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Mapping land suitability for irrigation in the Nile Basin:

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Document Sheet

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EXECUTIVE SUMMARY

The Nile Basin is home to some of the poorest communities in the world. Expansion and intensification of agriculture are crucial for ensuring food security, improving livelihoods and reducing poverty in the basin. Improving irrigation facilities is considered as a key strategy to enhance agricultural productivity. Spatial information about various aspects of irrigation suitability is an essential input to decision making on irrigation development. Irrigation suitability is determined by a combination of multiple factors such as land, water, climate, and environmental and socioeconomic conditions.

This study provides an update on previous estimations of 'land suitability' for irrigation in the Nile Basin, utilizing the improvements in spatial data on environmental variables. It focuses on the physical factors of land and does not consider water availability and economic costs. The study categorizes the agricultural land in the basin on a suitability scale ranging from 'permanently not suitable' to 'highly suitable' areas for irrigation. It provides baseline information for further more complex analysis of water and environmental suitability for irrigation development.

The methods used in the study broadly follow the framework of the Food and Agriculture Organization of the United Nations (FAO) for land suitability evaluation. Land suitability was evaluated by assessing the soil and terrain suitability for irrigation. Terrain suitability was evaluated based on the slope of the land derived from a digital elevation model (DEM). Soil suitability was assessed using parameters such as drainage, texture, available water storage capacity, pH, physico-chemical organic carbon, salinity, sodicity and soil depth. The Harmonized World Soil Database v1.2 (HWSD) and the Africa Soil Grids (AfSoilGrids250m) datasets were used to assess soil suitability. A multi-criteria evaluation (MCE) procedure following Analytic Hierarchy Process (AHP) method was used on a geographic information system (GIS) platform to develop a composite soil suitability index. The soil suitability index was combined with the terrain suitability categories to generate the final suitability map.

The study estimated that a total land area of 49.8 million hectares is suitable for irrigation in the Nile Basin, of which about 7.5 million hectares is 'highly suitable'. The area of planned irrigation schemes under each land suitability category is also provided. However, to determine the feasibility and actual design of specific projects, it is required to refine the land suitability classification by assessing water availability for irrigation and the economic viability of water supply.

The results of this study could be useful to identify land that is suitable for irrigation, provided that water can be supplied; and to eliminate land that is permanently not suitable for reasons other than water supply. The outputs could be suitable for basin-level land suitability assessments, and for the identification of potential regions for further exploration of water availability and subsequent irrigation development.

CONTENTS

1. INTRODUCTION

Irrigation expansion is seen as a significant leverage to food security, livelihoods, rural development, and agricultural and broader economic development in Africa (Altchenko and Villholth 2015). Irrigation development requires significant investments and credit facilities, and errors in planning would lead to major losses of resources (FAO 1985). Spatial information about land suitability for irrigation is an essential input to facilitate assessment and decision making on investments for irrigated agricultural development. A systematic irrigation suitability assessment, including the level of suitability, is essential to address this central information requirement. Suitability assessments can provide critical information about level of suitability and limiting factors, and assist the decision-makers for optimal allotment of valuable resources.

There is a dearth of updated and accessible information about the irrigation suitability of the Nile Basin in the public domain. Most estimates are available from continental assessments of irrigation suitability. One of the most commonly used estimate of irrigation suitability in the Nile Basin is based on an assessment of 'physical irrigation potential' by FAO (1997). The study had estimated the total irrigation potential of the Nile Basin as 8 million ha. Some of the more recent studies of irrigation potential of entire Africa, such as Altchenko and Villholth (2015) and You et al. (2011), do not provide basin-wise estimates of irrigation potential. Instead, these studies provide country-wise and region-wise estimation of irrigation potential. Apart from these, there are studies, which covers significant areas of the Nile Basin, but do not cover the entire basin. For example, Xie et al. (2014) estimate the potential for expanding smallholder irrigation in sub-Saharan Africa, which do not include Egypt in the analysis. Similarly, an earlier study on irrigation suitability supported by the Nile Basin Initiative (Droogers et al. 2012) also covers only a part of the Nile Basin. The study covers South Sudan, Uganda, Burundi, Rwanda, Kenya, Tanzania and D.R. Congo but do not extent to Egypt, Sudan, Eritrea and Ethiopia. Further, there are several studies on mapping the irrigation suitability at national scales (GIRDC 2018; Worqlul et al. 2017) and subbasin/catchment scales (Kebede and Ademe 2016; Worqlul et al. 2015). From the descriptions above, it is evident that most of the recent studies either do not cover the entire basin or the available information of the entire basin is presented as country-wise information, make it less usable for basin-wise planning requirements.

It may be noted that apart from the geographical coverage, the purpose and scope of these studies also vary. While Altchenko and Villholth (2015) and Worqlul et al. (2017) assess the irrigation suitability using groundwater resources, FAO (1997) and Worqlul et al. (2015) assess the suitability for surface water irrigation systems. Similarly, Xie et al. (2014) assess the potential for expanding smallholder irrigation.

Irrigation suitability is assessed differently in different studies. Some consider only land resources, others consider land and water resources, and some others consider additional aspects such as economic viability and environmental characteristics (FAO 2005, 2016). For instance, FAO (1997) assessed the 'physical irrigation potential' of Africa, by evaluating land and water resources and the irrigation water requirements. Similarly, GIRDC (2018) estimated the irrigation potential of Ethiopia by considering the land suitability and water availability. While Droogers et al. (2012) include market access in addition to land suitability and water availability, Worqlul et al. (2017) consider climatic parameters as well in addition to these three aspects. In general, the approaches need to be based on the requirements of the studies, ranging from reconnaissance studies concerned with regional or national level assessments to detailed actual implementation plans.

However, many studies assess the 'land suitability' as a precursor to more complex analysis, including water availability or climatic/economic suitability. The studies mentioned earlier (FAO 1997; GIRDC 2018) evaluate land suitability using soil and topographic characteristics, before proceeding to the assessment of water resource availability. FAO (1985) suggests that separate classifications of land suitability (provisionally irrigable) and irrigation suitability (irrigable) may be required at successive stages of evaluation. According to FAO (1985), *"In the early stages of irrigation investigations, the amount of water available for irrigation and the exact locations to which water can be economically transported are often uncertain. The suitability of the land must therefore be classified on condition that water can be supplied to it."* A separate land suitability classification will be helpful to eliminate land that is permanently not suitable for reasons other than the water supply. Besides this, land properties such as soil types and topographic slope are some of the most stable conditions compared to other factors of irrigation suitability, e.g., water availability and climate of economic conditions. The land suitability classification can provide a basis for future updates in the event of major shifts in water availability, climate or economic conditions, which are more susceptible to change.

1.1 Scope of the study

The most commonly used estimation of 'land suitability' for irrigation in the Nile Basin is from the FAO (1997). Probably, this may be the only study providing separate classification of land suitability and irrigation suitability for the Nile Basin. The assessment, which was done as part of a continental scale study, was based on the coarse scale global data set FAO-UNESCO Soil Map of the World (1: 5,000,000). Over the last two decades there has been significant improvements in the resolution and quality of spatial data sets. An updated land suitability map utilizing the advancements in spatial data will form an important baseline data set for irrigation development in the Nile Basin.

The objective of the current study is to map the present 'land suitability' for irrigation. The results presented here are derived from analyzing only the physical properties of the land, without considering the water/ infrastructure/ climatic/ socioeconomic factors. The evaluations are based on the present conditions, primarily available from various public domain data sets, and do not consider future possibilities of land modifications. The study estimates the degree of suitability of the land for irrigation and results are presented according to the categories suggested by the FAO framework for land suitability assessment (FAO 1985, 1997).

FAO (1976) proposes three successive stages of analysis in land suitability studies – (i) reconnaissance studies that provide regional or national scale assessments and generate information to prioritize areas for further development (ii) intermediate assessments concerned with more specific aims such as feasibility studies of projects and (iii) a detailed level, including actual planning and design of the project. This study aims to develop a land suitability data set, suitable for basin-level land suitability assessment and identification of potential regions for further explorations on water availability and subsequent irrigation development.

Most countries in the Nile Basin are actively developing irrigation resources. Information about the land suitability is a crucial input for planning future schemes. Several schemes in the basin are already at different stages of the planning process. This study will provide an overall estimation of the land suitability for irrigation in various countries and the planned irrigation schemes.

2. METHODS

2.1 Land suitability assessment framework

The study broadly follows the FAO framework for land suitability evaluation - FAO (1976). The framework suggests the land suitability classification to target two broad categories or orders: Suitable (S) and Not-Suitable (N) and further divide each order into suitability classes reflecting the degrees of suitability. The definitions of these classes are provided in Table 1.

Table 1: Structure of suitability classification (FAO 1976, 1985)

Order	Class	Description
Suitable (S)	Highly suitable (S1)	Land having no significant limitations to sustained application of a given use, or only minor limitations that will not significantly reduce productivity or benefits and will not raise inputs above an acceptable level.
	Moderately suitable (S2)	Land has limitations, which in aggregate are moderately severe for sustained application of a given use. Limitations may reduce physical productivity, benefits or costs compared with S1 land.
	Marginally suitable (S3)	Land has limitations, which in aggregate are severe for sustained application of a given use and will so reduce physical productivity, benefits or costs that the expenditure will only be marginally justified.
Not Suitable(N)	Currently not suitable (N1)	Land having limitations, which may be surmountable in time but cannot be corrected with existing knowledge at currently acceptable cost; the limitations are so severe as to preclude successful sustained use of the land in the given manner.
	Permanently not suitable (N2)	Land having limitations, which appear so severe as to preclude any possibilities of successful sustained use of the land in the given manner

2.1.1 Factors and analytical procedures

This section describes how the FAO framework was implemented in the current study (Figure 1). The suitability analysis has three major steps: (i) re-classify and rank each factor on the suitability-scale proposed by the FAO to develop constituent suitability layers (ii) exclude unsuitable areas by creating a constraint layer (iii) aggregate constituent suitability layers and constraints to develop the suitability classes.

The land suitability for irrigation was evaluated by assessing the soil and terrain suitability for irrigation (FAO 1997; GIRDC 2018). Topographic slope and various physical and chemical soil properties were considered as 'class determining factors' for the land suitability assessment. A class determining factor is an environmental phenomenon or condition affecting the suitability of a land for a given land use. Each input factor was re-classified to the suitability classes provided in Table 1. These factor-suitability classes were defined using a set of thresholds or critical limits obtained from literature. Details of the data sets and thresholds used to map the factor variables are described in Sections 2.2 and 2.3. A composite soil suitability index was derived from the soil variables and combined with the terrain suitability categories to generate the final suitability map.

Terrain suitability

Slope is considered as one of the most important terrain characteristic affecting the irrigation suitability. Slope of the land affects the suitability of an area in terms of land preparation for irrigation and irrigation operation (Worqlul et al. 2017). In this study, terrain suitability for irrigation was evaluated based on the slope of the land (FAO 1997; Droogers et al. 2012). The terrain suitability classes were derived from the topographic slope generated using digital elevation model (DEM).

Soil suitability assessment through multi-criteria evaluation

The soil suitability for irrigation was assessed using the parameters such as (i) drainage (ii) texture (iii) available water storage capacity (iv) pH (v) physico-chemical organic carbon (vi) salinity (vii) sodicity and (viii) soil depth. A GIS-based multi-criteria evaluation (MCE) procedure was used to combine various factors to obtain the pixel-wise composite soil suitability classification (Worqlul et al. 2017; Akinci et al. 2013). This study followed the Analytic Hierarchy Process (AHP) method (Saaty 1977) to perform the MCE. The AHP was carried out using the weights derived from a pairwise comparison matrix of the relative importance of suitability factors of the activity being evaluated. The factors were standardized by converting to the scale of suitability (Table 1) as defined by FAO, and assigning a standard suitability score to the suitability classes of individual factors. A composite soil suitability index was developed by applying the factor weights on the factor classes with suitability scores. The composite soil suitability index was categorized into the suitability classes defined by FAO.

Constraints delineation

As the land suitability for irrigation is restricted to agricultural land, a constraint layer was developed based on current land use. All nonagricultural areas such as built-up areas, forests, plantations, wetlands, waterbodies, barren lands, shrubs and grasslands were identified as not suitable areas for irrigation development. Hence, the constraint layer, aimed at excluding unsuitable areas, limited the potential areas to croplands, including cultivated and fallow areas.

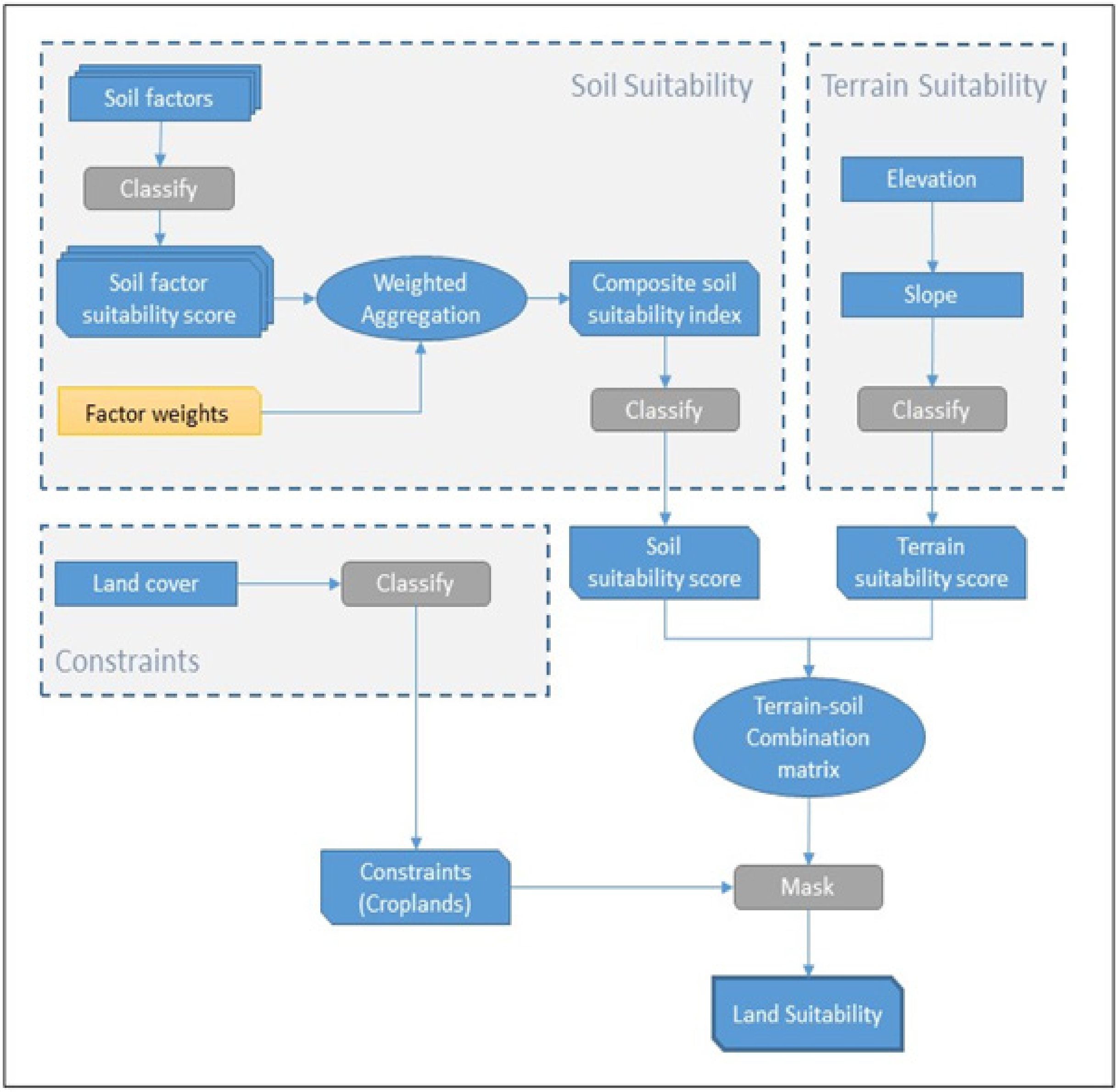
A special case of permanently not suitable land

Some of the terrain and soil properties severely limit the suitability of the land, even if there are several other favorable factors present. While such areas in nonagricultural land will be excluded by applying the constraint layer, such areas would continue to be present within the croplands also. These areas should be retained in the analysis as they are part of the croplands, but should be classified as permanently not suitable (N2), regardless of the level of suitability assigned to those areas through the analysis. Areas identified as permanently unsuitable based on slope, drainage capacity, topsoil percentage of organic carbon, topsoil texture and, top and subsoil levels of salinity and sodicity were considered as such properties, which severely limit the land suitability.

Aggregation of suitability layers

The final land suitability layer was created by combining terrain and soil suitability classes. The land suitability class was determined by evaluating each combination of the terrain-soil suitability categories using a terrain-soil composition matrix for the areas defined by the constraints layer.

Figure 1: Framework for land suitability mapping



2.2 Data and pre-processing

The analysis was performed in a GIS environment using the geo-spatial data sets representing the variables selected for the analysis. GIS analysis was done using ArcGIS 10.5 and Idrisi TerrSet software packages. All the spatial data sets used for this study are in the public domain and available free of cost from various online resources mentioned in Table 2 and in the following sections.

2.2.1 Slope

The Shuttle Radar Topographic Mission -1 Arc Second Global digital elevation model data (SRTM-DEM) with 30 m resolution was used to derive the topographic slope to assess terrain suitability. The data covering the entire Nile Basin was downloaded from NASA EARTHDATA data portal (https://earthdata.nasa.gov). The slope in percentage was derived in Cylindrical Equal Area projection using ArcGIS software.

2.2.2 Soil properties

The Harmonized World Soil Database v1.2 (HWSD) was used to assess the soil factors (Section 2.1.1) except the soil depth, which is not available in the HWSD. AfSoilGrids250m data was used for the soil depth information. The soil physico-chemical properties were assessed for the top soil (0-30 cm) and some were additionally assessed for the subsoil (30-100 cm).

The HWSD is composed of a GIS raster image file with a spatial resolution of 1 km, which can be linked to an attribute database of soil properties. The database provides standardized soil parameters for top- and subsoil, and the composition of each soil mapping unit. A soil mapping unit can have up to 9 soil unit/topsoil texture combination records in the database and the percentage of each combination is provided (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012). The attributes of the dominant soil type were used for the physical properties such as texture, drainage class and available water storage capacity. However, a weighted average based on the soil unit proportions was used for the chemical properties such as pH, organic carbon, salinity and sodicity. This difference is due to the availability of quantified measurements of chemical properties, whereas only qualitative class names were available for the physical properties. The soil depth data from the Africa Soil Grids data set, AfSoilGrids250m was used for the analysis. This data has a resolution of 250 m and the average soil depth of 4x4 pixel window was used to correspond to the 1 km resolution of the HWSD input.

2.2.3 Agriculture areas

As defined in the framework, the land suitability mapping was limited to the croplands in the basin. Two global data sets mentioned in Table 2 were used to map the croplands – (i) GFSAD30AFCE 30 m cropland map and (ii) the S2 prototype land cover map of Africa with 20 m resolution from ESA Climate Change Initiative. While the GFSAD30AFCE map is a Boolean map with only cropland class, the ESA CCI land cover map includes several other land cover types also. A comparison between these two maps brought out many differences between the cropland areas mapped by these two maps. A rapid checking with Google Earth images showed that many cropland areas were likely to be missed in either of the maps. Such issues are not unusual while using global maps at a regional or national scale. In order to retain maximum cropland areas in the analysis, a combined cropland layer was created by considering all the pixels mapped as croplands by either of these maps. The combined cropland map has a resolution of 30 m.

Table 2: Factors considered for the land suitability analysis and the data sets

Variable/ Factor	Data Set	Citation	Resolution
Terrain suitability	SRTM DEM v 3.0	National Aeronautics and Space Administration – Jet Propulsion Lab (NASA JPL) (2013)	30 m
Soil properties	Harmonized World Soil Database v 1.2	FAO, IIASA, ISRIC, ISS-CAS, and JRC (2012)	1 km
	AfSoilGrids250m	Hengl et al. (2015)	250 m
Land cover	GFSAD30AFCE: Global Food Security-support Analysis Data (GFSAD): Cropland extent 2015 Africa v 001	Xiong, et al. (2017)	30 m
	S2 prototype LC 20m map of Africa 2016	ESA-CCI (2017)	20 m

2.3 Classification of land suitability factors

2.3.1 Terrain suitability evaluation

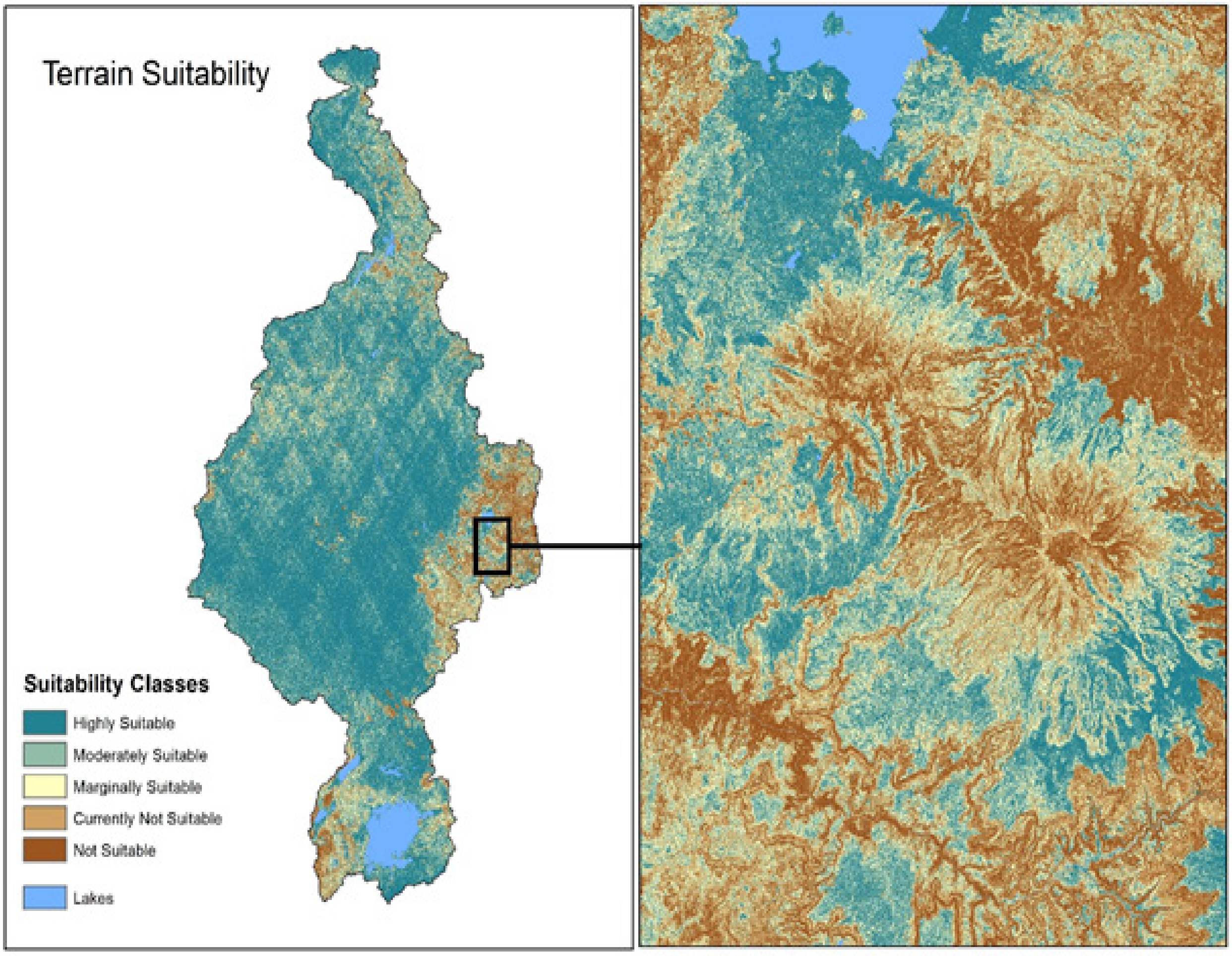
Terrain suitability was assessed using the slope data derived from SRTM-DEM. Generally, surface irrigation systems require uniform field slopes within the 0-5% range (FAO 2002). FAO (1997) suggests land with slope up to 8% is suitable for irrigation. However, based on the practice in Ethiopia, GIRDC (2018) reports that land with slope up to 15% is suitable for all types of irrigation. Worqlul et al. (2017) considered land with slope 8-12% as marginally suitable and 12-20% as less suitable. Nevertheless, the previous Nile Basin Initiative (NBI) study on irrigation suitability had considered land with slope up to 20% is suitable for irrigation (Droogers et al. 2012). The critical limits used for classifying the slope suitability in this study are provided in Table 3.

Table 3: Critical limits of land slope to determine the slope suitability

Slope range (%)	Suitability class	Suitability code
0 - 5	Highly suitable	s1
5 - 8	Moderately suitable	s2
8 - 15	Marginally suitable	s3
15 - 30	Currently not suitable	n1
> 30	Permanently not suitable	n2

The terrain suitability was mapped by categorizing the slope layer into the suitability classes by applying the critical limits (Figure 2).

Figure 2: Terrain suitability for irrigation in the Nile Basin



2.3.2 Soil suitability evaluation

The soil physico-chemical properties extracted from HWSD and AfSoilGrids250m data sets (Section 2.1.1) were ranked on the suitability scale based on the classification criteria obtained from literature. The ranked soil factors were integrated through a Multi-Criteria Evaluation to derive the soil suitability. The criteria used to classify each soil property is provided in the following section. The classified soil factor suitability maps are provided in the Figure 3.

Soil factors and suitability classes

Drainage Classes
HWSD data maps five drainage categories in the Nile Basin. These categories were mapped into the drainage suitability classes as shown in Table 4. The classification was assigned similar to the previous NBI study on irrigation suitability (Droogers et al. 2012), but using a qualitative category instead of the % suitability used in that report.

Table 4: Conversion from drainage classes to suitability for drainage capacity

Drainage class	Suitability class
Somewhat excessively drained	Not suitable
Moderately well drained	Moderately suitable
Imperfectly drained	Marginally suitable
Poorly drained	Marginally suitable
Very poorly drained	Not suitable

Soil Texture

The soil texture classification in HWSD is based on the USDA classification method. The data for both topsoil and subsoil were used for the analysis. The texture classes were classified to texture suitability classes following the class limits and the % suitability values used in Droogers et al. (2012). The texture classes and the corresponding suitability classes are shown in Table 5.

Table 5. Conversion from texture classes to soil texture suitability for irrigation in topsoil and subsoil

Texture class	Suitability class
Clay(heavy)	Not suitable
Clay (light)	Marginally suitable
Silty clay loam	Moderately suitable
Clay loam	Highly suitable
Silt loam	Highly suitable
Sandy clay	Moderately suitable
Loam	Moderately suitable
Sandy clay loam	Marginally suitable
Sandy loam	Marginally suitable
Loamy sand	Currently not suitable
Sand	Not suitable

Available Water Storage Capacity (AWC)

The criteria used to classify the 'Available Water Storage Capacity' of the soil unit are provided in Table 6. The AWC classification is provided in HWSD, and the corresponding suitability classes were assigned based on the % suitability assigned by Droogers et al. (2012).

Table 6: AWC categories and corresponding suitability classes

AWC (mm/m)	Suitability class
> 150	Highly suitable
125 - 150	Moderately suitable
100 - 125	Marginally suitable
50 - 100	Currently not suitable
15 - 50	Not suitable

Soil Depth

Soil depth to bedrock up to 175 cm was obtained from the Africa Soil Grids database, at 250 m resolution. The data was coarsened to 1 km to match with the resolution of other soil factors selected from HWSD. The resolution change was achieved by pixel aggregation using mean of 4x4 pixels. The soil depth criteria used to classify the suitability are provided in Table 7 (GIRDC 2018).

Table 7: Depth to bedrock classes and corresponding suitability classes

Depth to bedrock (cm)	Suitability class
120 - 200	Moderately suitable
60 - 120	Marginally suitable
30 - 60	Currently not suitable
< 30	Not suitable

pH of top soil

Topsoil pH was used as a factor for the suitability analysis. The five major pH classes considered here have specific agronomic significance (FAO, IIASA, ISRIC, ISS-CAS, and JRC 2012) and their corresponding suitability classes based on the % suitability provided in Droogers et al. (2012), are shown in Table 8.

Table 8: Topsoil pH categories and corresponding suitability classes

pH class	Suitability class
<4	Currently not suitable
4 - 5.5	Marginally suitable
5.5 - 7.3	Highly suitable
7.3 - 8.5	Marginally suitable
> 8.5	Currently not suitable

Organic carbon

Data on percentage of organic carbon in topsoil was categorized to suitability classes as shown in Table 9. The classification was based on FAO, IIASA, ISRIC, ISS-CAS, and JRC (2012) and the % suitability Droogers et al. (2012).

Table 9: Conversion from percentage of organic carbon in topsoil classes to suitability classes

Organic carbon (%)	Suitability class
< 0.2	Not suitable
0.2 - 0.6	Currently not suitable
0.6 - 1.2	Marginally suitable
1.2 - 2.0	Moderately suitable
> 2.0	Highly suitable

Salinity

The salt content of soil can be roughly estimated from the Electrical Conductivity of the soil (EC, expressed in dS m^{-1}). The electrical conductivity measurements of top and subsoil were used as salinity estimations and was categorized to suitability categories. The agronomic relevant limits and the suitability categories are provided in Table 10 (FAO, IIASA, ISRIC, ISS-CAS, and JRC 2012; Hammam and Mohamed 2018).

Table 10: Agronomic classification and suitability classes of topsoil and subsoil salinity

Electrical conductivity (ds m-1)	Suitability class
< 2	Highly suitable
2 - 4	Moderately suitable
4 - 8	Currently not suitable
>8	Not suitable

Sodicity

Sodium concentration levels in the top and subsoil were classified using the exchangeable sodium percentage. Agronomic limits used for the classification and the corresponding suitability classification are given in Table 11 (FAO, IIASA, ISRIC, ISS-CAS, and JRC 2012).

Table 11: Agronomic limits used for the classification of sodicity and the corresponding suitability classes

Exchangeable sodium percentage	Suitability classes
< 6	Highly suitable
6 - 15	Moderately suitable
15 - 25	Currently not suitable
> 25	Not suitable

Figure 3: Suitability classes of various soil factors influencing land suitability for irrigation

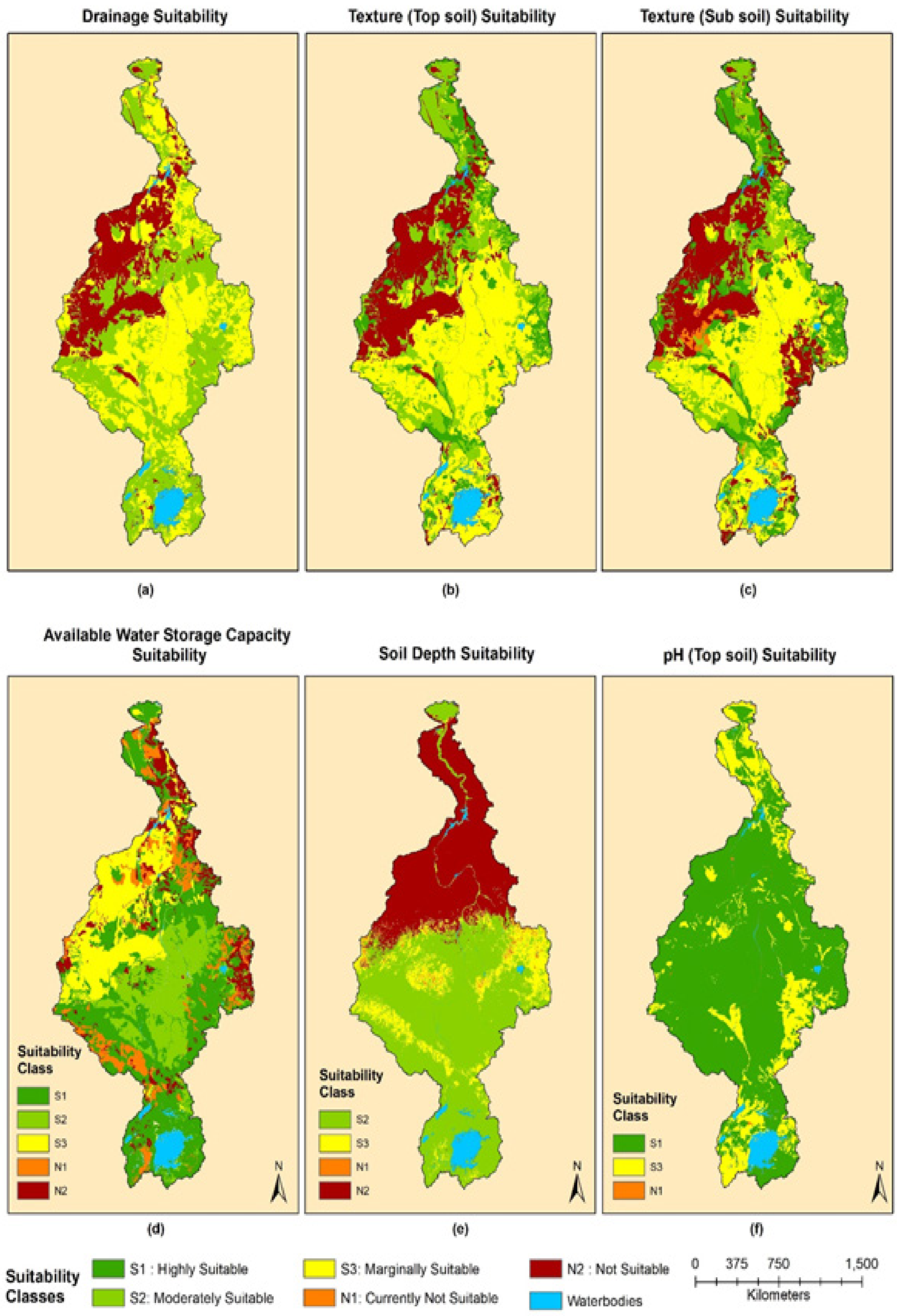
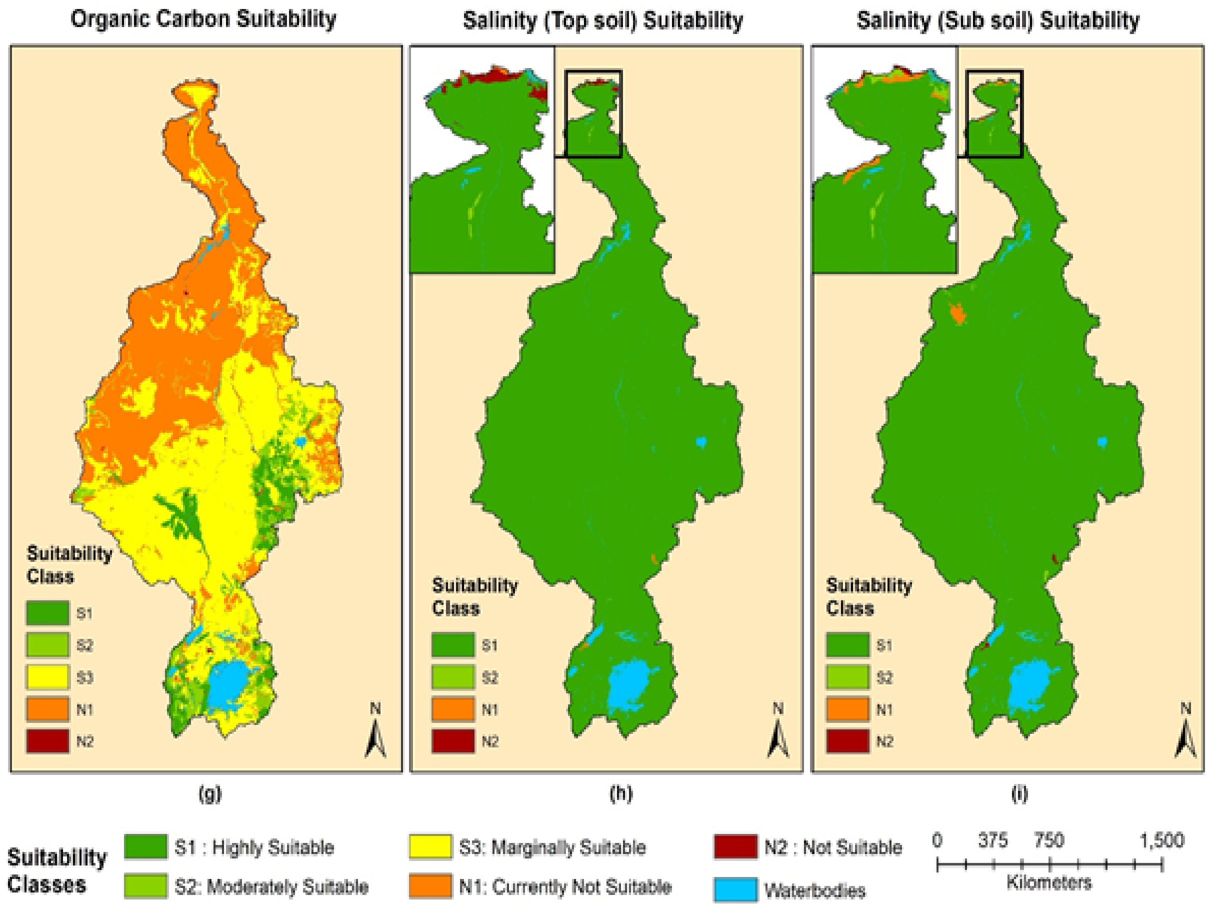


Figure 3: Suitability classes of various soil factors influencing land suitability for irrigation (Continued)



Integration of soil suitability factors using multi-criteria analysis

The soil factors classified to the suitability classes were combined to form a composite soil suitability index. A suitability score was assigned as shown in Table 12 to the suitability classes in each of the soil factor suitability maps.

Table 12: Suitability score assigned to the soil factor categories converted to suitability scale

Suitability class	Suitability score
Highly suitable	10
Moderately suitable	8
Marginally suitable	6
Currently not suitable	2
Not suitable	0

Since the influence of each selected soil factor on the overall soil suitability varies, the factors were combined by assigning weightages based on the importance of each factor. The weightages were determined using a pairwise comparison matrix as suggested in the AHP method. The ratings were assigned on a 9-point continuous scale shown in Table 13 as suggested by Saaty (1977). Intermediate values such as 2, 4, 6, 8 and inverse fractions were used when importance was assumed between two adjacent ratings.

Table 13: The scale of ratings for pairwise comparison of factors

Less Important					More Important			
1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely

The pairwise matrix contain all possible pairs of the 11 soil factors selected, and all pairs were rated based on the scale shown in Table 13. The relative levels of importance/ratings of the factors were decided based on expert consultation. The relative ratings and the derived factor weightages are provided in Table 14. The pairwise matrix has a consistency ratio of 0.05, which is within the acceptable limits (Saaty 1977).

Table 14: Pairwise relative ratings and the weights of the soil suitability factors

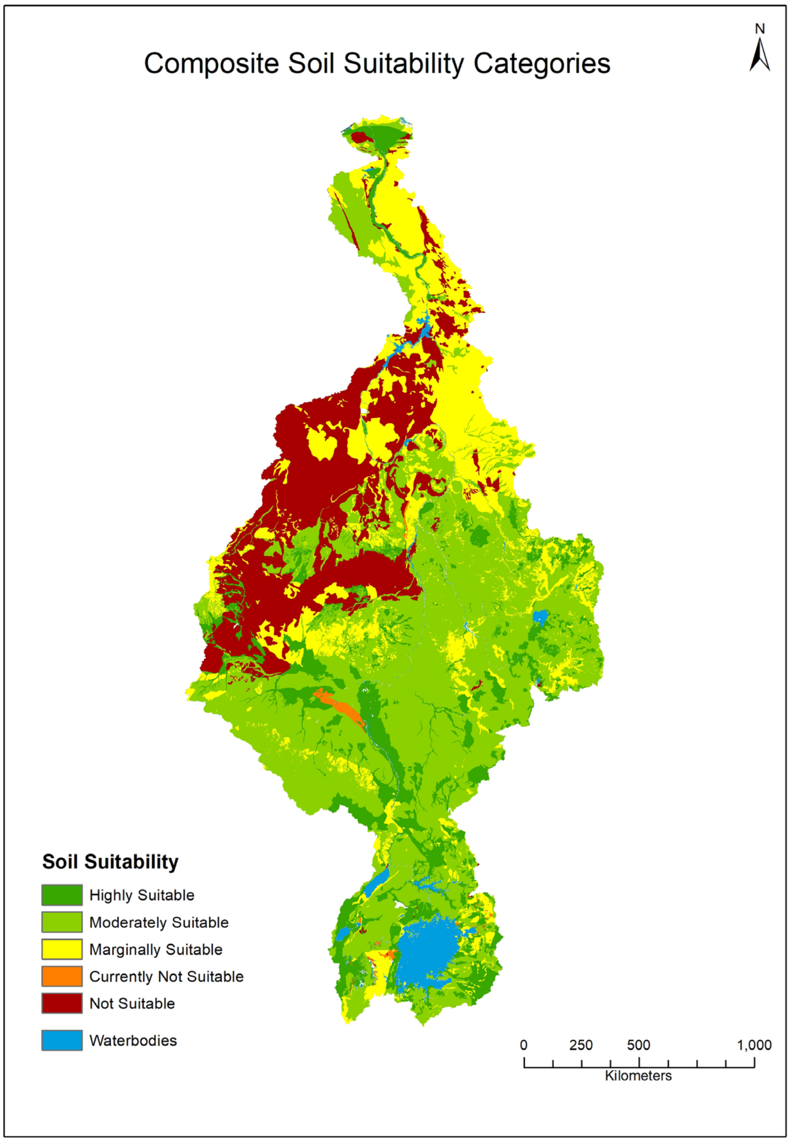
Factors	Drainage	Texture (topsoil)	Soil Depth	pH (topsoil)	AWC	Organic Carbon (topsoil)	Texture (subsoil)	Salinity (topsoil)	Sodicity (topsoil)	Salinity (subsoil)	Sodicity (subsoil)	Weights
Drainage	1	2	4	4	4	5	5	6	6	7	7	0.2639
Texture (topsoil)	1/2	1	4	4	4	4	5	5	5	6	6	0.2200
soil depth	1/4	1/4	1	1	1	3	4	5	5	6	6	0.1133
pH (topsoil)	1/4	1/4	1	1	1	2	3	4	4	5	5	0.0957
AWC	1/4	1/4	1	1	1	2	4	4	4	5	5	0.0993
Organic Carbon (topsoil)	1/5	1/4	1/3	1/2	1/2	1	1	3	3	5	5	0.0619
Texture (subsoil)	1/5	1/5	1/4	1/3	1/4	1	1	1	1	4	4	0.0422
Salinity (topsoil)	1/6	1/5	1/5	1/4	1/4	1/3	1	1	1	3	3	0.0337
Sodicity (topsoil)	1/6	1/5	1/5	1/4	1/4	1/3	1	1	1	3	3	0.0337
Salinity (subsoil)	1/7	1/6	1/6	1/5	1/5	1/5	1/4	1/3	1/3	1	1	0.0181
Sodicity (subsoil)	1/7	1/6	1/6	1/5	1/5	1/5	1/4	1/3	1/3	1	1	0.0181

The composite soil suitability index was generated by calculating a weighted sum of the suitability scored factors using the derived weights. The suitability index value ranges from 1.5 to 9.2, where higher values indicate higher soil suitability. The suitability index values were converted to percentages with respect to the highest suitability score (which is 10) and classified into five categories as shown in Table 15, and the composite soil suitability map was generated (Figure 4).

Table 15: Classification of composite soil index into suitability categories

Composite soil index (%)	Suitability class	Suitability code
< 80	Highly suitable	s1
70 - 80	Moderately suitable	s2
50 - 70	Marginally suitable	s3
40- 50	Currently not suitable	n1
<40	Not suitable	n2

Figure 4: Composite soil suitability categories derived by integrating the individual soil factor suitability maps



2.4 Constraint layer

The land suitability analysis was limited to the agriculture areas in the basin. The land cover maps were processed and reclassified to form a cropland map (Section 2.2.3), which was used to define the constraint layer for the analysis.

2.5 Land suitability mapping

The final land suitability mapping was created by combining the terrain suitability and soil suitability layers. Both soil and terrain suitability layers are classified into five levels of suitability each. The land suitability classes according to FAO suitability classes (Table 1) were determined by evaluating each combination of the terrain -- soil suitability category. The assigned land suitability category, and its relative position in the terrain -- soil combination matrix is shown in Table 16.

Further, the areas with the properties that severely limit the land suitability (Section 2.1.1) were reclassified to 'Permanently Not Suitable (N2)' category. The resultant land suitability layer was masked using the constraint layer to exclude the areas, which were not considered for the analysis.

The land area under different suitability categories for the entire basin and for each country was estimated separately. The land suitability status of the planned irrigation schemes was also estimated using the scheme boundary data provided by NBI. The areas were estimated for the 134 schemes, which have a polygon boundary available. Several of the planned schemes include significant areas of nonagricultural lands. The land suitability was mapped only for the current agriculture areas. Therefore, nonagricultural area was included as a separate category in addition to the suitability classes in the final map.

Table 16: Terrain -- soil suitability class combination and final suitability classes

		Soil suitability				
		s1	*s2*	*s3*	*n1*	*n2*
Terrain suitability	s1	S1	S2	S3	S3	N2
	s2	S2	S3	S3	S3	N2
	s3	S3	S3	S3	N2	N2
	n1	N1	N1	N2	N2	N2
	n2	N2	N2	N2	N2	N2

S1: highly suitable *S2: moderately suitable* *S3: marginally suitable*
N1: currently not suitable *N2: permanently not suitable*

Note: Uppercase letters denote the final land suitability class. Lowercase letters represent the suitability class of the terrain and soil factors

3. RESULTS AND DISCUSSION

The final output of this study is a GIS raster layer depicting the 'land suitability' to irrigation in the Nile Basin (Figure 5). The results are presented in a categorized format indicating the level of suitability according to FAO guidelines for land suitability evaluation. The map includes the areas identified as 'constraints' also for which the land suitability was not evaluated. The resolution of the output layer is kept as 30 m to retain the complete information gained from the slope layer. The study estimated a total of 49.8 million-hectare area as suitable land for irrigation in the Nile Basin. Table 17 provides the distribution of various land suitability categories in different Nile-basin countries.

Figure 5: Land suitability for irrigation developed by evaluating soil and terrain suitability conditions

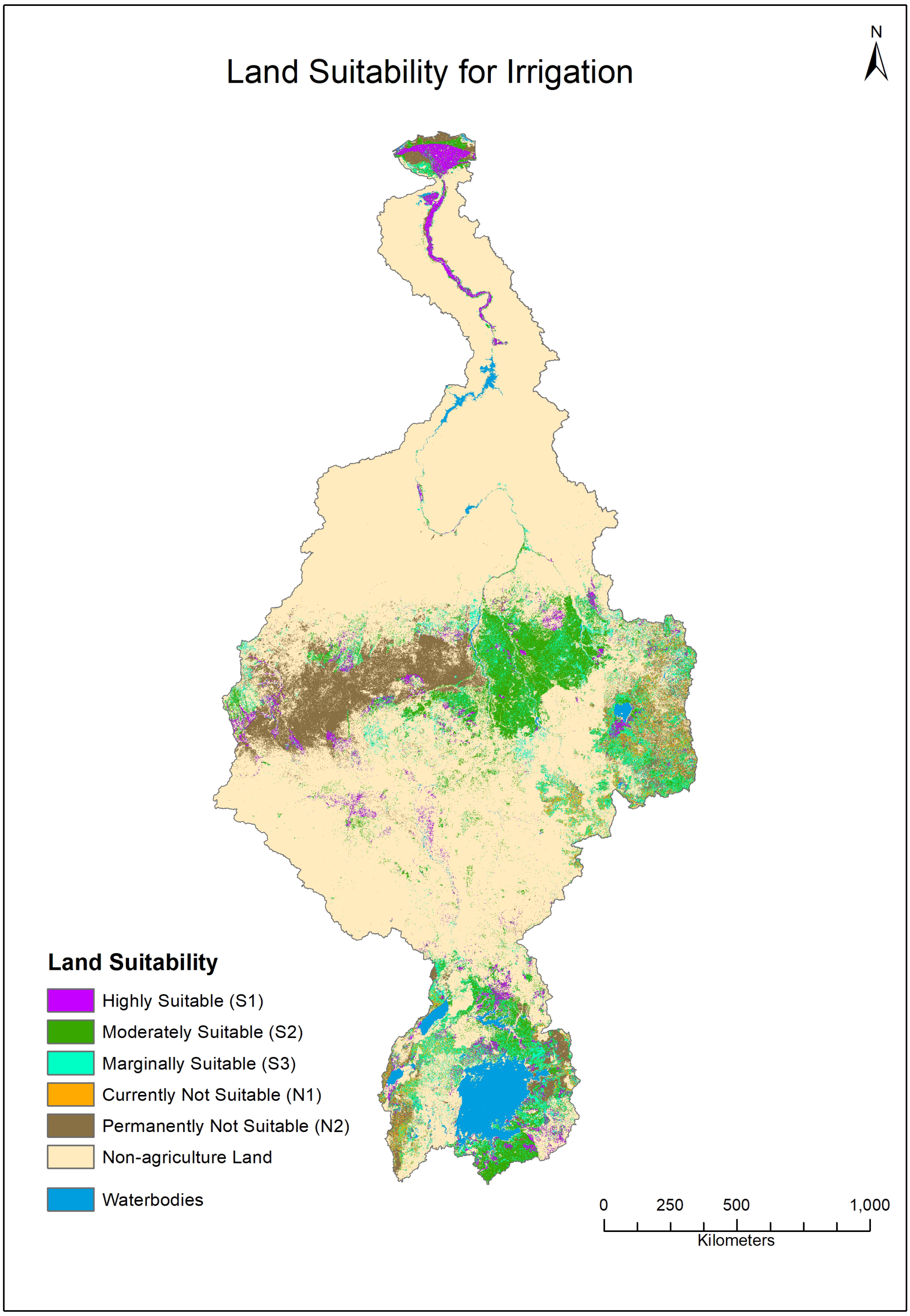


Table 17: Land suitability for irrigation in different Nile-basin countries (area in hectares)

Country	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Currently not suitable (N1)	Permanently not suitable (N2)	Total suitable area
Egypt	2,058,618	934,464	384,889	17,015	912,465	3,377,971
Sudan	2,029,709	12,951,431	5,105,662	78,472	15,603,451	20,086,802
South Sudan	648,062	2,348,819	583,697	13,380	377,312	3,580,578
Eritrea	12,701	49,418	92,514	9,335	20,531	154,632
Ethiopia	527,252	2,572,133	4,870,069	2,929,135	3,628,868	7,969,455
Uganda	1,016,065	3,392,659	2,899,810	653,247	638,700	7,308,534
Kenya	269,954	690,564	967,090	241,490	1,190,718	1,927,607
Democratic Republic of the Congo	146,802	107,837	233,177	208,954	214,111	487,817
Rwanda	71,598	105,010	288,057	333,744	402,535	464,665
Burundi	3,151	33,371	126,387	128,919	213,538	162,909
United Republic of Tanzania	697,575	2,383,872	1,191,816	81,878	133,004	4,273,263
Total	7,481,487	25,569,578	16,743,168	4,695,569	23,335,233	49,794,233

3.1 Comparison of the results with previous studies

Land suitability as a separate estimate is available in only few studies from the Nile Basin. Table 18 provides the results of some of the previous studies from the region. It is important to note that these studies are not exactly comparable with the current study. There are significant differences in spatial coverage, factors considered and methods used for the analysis. However, the table was prepared to provide an overview of existing information and the contribution of this study.

FAO (1997) is one of the few studies that estimated land suitability and irrigation suitability in successive stages and provided a spatially and methodologically comparable estimation with the current study. In that study (FAO 1997), land suitability for irrigation in the Nile Basin was estimated as 92 million hectares. The land suitability estimate for the entire basin, and for each country is provided separately. However, it doesn't give the estimates for the Nile Basin area within each country. The estimates provided for the entire country include also areas outside of the Nile Basin. Except for Sudan, South Sudan, Uganda and Rwanda, the majority of the countries falls predominantly outside of the basin.

A major reason for the differences between land suitability estimates of the current study and FAO (1997) could be the use of the high resolution cropland maps (ESA-CCI 2017; Xiong et al. 2017) for the current analysis. The present study limits the analysis to the current croplands, including fallow areas. The total area of the croplands in the Nile Basin, according to these maps is estimated as 77.8 million ha, which is lower than the FAO (1997) estimation of land suitable for irrigation. This difference is clearly reflected in the area estimations.

The FAO (1997) estimation is based on coarse scale data sets and literature review. The study had used the FAO-UNESCO Soil Map of the World with 1: 5,000,000 scale. Such coarse scale maps may not be efficient in capturing the finer scale variabilities. Whereas, the soil map used for this study has a pixel resolution of 1 km, which is a comparatively finer resolution. Further, there are differences in the set of soil factors used in both studies. Both studies use drainage, texture, soil depth and salinity for the analysis, but organic carbon, AWC and sodicity are used only in this study. Similarly, stoniness, calcium carbonate, gypsum and alkalinity are used only by the FAO study.

Table 18: Comparison of the results of various studies on irrigation suitability. Please note that estimates of FAO (1997) is for entire countries and may not be directly comparable to this study in some cases

Country	This Study	FAO (1997)		Droogers et al. (2012)
	Land suitability	Land suitability for entire country	% of the country within the Nile Basin	Irrigation potential
Egypt	3,377,971	7,133,300	32.6	NA
Sudan	20,086,802	68,769,200	79.0	NA
South Sudan	3,580,578			24,145,300
Eritrea	154,632	4,268,400	20.5	NA
Ethiopia	7,969,455	30,336,400	32.4	NA
Uganda	7,308,534	7,675,700	98.0	3,027,800
Kenya	1,927,607	17,384,700	7.9	421,725
Democratic Republic of the Congo	487,817	78,737,800	0.9	124,400
Rwanda	464,665	300,900	75.5	99,900
Burundi	162,909	588,800	47.6	28,338
Tanzania	4,273,263	24,253,400	8.9	1,611,600

Note: Result of Sudan include South Sudan as well.

The earlier NBI study on irrigation potential (Droogers et al. 2012) covers only a part of the Nile Basin. The study covers South Sudan, Uganda, Burundi, Rwanda, Kenya, Tanzania and D.R. Congo, but do not extent to Egypt, Sudan, Eritrea and Ethiopia. The study also does not provide the land suitability as a separate classification.

Droogers et al. (2012) uses a different definition and analytical approach to map the irrigation suitability. The methodology is significantly different from the FAO framework for land suitability assessment. The study expresses the suitability as a continuous surface with suitability values ranging from 0 to 100%. The area statistics is estimated in the study by considering areas with suitability > 60% as suitable for irrigation. The study uses soils, topography, water availability and socioeconomic factors to estimate the irrigation potential. The land suitability area of the current study is higher than the land suitable for irrigation estimated by Droogers et al. (2012) in all the countries (Table 18).

3.2 Land suitability of planned irrigation schemes

An overall scenario of land suitability status of the planned irrigation schemes based on the available scheme boundaries is provided in Tables 19, 20 and 21.

Area of planned irrigation schemes in each land suitability category, estimated for the 134 schemes for which boundary polygons are available, is given in Table 19. Since the land suitability was mapped only for the current agriculture areas, nonagricultural was included as a separate category in addition to the suitability classes. However, the percentage of each suitability class was calculated based on the current agriculture areas.

Table 19: Area of planned irrigation schemes* in each land suitability category

Land suitability category	Area (ha)	Percentage of land suitable within cropped areas
Highly suitable	158,689	5.5%
Moderately suitable	1,931,008	66.4%
Marginally suitable	581,736	20.0%
Currently not suitable	83,418	2.9%
Permanently not suitable	152,478	5.2%
Total croplands within the planned area	2,907,329	100.0%
Nonagricultural	7,343,420	
Total planned area, including nonagricultural areas	10,250,749	

Note: The area estimations are based on 134 planned irrigation schemes for which scheme boundaries are available.

Table 19 shows that majority of the area (66.4%), where irrigation schemes are planned has a moderate suitability for irrigation, and 20 % of the area was found marginally suitable for irrigation. Only 5.5% of the planned scheme areas is highly suitable for irrigation and 5.2% of the area was found to be permanently not suitable for irrigation. However, the largest area of the total planned irrigation schemes is currently nonagricultural (Table 19).

The land cover types present in the nonagricultural areas included in the planned irrigation schemes are provided in Table 20 and Figure 6. The table and the figure are based on ESA-CCI (2017). The data shows that 99.3% of the nonagricultural areas within the planned schemes are covered either by trees, shrubs or grasslands. It may also be noted that 40% of the nonagricultural areas within the planned schemes has some forms of tree cover.

Table 20: Area of nonagricultural land cover types present the planned irrigation schemes

Land Cover	Area (ha)	Percentage
Tree cover area	2,963,967	40.4%
Shrubs cover area	1,615,167	22.0%
Grassland	2,712,909	36.9%
Vegetation aquatic or regularly flooded	23,932	0.3%
Sparse vegetation	1,519	0.0%
Bare areas	25,927	0.4%
Total	7,343,421	100.0%

Figure 6: The land cover of the planned irrigation schemes in the Nile Basin. Boundary polygons are not available for the schemes represented as point locations. The cropland areas are derived as described in Section 2.2.3. The land cover of the remaining areas is from ESA-CCI S2 Prototype Land Cover 20 m map of Africa. (ESA-CCI 2017)

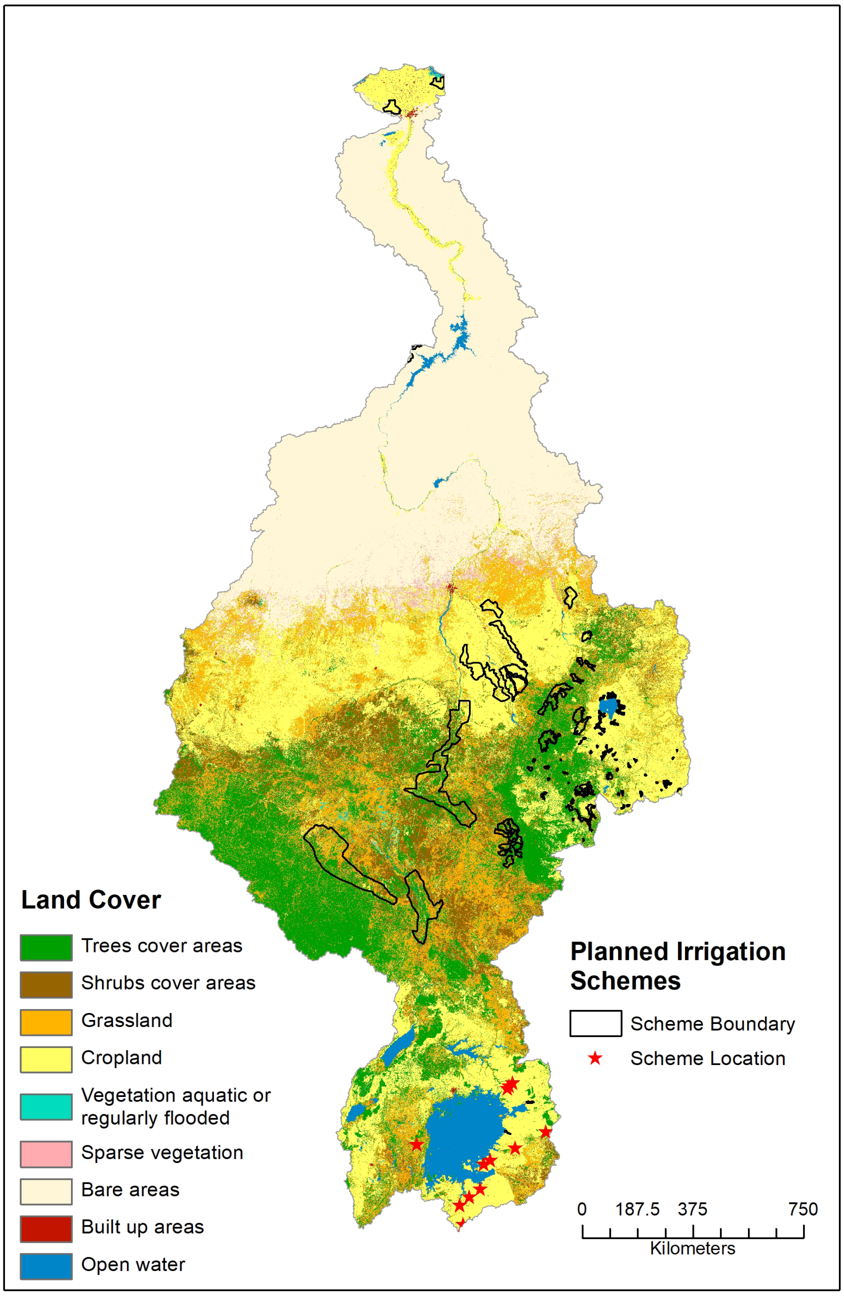


Table 21 shows the distribution of planned schemes based on the extent of suitable land within the proposed schemes. The area was estimated by considering high, moderate and marginally suitable areas (S1, S2 and S3) as suitable land, and currently and permanently not suitable areas (N1 and N2) as unsuitable areas. Results showed that 36.6% of the planned schemes have more than 90% of the current agricultural land suitable for irrigation. However, in 30.6% of the schemes, much of the land (>50%) is not suitable for irrigation. The data also show that eight schemes are planned completely in nonagricultural areas (based on the available land cover maps).

Table 21: Number of schemes and percentage of area suitable for irrigation

Suitable area %	Number of schemes	Percentage of schemes
<50	41	30.6%
50 to 70	19	14.2%
70 to 90	17	12.7%
>90	49	36.6%
Nonagricultural	8	6.0%
Total number of schemes	134	100.0%

Table 22 shows the number of planned schemes in each land suitability class. Most schemes include multiple land suitability class. The schemes were categorized based on the dominant land suitability class within the proposed boundary. Each scheme was assigned the suitability class occupying more than 50% of the current cropland extent within the proposed scheme.

Table 22: Number of planed irrigation schemes in each land suitability category

Dominant land suitability category (> 50% agricultural area)	Number of schemes
Highly suitable	4
Moderately suitable	36
Marginally suitable	16
Currently not suitable	0
Permanently not suitable	13
Schemes with no suitability class occupying more than 50%	57
Nonagricultural	8
Total number of schemes	134

Similar to the area statistics (Table 18), the moderately suitable areas have higher number of planned schemes. It may also be noted that the dominant suitability class was not determined for almost 39% the schemes, because none of the categories occupy more than 50% of the current croplands within the schemes.

The land suitability status of the planned irrigation schemes indicates that most of the future irrigation development is targeted in areas with moderate land suitability for irrigation. Since the study hasn't explored the suitability status of the existing schemes, it would be hard to reach a conclusion about the relatively less inclusion of highly suitable areas in the future plans. Another important aspect of the planned schemes is; that large areas of the future irrigation schemes are planned in areas which are currently not agriculture lands. This study hasn't assessed the land suitability of the nonagricultural areas.

3.3 Land suitability data as a baseline for further assessments

This study focused on assessing the land suitability for irrigation at the basin scale, and classified the basin on a suitability scale ranging from permanently not suitable to highly suitable areas. The assessment was carried out using terrain information and soil physico-chemical properties, but without considering water availability and socioeconomic viability. The results of this study can be overlaid with other information such as infrastructure, water resource availability and socioeconomic indicators when assessing irrigation potential.

The results of this study will be useful to (i) identify land suitable for irrigation, provided water can be supplied (ii) eliminate land that is permanently not suitable for reasons other than the water supply, and (iii) support project development even at a stage when the water availability and the economic and technological viability of water transportation is uncertain.

However, to meet the requirements of subsequent steps such as feasibility studies of specific projects and actual design and implementation, it is required to progressively refine the classification by assessing the water availability for irrigation and the economic viability of water supply.

There are not many studies in the past that have provided the land suitability of the Nile Basin as a separate classification. This study can form a baseline data set for future estimates of irrigation potential. The terrain and soil characteristics are much more stable compared to other factors influencing irrigation potential of an area, and the results of this study can be a basis for future updates in the event of major shifts in water availability, climate or economic conditions, which are more susceptible to change.

3.4 Limitations of the study

The main data inputs to the study were a DEM, map of soil properties and a cropland layer derived from two data sources. The uncertainty associated with the input data and the processing steps, including factor weights and class limits, have had impacts on the output of the suitability map. Some of the limitations of the study are described in this section.

The assessment was done on the agricultural areas defined using the GFSAD30AFCE and ESA CCI S2 land cover maps (Xiong et al. 2017; ESA-CCI 2017). The GFSAD30AFCE cropland map has a producer's accuracy of 85.9% and user's accuracy of 68.5% for the cropland class for entire Africa. The accuracy of ESA-CCI layer was not available at the time of this analysis. As explained earlier, the maps were combined to ensure maximum areas of croplands are included in the analysis. The accuracy of the spatial extent of the analysis is, therefore, dependent upon the accuracy of these maps. Improving the accuracy of the cropland area map will provide a better estimation of available areas for irrigation development.

The scope of the current study is to produce a land suitability data set, which can be used as an input to basin level planning. The resolution of the input data sets is appropriate for basin level assessments and identification of potential regions for irrigation development. While the terrain and land cover data are of 30 m resolution, the soil data used in the study have a resolution of 1 km^2. The final output has a pixel resolution of 30 m, which retains the terrain and land cover information at that scale. However, the soil suitability information is based on the input of the soil map. Either soil data sets, with resolutions comparable to high resolution land use or terrain data sets would not be readily available for most part of the developing world. However, the resolution is suitable for the defined scope of the study. The data would have limitations in supporting actual planning and design of irrigation schemes or precision farming systems. Detailed site level surveys required for project planning and design are often carried out after the implementation decision is made.

Another limitation is in defining the limits between the various suitability categories. The precise definition of a class limit between 'Suitable' and 'Not Suitable' may be subjective. The boundary of Class N2, Permanently Not Suitable, is normally physical and permanent. In contrast, the boundary between the two orders, Suitable and Not Suitable (i.e., between S3 and N1) is likely to be variable over time through changes in the economic and social context (FAO 1997).

4. CONCLUSIONS

This study provides an important update on the previous studies on land suitability for irrigation in the Nile Basin, utilizing the improvements in spatial data on environmental variables. It focuses on the physical factors of land and do not consider the water availability and economic costs. The results are presented in a suitability scale proposed in the FAO framework for land suitability evaluation.

The area estimations from the study are different from the results of past evaluations. These differences are due to differences in various stages of the analysis, such as the definition of land suitability, the class determining factors selected for the analysis, method of data integration, spatial resolution and quality of the data, etc. The resolution of the map is suitable for basin level assessments and identification of priority regions, whereas actual project design and implementation would require site level surveys, which usually happen after the implementation decisions are made.

The land suitability map developed in this study can provide valuable information to identify potential areas with high to moderate suitability and eliminate land that is permanently not suitable for reasons other than the availability of water. This land suitability data set forms a basis for successive stages of evaluation of water availability and economic conditions. This is particularly needed in feasibility studies for irrigation schemes where various aspects of water availability and economic feasibility need to be assessed in detail. Such an analysis would include an evaluation of seasonal water availability, crop water demand, water source and sustainability as well as access to markets and population density. Since land suitability is a relatively stable condition, this data provide a basis for future assessments in the scenario of major shifts in water availability, climatic conditions, technology or economic situations.

The successive refinements using additional criteria would eliminate marginal areas and further reduce the land area identified in this study. It may be noted that, in the FAO (1997) analysis, the land area suitable for irrigation was reduced from 92 million ha to 8 million ha (8.69%) after assessing the water resources and irrigation water requirements. This indicates the necessity to progressively refine the assessments as the planning process progress towards implementation.

5. REFERENCES

Altchenko, Y.; Villholth, K. G. 2015. Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. *Hydrology and Earth System Sciences* 19(2), 1055–1067.

Akinci, H.; Ozalp, A.Y.; Turgut, B. 2013. Agricultural land use suitability analysis using GIS and AHP technique. *Computers and Electronics in Agriculture* 97, 71-82.

Droogers, P.; Nkurunziza, P.; Bastiaanssen, W.; Immerzeel, W.; Terink, W.; Hunink, J.; Meijninger, W.; Hellegers, P.; Chevalking, S.; Steenbergen, F.; Brandsma, J. 2012. *Assessment of the irrigation potential in Burundi, Eastern DRC, Kenya, Rwanda, Southern Sudan, Tanzania and Uganda*. (Irrigation main report). Entebbe, Uganda: Nile Basin Initiative.

ESA-CCI (European Space Agency-Climate Change Initiative). 2017. S2 prototype land cover 20m map of Africa 2016 [Data set]. ESA Climate Change Initiative - Land Cover Project 2017. (as on December 2018).

FAO (Food and Agriculture Organization of the United Nations). 1976. *A framework for land evaluation*. FAO soils bulletin 32. Rome, Italy. Land and water division, Food and Agriculture Organization of the United Nations (FAO).

FAO. 1985. *Guidelines: Land evaluation for irrigated agriculture*. FAO soils bulletin 55. Rome, Italy. Land and water division, Food and Agriculture Organization of the United Nations (FAO).

FAO. 1997. *Irrigation potential in Africa: A basin approach*. FAO land and water bulletin 4. Rome, Italy. Land and water division, Food and Agriculture Organization of the United Nations (FAO).

FAO. 2002. *Irrigation Manual: Planning, development, monitoring and evaluation, of irrigated agriculture with farmer participation*. Harare, Zimbabwe. FAO-SAFR.

FAO. 2005. *Irrigation in Africa in figures: AQUASTAT survey – 2005*. FAO Water Reports 29. FAO Land and water division, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

FAO. 2016. AQUASTAT website. URL: http://www.fao.org/nr/water/aquastat/irrigationmap/glossary.pdf Rome, Italy. Food and Agriculture Organization of the United Nations (FAO) (accessed on May 10, 2019).

FAO/IIASA/ISRIC/ISS-CAS/JRC (Food and Agriculture Organization of the United Nations, International Institute for Applied Systems Analysis, International Soil Reference and Information Centre, Institute of Soil Science-Chinese Academy of Sciences, Joint Research Centre). 2012. Harmonized World Soil Database (version 1.2). Rome, Italy, FAO and IIASA, Laxenburg, Austria.

GIRDC (Generation Integrated Rural Development Consultant). 2018. Assessment of national water use and demand forecast. Addis Ababa, Ethiopia. Ministry of Water, Irrigation and Electricity, Federal Democratic Republic of Ethiopia.

Hammam, A.A.; Mohamed E S. 2018. Mapping soil salinity in the East Nile Delta using several methodological approaches of salinity assessment. *The Egyptian Journal of Remote Sensing and Space Science* https://doi.org/10.1016/j.ejrs.2018.11.002.

Hengl, T.; Heuvelink, G.B.M.; Kempen B.; Leenaars, J.G.B.; Walsh, M.G.; Shepherd, K. D.; Sila, A.; MacMillan, R. A.; Jesus, J.M.; Tamene, L.; Tondoh, J.E. 2015. Mapping soil properties of Africa at 250m resolution: Random forests significantly improve current predictions. *PLOS One*. https://doi.org/10.1371/journal.pone.0125814.

Kebede, T.; Ademe, Y. 2016. Evaluating land suitability for irrigation purpose in Abaya district, Borena zone, Ethiopia. *African Journal of Agricultural Research* 11, 4754-4761.

NASA-JPL (National Aeronautics and Space Adminstration-Jet Propulsion Laboratory). 2013. NASA Shuttle Radar Topography Mission Global 1 arc second [Data set]. NASA EOSDIS Land Processes DAAC. doi: 10.5067/MEaSUREs/SRTM/SRTMGL1.003.

Saaty, T.L. 1977. A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology* 15, 57–68.

Worqlul, A.W.; Collick, A. S.; Rossiter, D. G.; Langan, S.; Steenhuis, T. S. 2015. Assessment of surface water irrigation potential in the Ethiopian highlands: The Lake Tana Basin. *Catena* 129, 76-85.

Worqlul, A.W.; Jeong, J.; Dile, Y.T.; Osorio, J.; Schmitter, P.; Gerik, T.; Srinivasan, R.; Clark, N. 2017. Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. *Applied Geography* 85, 1-13.

Xie, H.; You, L.; Wielgosz, B.; Ringler, C. 2014. Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. *Agricultural Water Management* 131, 183–193.

Xiong, J.; Thenkabail, P.S.; Tilton, J.C.; Gumma, M.K.; Teluguntla, P.; Oliphant, A.; Congalton, R.G.; Yadav, K.; Gorelick, N. 2017. Nominal 30-m cropland extent map of continental Africa by integrating pixel-based and object-based algorithms using Sentinel-2 and Landsat-8 data on Google Earth Engine. *Remote Sensing, 9*, 1065. doi:10.3390/rs9101065.

You, L.; Ringler, C.; Wood-Sichra, U.; Robertson, R.; Wood, S.; Zhu, T.; Nelson, G.; Guo, Z.; Sun, Y. 2011. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy* 36, 770–782.

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