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Mango suitability evaluation based on GIS, multi criteria weights and sensitivity analysis

Ranya Fadlalla Abdalla Elsheikh[1,2] *, Abdul Rashid B. Mohamed Shariff[3] and Nilanchal Patel[4]
Department of GIS, Faculty of Engineering, School of Survey Sudan University of Science and Technology, Sudan[1]
Department of Geographic, Faculty of Arts & Humanities King Abdulaziz University, Saudi Arabia[2]
Geospatial Information Science Research Centre (GIS RC), Faculty of Engineering, University Putra, Malaysia[3]
Department of Remote Sensing, Birla Institute of Technology, Mesra, India[4]

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Abstract

The integration of Geographic Information System and Multi Criteria Analysis has proved to be an indispensible tool in land suitability evaluation, especially when the spatial problems are characterized by multiple alternatives. Nevertheless, in the execution of the models based on these methods and techniques, little attention has been paid to the evaluation of the final results and to priority of weights. The purpose of this paper is to produce an agricultural land suitability evaluation system using Geographic Information System and Multi Criteria Analysis. A new method based on GIS, Sensitivity Analysis and mathematical variations analysis is developed to determine the weights of the parameters. This method measures the stability of results with respect to the variation of different parameter weights, and displays spatial change dynamics. The criteria for spatial analysis comprised five factors viz. soil, flood potential area, erosion risk, topographic, and climate maps. The findings showed that soil, slope and erosion represented the most important factors in the study area. Conversely, climate and flood were found to be less important. This method would improve the reliability of multi criteria decision problem output and provides mechanism for non-experts to explore the priority of each criterion and reduce subjectivity of weights.

Keywords

GIS, Spatial, Evaluation, Suitability, Weight, Sensitivity Analysis.

*Author for correspondence

1. Introduction

Land evaluation process has changed through the time in terms of its scope and purpose; from broad based land use planning for development projects to solving multiple issues of land development, such as technical, environmental and socioeconomic [1, 2, 3]. Land evaluation is very important since there is a high demand worldwide for information on the suitability of land for a wide range of uses. Selection of the land use type that meets the objective of socio-economic, physical and environmental conditions is an issue of hot debate between scientists and land users [4]. Land use could be in the context of agriculture, engineering, forestry, or recreation. Agricultural resources are considered to be one of the most important renewable and dynamic natural resources. Hence, agriculture becomes one of the most popular area where land suitability is applied [5, 6, 7] .In recent times, specialists have been resorting to formulate agricultural land suitability assessment as a Multi-Criteria Decision Making (MCDM) issue in a GIS environment [8]. Determination of optimum land use type for an area involves integration of data from various sources like soil, topography and meteorology [7]. All these are considered as criteria in MCDM. However all the criteria are not equally important; every criterion will contribute towards the suitability with different magnitudes. Relative importance of these parameters should be well evaluated to determine the suitability by multi criteria evaluation techniques [9]. To generate the criterion values for each evaluation unit, each factor is weighted according to the estimated significance for particular project. One of the popular multi criteria methods is ranking. Although this method is simple, it lacks the mathematical foundation and it is difficult to get accurate expression of relative preferences on the criteria due to the limitations of the 9-value scale

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of Saaty [10]. To overcome this problem Saaty proposed the pairwise compression. This method was developed in the context of the Analytic Hierarchy Process (AHP) [11]. The AHP has been employed in the GIS-based land use suitability procedures [12, 13, 14]. This method involves pairwise comparisons to create ratio matrix. It takes as an input, the pairwise comparisons and produces the relative weights as output. Most of the previous studies in land suitability analysis created the pairwise comparison matrix subjectively [15, 16, 17, 18, 19, 20]. In many practical cases the human preference model is uncertain and decision makers might be reluctant or unable to assign exact numerical values to the comparison judgments [21]. Since criteria weights are subjectively defined and can affect decision outcomes substantially, they are often the source of the greatest controversy and uncertainty, especially in pluralistic decision-making contexts [22, 23]. Therefore, MCDA models should be thoroughly evaluated to ensure their robustness under a wide range of possible conditions [10].

Sensitivity Analysis (SA) is a way to address this uncertainty in estimating the parameters [24]. [25] review how sensitivity analysis has been applied to GIS-based MCDM models. They found that SA method most frequently used is based on the variation of the weights of the factors implied in the process to test whether it significantly modifies the results obtained. SA offers interesting possibilities to determine what the most important parameters are in a given model. On the other hand SA is not as common as it ought to be [25]. The most critical shortcoming of SA procedures found in GIS-MCDM applications is the lack of insight into the spatial aspects of weight sensitivity [26].

Improved methods for assessing criteria weight sensitivity are required. This paper presents a novel and simple approach to reduce subjectivity of weights and it also aims to improve current GIS-based multi criteria methods by producing more realistic weights. A comprehensive case study of land suitability evaluation focusing particularly on mango cultivation in Terengganu, Malaysia as a practical case study is described to illustrate the procedures.

This method measures the stability of results with respect to the variation of different parameter weights, and displays spatial change dynamics. The land suitability assessment relied on the FAO framework of 1976, with some necessary modifications to suit the local environmental conditions. Fourteen land characteristics and their threshold values were determined for the study area and grouped into nine land qualities. The criteria for spatial analysis comprised five factors viz. soil, flood potential area, erosion risk, topographic, and climate maps. The investigation was performed based on a weighting scheme where in weighting for each factor within the model was varied in turn while keeping the weights of the other factors unchanged. This method would improve the reliability of multi criteria decision problem output and provides mechanism for non-experts to explore the priority of each criterion and reduce subjectivity of weights.

2. Methodology

2.1 Study Area

This study was conducted in the State of Terengganu, West Malaysia. Terengganu is located at the east coast of Peninsular Malaysia. It is located between latitudes 05°51′ 06″ N and 03°55′ 37″ N and longitudes 102° 21′ 11″ E and 103° 31′ 28″ E (Figure 1).

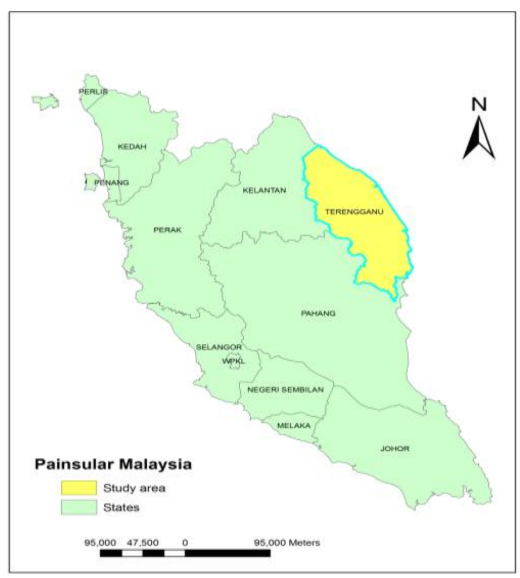

Figure 1: Location of the study area (DID, 2006)

2.2 Material and Criteria

Different data sources were used to analyze the land suitability. The list of data sets and their description are summarized in Table 1.

Table 1: List of data sets used in the study

Type of Data	Description	Source
Soil chemical and physical values	Profile data for each type of soil	1992-2006 Department of Agriculture (DOA)Kuala Lumpur
Soil map	Soil semi detail map, scale 1:25000	2006 DOA Kuala Lumpur
Terrain	The terrain value extracted from the topographic map for each soil type	2006 DOA Kuala Lumpur
Landuse map	Scale 1 :50000	2006 DOA Kuala Lumpur
Rainfall precipitation	Monthly rainfall from 34 stations during 10 years	1996-2006 Department of Irrigation and Drainage (DID)
Length of dry season map	Scale 1: 50000	2006 DOA Kuala Lumpur
Drainage network	Scale 1:25000	2006 DOA Kula Lumpur

Three criteria were used to select the land qualities such as the effects of land quality upon use, occurrence of critical values for the land quality within the study area and the practicability of obtaining information on the land quality [2]. A spreadsheet was formulated to examine the three criteria. The land quality was selected only if it was very important or moderately important, while less important land quality was omitted from land suitability assessment. As a result, a set of required land qualities and their associated land characteristics have been selected. These land characteristics comprise annual precipitation, length of the dry season, slope, texture and structure, base saturation, depth to sulphuric horizon, soil depth, soil reaction (pH), soil organic matter, cation exchange capacity, coarse fragment (gravels and stones), drainage class, soil erosion and flood risk. The basis, upon which the threshold values were selected, was data and information and trials available from the local studyarea. The previous studies considered the analysis of geo-environmental factors and produced two layers for erosion [27, 28, 29] and flood [30, 31] that are reclassified into five classes to produce suitability input layers. The Universal Soil Loss Equation (USLE) was applied in the GIS to determine the average annual soil loss in the study area (Figure 2). The flood risk map was created using the GIS and AHP method (Figure 3). Five layers (soil, climate, erosion hazard, flood and topography) were overlaid and ranked based on the suitability of mango. All the spatial criteria were prepared considering the suitability of Mango, which were further formatted to make them compatible with GIS environment and finally converted to raster format.

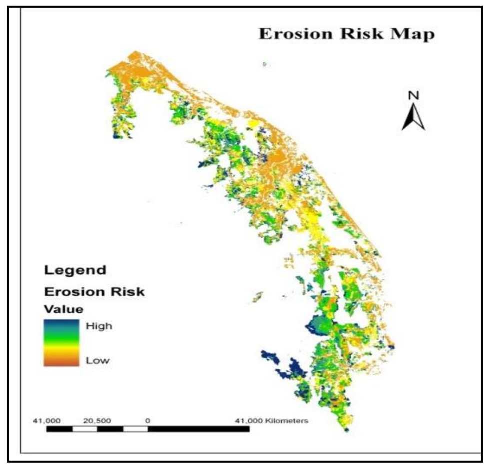

Figure 2: Erosion risk map of the study area

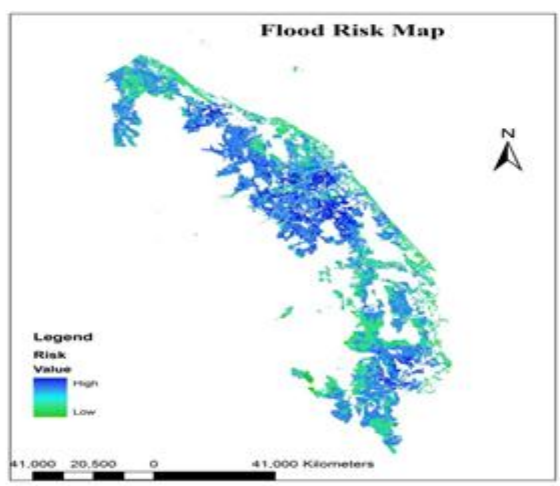

Figure 3: Flood risk map of the study are

2.3 Model Builder

In the model builder of GIS, the function 'classify' was created for each of the five criteria to replace the values with the new information. The five classification layers were overlaid to generate the suitability layer for mango.

2.4 Sensitivity Analysis

Sensitivity analysis was employed to find out the influence of the different criteria weights on the spatial pattern of the suitability classification for mango plantation. This is useful in situations where uncertainties exist in the definition of the importance of different criteria [32]. Sensitivity analysis was employed to determine the level of importance of each criterion used in the study and also, to reduce the subjectivity of weights.

If R5 is the five dimensional space, function S, the suitability classification for mango is defined on R5, as a function of five variables:
S = f(so; sl; c; f; e);

Where so is soil, sl is slope, c is climate, f is flood and e is erosion. The arguments of this function satisfy the condition: R5 = W1so + W2sl + W3c + W4f + W5e = S (S1, S2, S3, S4, S5)
W1+W2+W3+…+Wn= 1 (1)

Where W is the level of importance (i.e. the influence of the criteria in the dimensional space).
n is number of criteria.
The function S takes values from 0 till 100.
S1: Highly suitable S2: Moderately suitable
S3: Marginally suitable , S4: Marginally not suitable
S5: Permanently not suitable

Different scenarios were applied for each criterion. The aim of each scenario is to identify criteria that are especially sensitive to weight changes and visualize the spatial change dynamics. The most important parameter is considered as the one that is most sensitive to input weight changes. Accordingly, the level of importance for each criterion can be determined. To achieve this, different weighting schemes were applied for the suitability criteria. If the first scenario was to test the sensitivity of soil weights on the output and W1 refers to weight of soil, then

W2=W3=Wn= (100-W1)/ n-1 (2)

In the basic computation, an equal weight of 23.75% was given to each of the five criteria viz. climate, soil, slope, flood and erosion. Twenty six weighting schemes were constructed and run using the model's implementation in ArcGIS (Table 2).

Table 2: Weighting Scheme

Scenario	Model Run	Soil%	Slope%	Climate%	Flood%	Erosion%
	1	5	23.75	23.75	23.75	23.75
	2	20	20	20	20	20
Soil	3	35	16.25	16.25	16.25	16.25
1	4	50	12.5	12.5	12.5	12.5
	5	65	8.75	8.75	8.75	8.75
	6	80	5	5	5	5
	7	23.75	5	23.75	23.75	23.75
		20	20	20	20	20
Slope	8	16.25	35	16.25	16.25	16.25
2	9	12.5	50	12.5	12.5	12.5
	10	8.75	65	8.75	8.75	8.75
	11	5	80	5	5	5
	12	23.75	23.75	5	23.75	23.75
		20	20	20	20	20
Climate	13	16.25	16.25	35	16.25	16.25
3	14	12.5	12.5	50	12.5	12.5
	15	8.75	8.75	65	8.75	8.75
	16	5	5	80	5	5

	17	23.75	23.75	23.75	5	23.75
		20	20	20	20	20
Flood	18	16.25	16.25	16.25	35	16.25
4	19	12.5	12.5	12.5	50	12.5
	20	8.75	8.75	8.75	65	8.75
	21	5	5	5	80	5
	22	23.75	23.75	23.75	23.75	5
		20	20	20	20	20
Erosion	23	16.25	16.25	16.25	16.25	35
5	24	12.5	12.5	12.5	12.5	50
	25	8.75	8.75	8.75	8.75	65
	26	5	5	5	5	80

2.5 Variations of Function

The influence of each criterion can be visualized in the spatial pattern for each scenario while the variations of function were used to test the stability of the result. The primary aim of the study is to determine the most important indicator for mango; therefore the consideration was given to the highly suitable (S1 class). The following equation was used to calculate the variations in function for S1

$$Vj = \sum \left| f(xi+1) - f(xi) \right| \qquad (3)$$

Where V= Variation of function, j= Number of scenario.
The weights for each criteria based on variations of function were determined by dividing the variance of each criteria by the total variance.

3. Results and Discussion

For the purpose of sensitivity analysis, suitability map for every weighting scheme was created in the GIS. The outputs (suitability maps) were compared to assess the influence of each criterion on the overall suitability for mango. Tables 3 to 7and figures 4 to 9 illustrate the visual assessment of the suitability classes and the percentage area calculation of the suitability classes that were performed to interpret the output of the sensitivity analysis. From the tables, and by comparing the percentage area of the high suitable class (S1) for the different weighting scheme, the sensitivity of the suitability criteria was assessed. Table 8 summarizes the calculations of weights for each parameter based on the results of variations of function. From the table, based on the outputs of sensitivity analysis for mango it can be noticed how the suitability patterns have changed with the variations of the weighting schemes. For soil and slope criteria, there were significant changes in the highly suitable class when the soil weighting changed. For erosion criterion, the result indicated that there were minor changes in the highly suitable class, but lesser changes in the soil and slope criteria. The sensitivity analysis for the flood and climate revealed that there was only slight change in the highly suitable class when the slope weighting varied.

Table 3: The result of weighting schemes for soil scenario (1)

Model Run	S1%	S2%	S3%	N1%	N2%	Sum
1	17	11	52	15	5	100
2	27	14	43	10	6	100
3	18	56	19	4	3	100
4	30	45	12	8	5	100
5	59	19	12	5	5	100
6	64	14	12	2	8	100

Example for calculation of the weight of criteria (e.g. soil); after determining the variance of each criterion ($V1_{soil}$ = |(17–27)| +|(27–18)| + |(18–30)| + |(30–59)| + |(59–64)| = 65;

The weight for each criteria based on variations of function were determined by dividing the variance of each criteria by the total variance.(Refer to data in Table 8)

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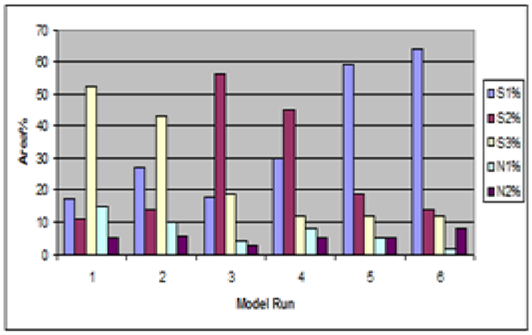


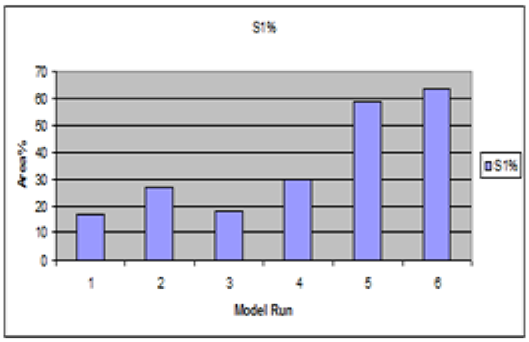
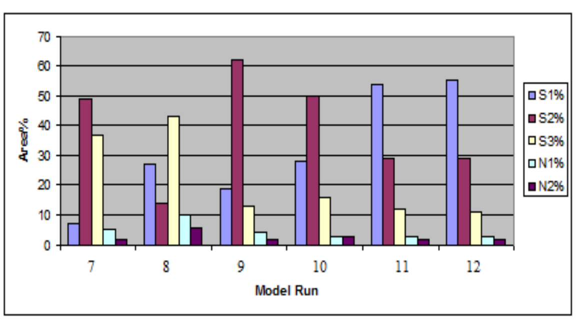


Figure 4: The area of land suitability classes for soil scenario.

Table 4: The result of weighting schemes for slope scenario (2)

Model Run	S1%	S2%	S3%	N1%	N2%	Sum
7	7	49	37	5	2	100
8	27	14	43	10	6	100
9	19	62	13	4	2	100
10	28	50	16	3	3	100
11	54	29	12	3	2	100
12	55	29	11	3	2	100



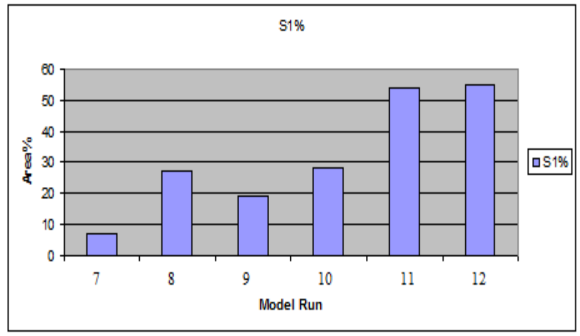
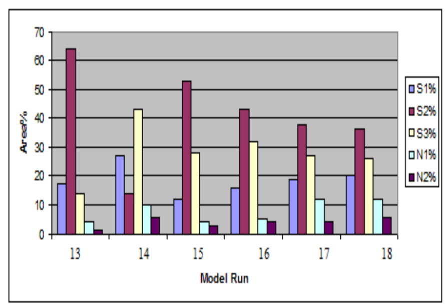


Figure 5: The area of land suitability classes for slope scenario

Table 5: The result of weighting schemes for climate scenario (3)

Model Run	S1%	S2%	S3%	N1%	N2%	Sum
13	17	64	14	4	1	100
14	27	14	43	10	6	100
15	12	53	28	4	3	100
16	16	43	32	5	4	100
17	19	38	27	12	4	100
18	20	36	26	12	6	100



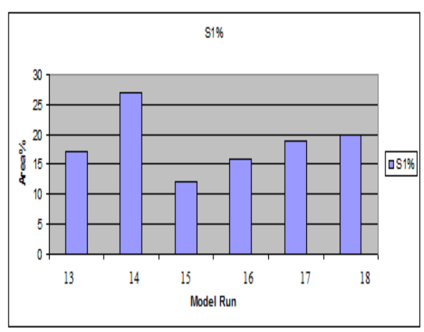


Figure 6: The area of land suitability classes for climate scenario

Table 6: The result of weighting schemes for flood scenario (4)

Model Run	S1%	S2%	S3%	N1%	N2%	Sum
17	32	54	9	3	2	100
2	27	14	43	10	6	100
18	3	44	45	6	2	100
19	1	26	45	26	2	100
20	1	29	23	45	2	100
21	1	33	2	56	8	100

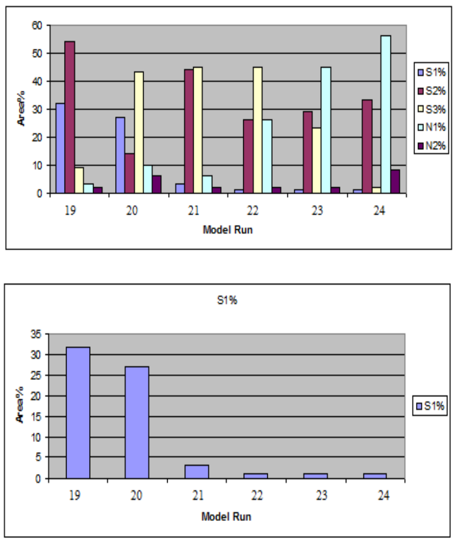
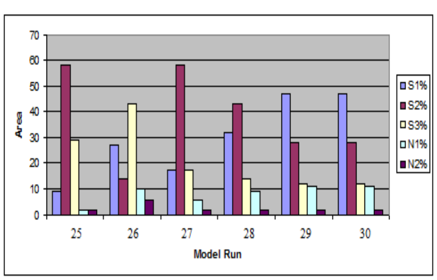


Figure 7: The area of land suitability classes for flood scenario

Table 7: The result of weighting schemes for erosion scenario (5)

Model Run	S1%	S2%	S3%	N1%	N2%	Sum
25	9	58	29	2	2	100
26	27	14	43	10	6	100
27	17	58	17	6	2	100
28	32	43	14	9	2	100
29	47	28	12	11	2	100
30	47	28	12	11	2	100



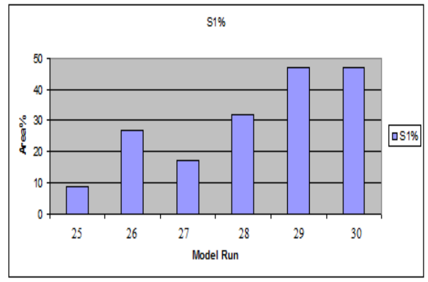


Figure 8: The area of land suitability classes for erosion scenario

Table 8: Weight of each parameter based on variations of function

Criteria	V	Weight
Soil	65	0.26
Slope	64	0.25
Climate	33	0.14
Flood	31	0.12
Erosion	58	0.23
Total	251	1
Criteria	V	Weight

3.1 Conventional Scenarios

Conventional method was used for further validation of the parameter weights. Different range of weights was used for each scenario and forty schemes were applied. The variation of function was calculated again and the results were compared with the results from first weighting scheme. The results of the conventional weighting schemes for each scenario indicated the same level of importance for each parameter. The soil parameter is the most important factor, followed by slope, erosion, climate and flood. The value of variation can be changed from one method to another, depending on the number of weighting schemes (model runs). The variation increased when sample number increased.

3.2 Overall Evaluation

The overall suitability map for mango was produced based on five layers of data: soil, slope, climate, flood and erosion. Figure 9 presents the overall suitability map for mango. The weighted overlay process was used, and the weights generated from sensitivity analysis and variation of function, were applied to different thematic layers. The results of the analysis indicated that 31% of the study area was identified as the most suitable place for mango (class 1), 55% of the area as moderately suitable area (class 2), 9% percent as marginally suitable area (class 3) and the remaining portion (5% percent) as not suitable area (class 4 and class 5).

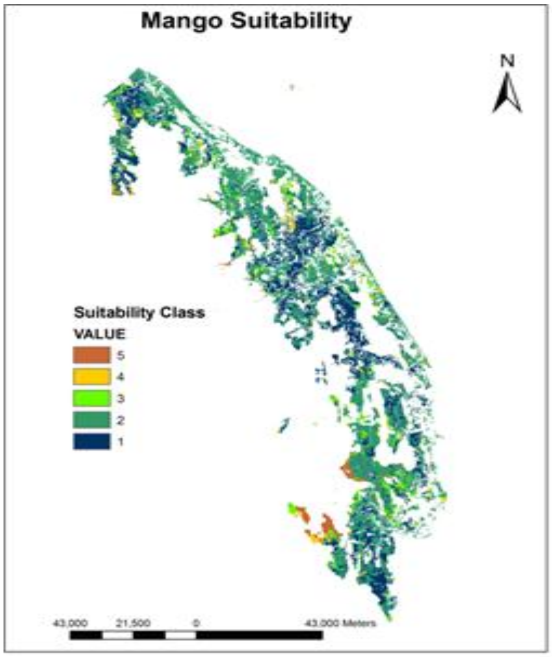


Figure 9: Mango suitability classes

4. Conclusion

The integration of GIS-based Multi-Criteria Evaluation with Sensitivity Analysis was employed to determine more flexible and more accurate decisions. The concept was used to determine the relative importance of the different influencing criteria such as climatic, soil, topographic and environmental components on the optimal growth of mango cultivation and thereafter delineating the suitable areas. The study clearly demonstrated the potential of the GIS-based Multi-Criteria Evaluation with Sensitivity Analysis in determining the spatial distribution of mango suitability scales. Sensitivity analysis and variation of function provided further refinement in the model and delineation of the priority areas.

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Dr. Ranya Fadlalla Abdalla ELSheikh is from Kasala- Sudanese and was born on 5th August 1978. She received her PhD in GIS and Geomatics Engineering from Institute of Advance Technology University Putra Malaysia, Serdang, Selangor, Malaysia, in 2011, M.Sc. in GIS and Remote Sensing from Faculty of Engineering University Putra Malaysia, Serdang, Selangor, Malaysia, in 2006 and her B.Sc. (Honours) in Survey Engineering from Faculty of Engineering Sudan, University of Science and Technology, Khartoum, Sudan, in 2002. Currently, Dr. Ranya Fadlalla Abdalla ELSheikh is an Assistant Professor in the Faculty of Engineering, School of Survey Sudan University of Science and Technology, 407 Khartoum, Sudan. She has various publications in referred journals and conference proceedings.
Email: Rania58@gmail.com

Dr. Rashid Mohamed Shariff is an Associate Professor in the Spatial and Numerical Modelling Laboratory, Institute of Advance Technology, University Putra Malaysia. Dr. Rashid has a passion for teaching and student activities. Students have ranked him excellent in teaching since 1999. Dr. Rashid loves collaborative projects and he has travelled to

Australia, Japan, Hong Kong, Macao, China, Oman, and Saudi Arabia to pursue these objectives. Dr. Rashid has received several international recognitions for his work. Among these is the DuoDenmark Fellowship in 2005, while in 2008, he was awarded the Endeavour Award Scholar by the Australian government; for 2009, he has been awarded the Erasmus Mundus Scholar award by the European Union and will be lecturing and researching at the Munster University, Germany for a semester in 2009.

As a specialist in GIS, Dr. Rashid helps the expansion of GIS into Agriculture, Healthcare, and Environment that depends on GIS. Thus, his work is of significant benefit to society and it is only appropriate that he serves the community that has done so much to place him where he is today.

Dr. Rashid is active in research, having published or co-authored about 200 articles in journals, conferences, workshops, invitational talks and technical reports. His contributions on Geographical Information Systems for Agriculture were included in the CIGR Handbook of Agricultural Engineering Volume VI: Information Technology. He has received a host of awards including the National Excellent Scientist Award, Gold Medal at Geneva's Inventors Competition, and the best speaker in an international GIS and Remote Sensing conference, being some of these accomplishments.

Dr. Nilanchal Patel is Professor at the Birla Institute of Technology Mesra, India. He previously served as lecturer in Remote Sensing and Geology at IIT-D. He completed his Ph.D. from Indian Institute of Technology Kanpur on Digital Image Processing of Remotely Sensed Data for Lithological Discrimination in Rajasthan (India) after his M.Tech. in Applied Geology from Indian Institute of Technology, Roorkee. He has many international awards/fellowships from China, Denmark, Portugal, France and South Africa. He is in the editorial boards of a number of journals under reputed publications like Springer and Taylor & Francis. Because of the quality of his work and determination, he has earned various prestigious awards and is a life member of various scientific communities. His research areas include Landslide hazard zonation, Assessment of forest degradation and fragmentation, Pattern recognition and image processing, Spectral characterization of water, soil and vegetation characteristics, GIS-based landscape pattern analysis, NPP estimation of vegetation and crop, Habitat assessment through GIS, Estimation of soil organic carbon content, Urbanization pattern analysis, Vulnerability Analyses of Wetlands, Digital land use and land cover change detection studies, Rainfall-runoff modelling.