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Irrigation suitability mapping examples from Zimbabwe, Zambia, Malawi and Kenya

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The CGIAR Initiative on Diversification in East and Southern Africa aims to help smallholders transition to sustainably intensified, diversified, and derisked agri-food systems based on maize in 12 ESA countries. Specifically, it seeks to enable 50,000 value chain actors, including farmers (at least 40% women, 40% youth), to adopt climate-smart maize based intensification and diversification practices and one million to access digital agro-advisory services. Emphasizing the role of the private sector in driving such transformation, UU targets to support at least 30 start-ups and SMEs.

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Executive Summary

This report forms Part 1 of a two-phased project of the CGIAR initiative called Ukama Ustawi (UU) on Diversification of East and Southern Africa. It describes provides an integrated geospatial and multi-criteria decision approach to delineate irrigation suitability areas in selected districts of the UU project countries Zimbabwe, Malawi and Kenya. This current report covers the first phase, Part 1, which Part 1 details the irrigation suitability mapping methodology and Part 2 applies the methodology in other countries in Africa, South America and Asia, assessing the applicability of the methodology in different regions.

The irrigation suitability classification was achieved by using physical factors that include slope, rainfall, landuse, closeness to waterbodies (surface and groundwater) and soil characteristics for selected districts in Zimbabwe, Zambia, Malawi, and Kenya, some of the UU target countries. As cereals form the main food basket of the selected countries, and cereals are not tolerant to saline conditions, the report also provides maps showing high soil salinity areas of Makueni and Nakuru of Kenya, where soils are highly saline (Annexures 11 and 12). However, soil salinity is insignificant in the other study districts and therefore not mapped. However, socio-economic factors were excluded in this instance as they are ideal for indicating optimal areas for immediate implementation of irrigation projects under a set of given priority socio-economic conditions. Selected physical factors for irrigation suitability mapping were classified into four suitability classes (S1, S2, S3, and N) as proposed by the Food and Agricultural Organization (FAO). Irrigation suitability areas were delineated by initially weighting the physical factors through the Analytic Hierarchy Process (AHP), a multi-criteria decision method, and combining the layers using the weighted overlay tool in ArcGIS. This report provides (a) a conceptual framework and detailed methodology for irrigation suitability mapping, including details of identified boundary maps and geospatial data, and (b) a synthesis model and maps on irrigation suitability mapping for the selected districts in the four target countries. The main objectives include to:

1) Identify official boundary maps for the delineation of irrigation suitability areas in selected districts in Zimbabwe, Zambia, Malawi, and Kenya
2) Identify the factors required in delineating irrigation suitability areas
3) Classify and map irrigation suitability areas in the selected districts according to each suitability class
4) Assess the difference in irrigation suitability classes in each district of the study countries

Irrigated agriculture not only increases crop productivity but also augments efficient water management, enhances the resilience of communities to climate change and promotes rural development. In response to the African Union's (AU) investment drive aimed at improving water management for agricultural transformation in the continent by operationalising the Irrigation Development and Agricultural Water Management (IDAWM) strategy, this study applied an integrated Geographic Information System (GIS) based and multi-criteria decision-making procedure to delineate irrigation suitability areas. The aim was to develop evidence for policy and decision-makers to formulate strategic policies on irrigation development and expansion as current processes in irrigation suitability mapping, as well as information on irrigated area spatial distribution and extent, are varied and generally developed at coarse global spatial scales. Accurate statistics on irrigation suitability. spatial distribution and extent are prerequisites

for coherent and strategic policies on irrigation development and expansion. They are critical for designing and implementing worthwhile irrigation projects. Also, there has been no consensus on the factors to consider in irrigation suitability mapping, physical, socio-economic factors, or combining both. Apart from providing information on the spatial distribution and extent of irrigation suitability areas and support policies on irrigation development and expansion decisions, the study also highlights the factors required to delineate irrigation suitability areas.

The study, therefore, used physical factors as input layers and adopted a geospatial and multi-criteria decision method approach to delineate irrigation suitability areas of the UU Project target countries. Irrigation suitability maps at the district level were developed and classified according to the FAO classification (S1, S2, S3, and N), respectively. The approach distinguished biophysical and socio-economic factors as the two sets of factors contribute differently to land suitability mapping. Physical factors identify areas suitable for irrigation in space and time. Yet socioeconomic factors guide policy to identify optimal irrigation suitability areas to initiate irrigation projects under a set of given socioeconomic conditions. The distinction between physical and socioeconomic factors has improved irrigation suitability mapping as previous studies combined both factors for general irrigation suitability mapping, thereby eliminating other suitability areas. The approach is applicable at any spatial scale; however, the availability of datasets at an acceptable spatial resolution remains a major challenge. The essence of irrigation suitability mapping is its support for policy and decision-making on strategic and sustainable irrigation planning and development. The adopted approach and the results are essential for designing and initiating new irrigation projects by providing policy with a technique that can reliably inform future irrigation development.

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List of Acronyms

AHP	Analytic Hierarchy Process
AU	African Union
BGS	British Geological Survey
CAADP	Comprehensive African Agriculture Development Program
CR	Consistency Ratio
DEM	Digital Elevation Model
ELECTRE	Elimination and Choice Expressing the Reality
FAO	Food and Agricultural Organization
GDP	Gross Domestic Product
GIS	Geographic Information System
IDAWM	Framework for Irrigation Development and Agricultural Water Management
IWMI	International Water Management Institute
MAUT	Multi-Attribute Utility Theory
Mbgl	metres below ground level
MCDM	Multi-criteria Decision Method
N	Not suitable
NEPAD	New Partnership for Africa's Development
NIP	National Investment Plans
PCM	pairwise comparison matrix
PROMETHEE	Preference Ranking Organization Method for Enrichment Of Evaluations
RECs	Regional Economic Communities
S1	Highly suitable
S2	Moderately suitable
S3	Marginally suitable
SAW	Simple Additive Weighting
SDGs	Sustainable Development Goals
SOP	Strategic and Operational Plan
SOTER	Soil and Terrain Digital Database
SRTM	Shuttle Radar Topography Mission
SSA	sub-Saharan Africa
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UNGA	United Nations General Assembly
UU	Ukama-Ustawi

Chapter 1: Background and Introduction

Land is an important resource that determines the wealth of countries as its management promotes resource security and sustainable development (Lambin and Meyfroidt, 2011; Nhamo et al., 2022). Land quality is often defined by agricultural development and how it contributes to food and water security (Viana et al., 2022). In this context, accurate information on irrigation and agricultural production play a pivotal role in formulating agricultural and rural development policies (Nhamo et al., 2022; Pawlak and Kołodziejczak, 2020). However, the pressure on land resources continues to mount due to population increase, degradation, and climate change (Barbier and Hochard, 2018). As land is a key resource, its allocation and distribution are generally influenced by the need to meet socio-economic and food security needs (Nhamo et al., 2022). The close interlinkages between socio-economic development, available natural resources and the policies that guide the use of these resources are, therefore, quite evident in land planning (Gebre and Gebremedhin, 2019; Sinding, 2009). The increasing pressure on land resources from the growing population and the competition emanating from different land uses requires integrated, efficient and sustainable land use and management practices (Calicioglu et al., 2019). Sustainable land management is a guarantor of resource security for both the present and future generations, yet current unsustainable land management practices lead to irreversible consequences (Lampert, 2019). The recognition of land degradation amidst the increasing population and climate change, among other challenges, contributed to the formulation of the 2030 Sustainable Development Goals (SDGs) by the United Nations General Assembly (UNGA) in 2015 (UNGA, 2015).

There are, therefore, broad interlinkages between land, agricultural development, water-use efficiency and food security (Viana et al., 2022). Thus, efficient agricultural water management is key to improving crop-water productivity, providing pathways towards the water and food security and enhancing climate change resilience (Hafeez et al., 2022; Hatfield and Dold, 2019; Iglesias and Garrote, 2015; Nhemachena et al., 2020). On the other hand, a sustainable agricultural system promotes rural and economic development and catalyses environmental and human health (Nhamo et al., 2022; Vågsholm et al., 2020). However, sustainable agriculture has been evasive, particularly in developing countries where most farmers still depend on rainfall for crop production, practising traditional methods of agriculture that are generally environmentally unsustainable (Ahsan et al., 2021; Nhemachena et al., 2020). The challenges are compounded by the observed late onset of rains, resulting in shortened growing seasons, prolonged intra-seasonal drought spells, and higher-intensity rains that cause floods (Mpandeli et al., 2019; Nhemachena et al., 2020). Without adaptation strategies, farmers have been experiencing reduced quantity and quality of crop yields, crop damage, and even loss of entire harvests and livestock mortality (Nhamo et al., 2019b; Raza et al., 2019; Serote et al., 2021). With the increasing demand for water and food resources, agro-food systems need to produce more with less water and meet the rising food demand (Uhlenbrook et al., 2022).

Irrigation has been identified as key to increasing crop productivity, promoting water use efficiency and catalysing agricultural sustainability and economic development (Uhlenbrook et al., 2022). In Africa, where the economies of most countries' Gross Domestic Product (GDP) are reliant on agriculture, the calls are even more pronounced (AU, 2014). Moreover, irrigation is an indispensable climate change adaptation strategy, particularly for smallholder farmers who contribute over 90% of the agricultural produce in sub-Saharan Africa (SSA) (Magidi et al., 2021a; Mango et al., 2018). Based on these challenges and the need to boost African economies, the African Union (AU) and regional economic blocs have

prioritised increasing the area under irrigation to promote the resilience and sustainability of agriculture (AU, 2014; NEPAD, 2003).

The transitioning of the agriculture sector from a rainfed-based system to an irrigated-oriented one has witnessed a shift in national, regional and continental developmental goals in the African continent towards increased investment in irrigation projects (Nhemachena et al., 2020). National and regional irrigation strategies have been informed by continental and international policy frameworks such as the African Union (AU) Agenda 2063 and the United Nations' 2030 SGDs, which emphasise reducing unemployment, hunger and poverty by investing in agriculture (AU, 2015; UNGA, 2015). Based on these frameworks, the AU, through the 2014 Malabo Declaration, defined the immediate growth of African economies around agricultural growth and transformation (AU, 2014). This was followed by a series of other frameworks and declarations that promote the adoption of sustainable irrigation and agricultural water management as well as the widespread and rapid expansion of irrigation, particularly among smallholder farmers, including the Strategic and Operational Plan, 2014-2017, Fostering the African Agenda on Agricultural Growth and Transformation and Sound Environmental Management, AU/DREA January 2014) and Regional Economic Communities (RECs: IGAD, ECOWAS, among others), in National Investment Plans (NIP) and National Agricultural Investment Plans (NAIP). These augment the high level of political and strategic will on agriculture as expressed in the Comprehensive African Agriculture Development Program (CAADP) of the New Partnership for Africa's Development (NEPAD) (NEPAD, 2003). Pillar 1 of the CAADP focuses on land and water management, with irrigation as one main sector that is well highlighted. The AU's Framework for Irrigation Development and Agricultural Water Management (IDAWM) was conceived against the backdrop of increasing climatic shocks with associated negative agricultural production impacts and reduced livelihoods capacities of rainfed agriculture in the African continent (AU, 2020).

In response to the AU's investment drive to improve water management for agricultural transformation in the continent by operationalising the IDAWM strategy, this study applied an integrated Geographic Information System (GIS) based and multi-criteria decision-making procedure to delineate irrigation suitability areas. Irrigation suitability mapping assesses irrigation performance when used to produce crops (Jahanshiri et al., 2020). It refers to the fitness of a given type of land for irrigation purposes (FAO, 1976). It is a prerequisite to optimum utilisation of the available land resources for sustainable agriculture production through irrigation (FAO, 1976; Hagos et al., 2022). Therefore, irrigation suitability mapping is useful for identifying irrigable and non-irrigable lands and for strategic policy formulation on irrigation development. It is essential for landuse planning according to its agricultural potential and is required for conserving natural resources to meet the needs of future generations (Jahanshiri et al., 2020).

The main aim of the exercise was to enhance the intensification and diversification of cropping systems in the study areas, target highly suitable areas for irrigation, and guide policy decisions on irrigation development and expansion. This was possible by providing more accurate information on irrigated area distribution and extent, as current information is varied and generally developed at coarse global spatial scales (Cai et al., 2017; Magidi et al., 2021a; Massari et al., 2021). Accurate spatial statistics on irrigation suitability, spatial distribution and extent are prerequisites for coherent and strategic policies on irrigation development and expansion. They are critical for designing and implementing worthwhile irrigation projects. Also, there has been no consensus on the factors to consider in irrigation suitability mapping, physical, socio-economic factors, or combining both. Current studies on irrigation suitability classification use different factors that generally combine both physical and economic factors (Hagos et al., 2022;

Mandal et al., 2018; Worqlul et al., 2017). Apart from providing information on the spatial distribution and extent of irrigation suitability areas and support policies on irrigation development and expansion decisions, the study also highlights the factors required to delineate irrigation suitability areas.

Chapter 2: Methods and Approaches

2.1 Description of the study areas

The study was conducted in five districts of four southern and eastern African countries selected based on different climatic and agro-ecological zones, forming the Ukama Ustawi (UU) Project target countries. The selection was informed by assessing the irrigation suitability methodology, which is replicable, in different regions and evaluating the output maps. The selected districts are in Kenya, Malawi, Zambia and Zimbabwe (Fig. 1), some of the UU target countries. The target countries form part of assessing the status and suitability of both crops and livestock options, including a needs assessment for mechanization and irrigation targeted towards the agribusiness environment.

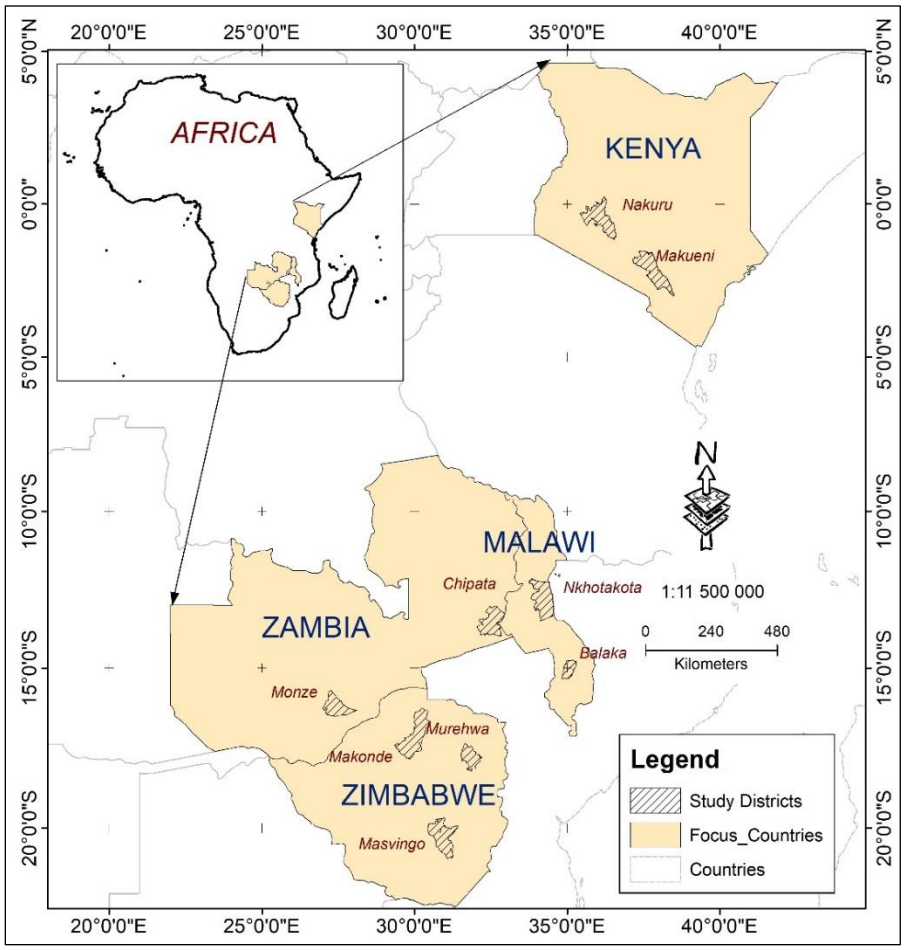

Fig. 1. Location of the study districts

2.2. Methodological framework

Fig. 2 represents the overall modelling flowchart developed for irrigation suitability mapping. The flowchart comprises five steps (Fig. 2). Step 1 includes the selection of the variables needed in irrigation suitability mapping and input data preparation. The input data and preparation included the digital elevation model (DEM), soil data, surface water and landuse/cover datasets. Step 2 consists of selecting of the criteria from the variables and data cleaning and pre-processing. Step 3 involves reclassifying

criteria layers and assigning suitability classes (S1, S2, S3, and N). Step 4 involves applying the Analytic Hierarchy Process (AHP) in a multi-criteria decision method (MCDM). This step includes the application of the pairwise comparison matrix (PCM) and the weighting of the criteria as each criterion is given a unique weight as the influence of each criterion on irrigation suitability mapping is different from the others. Lastly, Step 4 includes integrating the MCDM with GIS with the ultimate output of an irrigation suitability map. Each step is further explained in detail in subsequent sections.

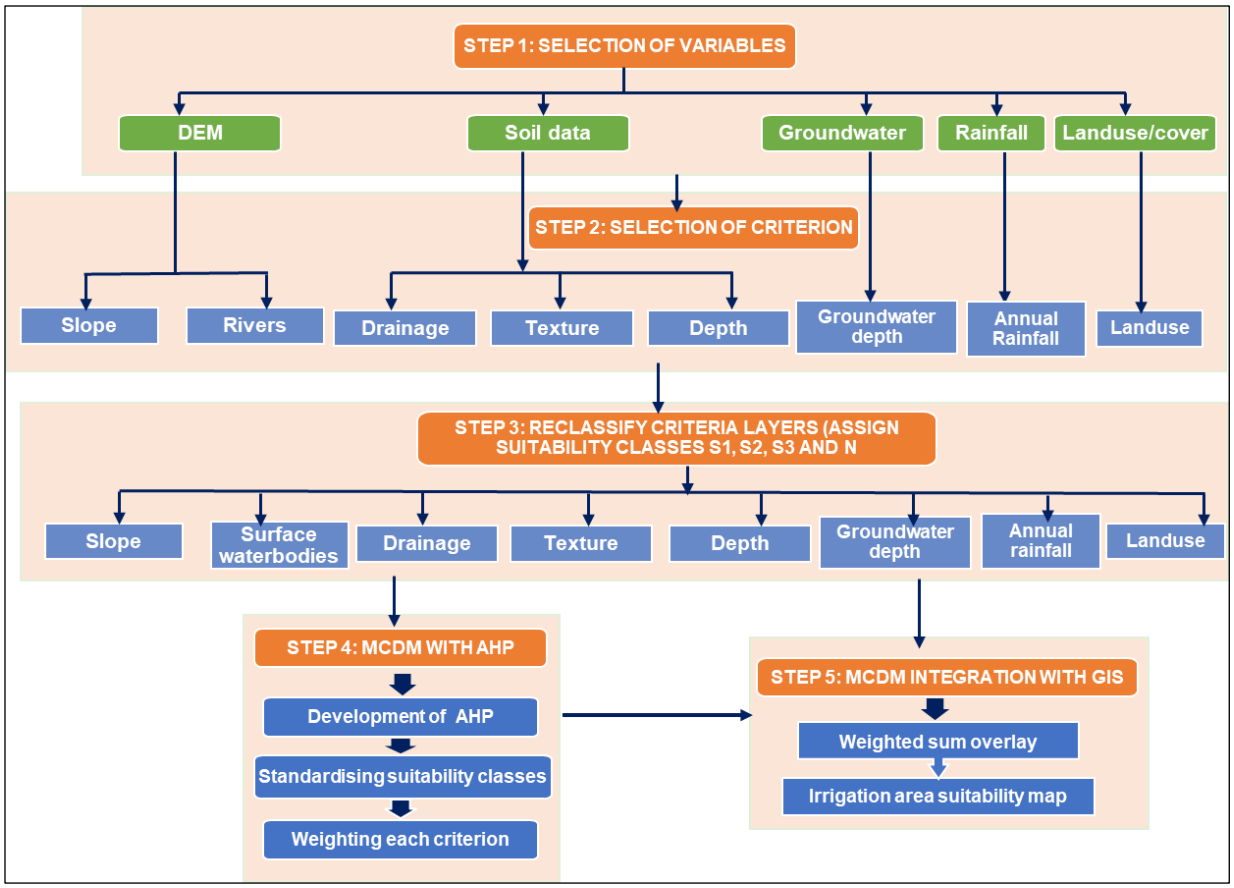

Fig. 2. Overall conceptual flowchart to delineate areas suitable for irrigation

2.3. Criteria/factors for irrigated areas suitability mapping

The irrigation suitability areas were processed in ArcGIS Spatial Analyst's Weighted Overlay tool, which is based on Multi-Criteria Decision Method (MCDM) method. The main factors were developed, classified and weighted to determine irrigation suitability areas using the Analytic Hierarchy Process (AHP). The weights for each factor were determined through the pairwise comparison matrix PCM of the AHP (Hagos et al., 2022; Saaty, 1977; Worqlul et al., 2017). As the criteria or layers (as known in GIS) are not equal in importance, they are compared or differentiated from each other through weights. The weights were determined through expert opinion and literature search and are ranked according to their importance to irrigation suitability delineation applying the PCM. The weights are then used as input data to the layers in ArcGIS using Saaty's AHP pairwise comparisons scale (Saaty, 1987; Saaty, 1977).

The irrigation suitability criteria (also known as factors) include slope, rainfall, soil texture, soil drainage, soil depth, closeness to a water source (both surface and groundwater), and land use/land cover (Hagos et al., 2022; USDIBR, 2005). These biophysical factors are key in delineating irrigation suitability areas in a given landscape (García-Llorente et al., 2015; USDIBR, 2005). Socioeconomic factors including population density, proximity to markets and roads are excluded at this stage as they are useful for identifying optimal irrigation areas for immediate implementation of irrigation projects under a set of prioritised socio-economic factors (Elliott et al., 2014; USDIBR, 2005). Economic factors are applied to already identified irrigation suitability areas. Population density, closeness to markets, transport networks, or other socio-economic factors do not influence whether an area is suitable for irrigation but are applicable for identifying optimal areas for immediate implementation of irrigation projects under a set of preferential economic factors (Baker and Capel, 2011; Elliott et al., 2014; USDIBR, 2005). Therefore, socio-economic factors are only essential during the second phase, informing policy and decision-makers on optimal areas for immediate irrigation development but do not determine an area's suitability for irrigation (Elliott et al., 2014; Rossiter, 1996; USDIBR, 2005).

2.3.1. Edaphic factors

Soils are a prerequisite for the success of agriculture and irrigation development as they have always influenced human civilisation (Brodt et al., 2011; USDIBR, 2005). The soil characteristics (Fig. 3) considered in delineating irrigation suitability areas include texture, drainage and depth (USDIBR, 2005).

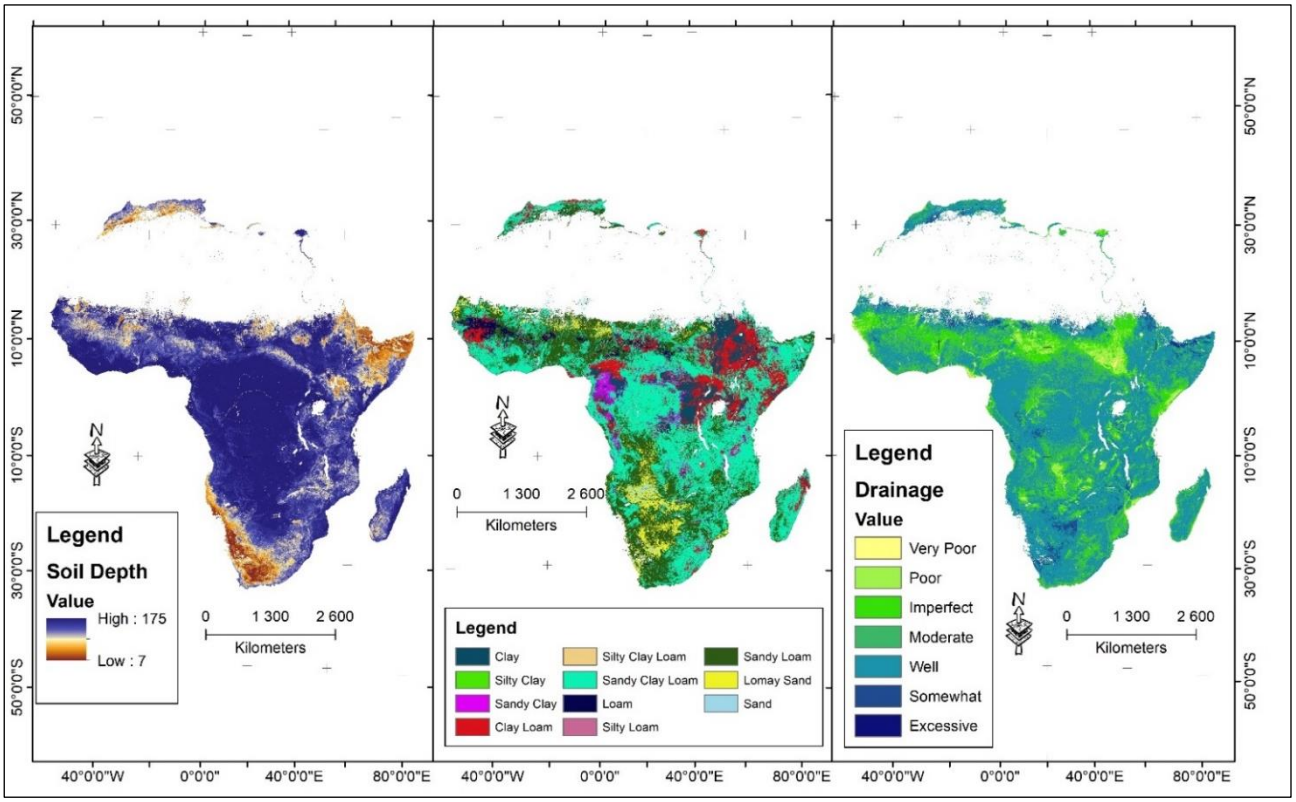

Fig. 3. Soil characteristics (depth, texture, and drainage) of Africa

Soil depth is important for anchoring plant nutrients and promoting plant growth (Galindo-Castañeda et al., 2022). Soil texture is vital in irrigation by determining the rate at which water drains through and

regulating erosion. Water generally moves more freely through sandy soils than clayey soils (Bhattacharya et al., 2021; FAO, 1976; Sarwar et al., 2021). Soil texture also influences the quantity of water available to the plant and the period it stays in the soil (Schoonover and Crim, 2015). Clay soils have greater water-holding capacity than sandy soils (Leenaars et al., 2018; Schoonover and Crim, 2015). On the other hand, drainage ensures that the soil is properly aerated, a condition that favours root growth and is conducive to a healthy crop (FAO, 1976).

Other factors that relate to soil properties like pH and soil salinity, among other properties, are excluded in a general irrigation suitability mapping as some crops do well with high pH values whilst others favour low values (Neina, 2019). The same with salinity, some crops do well under saline conditions, while others do not survive (Egamberdieva et al., 2019). These soil properties are applicable when assessing optimal areas for cultivating specific crops, as crop growth conditions vary from crop to crop. However, as cereals form the main food basket of the selected countries, and cereals are not adapted to high-saline conditions, this report provide maps that show high saline areas of the study districts. High saline areas should be excluded from irrigation suitability areas of cereals but should be included in a general irrigation suitability mapping.

2.3.2. Topographic factors

Slope is the only topographic factor with significant influence on irrigation suitability mapping as it has a bearing on the method of irrigation, erosion susceptibility and control, land development, soil tillage, irrigation systems design, drainage requirements, crop management and production costs (USDIBR, 2005). Slope in percentage was derived from the 30 m resolution Digital Elevation Model (DEM) dataset from the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (SRTM), which is available at https://lpdaac.usgs.gov/products/ast14demv003/) (Fig 4).

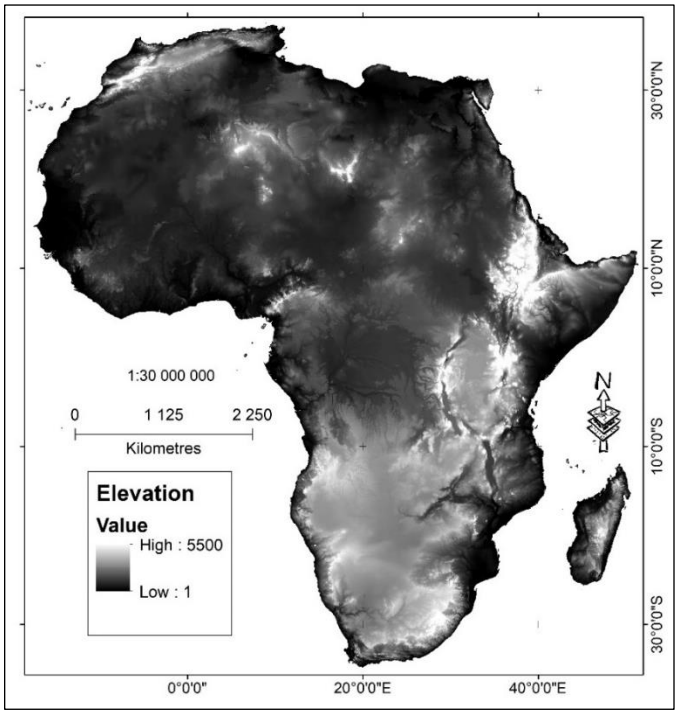

Fig. 4. Elevation map of Africa

2.3.3. Hydrologic factors

Proximity to water sources (both surface and groundwater) is key in irrigation suitability mapping and is weighted highly as it provides moisture to crops (Paul et al., 2020). For surface water, the Euclidean distance was used to determine the irrigation suitability from perennial rivers. In terms of groundwater availability, the groundwater depth (metres below ground level – mbgl) (Fig. 5) dataset obtained from the British Geological Survey (BGS) was used to assess the potentially irrigable land using groundwater (MacDonald et al., 2012). Although groundwater could be more expensive to extract as compared to surface water, it has become a major source of water, not only for irrigation but also for other uses, including urban water supply and industrial use in many countries as surface waterbodies have become depleted and degraded due to population increase, pollution and climate change (Nhamo et al., 2020a; Siebert et al., 2015).

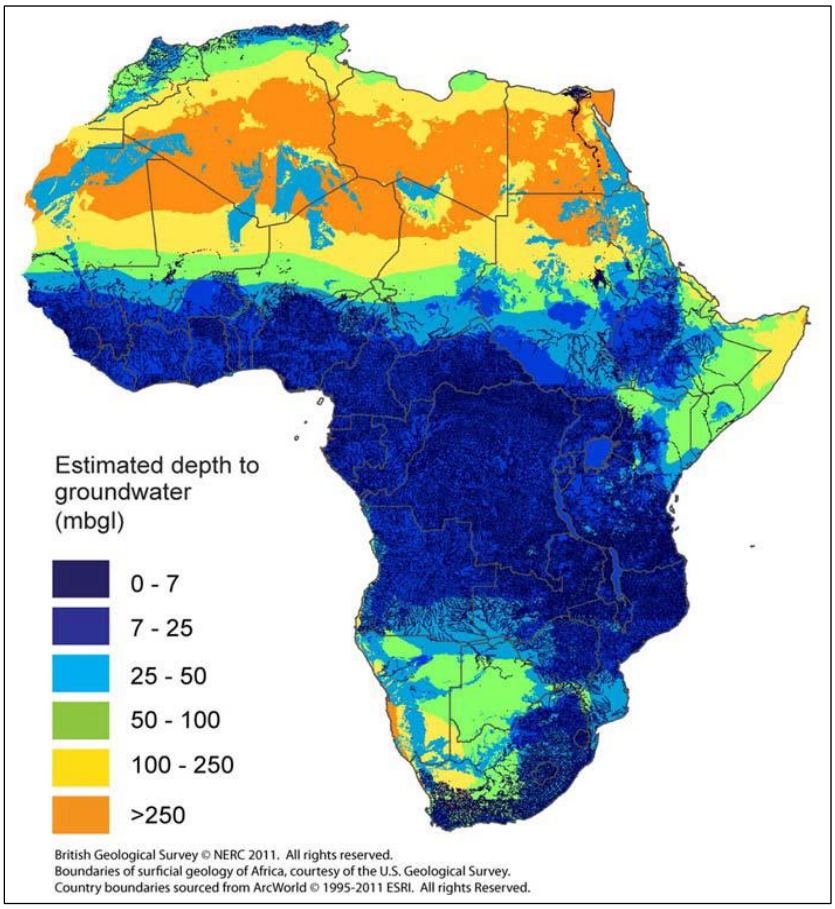

Fig. 5. Groundwater depth (metres below ground level – mbgl)

2.3.4. Landuse/cover

The landuse/cover criterion is also important in irrigation suitability mapping. It eliminates unsuitable areas, such as built-up areas and nature and game reserves, while optimising the most suitable areas, like cultivated lands. The landuse layer (Fig. 5) was generated using a combination of machine learning and other image processing algorithms using the most recently acquired satellite Sentinel images (Magidi et

al., 2021a). The land use classes used to map the landuses include cultivated areas, grassland, shrubland, forest land and built-up areas. The classes were divided into four suitability categories (S1, S2, S3, and N).

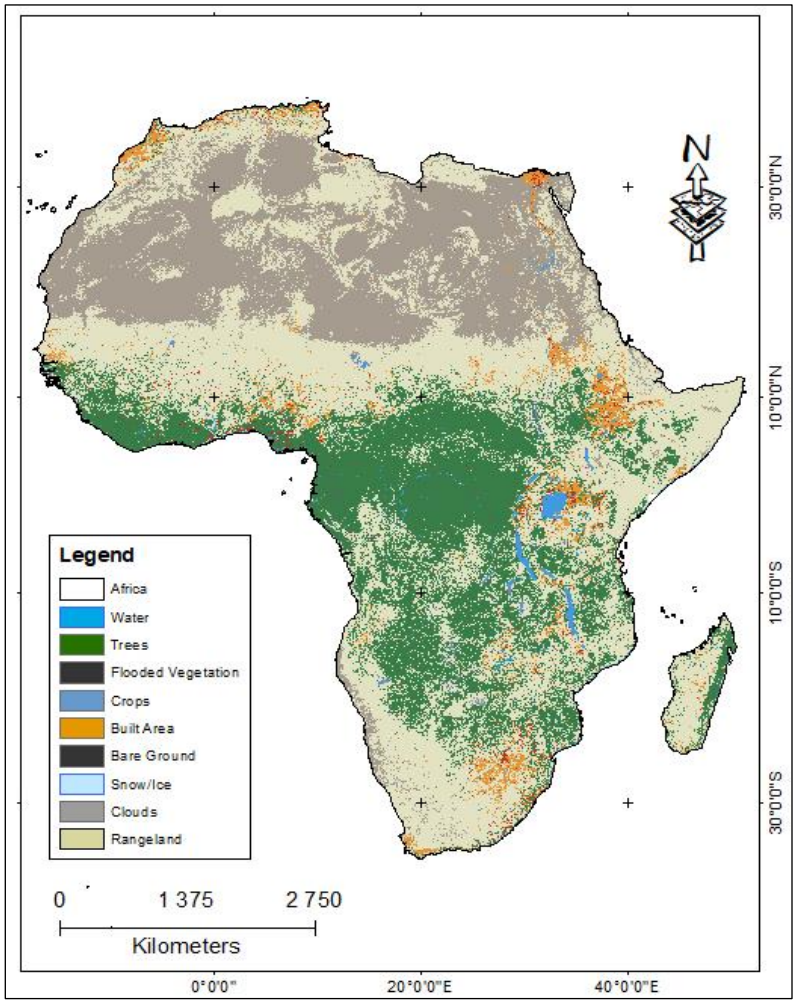

Fig. 6. Land use/cover map of Africa

2.3.5. Climatic factors

From a climate perspective, rainfall plays an important role in irrigation suitability mapping as it contributes to water recharge for both surface and groundwater sources (Worqlul et al., 2017). Generally, where average annual rainfall is low, the water table is found to be too deep to the extent that it becomes very difficult and expensive to abstract (Sorensen et al., 2021) (MacDonald et al., 2012). However, rainfall is critical for recharging water sources for irrigation, and it can be harvested for irrigation purposes during intra-seasonal dry periods (Scanlon et al., 2012; Siebert et al., 2015). Nevertheless, as irrigation is provided when there are moisture deficiencies or during dry periods or seasons, rainfall is weighted the lowest of all the factors. Fig. 7 is a map of rainfall distribution in Africa.

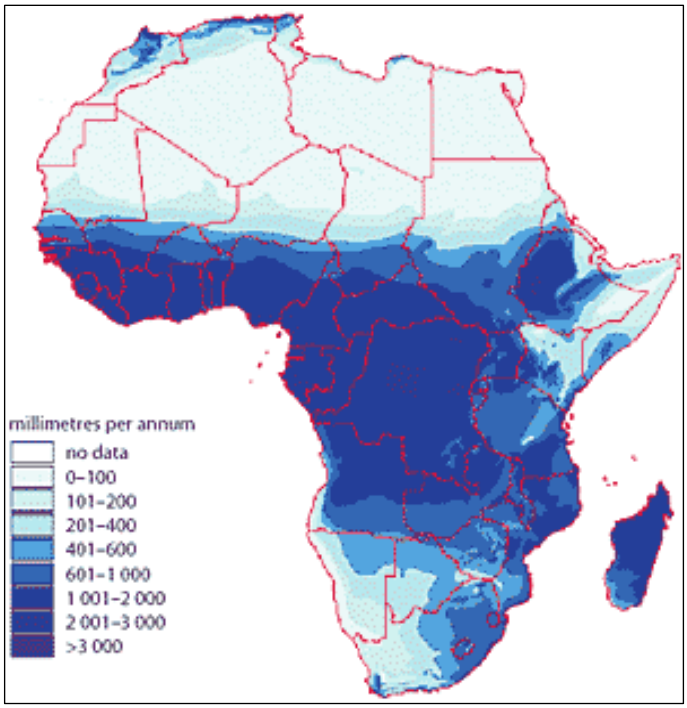

Fig. 7. Rainfall distribution in Africa.

2.4. Data sources, collection and processing

The fundamental task to achieve the objective is to access and prepare the various datasets needed for input and resample them to a uniform spatial resolution (Table 1). The datasets were obtained from the Soil and Terrain (SOTER) Digital Database (for soil factors), the British Geological Survey (BGS) (from where the groundwater depth in mbgl was downloaded), ASTER GDEM (from where slope in degrees and river systems where derived), Sentinel (for the classification of landuse/cover layer) and the Food and Agriculture Organisation (FAO) (where the rainfall dataset was downloaded. Following the collection of data, additional analysis, like the reclassification of layers and their weighting was conducted. The datasets were processed and prepared in ArcGIS.

Table 1. Data sources resolution and derived layers

Data type	Data format	Spatial resolution	Source	Derived layers
Soil map	Vector	1:250 000	AfriSIS	Soil texture, drainage and depth
DEM	Raster	30 m	Aster GDEM	Slope and altitude
Rainfall	Raster	5km	FAO	Annual rainfall
Groundwater	Raster	5km	BGS	Groundwater depth
Landuse/cover	Raster	30 m	Sentinel	Landuse/cover
Surface waterbodies	Vector	1.50 000	FAO	Waterbodies

2.5. Criteria/factor classification for irrigation suitability

The land suitability classes proposed by the Food and Agricultural Organization (FAO) describe four levels of the suitability of a given type of land for specific use (FAO, 1976; Rossiter, 1996). The FAO classes range from highly suitable to not suitable based on the suitability of land characteristics. Land suitability maps are classified into four classes: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N) (Table 2).

Table 2. Land suitability classes

FAO symbol	Suitability class	Description
S1	Highly suitable	Land without significant limitations. This is the best possible land that does not reduce productivity or require increased inputs.
S2	Moderately suitable	Suitable land but has some limitations that either reduce productivity or require an increase of inputs to sustain productivity compared with those needed on S1.
S3	Marginally suitable	Land with severe limitations that benefits are reduced and/or the inputs required to sustain production need to be increased so that this cost is only marginally justified.
N	Not suitable	Land that cannot support the particular land use on a sustained basis or land on which benefits do not justify inputs

Source: Adapted from FAO, 1976

Criteria layers (maps) are then standardised according to the FAO classes (S1, S2, S3, and N), representing the degree of suitability of one attribute class from the other based on the optimal requirements for irrigation suitability. Each class is rated according to how important class S1 is with respect to a particular criterion to contribute to the final goal.

2.6. Categorising the irrigated area suitability mapping factors

Table 3 provides the sub-factors, and the suitability classes assigned to each factor. The factor layers are reclassified in ArcGIS according to the respective ratings and are assigned weights developed through the PCM.

Table 3. Irrigated area suitability mapping factor classifications

Factors	Sub-factor	Factor classifications				Source
		S1	**S2**	**S3**	**N**	
Topographic	Slope (%)	0-2	2-5	5-8	>8	(Mandal et al., 2018)
Climatic	Av. annual rainfall (mm)	>800	600–800	600–400	<400	(FAO, 1976)
Edaphic	Drainage class	Well	Moderately well	Imperfectly	Poor	(Mandal et al., 2018) (Nachtergaele et al., 2010)
	Depth (cm)	>100 (Very deep)	50–100 (Moderately deep)	10–50 (Shallow)	<10 (Very shallow	
	Texture	L–SiCL, C	SiL, SCL, CL	SL	LS, Si–L	
Hydrologic	Groundwater depth (mbgl)	<50	50–75	76–100	>100	(MacDonald et al., 2012)
	Distance from rivers (m)	0—721	721—1442	1442—2163		(Hagos et al., 2022)
Landuse	LU/LC	Cropland	Grassland	Barren & shrub land	Constraints (Forest, built-up, water, wetland)	(Yohannes and Soromessa, 2018)

2.7. Consistency ratio

In applying the AHP method, the weights derived from a PCM should always be consistent at an acceptable ratio. The consistency ratio (CR) indicates the likelihood that the matrix judgments were generated randomly and are consistent (Alonso and Lamata, 2006). CR indicates the amount of allowed inconsistency (0.10 or 10%). Higher CR values indicate that the comparisons are less consistent, while smaller values indicate that comparisons are more consistent. When CRs are above 0.1, the pairwise comparison is inconsistent and should be re-evaluated (Saaty, 1977). The CR is calculated as (Teknomo, 2006):

$$CR = \frac{CI}{RI} \tag{1}$$

where CR is the consistency ratio, CI is the consistency index, and RI is the random index, the average of the resulting consistency index depending on the order of the matrix given by Saaty (Saaty, 1977) (Table 5). CI is calculated as:

$$CI = \gamma - \frac{n}{n-1} \tag{2}$$

where, γ is the maximum Eigen value, and n is the number of criteria or sub-criteria in each pairwise comparison matrix.

Chapter 3: Results and discussion

3.1. Factor weighting

As already alluded to, the GIS layers (or the factors) are not equally importance; they are compared or differentiated from each other through weights (Table 4). The PCM is determined through expert opinion and literature search. The ranking of the layers (Table 4) is based on their importance to irrigation suitability delineation. The weights are then used as input data to the layers in ArcGIS using Saaty's AHP pairwise comparisons scale (Saaty, 1987; Saaty, 1977).

Table 4. Pairwise comparison matrix for assessing the relative relevance of eight factors

	Dist. from rivers	Groundwater depth	Soil depth	Slope	Soil texture	Drainage class	LU/LC	Rainfall	Average weights	Weights (%)
Dist. from rivers	1	0.5	0.33	0.25	0.2	0.17	0.14	0.12	0.331	33.1
Groundwater depth	0.5	1	0.5	0.33	0.25	0.2	0.17	0.14	0.231	23.1
Soil depth	0.33	0.5	1	0.5	0.33	0.25	0.2	0.17	0.157	15.7
Slope	0.25	0.33	0.5	1	0.5	0.33	0.25	0.2	0.106	10.6
Soil texture	0.2	0.25	0.33	0.5	1	0.5	0.33	0.25	0.071	7.1
Drainage class	0.17	0.2	0.25	0.33	0.5	1	0.5	0.33	0.048	4.8
LU/LC	0.14	0.17	0.2	0.25	0.33	0.5	1	0.5	0.033	3.3
Rainfall	0.12	0.14	0.17	0.2	0.25	0.33	0.5	1	0.024	2.4
CR = 2.9% (0.029)										

The PCM is applied when weighting the irrigation suitability mapping factors, comparing them one-to-one according to Saaty's scale (Saaty, 1977). The reliability and integrity of the comparison matrix are evaluated using the consistency ratio, calculated at 0.029, which is within the acceptable range.

The distance from surface water sources and groundwater depth is weighted the highest (Table 4) as the ease of access to water sources (rivers, dams and groundwater) is fundamental to irrigation development and reduces abstraction and pumping costs from the water source to the field. Adequate water supply and availability are at the centre of a successful irrigation system (Levidow et al., 2014). Proximity to groundwater is ranked high in irrigation development due to the depletion of surface water-bodies. It is now the main source of irrigation during dry seasons, particularly in water-scarce countries (Cai et al., 2017; Magidi et al., 2021a). Although surface and groundwater sources are key for irrigation development, groundwater has been ranked second after surface water (Table 4) as it is more expensive to abstract than pumping from surface water bodies. Where surface water is readily available, abstracting groundwater resources may not be necessary (Carrard et al., 2019).

As already alluded to, soil depth is key as it provides root anchorage and accessibility to water and crop nutrients, crucial factors that promote and favour increased agricultural production, and therefore is ranked third. On fourth ranking is the slope factor which determines the type of irrigation practised in an area (Hagos et al., 2022; Worqlul et al., 2017). Irrigation is preferred in low slopes to flat areas, while steep slopes are considered unsuitable for irrigation (Hagos et al., 2022). Other edaphic factors like soil texture and drainage class are ranked fifth and sixth, respectively, as they play an important role in plant growth, aeration, and water-holding capacity (Hagos et al., 2022). The landuse/cover and rainfall factors are ranked seventh and eighth, respectively. The landuse/cover factor is important for discarding unsuitable

areas (built-up areas, nature and game reserves, etc.) and, at the same time, optimising the most suitable areas like cultivated lands.

Rainfall is the least ranked factor as irrigation is applied only where rainfall is absent for prolonged periods to support plant growth during the dry seasons, drought, or intra-seasonal dry periods. However, rainfall is needed to recharge both surface and groundwater sources. Weights are, therefore, assigned according to a factor's characteristics, relationship and importance to irrigation suitability.

3.3. Irrigation suitability area

As shown in Figs. 8-11, the optimal irrigation suitability areas in the study districts are highly shaped by their proximity to waterbodies (both surface and groundwater). This is based on the fact that water-bodies were given the highest weights as irrigation is only possible in areas close to water sources. The further an area is from waterbodies, the more likely it may become unsuitable for irrigation if it does not meet other factors. Tables 5-8 show the statistics by suitability classes per district by country. The Euclidean process was run on perennial rivers as they provide water for irrigation during the dry season.

Although irrigation suitability areas marked as S2 and S3 fall behind the S1 categorised lands in terms of irrigation suitability, they are still optimal for irrigation and could improve crop-water productivity if the best irrigation type is applied (Irmak et al., 2011; Reinders, 2011). Recent technological advances in irrigation have made it possible to apply irrigation efficiently even in areas formerly deemed unsuitable (Koech and Langat, 2018; Levidow et al., 2014). This has been quite beneficial in regions where land has been extensively degraded or scarce to support agricultural development (Vera et al., 2021; Zinkernagel et al., 2020). Irrigation technologies could be aided by cultivating indigenous crop species adaptable to local conditions and do not require much water (Mabhaudhi et al., 2019).

3.3.1. Balaka and Nkhotakota districts, Malawi

The two districts of Malawi, Balaka and Nkhotakota (Fig. 6), offer a contrasting narrative regarding irrigation suitability (Table 5). However, in general terms, the areas suitable for irrigation are shaped by water presence. In Balaka District, only 3.3% is classified as not suitable for irrigation, yet in Nkhotakota 73% is not suitable for irrigation. Most of the area of Nkhotakota is covered by dams, rendering it unsuitable for irrigation. However, of the area that is not covered by surface water, most of it is suitable for irrigation. The main contributing factor to the high percentage of land suitable for irrigation is a huge endowment of groundwater and surface water resources. Besides this water endowment, agriculture remains rainfed, making the districts vulnerable to climate change impacts. Malawi remains highly food insecure (Hajdu et al., 2009; Nhamo et al., 2019a). The country should prioritise winter irrigation development as the country is always devasted by extreme weather events like cyclones and drought during the rainy season. Floods and droughts in Malawi have caused total crop failure during the rainy season (Nhamo et al., 2019a). However, the results indicate huge irrigation potential yet to be tapped.

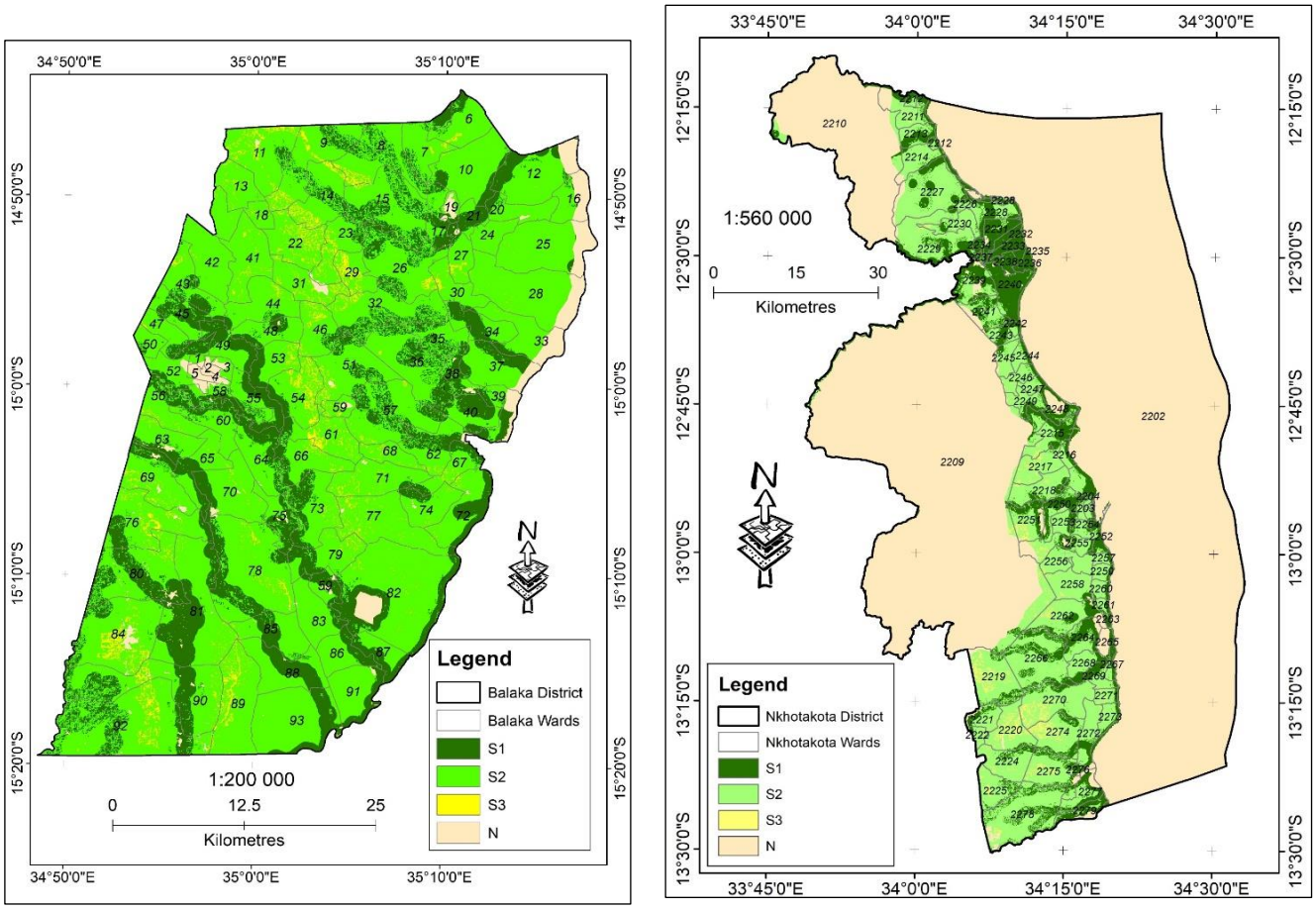

Figure 8. Suitability classes for Balaka and Nkhotakota districts in Malawi

Table 5. Irrigation suitability classes by category in Balaka and Nkhotakota districts in Malawi

Malawi				
	Balaka		Nkhotakota	
Class	**Area (Ha)**	**Percentage (%)**	**Area (Ha)**	**Percentage (%)**
S1	44 929.61	21.06	68 101.80	8.68
S2	154 896.24	72.60	135 016.42	17.20
S3	6 476.90	3.04	7 011.49	0.89
N	7 066.05	3.31	574 827.06	73.23
Total	213 368.80	100	784 956.78	100

3.3.2. Monze and Chipata districts, Zambia

The two districts of Zambia, Monze and Chipata (Fig. 9), offer huge irrigation potential as they have abundant surface and groundwater resources. Although Monze has a huge nature reserve it still offers 23.7% (Table 6) of land classified as S1 as it is endowed with abundant surface and groundwater resources. Besides, the district, Monze, is close to the Barotse wetland, the source of the Zambezi River. Most of Chipata District falls in the S2 classification (84%) as it is within a relatively dry zone with abundant groundwater resources. Zambia has been performing well in terms of food security, but agriculture

remains rainfed, risking it to the vagaries of climate change. The country still has to fully exploit its abundant water resources through irrigation development. If well developed through irrigation developed, the country has the potential to feed the whole of southern Africa (Nhamo et al., 2019a). However, the current and predominant rainfed agriculture practices have been highly vulnerable to extreme weather events of flooding and droughts, risking the country to food insecurity challenges.

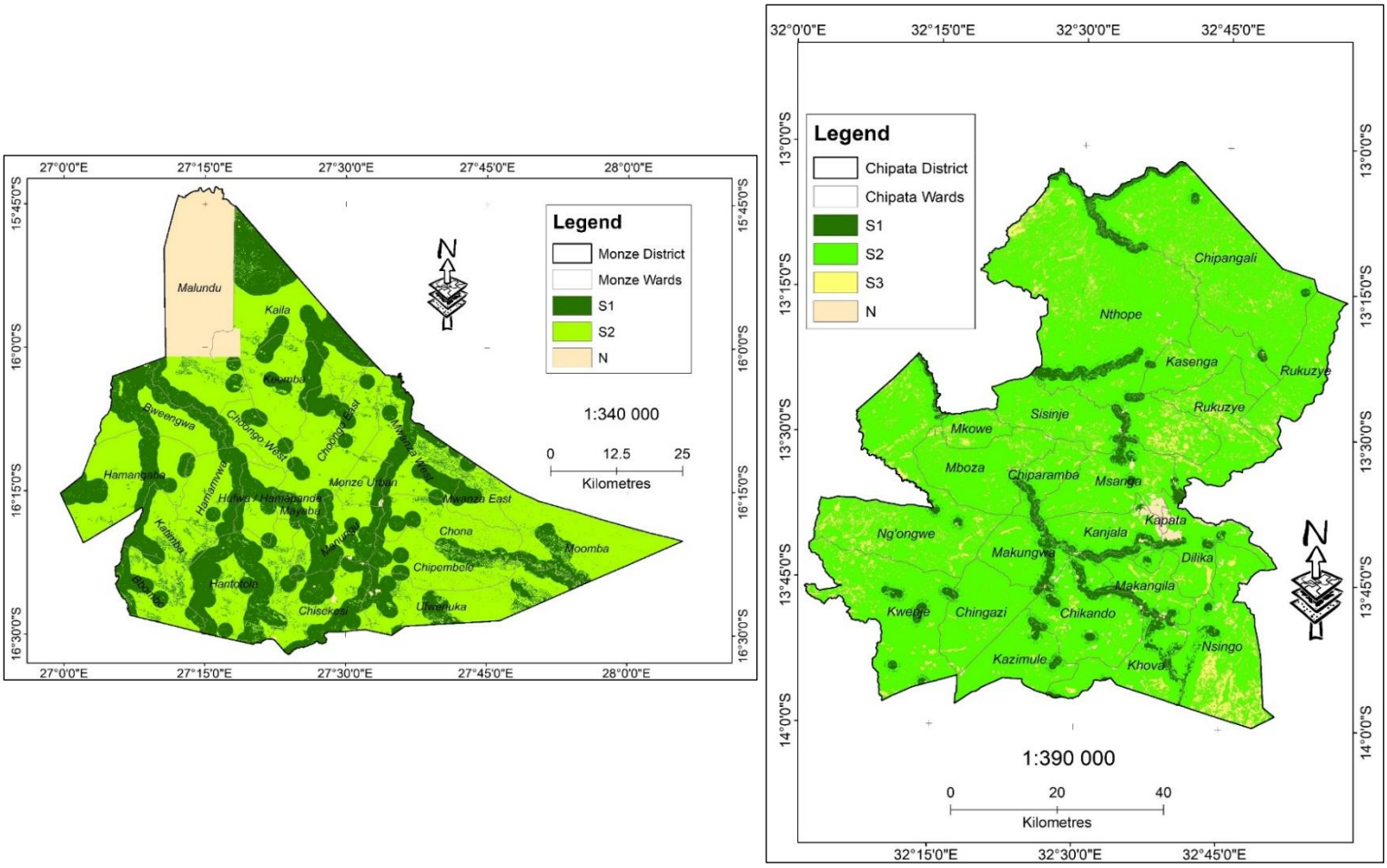

Fig. 9. Suitability classes for Modze and Chipata districts in Zambia

Table 6. Irrigation suitability classes by category in Monze and Chipata districts in Zambia

Zambia				
	Chipata		Monze	
Class	Area (Ha)	Percentage (%)	Area (Ha)	Percentage (%)
S1	36 995.56	5.82	172 772.84	35.75
S2	534 495.39	84.04	269 336.92	55.73
S3	57 144.36	8.98	0.00	0.00
N	7 398.70	1.16	411 55.86	8.52
Total	636 034.00	100	483 265.63	100

3.3.3. Nakuru and Makueni districts, Kenya

The districts of Nakuru and Makueni in Kenya (Fig. 10) are adjacent to each other and have similar climatic and topographic characteristics. Although they are dry districts, they have abundant groundwater resources and a high density of perennial river systems. However, agriculture remains rainfed under smallholder farming. This is besides the favourable attributes that promote irrigated agriculture. The high density of rivers resulted in the small Euclidian distance from the water source, making the land highly suitable for irrigation. Besides, there are deep soils, characterised by flat slopes and high available water storage capacity, making them highly suitable for irrigation. Therefore, the districts have huge irrigation potential. However, in most of Makueni District, 69.5% (Table 7) is not suitable for irrigation as most of the land is reserved for nature reserves and national parks. Yet for Nakuru Districts, only 2.6% is not suitable for irrigation. However, the soils of the two districts of Kenya are highly saline, which makes them generally not suitable for their production. Saline areas in the two districts are shown in Annexures 11 and 12.

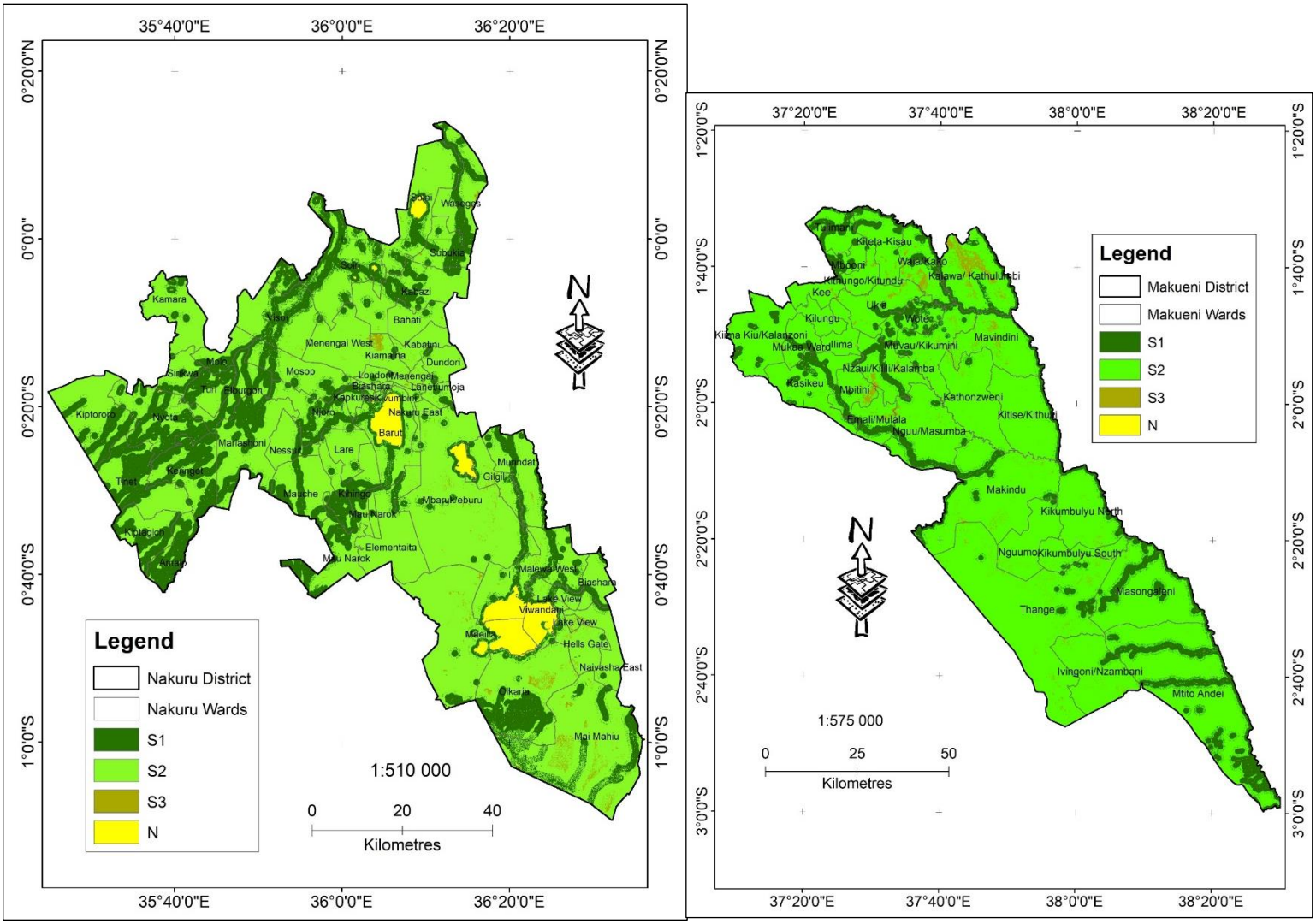

Fig. 10. Suitability classes for Nakuru and Makueni districts in Kenya

Table 7. Irrigation suitability classes by category in Nakuru and Makueni districts in Kenya

Kenya				
	Nakuru		Makueni	
Class	Area (Ha)	Percentage (%)	Area (Ha)	Percentage (%)
S1	218 311.95	29.13	117 756.96	14.70
S2	500 162.70	66.73	666 919.07	83.27
S3	5 759.22	0.77	15 604.95	1.95
N	25 280.75	3.37	600.77	0.08
Total	749 514.63	100	800 881.75	100

3.3.4. Masvingo, Makonde and Murehwa districts in Zimbabwe

The three districts of Zimbabwe, Masvingo, Makonde and Murehwa (Fig. 11), offer highly contrasting statistics regarding irrigation suitability, mainly because they lie in different agro-ecological regions. Masvingo has the largest number of unsuitable areas for irrigation (67.8%) as it lies in one of the country's driest regions. Due to the dry conditions, the district has a small density of perennial river networks. The district is predominantly a smallholder farming area under rainfed agriculture. Groundwater resources are also limited. The irrigation suitability areas (22.2%) around the major river network and dams.

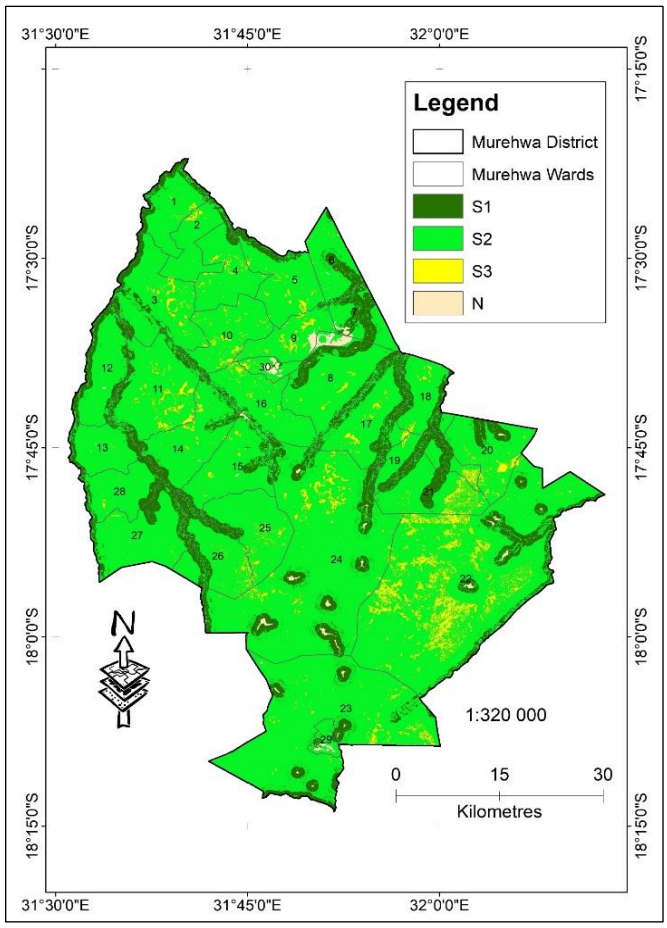

Fig. 11. Suitability classes for Murehwa Districts, Zimbabwe

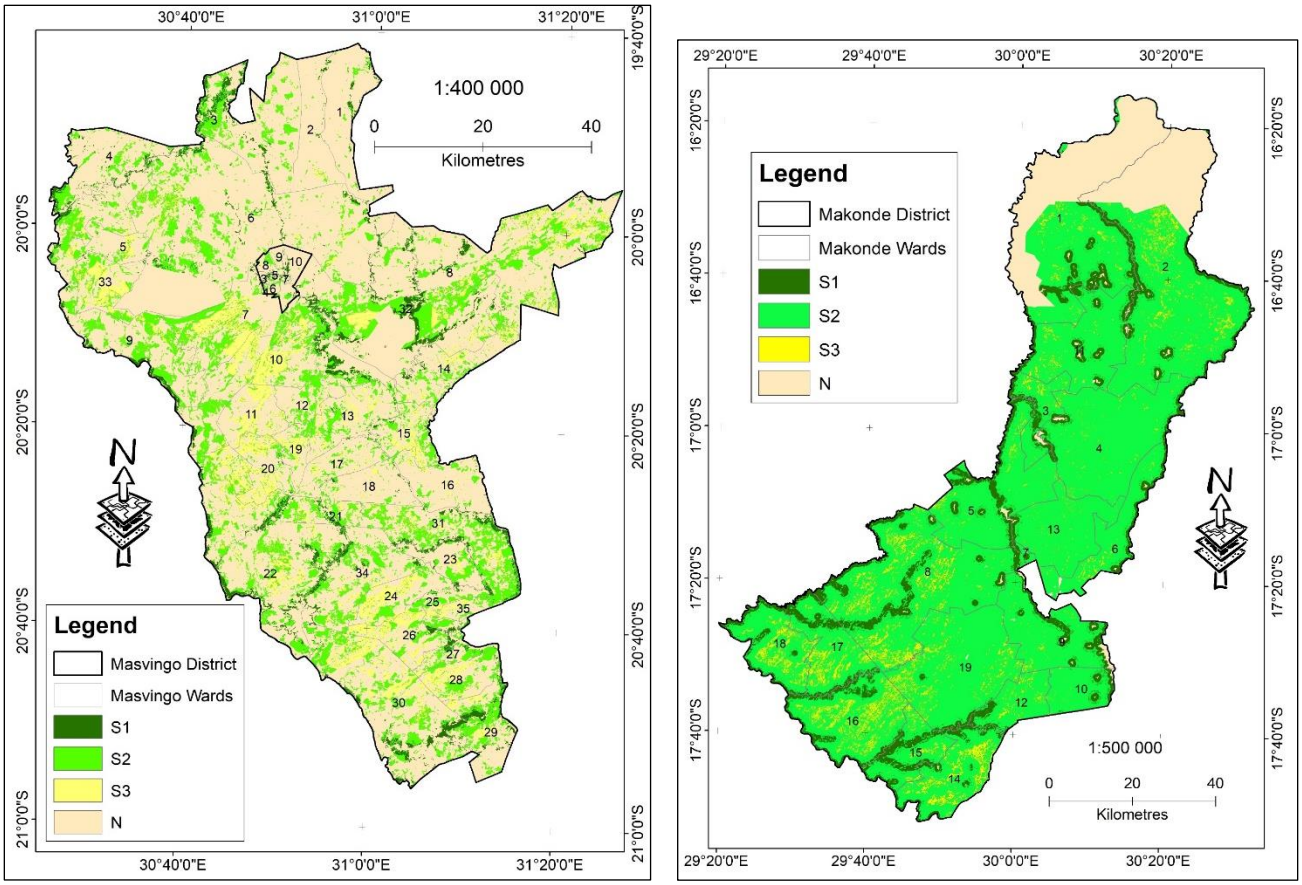

Fig. 12. Suitability classes for Masvingo and Makonde districts, Zimbabwe

Yet, for Makonde District, only 11.6% is not suitable for irrigation as the district has a higher river network and abundant groundwater resources. Besides, the district is also endowed with rich agricultural soils that attract commercial irrigation. Makonde District already has abundant irrigated agriculture and is one of the major agricultural districts of Zimbabwe in Mashonaland West Province. Over 88.4% of the land is suitable for irrigation, but most remains rainfed under smallholder farming. The same applies to Murehwa District, one of the prime agricultural lands of Zimbabwe but is also densely populated with smallholder farming under rainfed agriculture. Total irrigation potential stands at over 99%, mainly due to abundant groundwater resources and a good density of perennial rivers. There is a huge irrigation potential, yet food insecurity remains high. This irrigation potential is still to be exploited

Table 8. Irrigation suitability by category in Masvingo, Makonde and Murehwa districts, Zimbabwe

Zimbabwe						
	Makonde		Masvingo		Murehwa	
Class	Area (Ha)	Percentage (%)	Area (Ha)	Percentage (%)	Area (Ha)	Percentage (%)
S1	86 829.93	10.12	45 875.15	12.83	26 369.94	3.80
S2	623 070.09	72.63	294 162.43	82.25	135 476.27	19.51
S3	48 219.03	5.62	15 442.62	4.32	60 898.54	8.77
N	99 806.94	11.63	2 163.09	0.60	471 687.86	67.92
Total	857 925.99	100	357 643.29		694 432.61	100

3.4. Accuracy Assessment

Accuracy assessment of the mapped irrigation suitability areas was verified by comparing the created dataset with six ground truth points taken from fieldwork done in Monze District in Zambia, as well as from high-resolution Google Earth images (Fig. 12 and Annexure 10). This was enhanced by combining the ground-truth points generated from Google Earth with those from existing datasets using the accuracy assessment tool in ArcMap. This visual interpretation, coupled with the fieldwork points was used to assess the accuracy of the mapped irrigation suitability areas. The accuracy assessment was essential for determining the quality of the classified irrigation suitability maps. All the points of the irrigated areas taken from the field were found to be in S1 (Fig. 12), providing a good mapping accuracy of the mapped irrigation suitability areas.

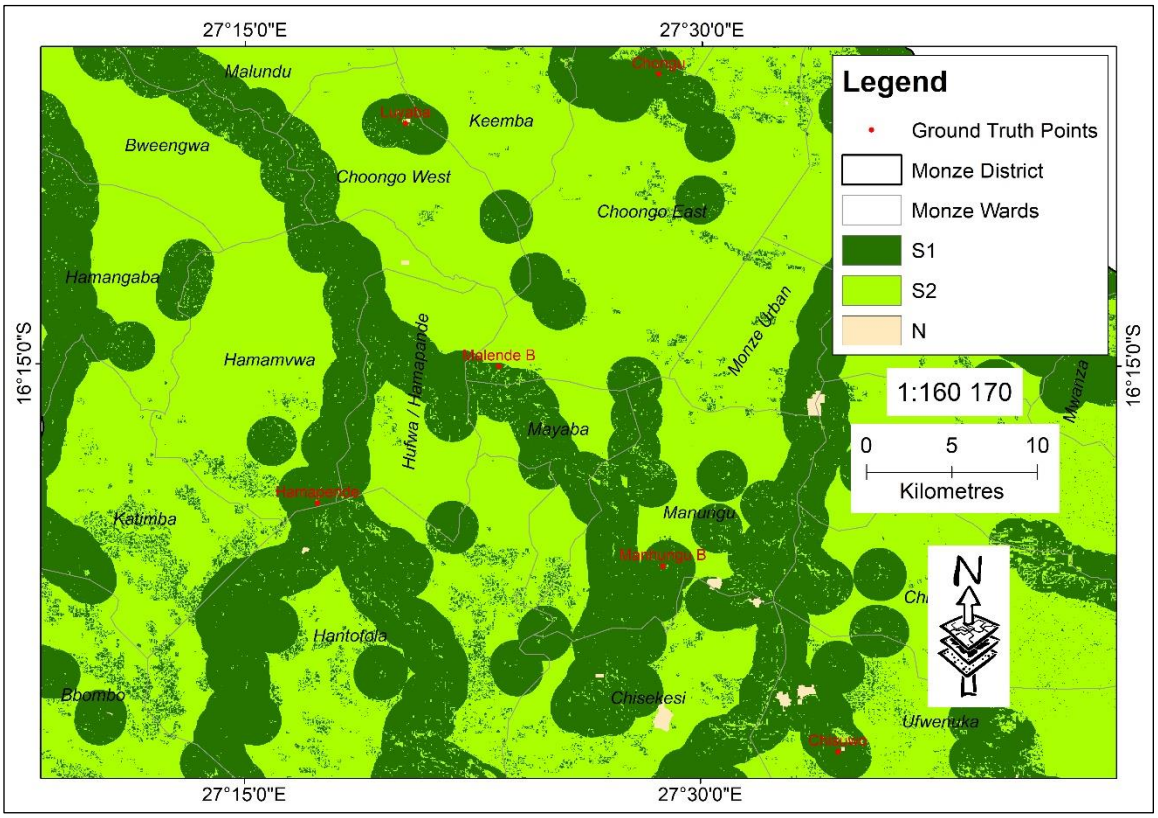

Fig. 13. Ground truthing points (in red) in some of the wards in Monze District, Zambia

Chapter 4: Overview of multi-criteria decision method and its limitations

Of the many MCDM methods that have been developed and are available in the literature [Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Simple Additive Weighting (SAW), Analytic Hierarchy Process (AHP), Multi-Attribute Utility Theory (MAUT), Elimination and Choice Expressing the Reality (ELECTRE), Preference Ranking Organization Method for Enrichment Of Evaluations (PROMETHEE), etc.], the AHP remains the most used and widely accepted as demonstrated by comparative studies on MCDM methods (de FSM Russo and Camanho, 2015; Tscheikner-Gratl et al., 2017; Velasquez and Hester, 2013). Some methods like the TOPSIS apply the AHP in their applications (Tscheikner-Gratl et al., 2017). The AHP is used in many fields and various specialties such as Environmental Sustainability, Economic Well-being, Sociology, Programming, Suitability Mapping, Resource Allocation, Strategic Planning, and Project/Risk Management to aggregate distinct indicators and monitor performance for benchmarking, policy analysis and decision-making (Cherchye and Kuosmanen, 2004; Dizdaroglu, 2017; Forman and Gass, 2001; Nhamo et al., 2020b; Zanella et al., 2013). These fields, and more recently WEF nexus, cannot be measured using a single indicator but through a set of distinct indicators that need to be standardised and normalised (Nhamo et al., 2020b).

The advantages of using the AHP over other methods are its usefulness in the hierarchical problem presentation, the appeal of pairwise comparisons in preference elicitation and its flexibility and ability to check inconsistencies (Emrouznejad and Marra, 2017; Saaty, 2008; Schmidt et al., 2015; Tscheikner-Gratl et al., 2017). Despite the subjective judgments in an AHP, results remain vital for policy evaluation, and performance assessment as the method captures both subjective and objective evaluation measures (Cherchye et al., 2007). This uncertainty is dealt with by engaging experts and using reliable baseline data to establish relationships between different but related factors that need to be assessed together (Brunelli, 2014; Zhou et al., 2007). However, studies have shown that the AHP accuracy can be compromised if too many criteria or factors (more than 9) are used during the pairwise comparison (Görener, 2012; Tscheikner-Gratl et al., 2017; Widianta et al., 2018). Therefore, the CR is very difficult to attain, with more than 9 criteria/factors under consideration (Fortunet et al., 2018; Pamučar et al., 2018). Yet, its ability to measure consistency is one of the factors that gives the AHP an age over the other methods.

Chapter 5: Recommendations and conclusions

As irrigation is identified as an important climate change adaptation strategy, accurate information on its distribution and extent is vital for strategic irrigation planning and development. However, if the planning and development are not based on accurate information, irrigation could become one of the most disturbing anthropogenic interventions in the terrestrial water cycle (Magidi et al., 2021b). Knowledge of the distribution and extent of irrigated areas, together with the amount of water used in irrigation, plays an important role in modelling irrigation water requirements and allocation, and also quantifies the impact of irrigation on regional climate, river discharge, and groundwater depletion (Borsato et al., 2020). Therefore, delineating accurate irrigation suitability areas improves decisions on irrigation development and expansion and promotes food and water security initiatives in an era of climate change. However, accessing reliable input data required for irrigation suitability mapping remains challenging, particularly in terms of accessing datasets at reasonably and acceptable high spatial resolution. There is still more that needs to be done on developing input datasets at acceptable spatial resolution as the current ones are too coarse to derive accurate statistics on spatial distribution and extent on irrigation, and the quantification of the water needed for irrigation.

Equally important is selecting the correct factors needed for irrigation suitability mapping. Understanding and distinguishing the role of physical and socio-economic factors in irrigation suitability mapping is essential. Physical factors qualify the suitability of an area for irrigation, whereas socio-economic factors form part of conditions set to identify optimal areas to implement irrigation projects under a set of given economic factors (FAO, 1976; USDIBR, 2005). This study identified irrigation suitability areas under a set of physical criteria regardless of whether it is close or far from markets and roads, and economic factors that are considered for initiating irrigation projects (USDIBR, 2005).

Apart from being important for strategic policy decisions on irrigation development, an assessment of irrigation suitability also provides pathways towards the efficient use of the limited and depleting water resources, enhances the sustainable production of crops, and promotes food and water security (Borsato et al., 2020). Irrigation planning and development need to integrate information about the suitability of the land, availability of water resources and the water requirements of irrigable areas in space and time to derive the essential information required in the formulation of coherent policies on sustainable irrigation development and improved crop water productivity (Mabhaudhi et al., 2018; Paul et al., 2020).

On the other hand, irrigation investment is identified as key to enhancing and maintaining sustainable food security as it improves agricultural production, which is the foundation for southern Africa's economic growth, food security, and sustainable development. Sustainable irrigation development and policies in the region should consider the following to achieve the intended objectives:

- The actual implementation of irrigation projects needs to acknowledge the interlinkages between suitability constraints that include water quality, human and environmental health, and economic and social factors with sustainable development.
- Advances in GIS and remote sensing facilitate systematic land suitability assessment over time and delineation of updated land use and irrigation land suitability for sustainable resource planning and management. Therefore, GIS and remote sensing are important tools for generating more accurate and high-resolution input datasets.

- Policy-makers should be aware that accurate spatial information on irrigation statistics is important for irrigation development, management, and planning but is also beneficial for economic growth and for informing future needs, including meeting future land, water, and food demands.

Irrigation suitability classification is important for landuse planning according to its agricultural potential and is required for conserving natural resources to meet the needs of future generations. Thus, this study is informed by the knowledge that classifying land suitability for sustainable use requires understanding and selecting of the correct land characteristics of the suitability theme being studied. The study used physical factors as input layers and adopted a geospatial and multi-criteria decision method approach to delineate irrigation suitability areas. The approach distinguished biophysical and socio-economic factors as the two sets of factors contribute differently to land suitability mapping. Physical factors identify areas suitable for irrigation in space and time. Yet socio-economic factors guide policy to identify optimal irrigation suitability areas to initiate irrigation projects under a set of given socio-economic conditions. The distinction between physical and socioeconomic factors has improved irrigation suitability mapping as previous studies combined both factors for general irrigation suitability mapping, thereby eliminating other suitability areas. The approach is applicable at any spatial scale; however, the availability of datasets at an acceptable spatial resolution remains a major challenge. The essence of irrigation suitability mapping is its support for policy and decision-making on strategic and sustainable irrigation planning and development. The adopted approach and the results are essential for designing and initiating new irrigation projects by providing policy with a technique that can reliably inform future irrigation development.

Of the studied districts, soils in the two districts of Kenya, Nakuru and Makueni, are highly saline, making them unsuitable for cereal cultivation. Therefore, soil salinity should be considered as a factor when mapping the irrigation suitability of cereals. However, for the other districts of the selected countries, soil salinity is insignificant, and, therefore, not necessary to map them.

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Annexures

Annexure 1. Irrigation suitability area by ward in Makueni County, Kenya

	Area (ha)			
Ward	**S1**	**S2**	**S3**	**N**
Tulimani Ward	5 046.75	7 515.45	0.09	18.00
Mbooni Ward	2 610.01	3 774.11	0.00	16.20
Kithungo/Kitundu Ward	224.02	7 361.28	178.21	0.72
Kiteta-Kisau Ward	3 793.73	13 388.08	366.04	10.80
Waia/Kako Ward	5 133.52	11 182.37	1271.48	15.57
Kalawa/ Kathulumbi Ward	6 066.49	22 429.27	4490.80	21.33
Kasikeu Ward	6 113.38	20 447.93	255.07	19.26
Mukaa Ward	1 779.72	8 150.52	144.82	5.22
Kiima Kiu/Kalanzoni Ward	2 544.21	24 490.43	160.21	11.88
Ukia ward	2 144.87	15 622.14	643.34	6.30
Kee ward	236.89	7 767.55	154.72	0.63
Kilungu ward	0.00	7 317.27	7.65	0.00
Ilima ward	26.64	8 325.30	43.65	0.18
Wote Ward	6 084.13	5 781.81	7.02	19.44
Muvau/Kikumini Ward	3 591.58	19 041.99	465.23	8.64
Mavindini Ward	2 187.62	22 269.96	1404.23	3.15
Kitise/Kithuki Ward	2 101.22	30 165.59	42.39	5.67
Kathonzweni Ward	493.22	29 312.63	278.47	11.43
Nzaui/Kilili/Kalamba Ward	4 748.48	14 324.83	675.20	14.22
Mbitini Ward	2 006.08	8 695.22	860.16	5.22
Makindu Ward	7 300.98	55 688.72	746.94	26.10
Nguumo Ward	290.80	20 582.13	182.17	0.36
Kikumbulyu North Ward	3 099.35	25 148.36	198.55	8.73
Kikumbulyu South Ward	572.60	11 165.36	184.42	0.81
Nguu/Masumba Ward	5 588.75	28 927.05	377.20	14.85
Emali/Mulala Ward	2 538.63	8 442.13	509.51	9.09
Masongaleni Ward	10 611.57	37 480.24	57.51	24.84
Mtito Andei Ward	25 708.72	65 881.41	56.61	312.40
Thange Ward	4 029.63	98 216.44	1469.21	6.30
Ivingoni/Nzambani Ward	1 083.37	28 023.51	374.05	3.42

Annexure 2. Irrigation suitability area by ward in Nakuru County, Kenya

	Area (Ha)			
Ward	**S1**	**S2**	**S3**	**N**
Elburgon Ward	6 292.31	3 400.41	0.00	20.43
Njoro Ward	6 359.27	6 061.18	0.00	26.64
Biashara Ward	1 296.68	5 685.33	5.13	3.87
Hells Gate Ward	767.55	8 067.53	233.56	48.87
Amalo Ward	7 484.85	1 241.06	0.00	30.87
Keringet Ward	11 852.89	5 539.61	0.00	58.14
Kiptagich Ward	5 932.93	5 450.60	0.00	18.36
Tinet Ward	9 795.78	9 782.37	0.00	36.63
Mariashoni Ward	9 861.84	14 671.88	2.16	33.84
Turi Ward	4 821.39	2 926.73	0.00	31.41
Molo Ward	2 342.07	3 466.39	0.09	8.91
Mau Narok Ward	6 651.24	9 236.59	12.15	26.91
Mauche Ward	7 793.02	10 632.99	0.00	23.76
Kihingo Ward	3 528.13	6 583.83	0.00	13.50
Nessuit Ward	1 466.15	6 047.41	0.27	2.88
Lare Ward	807.78	6 412.01	2.61	4.23
Lake View Ward	106.65	1 360.85	186.49	0.00
Mai Mahiu Ward	10 493.12	41 949.09	1 888.36	84.24
Maeilla Ward	2 923.94	33 193.21	325.99	6 334.43
Olkaria Ward	11 929.66	21 492.06	852.42	276.76
Naivasha East Ward	706.80	8 282.28	93.42	0.90
Viwandani Ward	2 414.70	3 368.37	22.32	4775.75
Gilgil Ward	2 061.35	6 184.22	172.81	12.33
Elementaita Ward	1 454.54	19 810.62	45.99	3.96
Mbaruk/eburu Ward	4 493.23	55 082.73	463.07	2 066.30
Malewa West Ward	7 639.03	15 652.92	82.53	4 027.92
Murindat Ward	5 075.91	10 438.94	60.12	17.82
Kiptororo Ward	6 827.56	14 682.23	0.18	24.57
Nyota Ward	11 749.03	7 724.98	0.00	76.68
Sirikwa Ward	2 157.92	4 175.79	0.00	7.20
Subukia Ward	3 822.98	5 047.38	22.05	20.70
Menengai West Ward	583.76	14 976.19	73.80	1.53
Visoi Ward	6 871.39	13 548.46	38.25	24.66
Dundori Ward	361.27	5 123.80	1.62	0.99
Kabatini Ward	289.54	5 868.30	46.89	0.00
Kamara Ward	1 741.11	12 691.27	3.15	18.45
Waseges Ward	5 866.77	9 316.42	179.65	29.88
Kabazi Ward	6 338.48	15 119.11	7.29	42.39
Kiamaina Ward	362.17	4 177.23	673.76	0.63
Soin Ward	14 833.26	14 205.31	0.27	217.18
Lanet/umoja Ward	957.54	3 968.42	91.26	2.07
Bahati Ward	664.22	7 152.83	31.95	0.90
Kaptembwo Ward	236.44	275.59	0.00	0.81
Kapkures Ward	929.64	1 666.50	0.00	3.60
Rhoda Ward	48.42	62.46	0.00	0.00
Shaabab Ward	2.07	233.47	0.00	0.00

Kivumbini Ward	106.65	112.59	0.00	0.00
Flamingo Ward	15.66	152.38	0.00	0.00
Menengai Ward	128.16	911.82	52.83	0.00
Mosop Ward	4 973.49	9 606.32	13.59	22.05
Solai Ward	5 626.10	15 248.72	35.64	1 171.75
Barut Ward	5 754.09	8 155.20	21.96	5 624.66
London Ward	250.57	1 838.23	2.43	0.00
Nakuru East Ward	460.82	2 100.50	13.14	0.36

Annexure 3. Irrigation suitability area by ward in Makonde District, Zimbabwe

	Area (Ha)			
Ward	**S1**	**S2**	**S3**	**N**
1	8979.57	43354.35	1679.85	56065.32
2	7979.22	78440.58	5859.90	38835.9
3	2790	11515.41	782.37	332.28
4	2236.95	61492.5	1115.82	303.75
5	7695.45	41734.44	1209.96	404.1
6	2601.45	22845.06	763.92	374.22
7	381.33	822.33	0.00	13.23
8	11876.94	74127.42	9503.10	261.45
9	5184.36	29950.47	581.04	1015.83
10	1643.13	13756.41	152.37	101.52
11	5118.12	35784.27	1092.87	450.9
12	1788.66	13957.02	1048.77	6.75
13	697.41	31963.14	618.30	54.54
14	3743.28	22902.75	4705.65	36.81
15	5407.02	13549.41	1144.26	3.78
16	6062.94	29696.31	6585.30	3.78
17	4520.25	19136.7	3206.43	9.54
18	3418.2	19754.37	3562.56	8.82
19	1207.35	56648.97	4492.89	95.85

Annexure 4. Irrigation suitability area by ward in Murehwa District, Zimbabwe

	Area (Ha)			
Wards	**S1**	**S2**	**S3**	**N**
1	0.00	5 307.54	91.26	0.00
2	279.90	5 137.40	159.97	0.00
3	1 624.17	10 457.40	497.32	0.00
4	352.56	6 903.13	290.44	0.00
5	903.75	7 554.83	315.27	3.39
6	1 143.07	4 806.19	49.48	12.55
7	2 088.88	2 848.05	3.30	136.88
8	2 334.24	9 684.21	162.72	544.60
9	68.99	5 001.16	453.25	239.59
10	209.36	7 258.71	464.80	0.00
11	1 411.34	11 207.60	805.63	0.00
12	2 266.35	6 382.63	3.57	13.01
13	937.10	5 146.10	16.68	0.00
14	1 182.10	8 738.40	230.15	9.25
15	989.51	8 344.89	127.90	55.71
16	407.53	7 929.47	270.74	6.41
17	2 411.66	7 789.29	348.07	0.00
18	1 605.94	5 070.70	150.26	0.00
19	1 706.63	3 373.05	326.26	0.00
20	1 302.40	7 125.31	514.09	21.62
21	1 573.42	6 597.30	764.31	0.00
22	4 607.83	45 512.15	6 386.75	202.76
23	3 109.72	32 220.62	786.85	95.38
24	6 073.77	40 791.63	1 368.46	393.97
25	345.96	8 563.40	355.95	1.47
26	2 157.50	6 730.79	297.86	0.00
27	1 991.39	9 440.59	55.34	0.00
28	1 118.79	5 542.18	43.34	0.00
29	215.95	1 238.54	1.74	136.33
30	84.57	1 459.16	100.88	290.17

Annexure 5. Irrigation suitability area by ward in Masvingo District, Zimbabwe

	Area (Ha)			
Wards	**S1**	**S2**	**S3**	**N**
1	465.28	658.27	12.15	16 118.02
2	135.92	265.90	158.51	13 242.89
3	1 942.22	5 360.13	436.66	21 526.76
4	1 174.77	2 771.16	103.61	13 761.46
5	60.40	1 089.97	710.21	5 281.01
6	1 661.74	12 315.39	2 048.44	77 981.14
7	1 827.82	9 314.52	5 410.27	16 956.41
8	946.58	9 359.35	4 695.02	33 648.71
9	1 130.66	6 423.82	666.37	15 653.28
10	411.54	5 312.15	5 337.63	15 414.65
11	0.00	557.81	2 728.49	6 584.95
12	0.00	1 774.26	184.44	4 167.27
13	169.14	2 538.65	1 272.88	9 658.28
14	238.54	2 367.36	1 147.94	10 104.57
15	161.21	2 181.21	1 210.05	5 663.93
16	134.03	1 110.14	465.28	11 595.02
17	69.85	1 062.79	438.19	7 652.60
18	132.50	607.50	248.35	8 941.14
19	6.03	898.25	915.35	3 035.44
20	55.63	983.22	3 105.20	4 917.80
21	1 478.83	6 344.43	3 719.27	13 909.00
22	2 264.92	7 102.16	2 324.51	21 742.34
23	447.73	1 473.34	338.00	4 892.06
24	41.50	1 706.48	2 766.12	5 124.75
25	333.05	1 743.02	395.16	2 819.59
26	391.92	1 962.57	2 751.81	5 310.26
27	196.68	1 361.64	202.44	2 129.09
28	82.00	2 272.03	1 922.24	4 556.13
29	1 139.48	3 452.29	910.04	7 385.80
30	2 398.95	9 057.89	4 404.55	26 130.60
31	1 687.22	9 451.70	1 489.37	11 054.03
32	3 561.66	11 027.39	2 924.54	34 109.49
33	638.38	5 746.92	3 902.00	15 113.11
34	973.32	5 147.07	991.59	13 778.48
35	10.44	675.46	561.87	1 727.81

Annexure 6. Irrigation suitability area by ward in Chipata District, Zambia

	Area (Ha)			
Ward	**S1**	**S2**	**S3**	**N**
Kazimule	1 108.76	16 998.43	414.53	235.76
Sisinje	767.95	18 687.18	1 621.77	48.25
Nthope	6 830.23	93 530.76	11 570.15	269.06
Chipangali	3 051.89	59 800.89	6 610.95	49.42
Kasenga	347.56	18 480.22	1 372.96	168.60
Rukuzye	176.34	38 252.3	5 440.89	177.70
Msanga	2 650.05	19 556.3	1 922.52	1 146.65
Kanjala	2 358.30	12 019.25	816.02	1 028.28
Dilika	1522.57	14 562.63	1 128.20	1 344.60
Kapata	0.81	93.719	0.27	659.83
Makungwa	2 229.93	12 776.39	483.85	95.78
Chingazi	388.07	20 372.14	721.14	20.52
Kwenje	2 260.72	36 918.50	2 972.05	55.54
Ng'ongwe	896.13	39 764.25	5 641.27	27.82
Mkowe	104.78	6 334.41	912.61	0.00
Chikando	4 474.36	23 795.09	1 026.84	846.26
Mboza	167.97	23 889.25	1 845.11	49.06
Chiparamba	1 113.89	8 627.81	785.41	0.00
Nsingo	1 477.38	30 787.17	7 473.32	468.10
Khova	2 529.61	15 246.14	915.76	325.60
Makangila	1 626.18	10193.5	905.76	204.16

Annexure 7. Irrigation suitability area by ward in Monze District, Zambia

	Area (Ha)		
Ward	**S1**	**S2**	**S4**
Hamangaba	9 846.345	21 174.17	0
Ufwenuka	10 671.06	19 166.16	153.55
Moomba	5001.75	24 880.93	0.00
Kaila	19 079.76	17 145.10	2 770.26
Keemba	6 997.78	15 944.26	5.580
Malundu	5 653.83	10 085.94	37 829.74
Choongo East	7 766.69	21 266.51	3.42
Choongo West	2 859.72	7 313.34	5.76
Monze Urban	1 677.78	5 061.51	67.32
Manungu	9 970.19	5 292.46	48.51
Mayaba	3 238.37	3 032.71	0.00
Hufwa / Hamapande	4 383.05	5 417.84	0.00
Hamamvwa	6 005.21	11 855.07	12.96
Katimba	4 894.64	9 562.11	0.00
Hantotola	21 169.49	1 6491.94	10.80
Bbombo	6 675.93	7 885.14	5.31
Chisekesi	11 094.80	10 086.66	202.87
Mwanza West	12 612.64	12 409.23	1.08
Mwanza East	2 394.13	6 718.68	0
Chona	5 924.30	13 380.65	38.70
Chipembele	4 830.20	14 418.23	0.00
Bweengwa	10 025.18	10 748.28	0.00

Annexure 8. Irrigation suitability area by ward in Balaka District, Malawi

	Area (Ha)			
Ward	**S1**	**S2**	**S3**	**N**
1	1.80	102.25	0.00	38.53
2	1.71	36.28	0.00	128.99
3	0.00	199.92	0.27	102.16
4	0.00	16.02	0.00	165.17
5	0.00	23.04	0.00	214.77
6	218.82	1461.27	42.49	0.00
7	379.32	1463.52	30.42	0.00
8	617.04	2265.54	144.56	0.00
9	449.35	2644.86	190.02	0.81
10	452.95	2853.33	11.79	0.00
11	133.22	2629.46	287.59	21.51
12	757.37	2148.61	3.69	520.19
13	0.00	1361.90	60.04	0.00
14	328.82	1802.51	248.62	0.00
15	1209.24	2651.25	23.76	0.00
16	46.81	684.28	0.00	665.92
17	538.82	554.30	0.00	12.78
18	0.00	1445.88	37.90	0.45
19	72.28	155.63	0.00	192.36
20	154.01	1069.45	1.53	23.76
21	452.05	254.74	0.00	9.81
22	0.00	1807.37	342.77	1.53
23	161.84	1445.43	152.57	31.23
24	12.33	944.60	5.22	0.00
25	52.21	3175.66	11.61	778.34
26	904.00	2593.28	69.22	1.44
27	146.90	845.13	60.58	17.46
28	0.00	4087.95	25.65	746.57
29	4.68	896.08	267.61	0.00
30	48.88	1141.37	54.10	0.00
31	0.00	1360.19	187.68	116.75
32	774.11	2627.66	95.77	0.00
33	175.35	1452.63	7.56	621.09
34	681.76	779.24	0.45	0.00
35	486.43	886.27	0.00	0.00
36	1187.45	2352.67	7.83	0.00
37	732.35	1382.06	0.00	297.58
38	536.66	274.81	0.00	48.97
39	502.00	466.54	0.00	396.87
40	859.99	599.76	0.00	0.00
41	0.00	2337.82	90.46	0.00
42	33.12	2295.07	12.96	0.00
43	444.03	1319.77	38.53	0.00
44	170.48	1960.31	47.89	0.00
45	739.37	718.57	0.00	0.00

46	161.66	1373.24	130.97	0.00
47	191.91	834.33	12.60	0.00
48	379.41	1026.96	3.69	8.55
49	865.21	570.59	0.00	0.00
50	43.21	560.33	3.06	0.00
51	520.19	2312.44	95.32	21.96
52	572.30	899.41	0.00	171.75
53	399.30	1006.44	79.75	0.00
54	253.75	1698.73	378.60	0.00
55	833.52	579.23	0.00	0.00
56	472.84	1333.27	42.04	3.87
57	1002.03	2833.07	42.94	0.00
58	506.95	508.30	0.00	55.09
59	440.34	718.48	48.07	104.33
60	394.44	1108.42	0.54	0.81
61	182.64	1543.46	239.52	0.00
62	687.70	1212.03	22.05	41.95
63	293.98	1231.20	25.38	55.63
64	849.54	1351.19	0.81	4.86
65	550.88	1213.11	12.51	0.00
66	344.12	1469.10	86.41	0.00
67	421.17	840.72	37.63	9.09
68	0.00	870.88	59.68	0.00
69	408.84	2052.57	130.16	84.16
70	460.42	2295.34	34.75	54.10
71	70.12	2160.68	105.77	14.94
72	918.76	1522.48	34.11	19.80
73	866.29	1753.01	50.23	0.72
74	223.86	1335.89	18.81	17.01
75	623.79	608.85	0.27	33.21
76	605.43	2703.18	222.60	27.99
77	59.41	3226.79	189.75	13.86
78	1349.21	4930.56	163.10	21.78
79	546.02	1520.32	71.29	0.00
80	1701.07	2529.55	65.53	90.91
81	2371.85	3619.79	75.25	42.31
82	1921.51	6216.94	57.25	585.63
83	219.63	1606.37	0.81	6.30
84	442.68	3725.37	484.90	226.02
85	611.91	1433.01	10.98	2.52
86	452.50	992.30	0.54	0.18
87	604.44	619.65	0.00	0.00
88	936.77	1624.56	6.57	4.32
89	0.00	3203.12	380.58	7.02
90	1641.48	3577.12	152.03	46.45
91	528.65	1639.68	1.62	30.96
92	1500.07	5726.55	335.03	89.65
93	1030.29	3603.32	2.25	14.13

Annexure 9. Irrigation suitability area by ward in Nkhotakota District, Malawi

	Area (Ha)			
Ward	**S1**	**S2**	**S3**	**N**
2202	3 696.62	1 264.21	0.00	35 0214.07
2203	161.81	361.50	0.00	0.18
2204	71.63	178.19	0.00	5.67
2205	40.86	13.50	0.00	0.00
2206	35.73	44.37	0.00	1.71
2207	91.07	21.87	0.00	0.18
2208	64.16	213.01	0.00	0.45
2209	2 465.61	5 355.09	308.94	17 1906.32
2210	682.59	1 658.83	5.58	42 657.87
2211	967.96	2 247.29	80.72	891.74
2212	490.19	417.39	0.00	0.00
2213	1 181.51	1 137.14	0.00	3.06
2214	398.13	2 502.69	1.08	250.90
2215	1 550.93	1 986.76	96.92	40.95
2216	379.86	552.10	0.00	15.66
2217	46.44	3 238.65	334.32	5.40
2218	713.19	3 538.23	82.70	9.00
2219	803.36	5 298.76	1 088.64	299.13
2220	152.00	3 696.08	1 016.37	90.53
2221	575.41	1 538.87	50.67	246.67
2222	70.37	687.99	9.45	23.22
2223	0.00	103.85	8.91	0.00
2224	573.97	4 008.35	157.85	3.78
2225	434.57	3 058.57	186.46	0.00
2226	940.78	454.37	0.00	46.80
2227	2 050.12	7 325.75	25.65	554.89
2228	1 676.47	1 594.04	0.27	91.61
2229	2579.27	6 697.33	72.53	137.15
2230	273.13	2 162.43	80.09	0.00
2231	2 147.58	198.61	0.00	100.70
2232	913.96	4.68	0.00	0.00
2233	1 327.39	5.22	0.00	0.00
2234	500.00	41.31	0.00	0.72
2235	469.04	2.07	0.00	0.00
2236	887.42	3.15	0.00	0.36
2237	132.38	46.26	0.00	2.43
2238	1 116.09	36.99	0.00	44.46
2239	2 337.01	1 479.30	0.00	472.19

2240	4 348.26	332.79	0.00	29.61
2241	1 402.17	1 650.37	0.00	523.94
2242	291.22	204.10	0.00	0.00
2243	701.13	771.06	0.00	57.69
2244	367.53	889.85	6.12	1.26
2245	200.95	1 549.40	42.75	175.31
2246	182.95	1 693.84	58.14	21.33
2247	202.03	798.05	7.20	4.14
2248	1 443.84	219.76	0.00	999.19
2249	616.90	1 659.10	48.87	40.86
2250	1 851.24	1 105.65	0.00	137.24
2251	1 259.71	1 884.08	335.13	341.70
2252	997.48	296.17	0.00	132.20
2253	432.86	1 238.30	0.00	0.00
2254	271.42	821.27	0.00	0.00
2255	652.09	2 210.58	178.01	866.18
2256	110.24	3 352.22	64.79	0.00
2257	156.59	530.42	2.16	0.63
2258	191.59	3 666.83	112.58	43.38
2259	171.26	887.96	9.54	0.18
2260	243.88	797.60	0.36	0.09
2261	207.43	355.11	0.00	1.89
2262	1 382.01	3 851.68	206.53	379.23
2263	273.85	32.67	0.00	3.87
2264	1 853.93	1 482.90	0.09	262.96
2265	325.14	31.68	0.00	941.23
2266	3 139.57	6 899.27	21.60	1.89
2267	492.35	335.94	0.00	1.44
2268	706.26	1 715.35	1.26	25.56
2269	821.90	955.72	11.97	2.43
2270	809.57	6 321.25	910.63	3.51
2271	164.96	962.83	73.34	0.00
2272	749.82	2 658.29	16.83	146.15
2273	337.38	1 213.64	13.59	0.90
2274	989.20	3 891.00	842.96	0.72
2275	1 096.74	4 058.93	352.68	167.75
2276	325.59	106.64	0.00	23.85
2277	1 288.06	1 270.42	0.00	497.30
2278	2 604.11	8 826.19	87.38	506.57
2279	1435.74	304.26	0.00	383.73

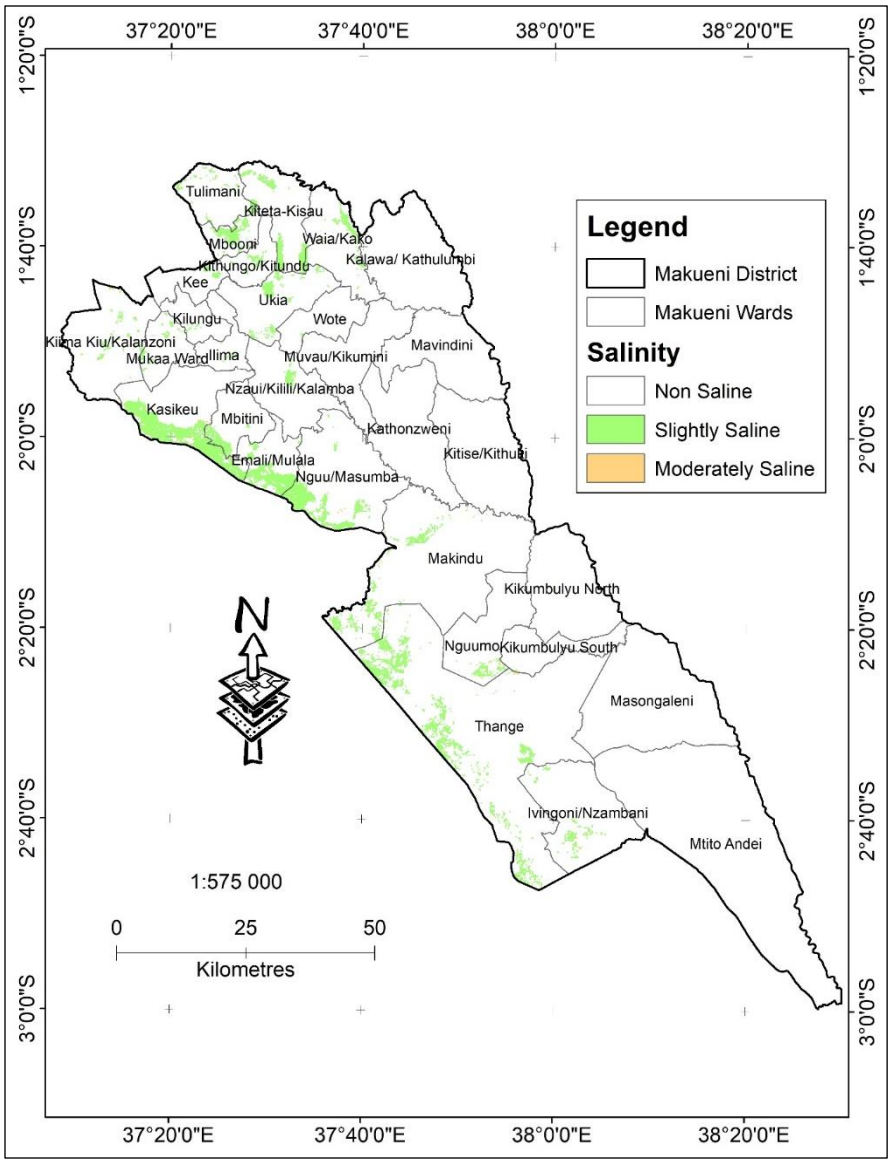
Annexure 10. Irrigation and mechanisation potential assessment

Sites	GPS Coordinates	Participants	Irrigation infrastructure & Mechanisation	Land Availability	Socio-economic factors
Manhungu B	-16.3573865, 27.4792568 Dam coordinates - 16.3582760; 27.4803394	9 Men: 11 women 35 cooperative members	**Irrigation infrastructure and potential** • Dam constructed in 1949, • Gravity flood irrigation with main canal running through 5 hectares of land but not operating • installed 2013 work for 2 years • Prefer solar irrigation • Rain season - Maize, groundnuts, sweet-potatoes, cowpea, sunflower, beans, African egg plant • Winter irrigation – tomatoes, onion, green beans cabbage carrots, eggplant, **Mechanization Potential** • Animal traction mainly used for ploughing, ripping and transport	Land to expand very limited.	• Community has 500-800 households • Only 35 farmers were participating in the irrigation scheme • Livestock and horticulture main source of livelihood • 35 km to the main market, only 10 km is gravel • Poor institutions and group cohesion • Dam siltation main challenge • Dam water used for multi- purpose brick making, washing and livestock • Pests & diseases – tomatoes, cowpea, cabbages, Maize • Drought spell have increased
Hamapende	Sikasiwa Dam -16.3241049; 27.2898262	14 Men; 17 Women	• Dam constructed in 2012/13 • Gravity flood irrigation with main canal running through 10 hectares where about 40% of the members are. 40% of the farmer are operating individually on the upside of the dam including the paramount chief Monze using water pumps. • Preferred irrigation – motorised fuel pump and furrow irrigation • Aware of solar irrigation but never used • Rain season - Maize, groundnuts, sweet-potatoes, cowpea, sunflower, cotton okra and pumpkins • Winter irrigation – tomatoes, okra, green mealies (maize) cabbage, green beans **Mechanisation Potential** • Ripping, ploughing and mechanised weed and groundnuts lifters • Mobile shellers	Land is not a limitation.	• Cooperative has 148 members, 20% are not actively participating in the irrigation scheme • Current constitution states that underutilised plots should be given to other farmers in the community • This was not implemented due to constitutional issues • Livestock, crop and horticulture production main income sources • Poor water use efficiency due to poor maintenance of the canal. • Fertiliser and transport cost, pest and diseases for tomatoes, okra and winter maize major constraints to production
Malende B	-16.2510581, 27.3891997 Habulonga dam	8 women & 6 males	• Both Dams constructed in 1960s for livestock production	Land to scale is a constraint	• Dam siltation a major problem • Livestock production main livelihood

	Hatambala dam (not visited)		• Siltation a major problem • Dam water is for multiple purpose but mainly livestock water • No active irrigation schemes. Only 11 members irrigating individually, 4 of these irrigators were from other communities renting land • 6 members sharing a water pump and drag horse, the rest are using the bucket system • 2 farmers in the resettlement were using solar drip irrigation via – submissible-tank -drip on their individual farm • Hatambala dams have 13 irrigators using the bucket system, 6 of the farmers are from other communities renting land **Mechanisation Potential** • Highly interested in mechanisation	More than a 40% of the irrigators are renting land	
Chisuwo	Singonya Dam - 16.456078, 27.5756397	63 men 33 women	• 4 dams in the camps along a watershed. • Singonya dam established in 1964 • Dam maintenance by Zambia National Service going on. • Strong community institutions for use and sustainability of the dam. • Only dam well maintained among the 6 dams visited with vegetation • Dam has multipurpose use, but people collect water from the taps around the dam for all domestic purposes • Individual irrigation mostly bucket system only 25% use water pump and drag horse • High willingness to operate as collective irrigation schemes • Rain season - Maize, groundnuts, sweet-potatoes, cowpea, soyabeans, sunflower, cotton okra and pumpkins, bananas • Winter irrigation – tomatoes, okra, green mealies (maize) cabbage, bananas, egg plant Mechanisation Potential	Land readily available at all the 4 dams only need to inform traditional authority to allocate the land for collective irrigation scheme.	• Strong community institutions to manage common property – resources such as dams and grazing lands. • Livestock, crop production and horticulture main source of income • Local market for horticulture products readily available but transport cost is the main challenge • Financial knowledge and access also main problem for increased production. • Market intelligence was also raised as major constraint to production. People do not have the knowledge of what and when to grow different crops. The normal practice is to follow what everyone is growing resulting in flooded markets.

			• Ripping, ploughing and mechanised weed and groundnuts lifters • Mobile shellers		
Chongu	Hachiwa dam -16.0949853, 27.4763584	11 men 4 women	• Dam established in 1970 • Low capacity dries up between October - November depending on the onset of rains • Mainly used as livestock water source for 19 villages • Bucket system individual gardens in the flood plains along rivers	Land is available but crop livestock conflicts very high.	• Strong constitution for dam maintenance for livestock production. • Willingness to form ana irrigation scheme if the water scarcity problem is solved.
Luyaba	-16.121555, 27.337819	Only discussed with key informants The extension office was not informed on time by the district office	Dam constructed in 1960s • Community garden funded by EU with solar -submissible-tank -drip • Individual with very big gardens using fuel water pumps • Winter irrigation – tomatoes, okra, green mealies (maize) cabbage	Land is available	• Community very close to the market about 35km from the main market with a tarred road • Livestock and crop production main sources of livelihood

Annexure 11. High salinity areas in Makueni District, Kenya



Annexure 12. High salinity areas in Nakuru District, Kenya