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GIS Based Site Suitability Analysis for Location of a Sugar Factory in Trans Mara District

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Abstract

Domestic sugar production in Kenya does not meet consumption demand. Consequently, expanded production and creation of more sugar mills within regions of high agricultural potential is necessary for expansion of the industry. Suitable arable land for such projects in Kenya is scarce, and essentially planners must select the best use of this resource to uphold sustainability. Although locating optimum sites for new industrial investments is important, it involves evaluation of conflicting criteria with large sets of alternatives. The complex nature of finding industrial investment locations requires a technique that can combine geographical data with value judgments. This research aims at finding the most suitable sites for a sugar factory in Trans Mara district in Kenya, using GIS based Multi-criteria evaluation. Nine factors including slope, an existing factory location, roads, rivers, electricity sources, land use, soil texture, rainfall, and temperature were selected based on reviewed literature and opinion of experts. Selected factors were then organized into two broad principal classes including physical site conditions and sugarcane crop requirements. Digital data on selected factors was acquired from various governmental institutions, stored, harmonized and geo-processed in Arc GIS 10.1 platform to generate factor maps.

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Analytical hierarchy process (AHP) was used to elicit weights which were assigned to each factor. Weighted factor maps were finally standardized, reclassified and combined by weighted linear combination (WLC) aggregation method. The composite suitability map produced shows that 2.02 % of the total area is highly suitable, 13.54% is moderately suitable, 82.33% is marginally suitable and 2.11 % is unsuitable. Highly suitable sites fall outside ecologically sensitive areas, and lie within reasonable distance to power lines and major roads. The implication of these results is that GIS-MCE application in industrial sites selection minimizes environmental risks and reduces engineering costs.

Keywords: AHP; GIS; Multi-criteria evaluation; Site suitability analysis.

1. Introduction

Sugar industry is a major contributor to agricultural sector gross domestic product (AGDP) and a key source of livelihood for most households in western Kenya [10]. Despite favorable sugarcane growing conditions in the region, low productivity has been reported during the past decade [11]. Domestic demand for sugar is currently estimated at 780,000 metric tons against an average production of 500,000 metric tons. This leaves a deficit of up to 280,000 tons [4] which is met through imports from external sugar producers [10]. Importation of sugar has been a worrying trend because it contributes to influx of cheap sugar from external markets and loss of foreign exchange [20]. Newly developed sugar mills can implicitly spur growth by subjecting existing ones to competition, while harnessing the benefits of industrial agglomeration. Although potential benefits for creating new sugar mills are many, scarcity of suitable arable land, rapid increase in population growth rate, dwindling governmental funding, and public health concerns, coupled with stiff political and social opposition complicates the task of identifying suitable locations [19, 14]. Moreover good sugarcane farming techniques require spatial analyses for crucial information and various key factors must simultaneously be considered to locate highly suitable areas for such a vital development [5, 9]. To alleviate high socio-economic impacts affecting farmers and millers due to the decline in the sugar sub sector, development of new sugar mills in high agricultural potential areas is critical. Although industrial location has become an increasingly important decision facing both national and international firms [30, 15], there are no operational measures of critical factors affecting such locations in the study area. Consequently determining capable sites and finding an optimal site among the alternatives are two key challenges that investors must face. In industrial site selection processes, final decisions are based on the evaluation of a number of alternatives in terms of a number of criteria [23, 8]. An effective technique that can integrate geographical data with value judgments to support decision making processes is therefore necessary. Among the geo-information techniques with widely recognized capabilities that are used for evaluation of suitability factors and allocation of various measures of suitability to specific sites [1, 28] are the GIS combined with MCE. To effectively analyze complex tradeoffs involving multiple criteria, GIS can perform deterministic buffers, overlays and other geo-processing operations, while multiple criteria procedures can be used to evaluate alternatives based on value judgments [6, 29]. This ideally has led to frequent application of GIS-MCE in identification of suitable areas for land development currently [25, 16, 22], which effectively reduces engineering costs and minimizes adverse impacts to the environment. GIS-MCE technology is fully integrated and widely accepted for assisting government agencies to manage programs that support farmers and protect the environment. The aim of this research is to apply GIS-MCE techniques in selecting sites which are highly suitable for construction of a sugar factory within Trans Mara District in Kenya. It should be mentioned however that there is an existing sugar factory in the study area. To select a suitable factory site several factors were considered such as slope, existing factory, roads, rivers, electricity sources, land use, soil texture, rainfall, and temperature.

2. Materials and Methods

2.1 Study Area

Trans Mara district is located in the south western part of Kenya. The district lies between latitude 0º 50' and 1º 50' south, and longitude 34º 35' and 35º 14' east, with a surface area of approximately 2,932 km^2, Topographically the district is classified into highlands and the plateau. The highlands are important watersheds for the numerous small streams and rivers flowing in the south western direction. These highlands rise from 2200 m to 2500 m above mean sea level, while the plateau rises from 900 m to 2200 m above mean sea level. Annual mean temperature ranges from 17^{0}c to 26^{0}c. Rainfall pattern is bi-modal with annual mean rainfall of 1600 mm. Principal wet season occurs between February and June while short rains are experienced between August and November. Most roads are loose surface type but sufficiently provide essential movements and linkage to spatial activities. A sparse network of telecommunications towers provides cellular phone coverage. Broadband services are not widely available and GIS is not readily used. The total population is approximately 274,532 with concentrations varying across administrative areas. Towns and market centers constitute pockets of high population density.

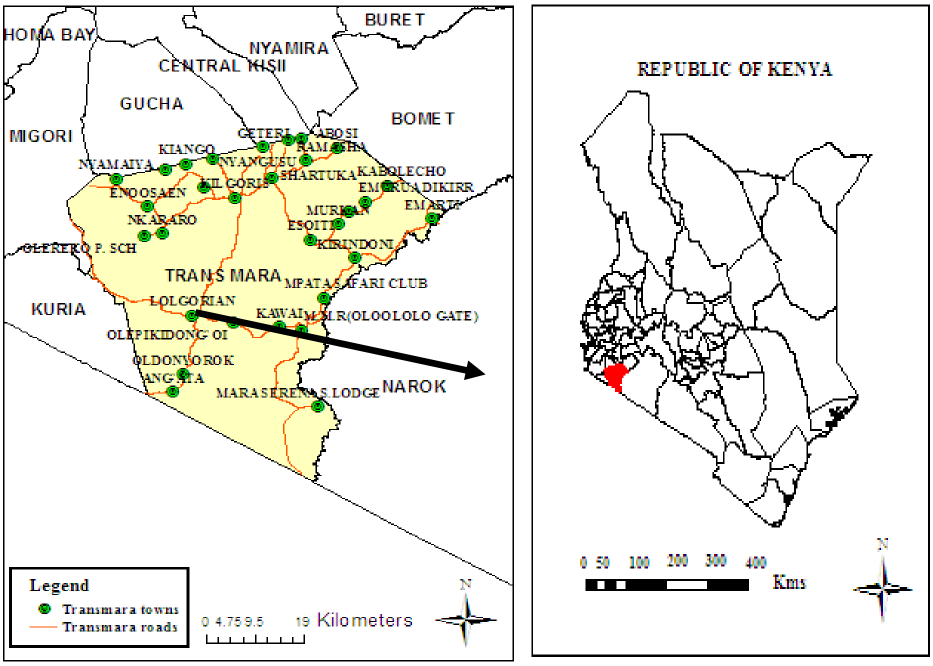


Figure 1: Study Area Map

A significant town is Enoosaen where an existing sugar factory is located. Soil texture is classified into four classes: sandy, loamy clay and clayey. Most parts have clay soils rich in fertility and water retention while some parts have large pockets of loamy soils suitable for agriculture. Despite the varied characteristics of the soils the district is classified as arable. Power transmission line share the same pattern with the road network. Existing land uses include agriculture, bush lands, wood lands, grass lands and forests. Tourism is the most significant economic activity in the region.

2.2 Data and Materials

Data is the raw material from which every information system is built. The ability of GIS to handle and process geographically referenced data distinguishes it from other information systems [1]. Digital data in raster and vector formats were collected from various governmental institutions for preparation of factor maps. The data collected include a 30m resolution digital elevation model (DEM), district boundaries, towns, rivers, soil texture, power line, land use and climate. Availability of all data in digital format enabled easy transfer of files into GIS system. Personal interviews with field experts provided vital information on suitability factors and value judgments for subsequent elicitation of weights. Literature from various publications was accessed through the internet and reviewed to identify knowledge gaps on suitability modeling and measures that can be put in place. A more significant aim in reviewing literature was to identify techniques used in similar studies and possible factors to incorporate in this analysis. To implement the suitability analysis practically, ArcGIS soft ware package and its extensions were used.

2.3 Study Approach

Nine suitability factors were selected based on reviewed literature and opinion of experts. The factors were classified into two principal classes including physical site and sugarcane crop requirements. Physical site factors are slope, distance to roads, distance to rivers, distance to existing sugar factory and distance to power transmission lines while sugarcane crop factors are soil texture, land use, rainfall and temperature.

Steps used to implement the analysis include data collection, database development, data processing, integrated analysis, display, and reporting. A single evaluation index was developed through the steps by integrating information from suitability factor maps. AHP process was used to elicit relative importance weights for each specific factor. Figure 2 shows the various steps used in the processing and analysis of data. A geo-database was developed using GIS functions for collecting, storing, transforming, analyzing, and displaying spatial data [2, 18]. Collected data on slope, roads, rivers, electricity, existing factory, soil texture, land use, rainfall, and temperature, were stored in Arc GIS 10.1 format and thematic layers prepared for each factor. The layers were harmonized by projecting to a common standard WGS 1984 UTM rectangular coordinate system [27]. The slope was developed from a 30m resolution DEM. Due to the numerous seasonal rivers the layer for rivers was edited to extract major streams and rivers. Using the distance operation raster datasets for rivers and roads were produced. Raster models are very useful for storing and analyzing data that is continuous across an area. To define a zone of a specified distance around existing factory location and power lines GIS buffer process was used. This process was further used to determine proximity relationship between defined zones [24]. Raster datasets for rainfall and temperature were generated using inverse distance weighted interpolation (IDW).

Subsequently the output raster datasets were clipped to the boundary shape file for the study area.

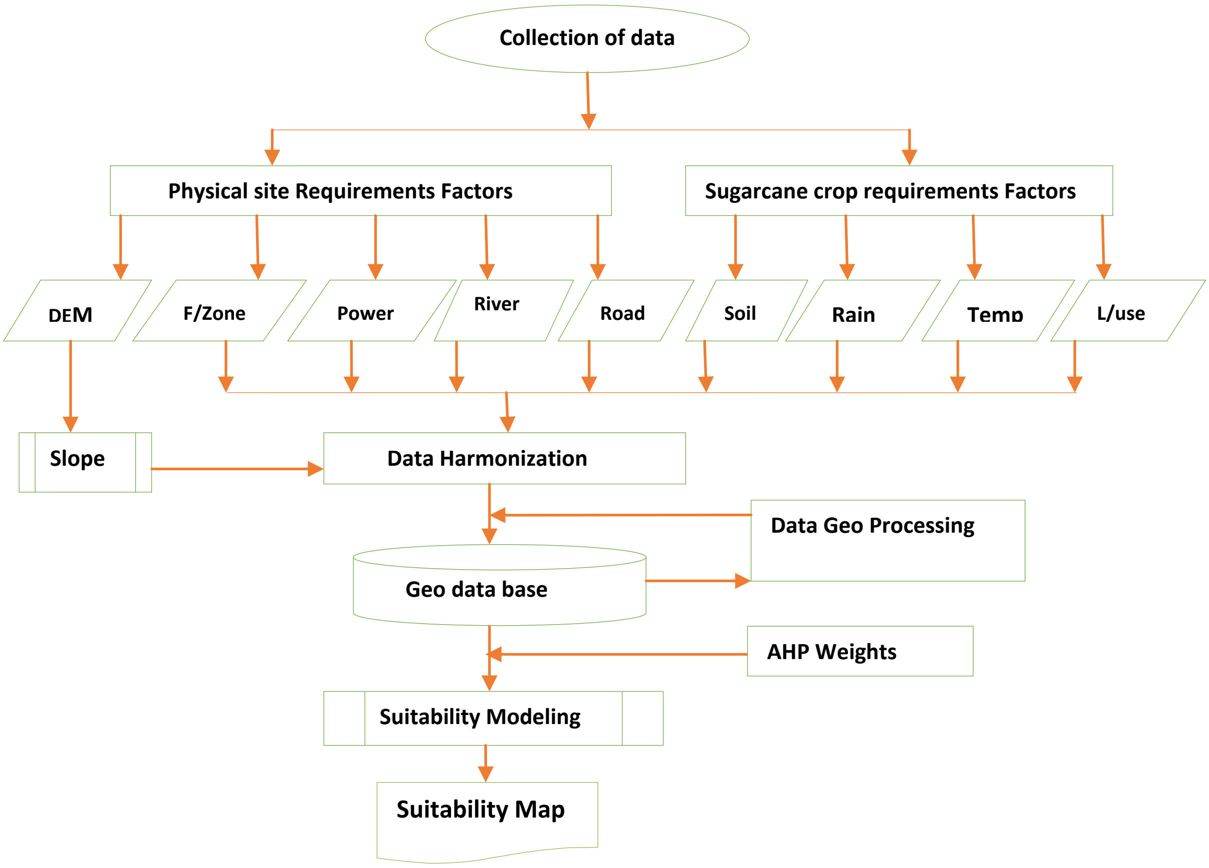


Figure 2: Flowchart for methodology

Table 1: Suitability Parameters

		Suitability Levels			
Suitability indicator	unit	S3	S2	S1	N
Slope	degrees	15-30	10-15	0-10	<30
Factory buffer	Kilometers	10-15	15-30	>30	0-10
Roads	meters	>7000	6000-7000	2000-6000	0-2000
Rivers	meters	>5000	3000-5000	1000-3000	0-1000
Electricity	Kilometers	5-10	1-5	0-1	10-33
Land use	Class	Woodland & Grass land	Bush land	Agriculture	Forest
Soil texture	class	Clayey	Clay	Loam	Sand
Rainfall	mm	1500-1570	1570-1670	1670-1975	1430-1500
Temperature	^{0} Celsius	19.2-19.3	19.3-19.5	19.5-20.5	19.1-19.2

Vector formats are very useful for representing and storing discrete features, however overlay analysis is more easily performed using raster datasets. Consequently vector data sets for land use, soil texture, power line and existing factory buffers were converted into raster formats and reclassified alongside other raster datasets. Reclassification into a common four point scale was based on the structure of Food and Agriculture Organization (FAO) for land suitability assessment. Suitability levels were ranked as highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N) as shown in Table 1. Relative importance weights (RIWs) were elicited by AHP process which is a decision support tool that can be used to solve complex decision problems [11, 3, 9]. The process applies a multi-level hierarchical structure of objectives, criteria, sub criteria, and alternatives [17, 32]. The developed hierarchy is shown in figure 3. It includes the goal at the first, two principal factors at the second, and nine subsidiary factors at the third, alternatives are at the last level respectively.

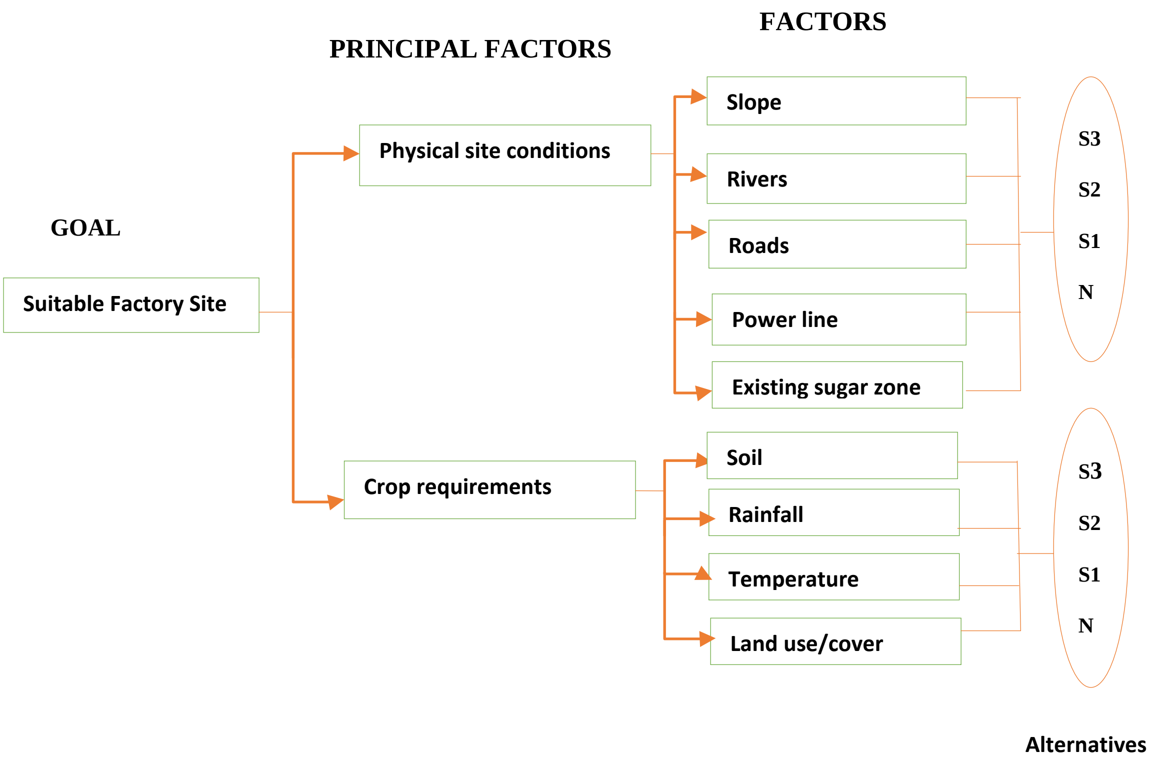


Figure 3: AHP Hierarchy Levels

The essence of AHP is to construct a comparison matrix expressing the relative values of a set of attributes. During personal interviews, the field experts expressed their opinions about the value of one single pair wise comparison at a time [26]. These opinions were useful in the construction of pair wise matrices and determination of RIWs. Principal factors' RIWs were derived in terms of the research goal while RIWs for subsidiary factors determined in terms of respective principal factors. Pair wise comparison employs an underlying scale with odd values from 1 to 9 to rate relative preferences for any two elements of the hierarchy [12]. Even values between odd values 2,4,6,8 indicate a compromise values between immediate odd values [31]. To determine RIWs, elements of each column are added and the respective sums used to normalize each individual elements in the respective column. Normalization involves dividing each matrix element by the respective column sum. The mean of the normalized elements along the row of a matrix determines the RIWs which are used in ranking of factors. Determination of RIWs demonstrates the ability of AHP in ranking of choices based on effectiveness in meeting conflicting objectives [13]. To derive consistency ratio value for each matrix, maximum Eigen vector value (λmax) was used to derive the Consistency Index (CI). λmax is a product of a row and a column vectors derived from the pair wise matrix. The row vector comprises of the sums of columns in the Pair wise matrix while the column vector comprises of the RIWs elements. To calculate consistency index the difference between the maximum Eigen vector and the number of elements (n) under comparison (λmax-n) is divided by a value (n-1). The consistency ratio is derived by dividing, consistency index with corresponding value of random index values generated by professor Saaty.

2.4 Weighted Overlay

Spatial analysis usually involves more than one geographic dataset and requires working through a series of steps to reach a final result [1].

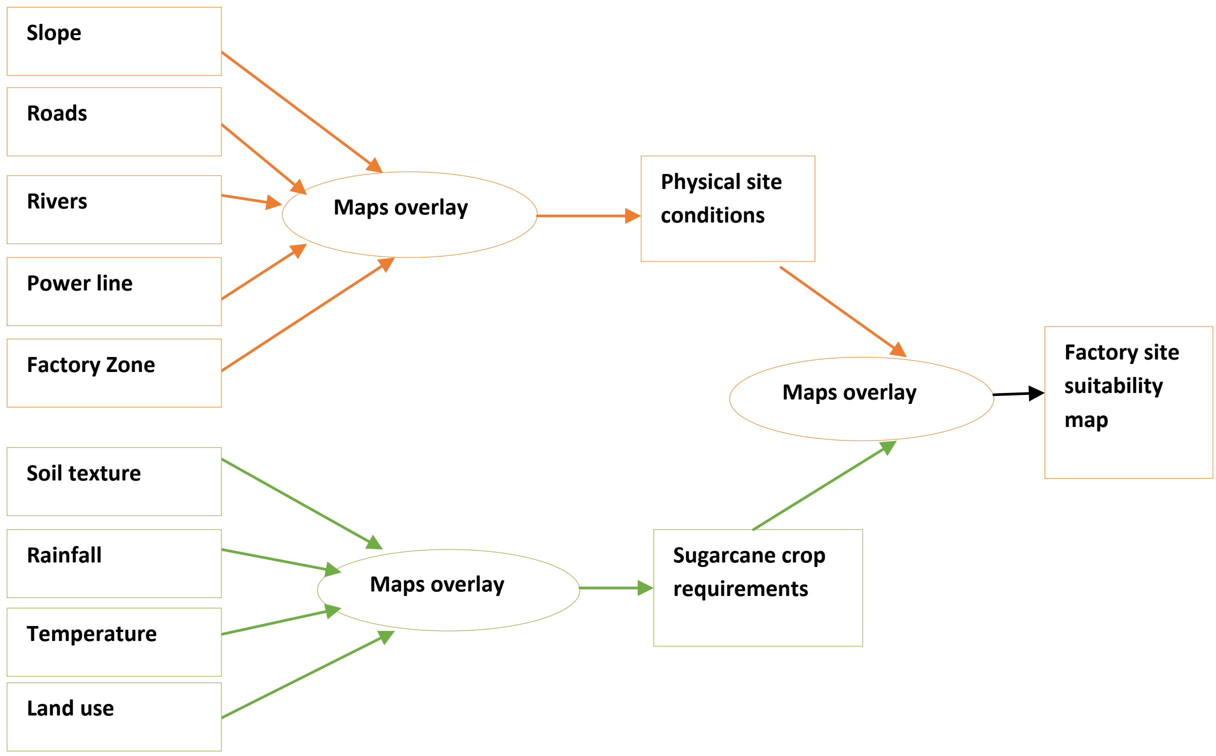


Figure 4: Flow chart for Modeling Suitability

Weighted overlay was performed in three stages. Physical site suitability layers were combined to produce the first composite map layer and sugarcane crop suitability layers combined to produce the second composite map layer. The final suitability map was produced by combining both the two weighted composite map layers. Figure 4 shows the flow chart for overlay analysis model.

3. Results and Discussions

Reclassifications maps of respective thematic layers using a common four point scale are shown in various maps from figure 5 to figure 13. The most suitable slope falls within 0-10 degrees sown in orange color. It covers a very large area. Steep slope is not suitable for construction purposes but fortunately this is a very small proportion of the study area. The most suitable zone for the roads is shown in figure 6. It is between 2000m - 6000m. This zone is shown in light blue color and covers an area which is sufficient in supporting industrial activities. Areas adjacently close to the rivers are ecologically sensitive hence not suitable for industrial use. These are olive colored areas between 0-1000m as shown in figure 7. Highly suitable areas on the rivers layer are limited and shown in light blue color. The most suitable land use class is agriculture which covers a large proportion of the study area as shown colored with light green in Figure 10. The most suitable class for the river falls between 1000m - 3000m which is farther away to avoid pollution and yet within reasonable distance for tapping the water resources.

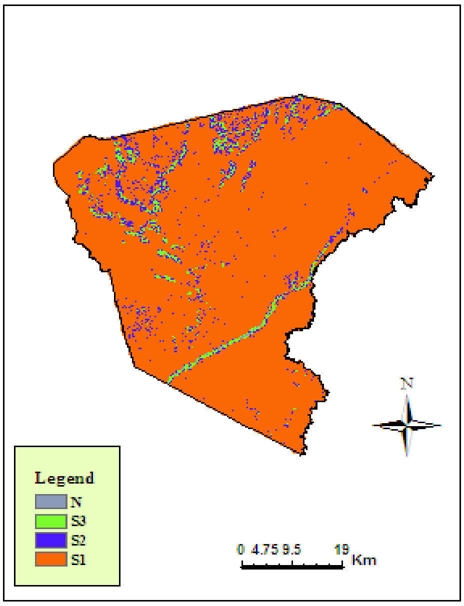


Figure 5: Reclassified slope map

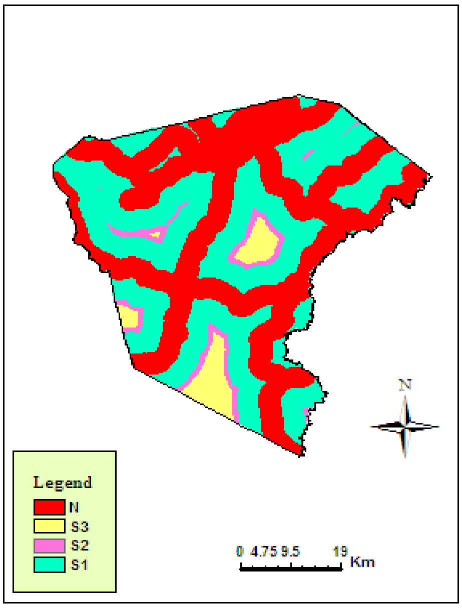
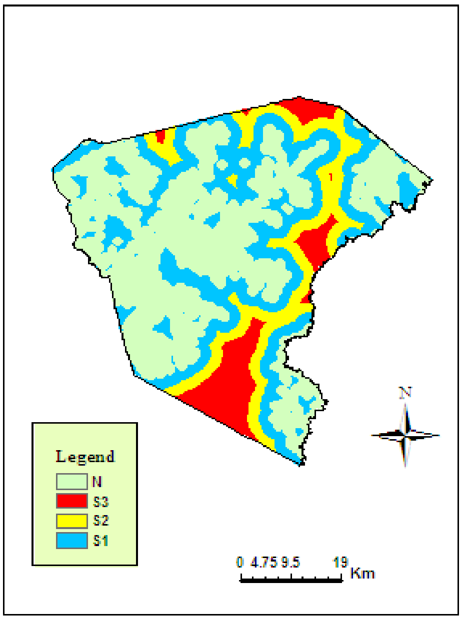


Figure 6: Reclassified Roads

The most suitable zone for existing factory is beyond 30 m radius and a region within which both the new and existing factory can constructively share limited resources constructively. The zone is shown using green color in figure 8. The most suitable zone on the power line map is a small proportion stretching between 0-1 Km. Beyond this zone the costs for extending new transmission lines and installation of power transformers is high. This class is shown in yellow color in figure 9.

Loamy soil texture class is very suitable for sugarcane crop cultivation. Large pockets of light green colored loamy soils are shown surrounded by the predominantly pink colored clay soils in figure 11. Highly suitable rainfall range is from 1670mm to 1975mm. It is shown colored orange in figure 12. The temperature pattern is similar to the rainfall pattern with higher temperatures experienced in the north and west of the study area. Figure 13 shows the most suitable temperature class colored in red.



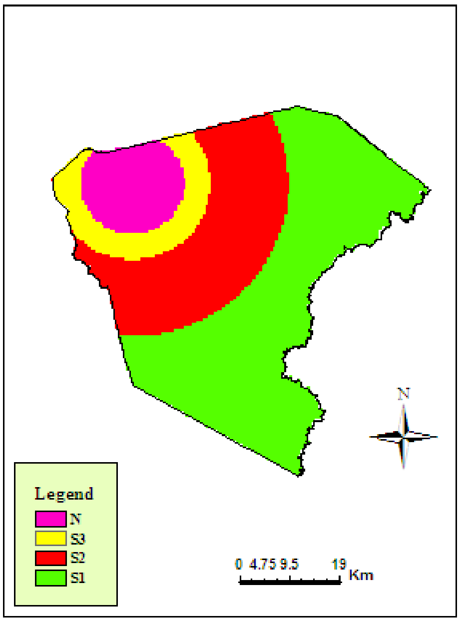
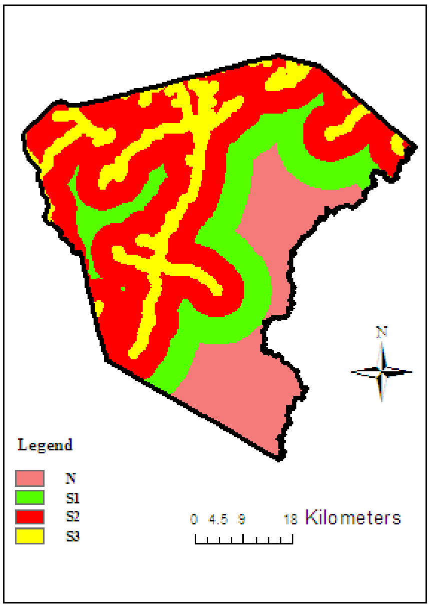


Figure 7: Reclassified Rivers

Figure 8: Reclassified Factory buffer



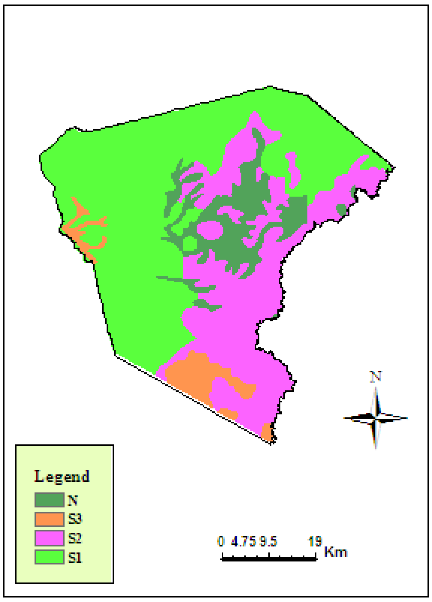


Figure 9: Reclassified power line

Figure 10: Reclassified land use map

3.1 Weighting of variables

Pair wise comparisons between the physical suitability factor and sugarcane crop suitability factor indicates that sugarcane crop suitability is three times more important than the physical site suitability. RIW for sugarcane crop factor is 0.75 while the RIW for physical site factor is 0.25. The maximum Eigen value for the principal factors' matrix is 2, consistency index value is 0 and the consistency ratio value is 0. Values of RIWs for slope, roads, rivers, power lines and existing factory in the physical site suitability matrix are shown in Table 2. Determined values for physical site suitability include maximum Eigen value which is 5.252316667, consistency index is 0.063079166 and the consistency ratio is 0.056320684. In the sugarcane crop suitability matrix, the maximum Eigen value is 4.073333333, consistency index is 0.024444444 and the consistency ratio is 0.027160493. Table 3 shows the pair wise matrix for the sugarcane crop requirement factors as well as the determined RIWs values and ranks. The consistency ratio values are below 0.1 hence acceptable.

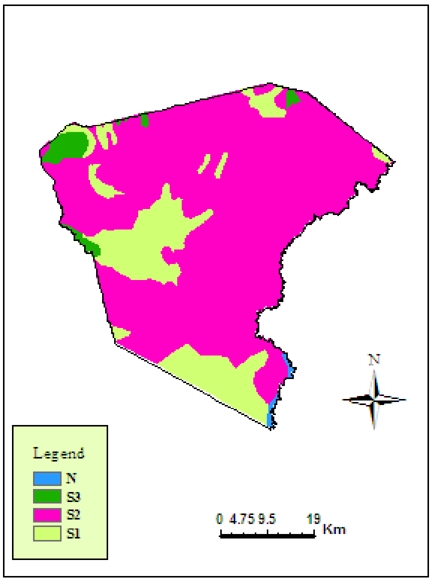


Figure 11: Reclassified soil texture map

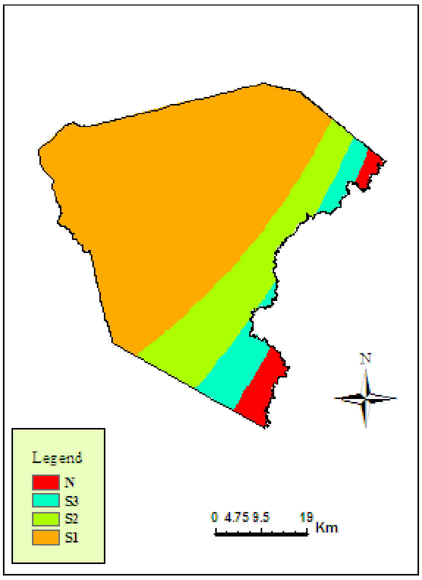


Figure 12: Reclassified rainfall map

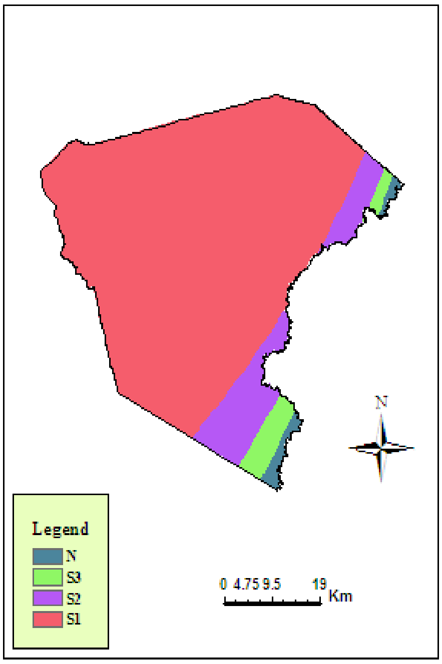


Figure 13: Reclassified temperature map

3.2 Weighted Overlay

Physical site suitability is represented on a map in figure 14. The shows that the most suitable class is 0.09 %

and covers 2.47 sq km, moderately suitable class is 10.59 % and covers 299.88 sq km, marginally suitable class is 82.50 % and covers 2335.48 sq km while the unsuitable class has 6.82 % and covers 193.10 sq km. Figure 15 show the map of sugarcane crop suitability which shows that the most suitable class is 2.05 % of the total area and covers 57.32 sq km, moderate suitability class is 81.82 % and covers 2283.68 sq km, marginally suitable class is 13.57 % and covers 378.61 sq km while the unsuitable class is 2.56 % and covers 71.37 sq km. The final suitability map is shown in figure 16. It is an overlay product of the physical site suitability map and the sugar crop suitability map. There are seven most suitable sites displayed in dark green color. A large section is moderately suitable and shown in light blue color while marginally suitable areas are shown in dark blue color. Areas not suitable are shown in pink color.

Table 2: Pair wise comparison matrix for physical site factors

Factors	slope	Rivers	Roads	Electricity	Factory zone	Priority vectors	Rank
Slope	1	2	1/2	1	2	0.2115	3
Rivers	1/2	1	1/2	1	1/2	0.1312	5
Roads	2	2	1	1	3	0.3050	1
Electricity	1	1	1	1	2	0.2165	2
Factory zone	1/2	2	1/3	1/2	1	0.1358	4
Total	5	8	10/3	9/2	17/2	1.0000	

λ_{Max} = 5.252316667 CI = 0.063079166 CR = 0.056320684

Table 3: Pair wise comparison matrix for sugarcane crop factors

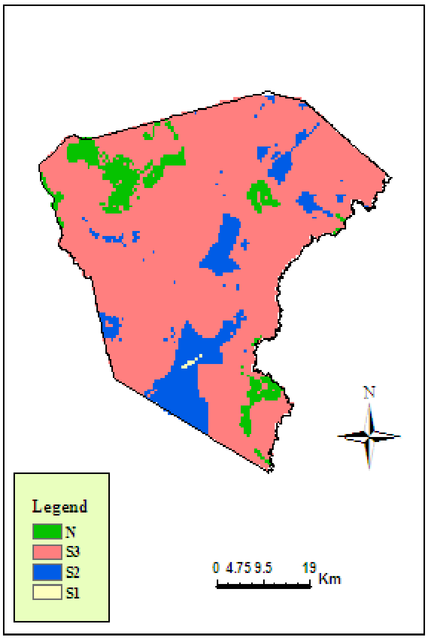
Factors	Soil	Rainfall	Temperature	Land use	Priority vectors	Rank
Soil	1	2	2	3	0.4168	1
Rainfall	1/2	1	1/2	2	0.1928	3
Temperature	1/2	2	1	2	0.2695	2
Land use	1/3	1/2	1/2	1	0.1203	4
Total	7/3	11/2	4	8	1.0000	

λ_{Max} = 4.073333333 CI = 0.024444444 CR = 0.027160493

Final suitability map show that the most suitable section is 2.02 % of the total area and covers 56.20 sq km. Moderately suitable area is 82.33 % and covers 2289.34 sq km. Marginally suitable area is 13.54 % and covers 376.46 sq km. Area not suitable is 2.11 % and covers 58.66 sq km.

4. Conclusion

Sugarcane is the third largest contributor to GDP after tea and horticulture. Local sugar producers are able to meet only two thirds of consumption needs. The low domestic production influences high social-economic impacts to farmers, a worrying situation that calls for urgent measures.



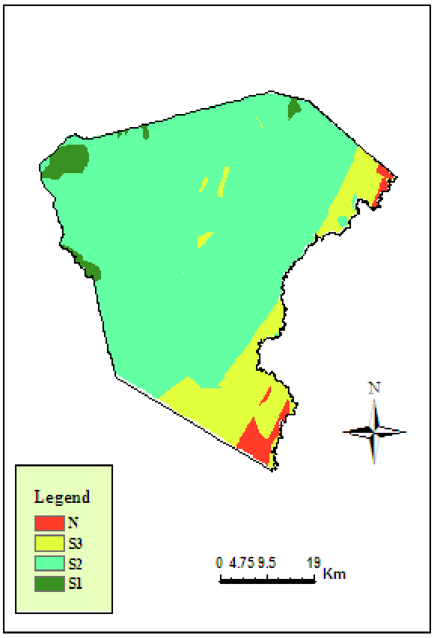


Figure 14: Physical site suitability map **Figure 15:** Sugarcane crop suitability map

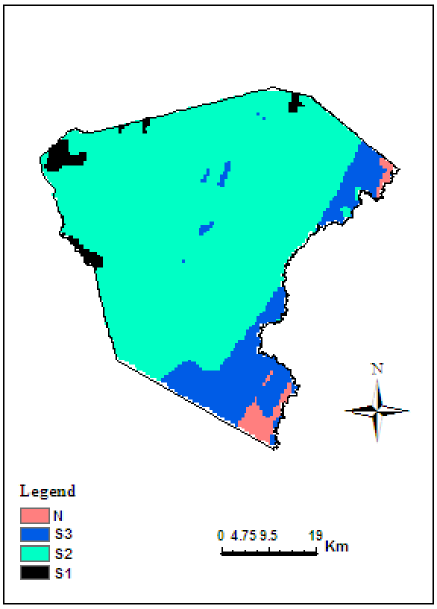


Figure 16: Final suitability map

A key strategy is to create more sugar mills within high agricultural potential areas. This will boost production and help bridge the gap. The newly created sugar industries will provide adequate jobs and elevate the standards of living of those in targeted regions while the government will benefit from increased tax base. Suitable land for such projects is however scarce and planners must selecting the best use for each specific land unit for sustainability. Respect for existing legislation, and increased public awareness of environmental issues increasingly makes the selection of suitable locations more complicated. Consequently a comprehensive evaluation of a set of factors and balancing of multiple feasible objectives is therefore necessary to determine suitable site locations. This calls for an approach that can integrate geographic data with varied decision makers' preferences. Accordingly GIS-MCE techniques have recognized capabilities that can combine geographic data with value Judgments. The objective for this study was to identify a suitable sugar factory site in Trans Mara district, Kenya using GIS-MCE techniques. To implement the suitability analysis based on AHP method, steps including database development, data processing, integrated analysis, display, and reporting were used to combine information from identified suitability factors. The results of the final suitability map show that 2.02% of the total area is most suitable, and 82.33% is moderately suitable. 13.54% is marginally suitable, and 2.11% of land is not suitable. Seven different sites were identified as highly suitable lie outside ecologically sensitive areas, are easily accessible and within reasonable distance to electric power and water resources. The soils and the weather conditions are equally favorable. This study has shown that GIS techniques are essential in selecting suitable sites for land development. Application of GIS technology can minimize negative environmental impacts by locating industries in safer locations and reduce engineering costs. More importantly application of GIS ensures sustainable industrial development that is vital in achievement of vision 2030 goals. The approach used should however be improved by enhancing public participation in order to reduce social opposition that is often associated with such investment decisions. Field work is necessary on the identified sites to ensure that there are no conflicts between the selected sites and the local communities' land interests hitherto not captured in the available GIS research data. Perhaps more importantly, the research project can be improved by incorporating land parcel data and population statistics.

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