
Lowland Rain-fed areas
Summary Dev Options for Irrigation Agriculture by agroecological gradients
Summary Dev Options for Rain-fed Agriculture by agroecological gradients

Figure 1. General flowchart of the model analyses

Access to river water for service to the command areas

Furthermore, river network analysis and run-off capacity of each permanent river were analyzed to quantify the run-off capacity and river water access within a given distance (buffer areas) so that possible irrigation service (command) areas can be derived with respect to irrigable potentials. Figure 2 shows river network analysis for irrigation command area quantification from a given distance to the permanent rivers. After analyzing the river network, we developed water access (service area, Fig. 2) from such a model (Smith, 2009).

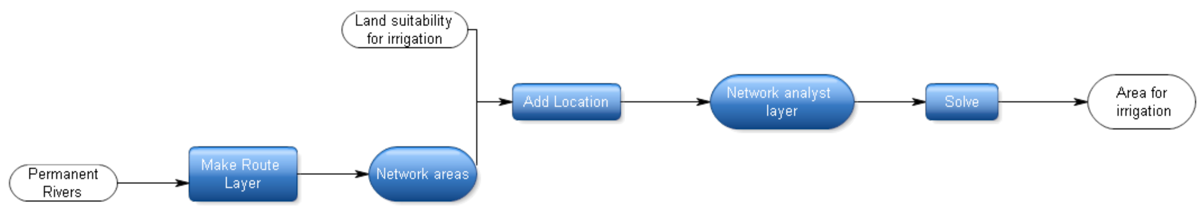


Figure 2. Permanent river network analysis model for irrigation command areas

3. Results

1. **Land suitability for irrigation potential**

Using the identified input indicators/factors and sensitivity analysis to identify the governing factors for irrigation areas, we found about 359360, 669424, and 28370 sq.km of highly suitable, moderately suitable, and marginally suitable areas, respectively (Fig. 3). There are many sites across the country, which can be developed by irrigation. Some parts of the Somali and Afar regions are highly suitable areas as there are rivers flow throughout the year.

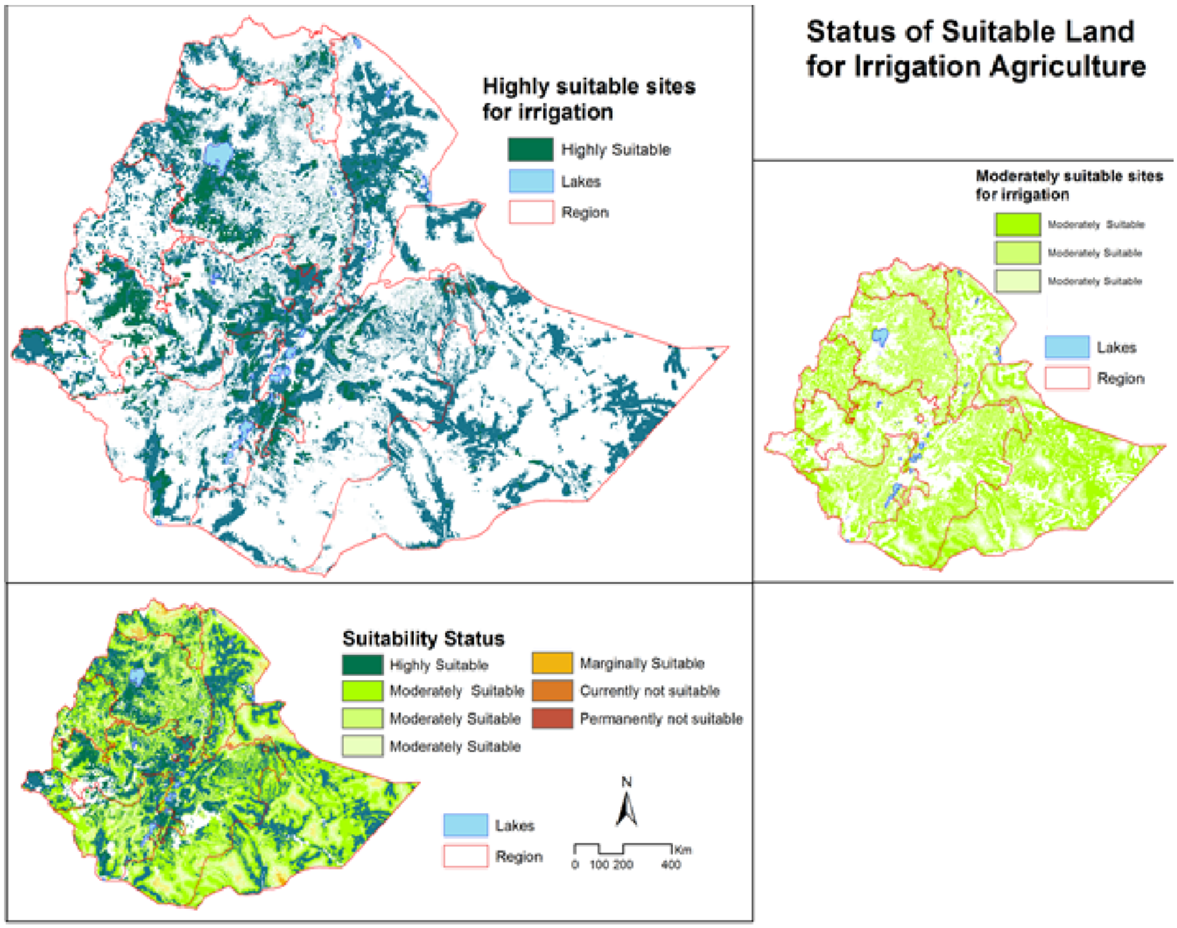


Figure 3. Irrigable land suitability for Ethiopia (lower left map is suitability status, upper left is high suitable sites, and right side map is moderately suitable sites for irrigation agriculture)

1. **Land suitability for irrigable areas by agroecology**

Agroecology or elevation change is an important determinant of climate, having a strong influence on temperature and rainfall in the tropical regions. The elevation is a fundamental dimension of the geographical context in which agriculture activities take place. The most basic understanding of Ethiopian land use and agricultural practices is defined by a distinction between highlands and lowlands. It has diversified topographic variations even within a given short distance. We have found highly diversified irrigable areas for five agro-ecological gradients from lowland to afro-alpine zones (Table 2). Agroecology gradients play an important role in Ethiopia, which determine the types of crop growing at each gradient and are used for crop-specific investment options.

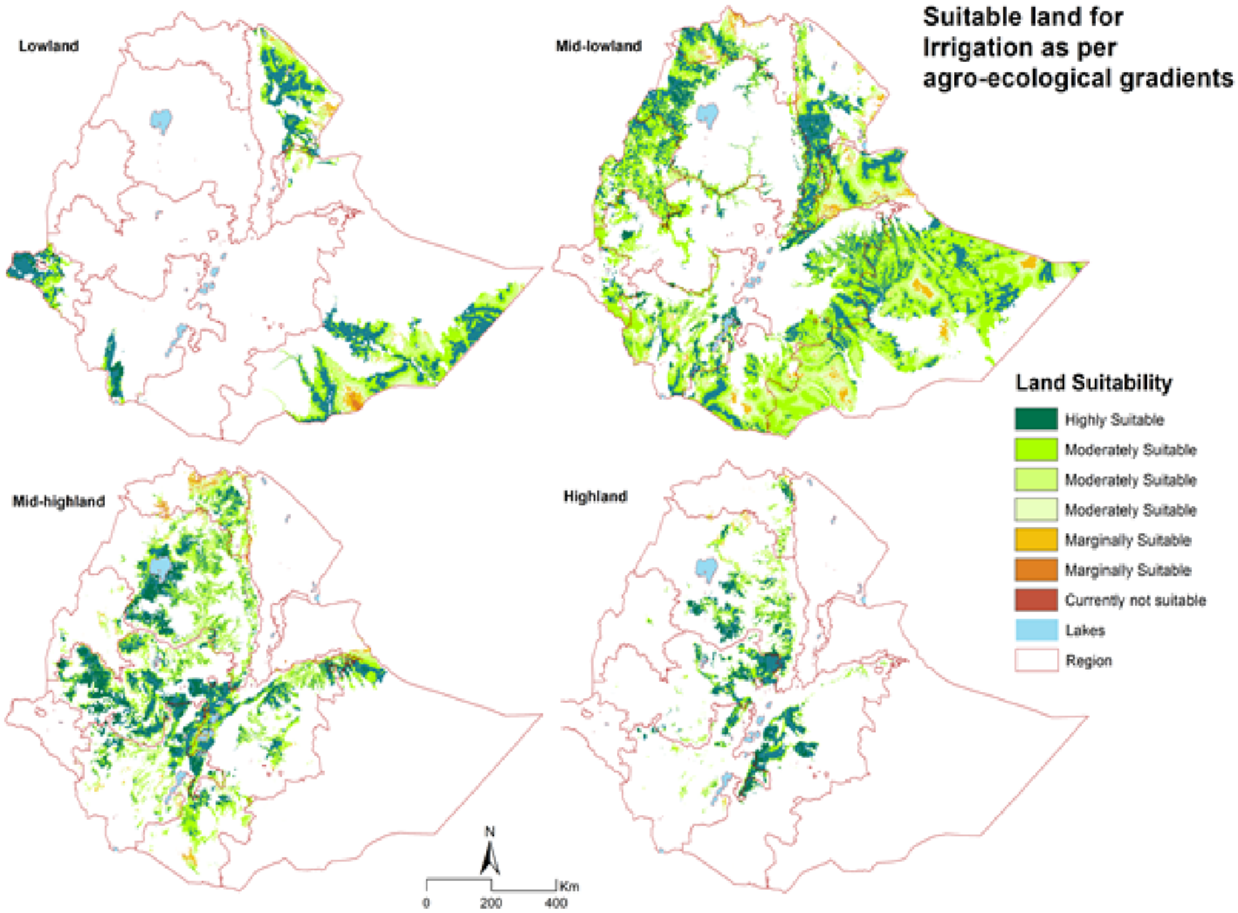
Suitable areas for irrigation agriculture, among the main four divisions of agro-ecological gradients (excluding afro-alpine and extreme afro-alpine), 13.8 % of highly suitable irrigable areas are found in the mid-lowlands. The second-largest highly suitable (10 %) areas are found in the mid-highland areas (Table 2 and Fig. 4). Among the suitable areas (highly and moderately suitable), about 34 % of the area are highly suitable while 63 % are moderately suitable areas for irrigation agriculture.

Table 2. Irrigable areas across agroecological gradients (area in sq.km excluding afro-alpine and extreme afro-alpine areas)

@ >p(- 12) * >p(- 12) * >p(- 12) * >p(- 12) * >p(- 12) * >p(- 12) * >p(- 12) * @

Agro-ecological gradients	Suitability area (sq.km)			Total suitable area by agro-ecology (sq.km)	% of highly suitable areas by agroecology	% of highly & moderately suitable areas by agroecology
	Highly Suitable	Moderate Suitable	Marginal suitable			
Lowland	64,904	83,089	4,570	152,563	6.2	14.1
Mid-lowland	144,876	396,689	14,853	556,418	**13.8**	51.6
Mid-highland	103,313	141,819	6,815	251,947	**9.8**	23.4
Highland	44,629	42,771	1,202	88,602	4.3	8.433
Total	357,722	664,368	27,440	1,049,530	34.1	97.4
% share by suitability	**34.1**	**63.3**	2.6	100		

Furthermore, considering moderately suitable areas for irrigable sites, about 63.3 % of the country can be developed by irrigation agriculture, of which 51 % is from mid-lowland areas and 23 % is from mid-highlands. Surprisingly, about 14 % of the moderately suitable areas are found in the lowland areas (< 500 m), which can also be developed by irrigation schemes.



Fig

4. Irrigable land potential for different agroecological gradients.

1. **Land suitability for irrigable areas by region**

We have found the national level suitable lands, which is about 34 % of irrigable areas are highly suitable areas and 63.4 % are moderately suitable areas for irrigation. Of the highly suitable areas (34 %) of the country, 10.8 %, 6.9 %, and 5.8 % are found in the Oromia, Somali and Amhara regions, respectively. Whereas considering moderately suitable areas for irrigation at regional level is about 21.3 %, 16.6 %, and 8 % for Somali, Oromia and Amhara regions, respectively (Table 3).

@ >p(- 12) * >p(- 12) * >p(- 12) * >p(- 12) * >p(- 12) * >p(- 12) * >p(- 12) * @ Region's name & Highly Suitable & Moderately Suitable & Marginally Suitable & Total suitable

Area (km^2) & % highly

suitable from the total suitable area & % moderately

suitable from the total suitable area
Afar & 38,953 & 49,267 & 3,593 & 91,813 & 3.7 & 4.7
Amhara & 61,235 & 84,748 & 2,165 & 148,148 & 5.8 & 8.0
Ben.Gumuz & 11,828 & 33,887 & 672 & 46,387 & 1.1 & 3.2
Dire Dawa & 87 & 951 & 22 & 1,060 & 0.01 & 0.09
Gambella & 10,765 & 8,187 & 8 & 18,960 & 1.0 & 0.8
Harari & 242 & 121 & - & 363 & 0.02 & 0.01
Oromia & 114,313 & 175,229 & 3,670 & 293,212 & 10.8 & 16.6
SNNP & 36,587 & 61,562 & 1,861 & 100,010 & 3.5 & 5.8
Somali & 73,356 & 224,977 & 10,844 & 309,177 & 6.9 & 21.3
Tigray & 11,828 & 30,689 & 5,204 & 47,721 & 1.12 & 2.9
Total & 359,194 & 669,618 & 28,039 & 1,056,851 & 33.9 & 63.4

Table 3 Land suitability for irrigation (suitable area in sq.km) by region

3.2. Land suitability for rainfed potential areas

Rainfed agriculture is the most ancient practice in Ethiopia depending on rainfall availability. It has a long history in this country and the production system is not much changed from the historical practice. However, this analysis could be more informative to get unseen areas based on the biophysical analyses using rainfall access (rainfall availability) for the last 10-58 years of data collected by the National Meteorological Agency (NMA) of Ethiopia beside other governing factors.

The potentially suitable areas are about 13802, 468208, & 382437 sq.km area for highly suitable, moderately suitable, and marginally suitable, respectively (Fig. 5 below). These accounted for 1.6 %, 57 %, and 41.5 % of highly suitable, moderately suitable, and marginally suitable, respectively of the total suitable areas of the country (Table 4). About 58.6 % (high plus moderately suitable areas) of the country can be developed properly for rainfed agriculture. We can be witnessed that highly suitable areas for rainfed agriculture are found in the western axis of the country (esp. Benshangul Gumuz, southwest Amhara, central Oromia, and SNNP regions) whereas the eastern axis is not suitable for rainfed (upper left map Fig. 5). Moreover, moderately suitable areas are distributed all over the country except in the far eastern part of the country (mainly the Somali region, right side map of figure 5). Hence, the Somali region is one of the hardest areas for rainfed agriculture but it has many potential sites for irrigation practice (Fig. 4, upper left and right).

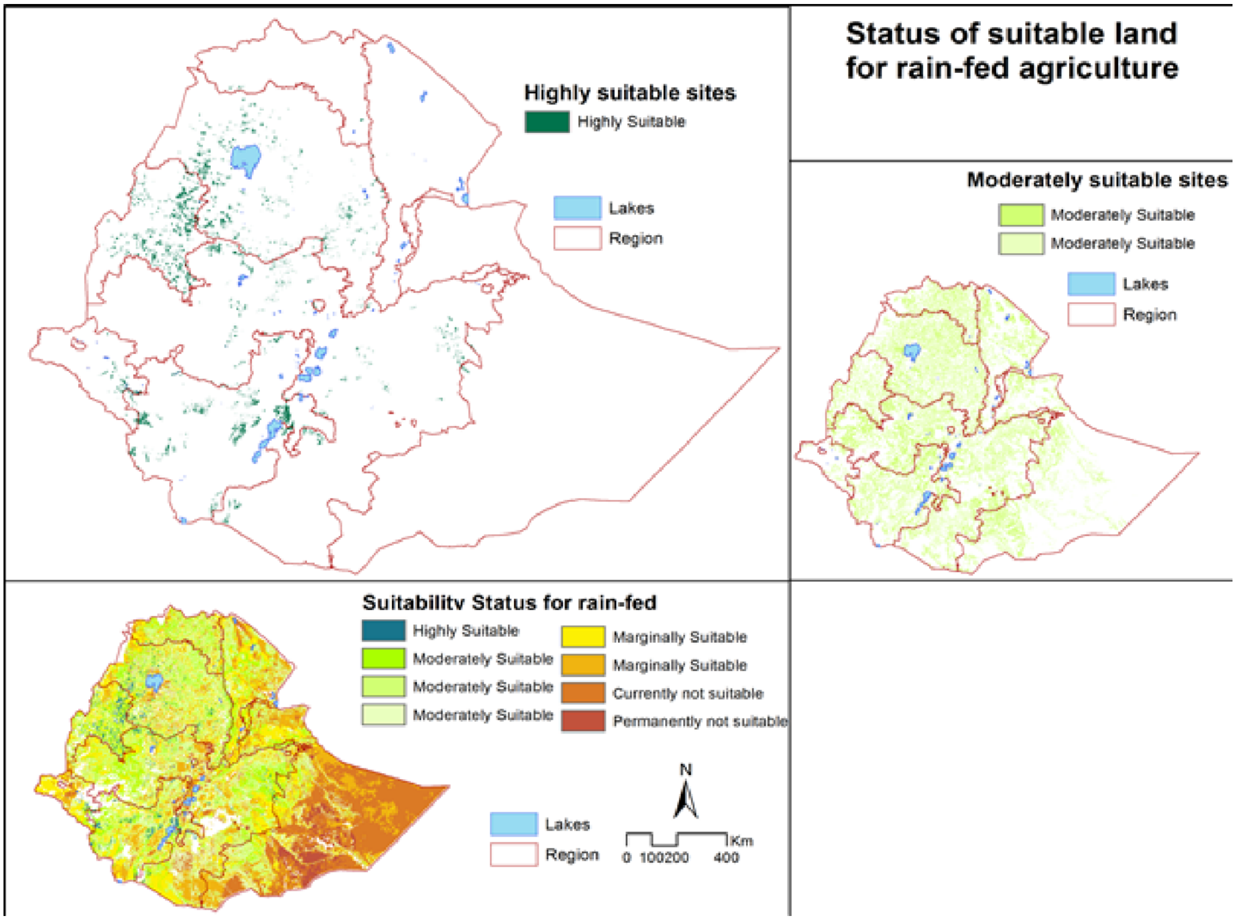


Figure 5. Rainfed agriculture suitable areas

3.2.1. Land suitability for rainfed areas by agroecology

It is known that Ethiopian agriculture is mainly based on rainfed practice. Suitability for rainfed agriculture is also ranging from highly to marginally suitable. Of the total, suitable areas, highly and moderately suitable areas accounted for 29 % from mid-lowland and 18.6 % from mid-highland areas; whereas 5.3 % and 5.7 % were from lowland and highland areas, respectively (Table 4, and Fig. 6). However, looking at the suitability status of rainfed areas, only about 1.6 % of the country is highly suitable. The rest of 98.4 % are moderately and marginally suitable sites for agriculture. We can imagine how agricultural production using rainfed practice is depending on the marginal areas (which do not in line with appropriate sites for rainfed agriculture). We will see this in the later sections by comparing the existing rainfed areas with the suitable sites, and how these sites are complimented and/or deviated. This may raise a question about land-use planning. If there were land use planning that was implemented in the country, it would not have been deviated.

Table 4. Rainfed areas across agroecological gradients (suitable area in sq.km)

Agro-ecological gradients	Suitability area (sq.km) Highly Suitable	Total suitable area (sq.km) by agroecology Moderately Suitable	% of highl Marginally
Lowland	32	45,585	31,097
Mid-lowland	9,416	238,354	208,388
Mid-highland	3,230	156,361	80,654
Highland	1,030	47,485	35,935
Total	13,708	487,785	356,074
% share by suitability	1.60	56.9	41.5

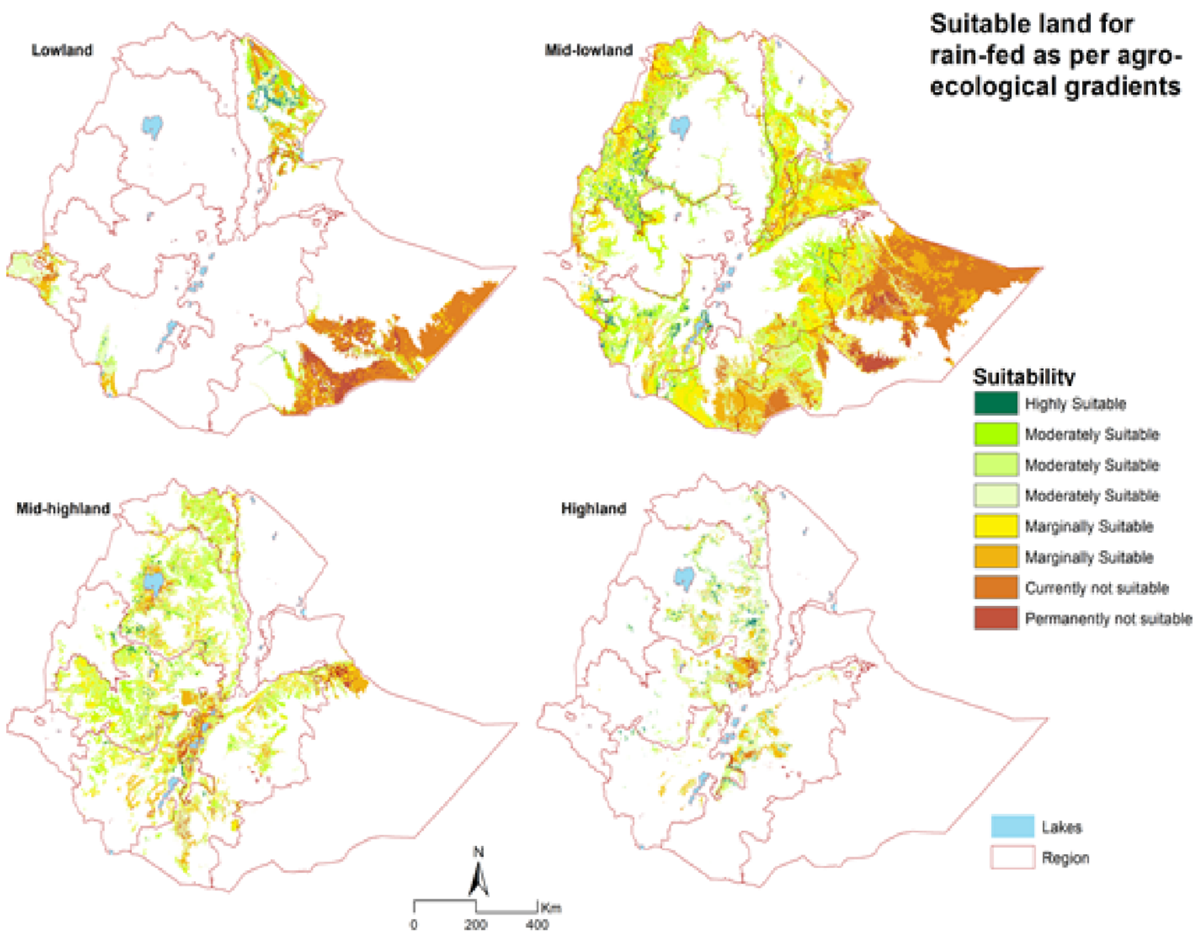


Figure 6 Rainfed agriculture potential for different agroecological gradients

3.2.2. Land suitability for rainfed areas by region

Regional levels of suitable land for rainfed potential areas are about 32 %, 16.6 %, and 16.4 % of highly suitable areas for Oromia, Amhara, and Somali regions, respectively (Table 5). Nationally, about 1.6 % of rainfed areas are highly suitable areas and 54 % are moderately suitable areas for rainfed agriculture on which we traditionally depend on these moderately suitable areas without having highly suitable areas even for rainfed since we have only limited sites of highly suitable for rainfed. This means our agriculture has been depending on moderately and marginally suitable areas. We can imagine how we can boost our agriculture based on land capability or appropriateness of the site for agricultural production.

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Region Name	Suitability area (sq.km)			total suitable area (sq.km)	% highly suitable from the total area	% moderately suitable from the total area
	Highly Suitable	Moderately Suitable	Marginally Suitable			
Afar	40	40,769	46,424	87,233	10.1	4.7
Amhara	3,508	96,188	44,944	144,640	16.6	11.1
Ben.Gumuz	3,763	28,009	14,594	46,366	5.3	3.2
Dire Dawa	-	857	203	1,060	0.1	0.1
Gambella	496	7,525	14,053	22,074	2.5	0.9
Harari	201	143	-	344	0.04	0.02

Oromia

& 2,699 & 162,263 & 117,198 & 282,160 & 32.4 & 18.7

SNNP

& 3,277 & 55,381 & 38,210 & 96,868 & 11.1 & 6.4

Somali

& - & 50,189 & 92,858 & 143,047 & 16.4 & 5.8

Tigray

& 75 & 30,423 & 15,654 & 46,152 & 5.3 & 3.5

Total

& 14,059 & 471,747 & 384,138 & 869,944 & 1.6 & 54.2

Table 5. Land suitability by regions for rainfed (area in sq.km)

1. **Development of potential options**

Development potential options for agricultural production is analyzed for both irrigation and rainfed scenarios. These options were classified into five classes such as the "highest option", "high option", "middle option", lower option", "lowest option", and sometimes "not good at all".

1. **Development potentials for irrigation agriculture** (combined land suitability, agroecology, travel time, population density)

The summary of development potential options by irrigable areas (Table 6) was based on the analysis made using irrigable suitable sites, market access, population density and agroecology. These were analyzed to identify the development potential options for irrigation areas and also disaggregated by agroecology (Table 7), and by region (Table 8). We have found that about 6.8 %, 33.3 %, and 40 %, of the area have very good development potential for irrigation with the highest, high and middle level options, respectively.

Table 6 Summary: Areas of different factors and development potentials for irrigation agriculture based on the model result and model result (development potential)

Land suitability (Irrigable areas)	**Area (sq.km)**	**%**	**Population density**
Highly Suitable	359,360	33.98	Low Pop. density
Moderately Suitable	669,424	63.32	Middle Pop. density
Marginally Suitable	28,075	2.66	High Pop. density

Currently Not Suitable	295	0.03	Very high Pop. density
Total	1,044,340	100.0	Total
Agroecology/elevation	**Area (sq.km)**	**%**	**Development Potential for irrigable a**
Lowland	141,064	13.5	Highest Option
Mid-Lowland	550,494	52.7	High Option
Mid-Highland	250,862	24.0	Middle Option
Highland	88,336	8.5	Lower Option
Afro-Alpine	5,686	0.5	Lowest Option
Extreme Afro-alpine	1,438	0.1	Not good for irrigation
Below Sea Level	6,460	0.6	Total
Total	1,044,340	100.0	
Market access	**Area (sq.km)**	**%**	
Non-Remote	451,689	43.3	
Remote	592,651	56.7	
Total	1,044,340	100.0	

1. **Development potentials for irrigation areas by agroecology**

Looking at development potential for irrigable areas, the highest potential options are found in the mid-lowland areas (41.8 %). This encourages large-scale investment potentials in these areas without affecting the livelihoods of many people (Table 7). On the other hand, Ethiopian people prefer to live in the mid-highland areas as evidenced by the figure (58.5 %) where only 17.7 % of areas have middle to the highest potential for irrigable agriculture. Hence, in the future, the greatest potential for irrigation agriculture would be in the mid-lowland and lowland areas of the country, which have enough suitable areas for agricultural investments using irrigation schemes such as for perishable horticulture: vegetables and fruit products, oilseeds, and other pulses depending on their ecological requirements and access to facilities and markets, and also less populated areas. Factors summary by development potentials for irrigable areas (Annex 4) were also calculated for both scenarios (irrigation & rainfed agriculture). The maps produced for irrigation development potential based on agroecology are presented in Annex 3.

Agroecology	Highest Potential Area (sq.km)	High Potential %	Middle Potential Area (sq.km)	Sum (highest to middle options) %	N A
Highland	1,489	2.1	10,729	3.0	29
Mid-highland	18,106	25.0	58,447	16.6	73
Mid-lowland	30,286	41.8	165,195	46.9	31
Lowland	22,530	31.1	118,190	33.5	
Afro-alpine	-	-	-	-	-
Total	72,411		352,561		42

Table 7. Development potentials and distributions of people for irrigation agriculture across different agroecological gradients (highest, high, and middle potential options) with respect to population number (projected for 2022) and by agroecology

1. **Irrigation potential versus the annual flow of rivers**

After knowing the amount of flow of a river in the record station, we calculated the capacity of that river by calculating the average water use. The amount of water use varies depending on the crop types. On average, we calculate one hectare of land can be irrigated by 10,000 m^3 of water (MWE, 2016). Hence, from the given station, we found out the amount of area covered rives at each point that the measurements took place. Fig. 7 and Fig. 8 showed the amount of average flow and capacity of river flow (at measured stations) that support irrigable areas. From these sample stations, we found about 63,532 sq.km can be irrigated using the measured river flows at the high suitable level. However, according to the development potential analysis, there is about 418,752 sq.km of land, which can be irrigable with both high and the highest development potential options.

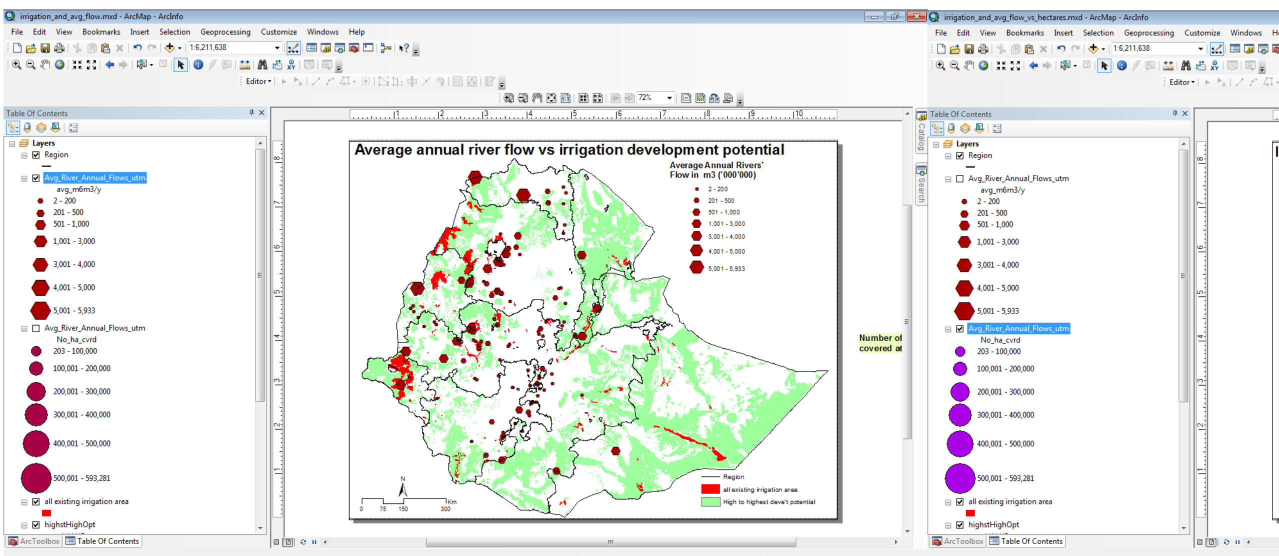

Figure 7. Average annual river flow and rivers capacity for irrigation versus irrigation potential (high to the highest development potential)

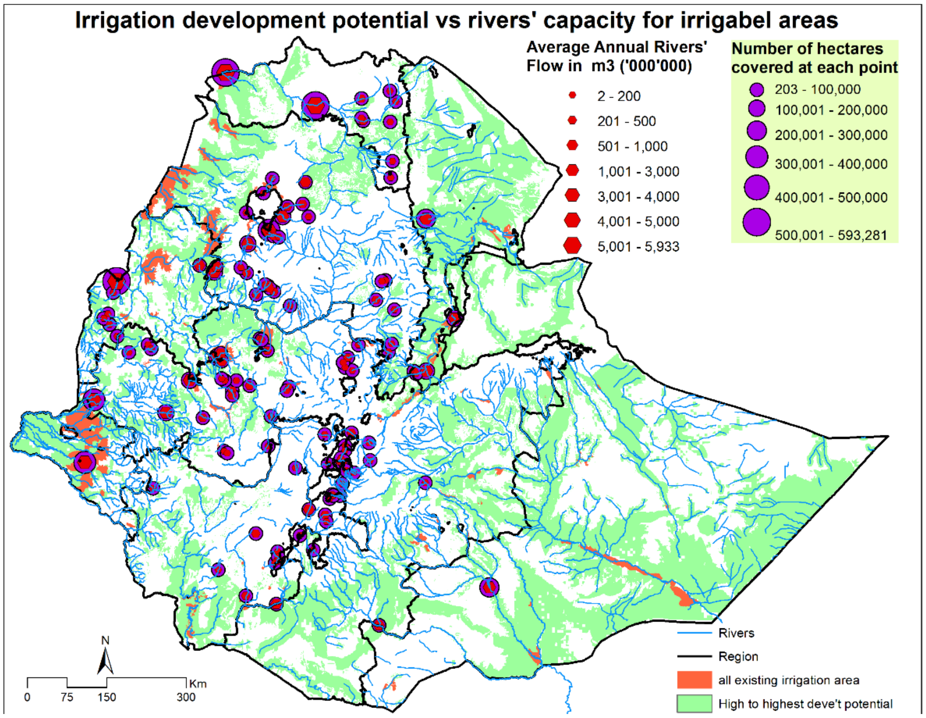

Figure 8. The highest and high development potential options versus average annual rivers' flow compared with existing irrigated sites (MWE, 2016) and irrigable area per command site (ha)

1. **Development potentials for rainfed agriculture (combine land suitability,** agroecology, market access, population density, and length of growing period-LGP)

Similar to the previous analysis, development potential options for rainfed agriculture was based on population density, land suitability for rainfed, market access, length of growing periods, and agroecology. The summary of its inputs and output is presented (Table 8, and Annex 4). The middle option comprises the biggest share with 37.6%, while the highest options is about 3.2% (Table 11).

Table 8. Summary: areas of different factors and development potentials for rainfed agriculture based on the model result and model result (development potential)

Land suitability (rainfed)	**Area (km^2)**	**%**	**Population density**	**Area (s**
Highly Suitable	13,770	1.3	Low Pop. density	654,274
Moderately Suitable	466,176	44.9	Middle Pop. density	127,722
Marginally Suitable	376,983	36.3	High Pop. density	138,992
Currently Not Suitable	158,233	15.3	Very high Pop. density	116,756

Permanently Not Suitable	22,582	2.2	Total	1,037,74
Total	1,037,744	100		
Agroecology/elevation	**Area (sq.km)**	**%**	**Length of the growing period**	**Area (s**
Lowland	137,343	13.2	Best	401,550
Mid-lowland	547,268	52.7	Better	130,245
Mid-highland	251,033	24.2	Good	167,938
Highland	88,374	8.5	Not Bad	124,027
Afro-alpine	5,685	0.5	Worse	213,984
Extreme-afro-alpine	1,439	0.1	Total	1,037,74
Below Sea Level	6,602	0.6		
Total	1,037,744	100		
Market access	**Area (sq.km)**	**%**		
Non-Remote	452,079	43.6		
Remote	585,665	56.4		
Total	1,037,744	100		
Development potential (rainfed)	**Area (sq.km)**	**%**		
Highest Option	33,821	3.2		
High Option	105,013	10		
Middle Option	392,109	37.6		
Lower Option	186,947	18		
Lowest Option	138,850	13.3		
Currently not for Rainfed	167,152	15.7		
Permanently Not for Rainfed	22,998	2.2		
Total	1,037,744	100		

Taking into account the three major development potential options (the highest, high and middle options) with respect to agroecology, middle highland has the highest option with about 86.9 % of the area are very good for rainfed agriculture (Table 9), and the first three options accounted for about 61.1 % but the highest options very low for highland and lowland areas to rainfed development potential options. We also looked at these options by agroecology and regional disaggregation.

1. **Development potentials for rainfed areas by agroecology**

Considering agroecological gradient, about 192, 4120, 29379, and 124 sq.km of land were found the highest potential for rainfed agriculture in the highland, mid-highland, mid-lowland, and lowland areas, respectively (Annex 4). On the other hand, for a high development potential of rainfed agriculture, the analysis result indicates that about 1768, 28084, 72876, 2241 sq.km of land were found in the highland, mid-highland, mid-lowland, and lowland areas, respectively. In both cases (the highest and high development potential options), wider areas for rainfed agriculture are found in mid-lowland areas, which are about

29379 and 72876 sq.km for the highest and high development potential options, respectively. Moreover, mid-lowland areas have wider areas for middle-level development potential with an area of 219,941 sq.km.

Agroecology/ change	Highest Option	High Option	Middle Option	Sum (highest to middle options)	No of People					
	Area (sq.km)	%	Area (sq.km)	%	Area (sq.km)	%	total areas (sq.km)	%	Pop.	%
Highland			,768		,816		,776		,973,421	
Mid-highland	,126		,084		,283		,493		,788,739	
Mid-lowland	,379		,876		,941		,196		,639,628	
Lowland			,241		,365		,730		,347,290	
Afro-alpine	-	-	-	-	-	-	-	-	,817	
Total	,821		,969		,405		,195		,807,895	

Table 9. Development of potential options for rainfed agriculture by agroecology (highest, high, and middle potential options)

1. **Development potentials for rainfed areas by region**

Looking at development potential areas from rainfed agriculture, about 86.9% and 12.2% of the mid-lowland and mid-highland areas were identified with the highest option, respectively. Of the total agroecological ranges, mid-lowland area has about 61.1% of the area is comprised from the highest to middle options (Table 9). This indicates that the mid-highland areas have the most suitable areas for rainfed development options of the country. Across all agroecology, the highest development option accompanied for about 33,821 ha while the middle option has about 388405 ha. All options comprise about 527,195 ha of the country.

1. **Comparing irrigable potential with existing irrigated sites**

Considering both smallholders and large and medium scales agricultural areas in the country, it is about 31,200 km^2 were reported by Woody Biomass and the Ministry of Water Resources. However, based on the current analysis, the country has about 72,411 sq.km and 347,435 sq.km of land for the highest and high potential of irrigable areas, respectively (Table 10, Annex 5). Regardless of how efficient the existing irrigated areas are, Ethiopia has an untapped potential of about 387,846 sq. km area with the highest and high potential for irrigation.

Table 10. Comparing irrigation potential and existing irrigated areas

Irrigation status	Compare with both the highest and high potential area (sq.km
Existing irrigated area	32,000
Highest potential area	72,411
High potential area	347,435
Difference: potential minus the existing area	387,846

The highest and high potential areas for both rainfed and irrigation agriculture areas were compared to the existing irrigation and rainfed areas (Fig. 9).

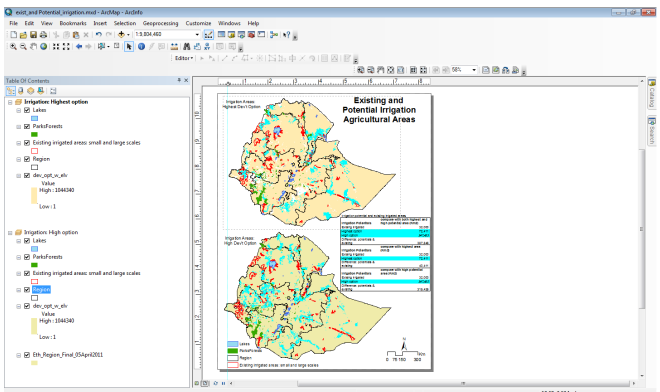

Figure 9. Potential irrigable area compared to existing large-scale irrigated sites

1. **Comparing rainfed potential with existing rainfed cultivated areas**

Existing and potential rainfed areas were compared and gaps were identified. So far, the country has about 176,996 sq.km of land covered by rainfed agriculture with the highest, high, and middle potential sites. Of course, the rest of the rainfed areas currently cultivated are found at below better potential, or in other words, we cultivated non-agricultural land that could be used for other purposes this is due to the lack of proper land use planning. In this analysis, about 33821, 105118, and 392109 sq.km areas of the highest potential, high potential, and middle potential, respectively, for rainfed agriculture are not used for the same purpose (Table 11). In total, there is still about 354,052 sq.km area, which can be used for rainfed agriculture with the highest, high, and middle potential (Fig. 10, Annex 6).

Table 11. Comparing rainfed potential and existing rainfed cultivated areas

Rainfed status	Compare with the highest, high
Existing rainfed area	176,996
Highest option area	33,821
High option area	105,118
Middle option area	392,109
Difference: potential minus the existing area	354,052

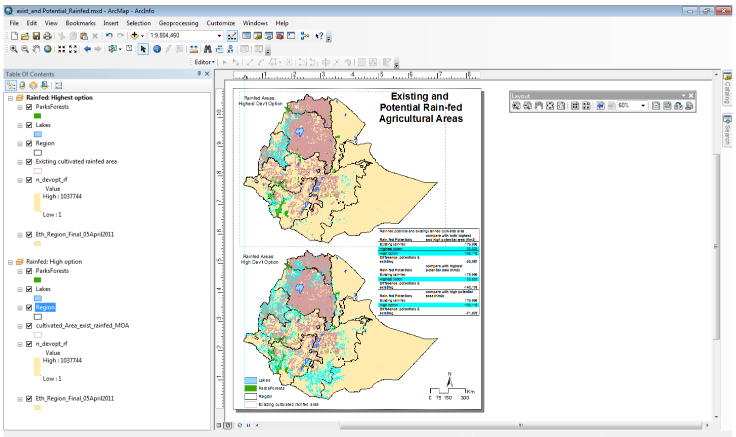

Figure 10. Comparing rainfed potential and existing rainfed cultivated areas

1. **Combined both irrigation and rainfed areas**

Irrigable potential versus irrigated: There are about 425,053 sq.km areas of highest and high potential irrigable areas (about 40 % of the country's land size); whereas only about 32,000 sq.km of irrigated areas are used by both smallholders and large to medium scale irrigation (which is about 7.5 % out of the potentially irrigable areas). However, considering middle option areas for irrigation, the potentially irrigable areas increase to 79 % of the country (Fig. 11 top) and the share of the existing irrigated area would be 4 % (out of 808,378 sq.km considering the highest to middle potential).

Rainfed potential versus rainfed cultivated: There are about 138, 939 sq.km areas for rainfed considering only the highest and high potential areas (which is about 13.4 % of the country's land size), and considering middle options for rainfed increases the potential areas for rainfed to 51 % from the country (Fig. 11 bottom). In this case, the share of the existing rainfed area would be 33.3 % (only 176,996 was used out of 530,943 sq.km, blue highlighted parts of the maps, considering highest to middle potential sites.

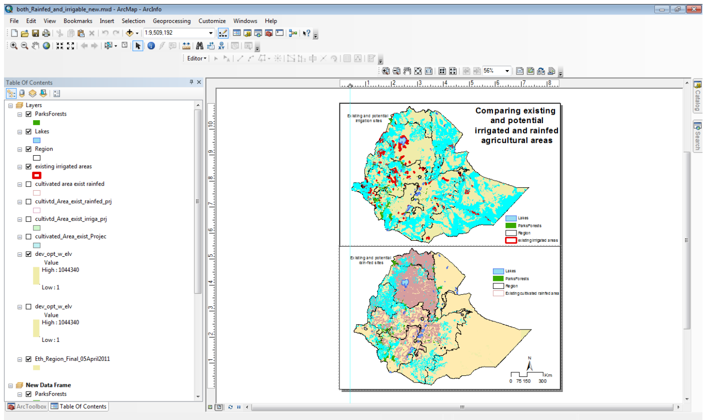

Figure 11. combined existing (red polygon) and potential irrigation with blue highlighted parts (top), and existing rainfed (red polygon) and potential rainfed with blue highlighted part (bottom).

1. **Discussions**

The underlying biophysical features and unique topographic environment of Ethiopia strongly influence, but may not strictly delineate the success of agricultural production and output within the country (Chamberlin and Schmidt, 2011). Now, not only do biophysical features are determining the agricultural production and productivity but also other important factors. Ethiopian agriculture is hindered by multiple factors including severe land degradation, nutrient depletion by poor soil fertility, rain-fed farming system, crop residue removal combined with low input, and resulted in low output (productivity). Low agricultural productivity is, in turn, attributed to limited access by smallholder farmers to financial services, lack of improved production technologies, and access to extension packages. The other main factor is lack of land suitability planning for irrigation, rainfed and by analyzing agricultural markets, population distribution, land capability for diversified development potential options (Shiferaw and Kidanu, 2021). The suitability of land is assessed considering a rational cropping system, for optimizing the use of a piece of land for specific use (Kassawmar et al., 2018). Based on the major determining factors to identify both scenarios (irrigation) and rainfed suitability, agricultural development potential is identified for both cases, the details for each of them are found in the subsequent subsections.

4.1. Irrigation agriculture

An increasing population pressure resulted in land fragmentation in rural Ethiopia. The demand for more food from productive land is very pressing. Irrigation in Ethiopia has been started in the 1950s with traditional irrigation systems with low water productivity; but modern irrigation systems like sprinkler and drip irrigation are practiced in some parts of the country (Eshete et al., 2020). Both large-scale and smallholders' irrigation programs are key strategies to achieving food security by resilience to climate change adaption (Amede, 2015; Assefa et al., 2020; Tesfaye et al., 2021) and mitigation and then improving household income and livelihoods of the society. Growing more food with less water by increasing agricultural productivity is the main challenge the future irrigation, which is often characterized by low water productivity in Ethiopia (Ambomsa et al., 2020; Derib et al., 2011).

However, agricultural production using irrigation schemes is still at slow growth in Africa (Lebdi, 2016), and it has not yet played a major role to break the imbalance between demand and supply of food production. Poor water use from irrigation resulted from different factors in combination with water availability, water allocation to irrigation fields, poor irrigation scheduling, excessive sedimentation, technical limitations, cost, inaccessibility of soil water or moisture monitoring tools, soil–water parameters, and lack of local level climate data (Yohannes et al., 2019). These are considered the major challenge to the sustainability of irrigation schemes, and low water productivity. High productivity, on the other hand, has double advantages: ensures food security and nutrition, and benefiting producers, and generates jobs along the process. Among African countries, Egypt and Sudan have better irrigation coverage than other African countries will Ethiopia has only the potential (FAO, 2007; Lebdi, 2016) but actual irrigated area is very limited (only 7.5%, CSA, 2020).

The current study also approves that the irrigation potential is very high (ca. 34%) as compared to existing irrigated land (7.5 %) in Ethiopian agriculture. This study is very instrumental to identify the irrigable potential of the Ethiopian agriculture that offers an alternative option for rainfed agriculture while climate change and its variabilities mainly affecting the crop productions of conventional farming systems. With the rainfed agriculture (see below), the food and nutrition security of the country is challenging. Therefore, to secure food and nutrition for more than 100 million people of the country, irrigation agriculture is required to be expanded and implemented by both smallholders and large scale schemes. Increasing agricultural productivity could help in achieving food self-sufficiency thereby alleviating poverty and food insecurity among smallholder farmers in Ethiopia (Alemu, 2019).

The current study on irrigation potential area reveals that about 71,317 sq.km (6.8%) of land is found with the highest development options (with highly suitability area, highest market access or non-remote, low populated, and mid lowland and mid-highland agroecology). Moreover, about 347,435 sq km (33.3%) of the land has high development option (with moderately suitable area, non-remote areas to market, middle population density, and mid-lowland agroecology). This indicates that based on the geospatial and socioeconomic analyses about 40% of the land has high to highest development options for irrigation agriculture.

4.2. Rainfed agriculture

African countries have a significant food security challenges, and is the challenge is the African smallholder farmers, typically engaged in rainfed subsistence farming systems (Abrams, 2018). One-third of people across the African continent are food insecure. Abrams further stated that smallholder farmers contribute up to 90% of food productions in some sub-Saharan African countries but crop productivities are amongst the lowest in the world. Water is the key governing factor in crop production. In sub-Saharan Africa, 95% of agricultural production is mainly depend on rainwater. Smallholder farmers are vulnerable to the variability in the distribution and intensity of rainfall, particularly in the drylands of Africa. Ethiopian farming is similarly dependent mainly on rainfed smallholder agriculture system as a means of food and income for its population (Hordofa, n.d).

Reviving the rural economies will only be crop water productivity, which is effective with the available water resources. However, crop water productivity requires capacity and technology inputs to smallholder rainfed farmers who are the front-line managers of water use but they often have little or no support like training in the management of these scarce rainfed water resources and beside to the challenge imposed by the increasing threat from climate change. Regarding climate change, it was reported that about two-thirds of the population are trapped in a cycle of poverty, exacerbated by climate change and rapidly rising population growth (Abrams, 2018). Moreover, rainfed agriculture depends on rainfall that infiltrated and stored in the upper layers of the soil. This is soil moisture, which is available to plant roots as “green water”. This resource feeds the crop for its production that helps farmers beyond subsistence farming towards sustainable livelihoods by ending hunger (sustainable development goal 2 – SDG 2, SDG, 2015), development and economic growth as well as builds climate resilience.

Actually, crop production is a function of different factors, mainly water, nutrient, climate and soil environment although rainfall rarely meets the time with required amount of water application for plant growth (Hordofa, n.d). Much of the increase in crop production in the past decade has been due to increases in area cultivated. To what extent the area cultivated can continue to expand remains an important question (Seyoum et al., 2011). Hence, intensive agriculture is mandatory to satisfy the current and future demands of food. And rainfed agriculture, in one hand, is not only enough with the conventional farming system, but also requires even identifying the best areas for rainfed beside to irrigation agriculture. However, there are numerous constraints to agricultural productivity, and water resource and its utilization has been identified as one of these constraints among low levels of input use (fertilizer, pesticide, improved seeds), low levels of irrigation, soil degradation and soil erosion, inadequate agricultural research and extension, and constraints in market development (Seyoum et al., 2011).

The current study on rainfed potential area reveals that about 33,821 sq.km (3.2%) of land is found with the highest development options (with highly suitability area, highest market access or non-remote, low populated, best length of growing period, and mid lowland and mid-highland agroecology). Moreover, about 105,013 sq km (10 %) of the land has high development option (with moderately suitable area, non-remote areas to market, middle population density, better length of growing periods, and mid-lowland agroecology). This indicates that based on the geospatial and socioeconomic analyses about 13.2% of the land has high to highest development options for irrigation agriculture. And middle potential option for rainfed agriculture has about 392,109 sq.km (37.6%) of the land in Ethiopia.

1. **Conclusions**

It is true that Ethiopia's agriculture is not only dependent on rainfed system but also affected by recurrent drought and global climate changes; which results in low production and productivity, which resulted in low socio-economic development. On the other hand, with the continuous demand for more agricultural productions for consumption and industrial inputs, Ethiopian agriculture should need paradigm shifts from rainfed to irrigation that foster in production of more and variable commodities by withstanding weather variability (climate changes) relative to rainfed practices. Irrigation practice has many advantages over rainfed. It resists short-term weather/climate anomalies, allows repeated productions (at least twice in one calendar year), is suitable to use different advanced technologies for agricultural inputs. Hence, it has the potential to improve agricultural productivity by having access to water even during dry spells and shortest length of growing periods.

The country is endowed with different agro-ecological spaces in nature that could support highly variable agricultural production systems for both rainfed and irrigation scenarios. Moreover, from this analysis, reliable rainfed and irrigable areas are identified at national and regional levels across different agro-ecological gradients that can support different agricultural production systems (lowland to highland production types). Since there are significant variations in altitude with different access to rainfall, land suitability, length of growing periods, population density, and infrastructure/market access, there are multitudes of different agricultural production potentials. These diversified aspects of the country were considered to come up with optimum sites identified for two basic scenarios: rainfed and irrigable areas. Those identified areas either for rainfed or irrigation or both scenarios would be important areas to implement the country's investment policy directions; advance our agricultural productions systems at the national and/or regional levels depending on their agro-ecological requirements; even though further studies are recommended to have a site and/or commodity-specific (micro-level) analyses.

In this study, we found that a very small amount of land (only 32,000 sq.km) is irrigated by both smallholders and mechanized farming, which is about 7.5% of the irrigable areas identified (425,053, 40%). This indicates that more than 393,000 sq km of irrigable area is waiting for further development and Ethiopia has large potential for irrigation agriculture even from the surface water resources. Furthermore, we tried to capture a very large area for irrigation agriculture (>40% of land of the country), we considered only surface water, particularly river access but groundwater resources could support a very substantial area for irrigation both for smallholder and large-scale mechanization practices. Having a large amount of water flows of rivers all-round the year at every corner of the country, and suitable land available for irrigation, Ethiopia can be benefitted from such an opportunity in three ways: (1) by enhancing agricultural production and productivity, its people can have food self-sufficiency, (2) food commodity import substitutions, and (3) delivering inputs for industry sectors, these all helps to achieve its planned development strategy (the ten years' development plan-10YDP) by 2030 so that it can be a middle level developed country. Finally, our result is validated using the following three approaches: (1) ground truth (checking with existing irrigation and rainfed sites), (2) performing sensitivity analysis or altering values and weights of indicators for suitability analysis, and (3) use expert knowledge and experience.

Data Availability

The data used for this study temporarily upload as Supporting Information for review purposes.

Software: mapping software used in this analysis is an open source called QGIS version 3.22.3. https://www.qgis.org/en/site/forusers/download.html.

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