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Mapping suitability for solar-powered irrigation systems using GIS–AHP in Baringo County, Kenya

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Abstract

Solar-powered irrigation Systems (SPIS) are critical for agricultural production enhancement, food security and climate change adaptation, especially in Arid and Semi-Arid Lands (ASAL). There is increased attention towards shifting to more abundant and cleaner energy potential sources for revitalising irrigation strategies in ASAL areas. This study employed a geospatial approach to identify suitable locations for solar-powered irrigation systems (SPIS) in Baringo County, Kenya. Based on an integrated use of GIS spatial analysis and analytical hierarchy procedure (AHP), suitable locations for solar-powered irrigation were mapped. Precipitation, irrigated areas, proximity to rivers, slope, and solar radiation were analysed and processed to derive spatially explicit SPIS suitability classes ranging from very low to very high suitability. The thematic layers were assigned weights based on Saaty's AHP method, where weights for each factor were determined from a pairwise comparison matrix, and a Weighted Linear Combination (WLC) approach was used to derive the final suitability classes for the county. The findings reveal that approximately 58% of Baringo County falls within the moderately suitable category for SPIS implementation, while 24% of the area demonstrates high suitability. In contrast, only 0.8% of the county's land area was classified as either very low or very high suitability. These results offer critical insights for guiding spatially informed planning and investment in suitable, solar-powered agricultural infrastructure within the region. Furthermore, the findings of the study contribute to the ongoing initiatives on the expansion of irrigable land using low-cost and innovative technologies such as SPIS to put marginally arable land under productive use in Kenya.

Keywords Solar, Irrigation, Suitability, Agriculture, Potential, Spatial analysis

1 Introduction

The global population continues to rise at an unprecedented rate, with projections estimating it will reach 11 billion by the year 2088 [10]. This rapid growth intensifies the demand for food, placing immense pressure on agricultural systems worldwide. Addressing this challenge requires not only expanding food production but also adopting sustainable, climate-resilient practices that safeguard environmental integrity [26, 28, 32]. Furthermore, there is a need to address pressing challenges, such as climate change and complexities in trade and food consumption, that are grappling the present economies [40]. Agriculture globally is affected by a myriad of challenges that need to be addressed in order to sustain livelihoods and reduce food insecurity [25, 40]. Among these challenges are low technological uptake, pests and diseases, and inadequate policies that do not support orientation towards market-based agricultural production, especially in emerging economies. Agriculture remains the backbone of Kenya's economy, employing more than 40% of the total population and over 70% of the rural population [11]. The sector plays a key role in Kenya's economy, contributing towards 33% of the Gross Domestic Product (GDP), 65% of the export earnings, and providing livelihood for more than 80% of the Kenyan population, contributing significantly to food security, income generation, and national development [11]. Despite its significance, the Kenyan agricultural sector is highly vulnerable to climate variability, particularly in arid and semi-arid lands (ASALs), where erratic rainfall and prolonged droughts constrain crop productivity [13]. To address these challenges, technologies, including irrigation, have been promoted as a critical strategy for improving agricultural resilience and productivity [14]. Even further, integrating solar-powered irrigation systems (SPIS) offers a transformative and promising solution to address persistent food insecurity and low crop productivity in regions vulnerable to drought and climate variability. This technology reduces the reliance on unpredictable rainfall and decreases the operational costs for farmers, making irrigation more accessible and affordable. SPIS is a sustainable irrigation solution alternative to conventional irrigation methods, which are often characterized by fuel-based energy sources and unsustainable water management practices, which are both environmentally and economically costly [7, 12]. The growing demand for clean energy alternatives has brought SPIS to the forefront as a sustainable and climate-smart solution, especially in off-grid and resource-constrained regions [16]. Solar energy, being abundant, renewable, and increasingly affordable, offers a viable option for powering irrigation systems, enhancing water-use efficiency, and improving agricultural outputs [17]. The successful deployment of SPIS requires careful spatial planning to ensure that sites meet critical criteria such as adequate solar radiation, proximity to water sources, suitable topography, and potential for irrigation development [17].

Recent advances in Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) provide powerful tools for identifying optimal locations for infrastructure such as solar-powered irrigation. The Analytical Hierarchy Process (AHP), a widely used MCDA technique, enables the integration of expert judgment with spatial data to systematically rank and weight multiple factors influencing site suitability [8, 24, 39]. By employing a Weighted Linear Combination (WLC) of key biophysical and environmental parameters such as precipitation, slope, solar irradiance, irrigation potential, and proximity to water sources GIS-AHP models can provide a robust framework for informed decision-making in resource-scarce settings [45]. Suitability and site selection analysis applying geospatial analysis is widely covered in the literature and the East Africa region. However, the present studies have conducted assessments of land for suitable crops [6, 18, 27], rainwater harvesting [30], and eco-tourism management [48]. The present study contributes to the growing knowledge of SPIS mapping and adoption in

Kenya and the Sub-Saharan Africa region with the ultimate objective of enhancing agricultural production and contributing to enhanced food security.

Baringo County, located in Kenya's ASALs, holds significant potential for agricultural production if supported by reliable irrigation systems, given its vast land area, availability of surface and groundwater sources, and high solar irradiation levels [3]. However, agricultural productivity in the region remains low due to erratic rainfall, recurrent droughts, and overdependence on rain-fed agriculture. Although SPIS present a sustainable, cost-effective solution to enhance water access and improve agricultural resilience, their adoption and implementation in Baringo County are hindered by the absence of spatially informed site selection strategies. This study bridges this research gap by applying a GIS-AHP framework to discover potential areas for solar-powered irrigation in Baringo County. Furthermore, there exists no fine-scale, spatially explicit analysis of SPIS suitability for the region, leaving policymakers without evidence-based site selection tools. The study aims to support evidence-based planning and investment in climate-resilient agricultural infrastructure by delineating priority areas for SPIS development. This approach not only enhances the efficient use of natural resources but also contributes to broader socio-development, including community climate action, food security, clean energy access, and adaptation to climate change. Therefore, the study objectives are (1) to determine the key environmental, technical, and socio-economic factors that condition the adoption and performance of SPIS in Baringo County and (2) to evaluate the spatial and contextual suitability of Baringo County for deploying SPIS technology.

2 Materials and methods

2.1 Study area description

Baringo County, located in the north-rift region, lies between latitudes – 0° 13′S and 01° 38′ N and longitudes 35° 21′ and 36° 30′ E. (Fig. 1). The County's total landmass coverage is 10,850 km^2, and its water mass is approximately 165 km^2. The main water features of the county include lakes (Lake Baringo, Lake Bogoria and Lake Kamnarok), rivers (Molo River, Perkerra River, Ol Arabel River, swamps (Loboi swamp), and flood plains within the region's lake catchments. Baringo County is characterized by four major agroecological zones ranging from humid highlands, sub-humid highlands, semi-humid midlands, and semi-arid lowlands. The county's population is about 609,000, based on the 2019 Kenya Population and Housing Census [23]. Rainfall distribution in the county is based on the diverse agroecological zones, with semi-arid areas receiving a precipitation of 450–900 mm. Semi-humid zones receive rainfall ranging from 800 to 400 mm. The sub-humid areas receive precipitation of between 1,000 and 1,600 mm, while humid zones receive precipitation ranging from 1,100 to 2,700 mm.

2.2 Data and data sources

The data used for this study were obtained mainly from free and open-access geospatial database sources (Table 1). The study considered critical factors for solar-powered irrigation, which comprise both environmental and landscape conditions variables. The selection of the factors was also guided by the availability of reliable spatial data. Therefore, environmental factors that were considered in the study include slope, solar radiation, irrigation zones, precipitation, and water sources. These factors have been

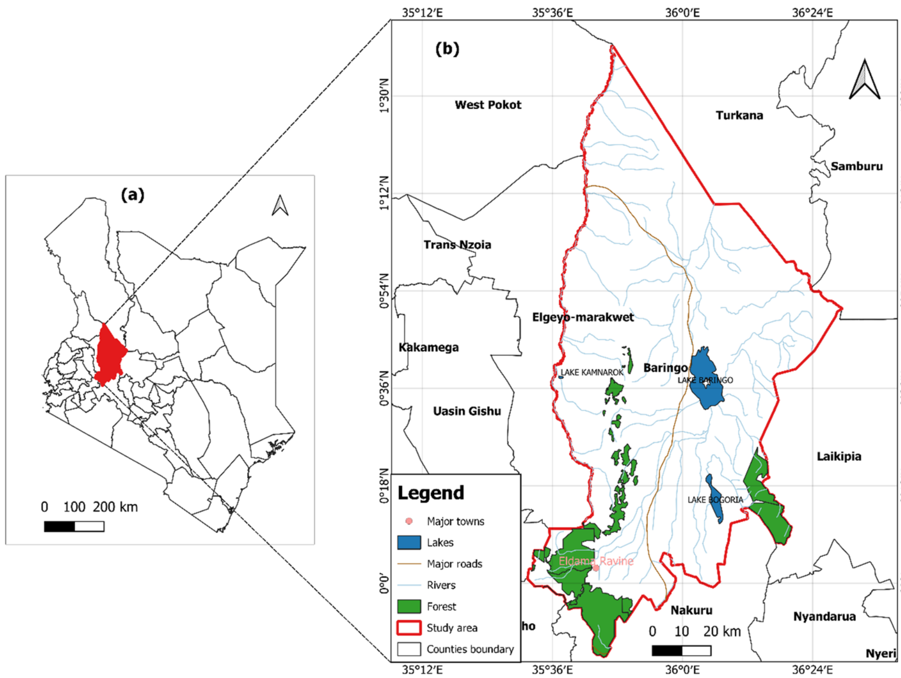

Fig. 1 Map of the Baringo County (**a**) Location of Baringo County within Kenya (**b**) Map of Baringo County. Adapted from Kipkulei et al., [21].

Table 1 Data, data sources and purpose

Data	Source	Resolution	Purpose
Digital elevation model (DEM)	RCMRD portal	30 m	To derive slope and aspect, which was further used in the computation of the solar radiation
Rivers network (Vector)	RCMRD portal	NA	To compute a proximity surface showing proximity to major river sources
Precipitation	Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS)	~ 5 km 1981-present	To derive the annual precipitation for Baringo County
Irrigated lands	International Water Management Institute (IWMI)	250 m	To show areas of different irrigation categories
Baringo County (Vector)	Global Administrative Areas (GADM) Website	NA	To subset all the files to the exact study area bounds

proposed as crucial factors for the development and establishment of solar-powered irrigation [47, 49]. Slope and aspect orientation affect solar energy as they affect the duration of sunshine [2]. Precipitation is another important factor in determining the water needs of the SPIS system. Agriculture in Baringo County and Kenya is predominantly rainfed. Therefore, assessing the variation in rainfall intensities across the region is important in revealing the areas that have huge potential for supporting high water productivity under the systems [9]. Proximity to river sources is another factor considered in the study. Water is a fundamental need for agricultural production. Proximity to river water supports small-scale agricultural activities, which is well established in some parts of Baringo County [19]. River sources also help to supplement precipitation water, especially in seasons of low precipitation. Therefore, a shapefile of major rivers in Baringo County was obtained from the Regional Centre for Mapping of Resources for Development (RCMRD) portal. For the irrigation, a map of irrigated lands was obtained from the International Water Management Institute (IWMI). The irrigation map shows areas for three major categories: water-managed, irrigated, and rainfed systems for both single and double cropping systems in Africa.

2.3 Data processing and harmonisation of datasets

The datasets were processed in the Geographical Information Systems (GIS) environment and the R statistical software environment [35]. Several geoprocessing tasks were implemented, including projecting data to a uniform coordinate system, subsetting it to the study area bounds, and resampling and reclassifying it. The datasets were projected to the UTM projection Zone 37 N, which defines the UTM zones for the region in ArcGIS. Subsequently, the data were resampled to the resolution of the DEM data, which was approximately 30 m. We used the resampling tool in ArcGIS and applied the nearest neighbour resampling technique. The purpose of the resampling is to standardize all the data in a uniform resolution, which permits overlay analysis and subsequent GIS map algebra analysis. Resampling does not necessarily improve the resolution of the specific dataset, but it permits overlay and computations with other datasets. All the datasets were clipped to the Baringo County study outline bounds. The Baringo County shapefile was projected to use the same coordinate system as the rasters before the clipping operation.

Slope and the aspect were derived from the DEM data, which was subsequently used to compute and derive the solar radiation data raster using the r.sun model of GRASS. We used the r.sun model to compute direct beam, diffuse and reflected solar irradiation for a given day for the entire county. In the present study, the clipped elevation, slope and aspect were used to compute the solar radiation data. We calculated the annual irradiation for the region by averaging the individual computed irradiance for days 1, 45, 90, 135, 180, 225, 270, and 315 of the year. This was necessary because computing the daily values is computationally demanding [1, 43]. Furthermore, the selected days considered the differences in the length of sunshine hours throughout the major seasons of the region. This approach of computing solar radiation using topography derivatives was necessary to obtain a high-resolution solar radiation map to incorporate with other variables and to obtain a high-resolution surface for improving smallholder SPIS mapping in the area. Proximity to rivers raster was derived using the Euclidean distance functions in ArcGIS. A cost distance function was not used in this case because, in the study area, irrigation practices are conducted close to water sources [20]. There are very few established infrastructural networks, such as piped infrastructure, that conventionally follow road networks.

All the criteria indicators used in the study are in different units. All the criteria values were standardized using a scale of 1–10 to perform a weighted overlay analysis. A value of 1 indicates minimum importance, whereas 10 indicates maximum importance. Therefore, we classified criteria/indicators using the natural Jenks method. For precipitation, slope, solar radiation, and proximity to river sources, the rasters were on a continuous scale and, therefore, natural Jenks with 10 classes were directly applied in ArcGIS Pro software version 3.4.0. For the irrigation, the values were descriptive, and therefore, we reclassified them on a continuous scale before uploading them to the R environment. In the reclassification, importance was assigned based on management, where areas with no agricultural practices and, therefore, lacked irrigation status were assigned zero, and areas with triple cropping systems and full irrigation were assigned the value of 10. All the maps were generated using the ArcGIS Pro software version 3.4.0.

2.4 Analytical hierarchy process approach

In the present study, we used the Analytical Hierarchy Process (AHP), introduced by Thomas Saaty in 1980. The AHP approach uses pairwise comparisons between variables derived from experimental judgements to derive priority scales [38]. The approach utilizes a multi-criteria decision analysis to enable users to evaluate the relative importance of various intervening factors on geographical phenomena. In assessing the suitability of SPIS, we assigned weights to each parameter/factor based on the relative significance of other parameters. In the AHP process, a value ranging from 1 to 9 is usually assigned to each parameter in the pairwise comparison matrix. A value of one shows equal importance between two parameters, and 9 signifies much higher importance for one factor over the other [46]. The corresponding reciprocal values (1/3, 1/5, 1/7 and 1/9) indicate less importance of a parameter relative to the other. In the present study, we adopted and updated the weights and criteria from previous studies to eliminate discrepancies in weight assignment [2, 4, 5, 10, 15]. Furthermore, we compared the weights and criteria of several factors in SPIS studies in various regions and noted the consistency of the criteria and factor assignment. Therefore, based on the literature criteria, we created a factor-to-factor comparison table and, subsequently, a pairwise comparison matrix (Table 2). We also checked for the consistency of the pairwise comparison using the Consistency Ratio (CR) parameter. CR is determined using Eq. (1), and the Consistency Index (CI) is derived from the comparison matrix, which is obtained using Eq. (2).

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Consistency Index (RI)}} \quad (1)$$

$$\text{Consistency Index} = \frac{\lambda - n}{n - 1} \quad (2)$$

where λ (the principal eigenvalue) is the average of the λi for each variable and n is the number of input variables. The λi value for each variable is calculated using the following formula:

$$\lambda_i = \frac{Sw_i}{w_i} \quad (3)$$

where wi denotes the derived weights for each input variable and SWi is the weighted sum for each variable. The RI in Eq. 1 is a predefined statistical value that provides a benchmark for computing the CR for the pairwise comparisons. The values for the RI for a corresponding matrix size have been provided by Saaty [37].

Table 2 Normalized Pairwise comparison matrix and determined AHP weights of parameters

	Solar radiation	Precipitation	Proximity to the river	Irrigation	Slope
Solar radiation	1	1	3	3	1
Precipitation	1	1	3	5	5
Proximity to the river	0.333	0.333	1	3	7
Irrigation	0.2	0.2	0.333	1	3
Slope	0.111	0.143	0.2	0.333	1
Sum	2.64	2.676	7.533	12.333	17

A CR value below 1.0 indicates correct matrix consistency, making it acceptable for further analysis. This study achieved a CR value of 0.09, indicating good consistency for further analysis.

A weighted linear combination approach was used to produce the final suitability map. Each factor was multiplied by the weights and cumulated to obtain a final suitability surface using Eq. 4.

$$\text{SPIS suitability} = \sum{}_{i=1}^{n} F_i \ X \ W_i \tag{4}$$

where Fi is the specific factor, and Wi is the corresponding weight obtained from the AHP process.

The preliminary processing of the data files was conducted in the ArcGIS environment. In contrast, the final processing, classification and combination of the factors was conducted in the R statistical environment [35]. Figure 2 presents the summary of the workflow adopted in the study.

3 Results

3.1 Thematic layers for SPIS suitability mapping

To assess the SPIS in Baringo County, five key thematic layers were selected and analysed using a GIS-based framework: slope, proximity to river, solar radiation, precipitation, and existing irrigation areas. These layers were chosen due to their efficiency for RWH suitability. The thematic maps are represented in Fig. 3a–e.

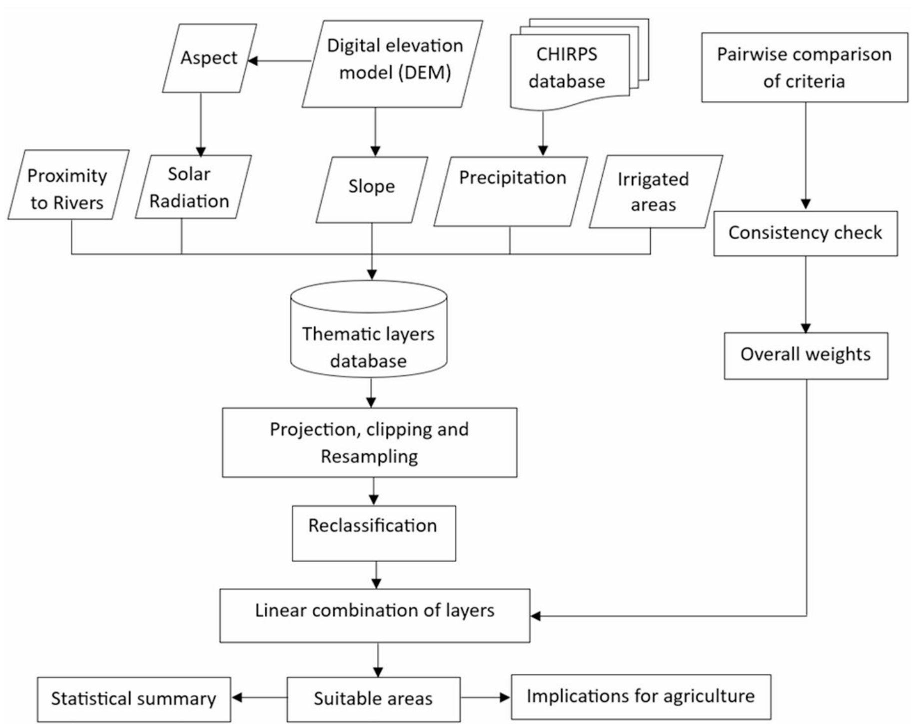

Fig. 2 The summary workflow adopted in the study

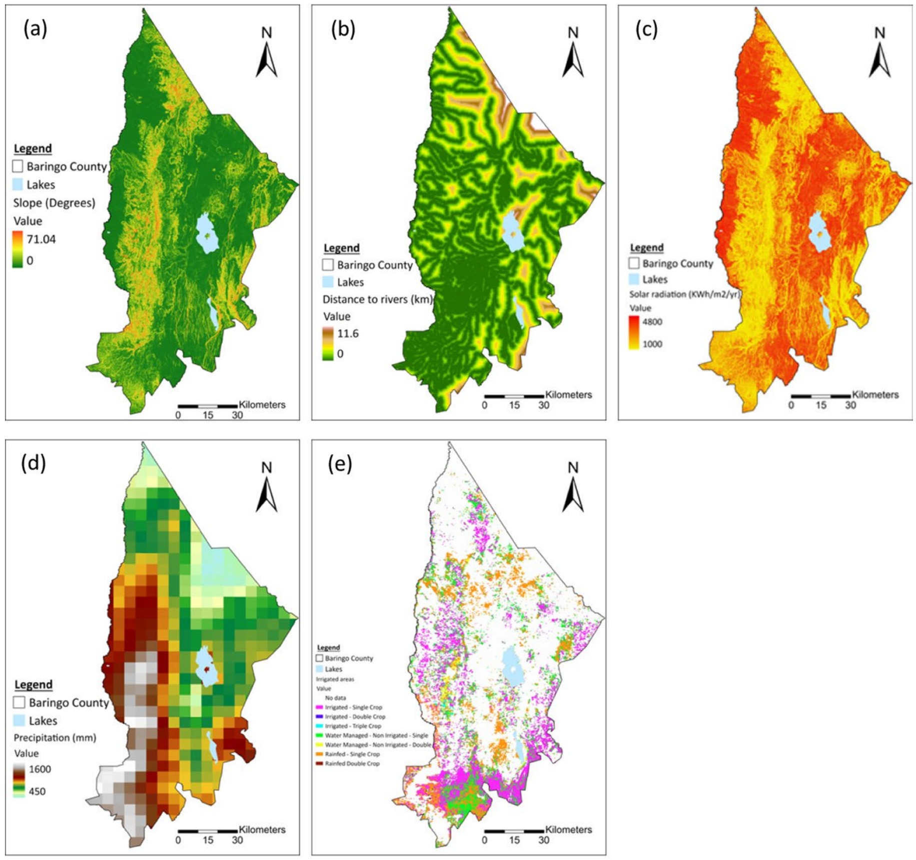

Fig. 3 Slope **a** Distance to Rivers; **b** Proximity to rivers; **c** Solar radiation; **d** Precipitation; **e** Irrigation areas

3.1.1 Slope map

The SRTM DEM was used to derive a slope map with the GIS environment. The slopes in the study zone vary widely from gentle to very rough terrains (Fig. 3a). The slope varies from zero degrees, and the relatively low-lying lowlands are in the north, eastern, and southern parts of Baringo County. The high slope areas representing the Tugen escarpment transcend the south-north central region of the county. Furthermore, gentle and moderate slopes have the largest coverage areas and are distributed across most parts of the county.

3.1.2 Proximity to rivers

The proximity to the river raster (Fig. 3b) shows that the southern regions of Baringo County are close to water sources, which could promote a high uptake of SPIS. The northern parts, however, characterize the Tiaty Constituency and Baringo North as having poor proximity, with regions more than 10 km from a reliable water source.

3.1.3 Solar radiation potential

The solar radiation map (Fig. 3c) reveals that most parts of Baringo County have reliable solar energy, which is required for powering pumps and other devices used to draw water from rivers and ground storage. The solar radiation ranges from 1000 KWh/m^2/year to 4300 KWh/m^2/year. These radiation values are optimal for SPIS systems and can support its uptake in the region.

3.1.4 Precipitation

Precipitation in Baringo County (Fig. 3d) varies from low precipitation areas in the north to high precipitation areas in the south and southwestern parts of Baringo County. Areas that receive high precipitation >1000 mm are in the hilly and forested zones of Eldama Ravine, Baringo Central and the highland parts of Baringo North. The maps also show low precipitation in the lowland regions, which are characterized by the lowland zones of Tiaty and Baringo North Constituencies.

3.1.5 Irrigation areas

The irrigation areas map (Fig. 3e) shows that fewer parts of Baringo County are under irrigation, with irrigation focused on single-crop systems. This is expected as most parts of Baringo are characterized by the cultivation of one crop within a cropping season. The single-crop irrigation areas are predominantly in the southern areas and a few areas around Lake Baringo. Also, irrigation is practised in the western parts, which are areas that border the Kerio River.

3.2 Weight assignment and multi-criteria analysis

In the present study, the thematic layers and features were assigned weights that range from 1 to 9. Subsequently, a pairwise comparison matrix was created for the research criteria, and a normalized pairwise comparison matrix was generated (Table 3). The AHP and eigenvector were used to obtain the normalized weights. The CR value computed from the study was 0.09, which is within the accepted limit of <0.1. Hence, the obtained value confirmed that the chosen criteria are consistent and desirable for further analysis.

3.3 Reclassified maps

The thematic layers were reclassified into 10 classes, reflecting the different suitability levels for SPIS considered in the study. The natural Jenks method was used, and therefore, 10 classes indicating low to high suitability for the individual thematic layers were created (Fig. 4). The Low solar radiation and precipitation values indicate low suitability for SPIS and vice versa. However, the values were reversed for the slope and the proximity to rivers category, where low slopes and proximity to rivers are desirable. For irrigated and water-managed systems had higher values assigned, with the highest value of 10 assigned to the Irrigated and triple-cropping system and a value of zero assigned to no data zones, as they are lowly suitable areas where agriculture is rarely practised.

Table 3 Priority vectors of the different parameters

	Solar radiation	Precipitation	Proximity to the river	Irrigation	Slope	Priority vector
Solar radiation	0.378	0.374	0.398	0.360	0.059	0.314
Precipitation	0.378	0.374	0.398	0.120	0.294	0.313
Proximity to the river	0.126	0.125	0.133	0.360	0.412	0.231
Irrigation	0.076	0.075	0.044	0.120	0.176	0.098
Slope	0.042	0.053	0.027	0.040	0.059	0.044

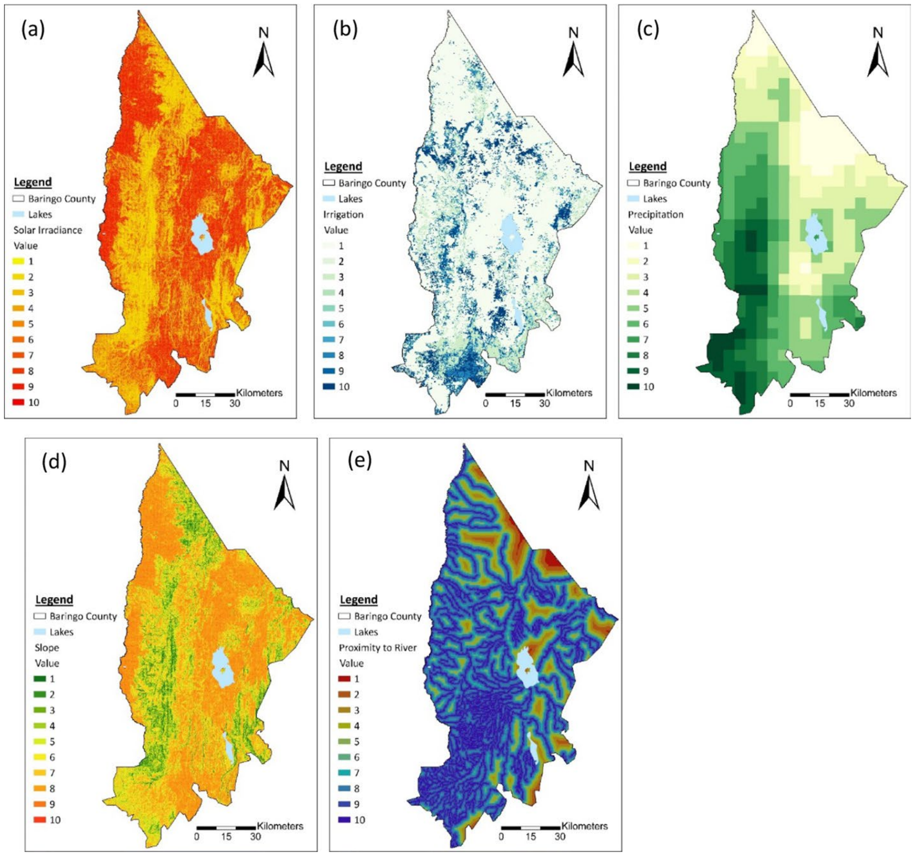

Fig. 4 Reclassified maps for different thematic layers **a** Solar radiation; **b** Irrigation areas; **c** Precipitation; **d** Slope; **e** Proximity to rivers

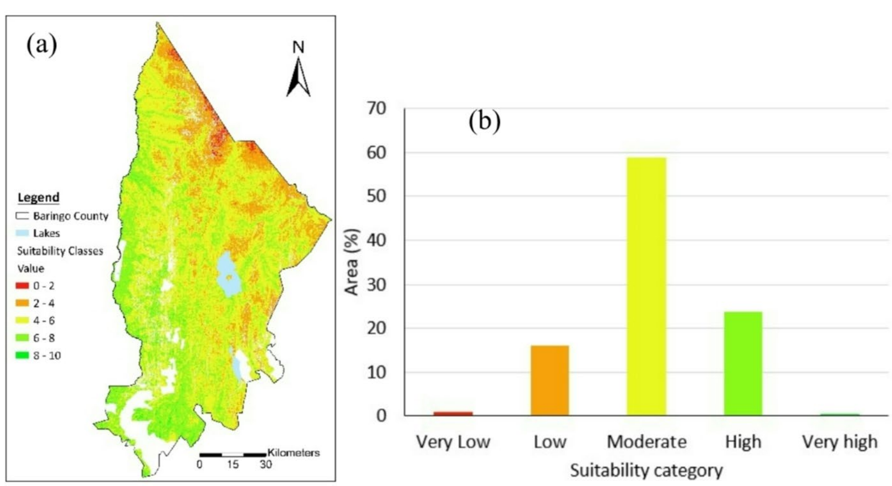

Fig. 5 **a** Solar-powered Irrigation Suitability for Baringo County using the Analytical Hierarchy Procedure and **b** Area proportion of the different suitability categories

3.4 Suitability for solar-powered irrigation systems in Baringo County

The reclassified maps (Fig. 4) and the WLC analysis were implemented to derive the suitability maps for SPIS irrigation for Baringo County. The technique was applied in the R statistical Software environment, and the final suitability map was generated (Fig. 5a).

The SPIS suitability is classified into five categories according to the value: very low (0–2), low (2–4), moderate (4–6), high (6–8), and very high (8–10). The proportion of the suitability categories is presented in Fig. 5b.

Based on the SPIS suitability maps, 0.4% of the county had very low suitability of SPIS. 16% of the land area revealed a low suitability. A large section of the study region (58%) showed moderate suitability, while 24% of the region had high suitability. Only 0.8% of the county reflected very high suitability for SPIS to enhance agricultural production in the region. In terms of location, the very low suitable areas are located in the northeastern part of the county, which are mostly the Tiaty dry areas. These areas do not support agricultural production. The low-suitable zones were mainly in the northern parts. Like the very low suitable zones, these zones have very few agricultural activities. 58% was moderately mapped as suitable for SPIS. The areas are mostly the transition zones between the lowland and the highland zones. The very high and highly vulnerable SPIS areas cover the southern and western regions of the county. These zones are well known for high agricultural production when practised under rainfed and irrigation systems. The stretch from the lower parts of Eldama Ravine along the Kerio Valley fringe to the northwestern parts of Baringo North.

4 Discussion

4.1 Solar power irrigation systems potential

The present study focused on the determination of SPIS suitability sites in Baringo County, Kenya. It is critical to monitor areas where SPIS technology can potentially be utilized to enhance agricultural production and improve food security [7]. SPIS serves to enhance production by utilizing the widely available solar energy in tropical regions. Thus, SPIS technology is crucial in reducing the reliance on expensive fuel-based pumping systems, which additionally adds to the extra burden of climate change in the region [26].

Solar-powered irrigation systems are among the readily available, low-cost, and affordable technologies that can be harnessed for agricultural production [2, 31]. However, limited studies have addressed the potential of these technologies in terms of spatially explicit feasible regions for scaling their uptake. Some studies have tested the viability of solar-powered irrigation systems, albeit at larger scales [31].

4.2 Solar power irrigation systems suitability

In the present study, we established the suitability of SPIS in Baringo County, one of the Arid and Semi-Arid counties of Kenya. Subsequently, various factors which have been tested to contribute to the suitability of the technology were utilized. The factors were derived from literature as implemented in other regions [10, 44]. The study region demonstrates moderate to high potential for SPIS. The suitability regions are mainly located in the western part of the county, which is characterized by sub-humid to arid zones. The northern regions and western parts, however, revealed minimal suitability. These areas are drought-prone, with few rivers and relatively low rainfall [33]. The study further shows that a large part of the region falls under the moderate suitability class. This confirms inherently limited capacities in the region; for instance, most parts of Baringo receive low to very low precipitation, which can lead to low volumes of water for irrigation. Nonetheless, rainwater harvesting structures, for example, bench terraces, check dams, percolation tanks, contour bunds, and contour ridges, could be harnessed for water harvesting in the region [30, 36]. Furthermore, the low suitable zones in the county are usually located in slopy areas where either agriculture is not practised or they do not support effective irrigation mechanisms [34].

Overall, the spatial distribution of suitability aligns with ecological and climatic gradients observed across Baringo County. The results reaffirm the strategic importance of geospatial planning for sustainable infrastructure development, particularly in resource-constrained regions. The study's outcomes can inform targeted investments, aid policymakers in infrastructure prioritization, and support broader goals in climate adaptation, food security, and clean energy deployment.

Future research should consider integrating socio-economic and institutional factors, such as farmer willingness, land tenure, market access, and policy frameworks, which are crucial for the actual implementation and scaling of SPIS [41, 42]. Additionally, ground-truthing and stakeholder engagement can validate model outputs and enhance the relevance of spatial recommendations in real-world agricultural planning. Nevertheless, the current suitability analysis provides a foundational framework to assist the county agricultural department in identifying areas with high potential returns on investment for Solar-Powered Irrigation Systems (SPIS). By leveraging the suitability maps, decision-makers can strategically optimize the deployment of SPIS technology, ensuring that limited financial resources are directed toward regions where they can have the greatest impact on agricultural productivity.

This study has several limitations that offer opportunities for refinement in future research. First, while we adopted commonly accepted conditioning factors for SPIS, other variables, such as groundwater availability, could further strengthen the suitability analysis [10]. However, given the relatively low groundwater potential in the study area compared to other regions in Kenya, its exclusion is unlikely to significantly affect the current suitability classifications. Second, the weighting of conditioning factors was based on values derived from existing literature, which may reflect expert bias from previous studies. To address this, incorporating insights from local experts through interviews could enhance the contextual relevance of the weights. Nonetheless, SPIS conditioning factors tend to be broadly applicable, and we anticipate minimal divergence in expert assessments across different environments. Furthermore, our analysis excluded groundwater and socio-economic factors, which can play a critical role in enhancing the accuracy of mapping SPIS suitability. Another limitation is the risk of bias from literature-derived weights and uncertainty introduced by resampling coarse precipitation data.

Finally, our analysis did not apply land-use constraints when defining suitability categories. The suitability map reflects the assumption that agriculture is uniformly practised across the County. In reality, the region is characterized by both crop farming and pastoralism, the latter of which could also benefit from SPIS, particularly for livestock watering and integrated crop and livestock systems. Future studies could incorporate land use masks to exclude conservation areas, such as forests and protected parks and focus exclusively on zones designated for crop production. Despite these limitations, the resulting suitability map offers a comprehensive regional perspective. It highlights the agricultural potential of Baringo County and underscores the importance of SPIS as a livelihood enhancement technology for local communities.

4.3 Implications of SPIS for enhancing agricultural production and food security

Solar-powered irrigation systems (SPIS) hold significant potential for enhancing agricultural production and food security, especially in the Arid and Semi-arid lands (ASAL) of Kenya. These regions have abundant solar radiation resources, which, if harnessed with water harvesting, could bolster agricultural growth and development in ASAL regions. SPIS adoption is increasingly being promoted in many regions, especially the developing regions of Sub-Saharan Africa, where food insecurity and the rates of land degradation are of major concern. SPIS is becoming a game changer, as shown by an increasing uptake in recent decades. However, there are still limitations that hinder its full uptake, including a lack of technological know-how for installation and maintenance of resources, low financial resources, especially among the smallholder farmers, and low water resources. However, research shows that when low-cost harvesting technologies are integrated with SPIS, agricultural productivity can be enhanced in low-production regions. Baringo County continues to face climate-related hazards, such as invasive species, among other challenges. These challenges can significantly impact agricultural production, which is currently not sufficient to sustain the food and livelihoods of farmers. The county depends on local imports from Nakuru, Uasin Gishu, and Elgeyo Marakwet Counties to bridge the production deficits. As the population increases and the suitability of agricultural areas decreases due to climate change and degradation, SPIS can be harnessed as a potential technology for sustainable agricultural intensification in the region.

Currently, farmers in Baringo County are shifting to cash crops such as coffee, which need attention at the initial stages of growth and establishment. The suitability maps combined with the mapped agricultural resources and water footprint for the county can be used to identify areas for scaling SPIS technologies. Furthermore, the strategy employed in the presented study can be expanded to other climate-change volatile regions in Kenya and East Africa [29]. Furthermore, such practices can be integrated with modelling strategies to mitigate effects brought about by increased abiotic and biotic stresses on food production in the region [22].

4.4 Limitations of the study

The present study assessed the suitability of Baringo County for SPIS implementation. Whereas the study presented a spatially varying potential of the region that could potentially guide policy interventions, the present study presents a few limitations that could be considered in future studies. The study did not present an accuracy assessment, which plays a key role in evaluating the robustness and generalizability of suitability outputs intended to inform decision-making. Future studies could align study findings with practicable interventions to assess the response of SPIS on outcomes such as crop production or crop health. Another limitation of our study is the identification of a very low percentage of the study region in the very high unsuitable category. This could be a result of our model being overly conservative. Nonetheless, future studies could assess the sensitivity of the parameters, especially to slope and solar radiation thresholds, which reflect more on the socio-economic barriers to SPIS adoption. Finally, future studies could consider expanded factors to aid more robust analysis in the region or other similar regions.

5 Conclusions

This study successfully applied a geospatial framework to map the suitability of Solar-powered irrigation systems (SPIS) across Baringo County, Kenya. Using GIS and the analytical Hierarchy Process (AHP), five critical parameters, including solar radiation, precipitation, proximity to rivers, slope, and existing irrigation areas, were integrated to create a comprehensive suitability map. A large share of the study areas shows moderate suitability, with localized high-suitability areas concentrated in the south and west. 58% of the county falls under the moderate suitability zone, whereas 25% is highly suitable for SPIS. The study revealed that only 1% of the county falls under the very highly suitable region for SPIS. Nonetheless, the study demonstrated that most parts of the county are suitable for SPIS and can be integrated as technologies to enhance food production and climate change adaptation in the region. These insights underscore the strategic potential of SPIS to enhance agricultural productivity, promote climate change adaptation, and improve food security in arid and semi-arid regions. The suitability maps generated in this study can serve as a critical decision-support tool for county governments, development partners, and smallholder farmers in prioritizing areas for irrigation investment and resource allocation.

Ultimately, this study contributes to the growing body of knowledge advocating for sustainable, clean, energy-driven agricultural solutions, especially in drought-prone and resource-limited settings. Additionally, the suitability maps can guide resource allocation, irrigation planning, and donor investment. Future efforts should focus on integrating socio-economic factors, ground truthing and farmers' adoption studies to further refine spatial planning and ensure the practical success of SPIS implementation. Furthermore, follow-up studies should incorporate farmer readiness, infrastructure accessibility, and groundwater availability.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44288-026-00535-0.

Supplementary Material 1.

Author contributions

HKK: Writing – review & editing, Writing – original draft, Visualization, Coordination, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. MB: Writing – review & editing, Writing – original draft. AA: Writing – review & editing. ASL: Writing – review & editing. GU: Writing – review & editing. MBM: Writing – review & editing. BR: Writing – original draft, Visualization, Formal analysis, Methodology, Writing – review & editing.

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Data availability

The datasets used to generate the present study findings and the R code used in the suitability modelling are available from the corresponding author upon a reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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