Modeling the Rice Land Suitability Using GIS and Multi-Criteria Decision Analysis Approach in Sindh, Pakistan

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Abstract: The objective of this research was to evaluate rice land suitability in Sindh, Pakistan, by designing GIS-based Multi-Criteria Decision Analysis (MCDA) spatial model to aggregate interdisciplinary aspects including factors of soil physical and chemical properties, ground water quality, soil pH, agro-ecological zones, canal command area and temperature. A constraint map of water bodies was also utilized in this model. On the basis of these parameters, standardized raster maps were created, and then Pair-Wise Comparison Matrix (PWCM) of Analytical Hierarchy Process (AHP) was developed to calculate significant weights by means of Principal Eigen vector by Saaty's method, with accepted Consistency Ratio (CR) of 0.10. Furthermore, Multi-Criteria Evaluation (MCE) employing Weighted Linear Combination (WLC) aggregated all the suitability maps to yield rice land suitability map. Final output map of this work demonstrated 30.2% increase in area suitable for rice cultivation with an increased production of 14,716,592.17 tonnes as compared to existing rice practices in Sindh. This increase in the area and production of the potential land shows the capability of our novel model and offers an opportunity to improve cultivation by providing the much required information at local level that could benefit farmers, vision scientists and decision makers to select appropriate cropping site and agricultural planning making the best use of available data.

Keywords: Suitability map, Factor, Constraint, AHP, Pair-Wise Comparison Matrix, Principal Eigen vector, MCE, Weighted Linear Combination, Overlay, Area, Production, ArcGIS, Erdas Imagine, Idrisi Selva.

1. INTRODUCTION

Rice is widely consumed staple food for a large part of population, especially in Asia with second highest worldwide production. Top rice exporting countries are: India, Thailand, Pakistan, United States, Vietnam, Uruguay, Brazil, and China [1]. Pakistan has produced 5.8 million tonnes of rice in 2013-14, from which Sindh contributes to 2.6 million tonnes (45%). The main research problem is that rice is grown in Sindh on 1.8 million acres (27%) from total rice arable land of 6.9 million acres of Pakistan, with 1420.8 Kg/acre yield in 2013-14, that does not reflect actual potential to fulfill high export demand [2].

The GIS-based land-use suitability analysis has been applied in ecological, agricultural activities, landscape evaluation, and planning the environmental impacts [3]. For rice land suitability in Sheikhupura and Nankana Sahib, Pakistan, AHP computes significant weights for soil, environment and ground water quality attributes by PWCM [4]. For the delineation of suitable soils for zero-till wheat cultivation in Gujranwala, Pakistan, GIS-based remote sensing and field data for soil texture, bulk density and ground water quality have been suggested. Overlay integrates the parameters for generating final map to identify best, normal, moderate and unsuitable soils [5]. For identification of maize land suitability in Okara, Pakistan, GIS-based AHP model has been employed using parameters of soil pH, electrical conductivity, soil texture, organic matter and ground water quality to recognize areas of highly, moderately, marginally and not suitable [6]. For the locations and distributions of rice cultivation in Nile Delta, PWCM and weighted overlay have produced suitability map [7]. For rice land suitability in Prachuap Khiri Khan, Thailand, GIS-based AHP ranking technique has been utilized to weight coefficients. Further WLC has produced diverse suitable lands for cultivation [8]. For rice land suitability map, based on physical and climatic factors in Great Mwea Region, Kenya, GIS-based MCE technique has been employed [9]. For rice suitability sites in Morobe, Papua New Guinea, parameters of topography, physical and chemical soil properties, and climate have been used to construct index model [10].

Due to current depleting resources and poor agricultural land management, in Sindh, Pakistan, this work proposed a GIS-based MCDA model for rice land suitability, to boost the production. Data analysis techniques, experts knowledge and individual requirements for rice were essential in this decision making process. This study aimed to evaluate practice

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of rice farming and to help decision makers to adopt a GIS based more flexible, comprehensive and reliable suitability map to elevate production.

2. MATERIALS AND METHODS

2.1. Study Area

Sindh is the third largest province of Pakistan with an area of 140,914 km^2 with coordinate extending from 23°42'02.79" N to 28°30'05.58" N latitude and from 66°39'12.83" E to 71°07'34.56" E longitude. It is geographically bounded by Thar Desert to the east, Kirthar Mountains to the west and Arabian Sea in the south. In the centre is a fertile plain around the Indus River. Agriculture is very important in Sindh with major crops as wheat, rice, cotton, and sugarcane constituting 75% of total cropped area. Temperature rises above 46°C between May and August, and minimum average temperature of 2°C during December and January. Average annual rainfall is about 7 inches, falling during July and August [11].

2.2. Environmental Variables

As a Kharif crop, rice is planted in summer while harvested in early winter. For 75 days rice fields should have 6 inches of slow moving water, so the deficiency of rainfall in study area has been met by canals and groundwater. Heavy clayey subsoil having water retaining capacity with level land is suitable. Rice requires high temperature during growing season of 4-6 months [12]. In this work, the data source for all the criteria for rice in Sindh was: statistical data for rice

Table 1: Suitability Criteria for Rice in the Study Area

Water bodies	**Suitable**: Land	**Not suitable**: River, Lakes
Mean maximum annual temperature	**Suitable**: 32°, 34° and 36°C	
Soil physical properties	**Suitable**: 1. Silty and clayey soil (Deltaic plains) 2. Clayey soil (River plains) 3. Piedmont plains: clayey soil	**Not suitable**: 1. Piedmont plains, rough mountains, rocks 2. Sand dunes and sandy soil 3. Open water, marsh, tidal flat and sea creek 4. High gypsiferous salinity soils (Deltaic plains) 5. Seasonally flooded soils (River plains) 6. Loamy soils (River plains) 7. Salt affected soils (River plains)
Canal command area	**Suitable**: Canal command area	**Not suitable**: 1. River and lakes 2. Non-canal command area
Groundwater quality	**Suitable**: 1. Fresh 2. Relatively fresh	**Not suitable**: 1. Marginal 2. Hazardous 3. Not available
Soil pH	**Suitable**: 6.6-8.4	**Not suitable**: > 8.4
Soil Chemical properties	**Suitable**: 1. Mildly alkaline soils: strongly calcareous 2. Moderately alkaline soils: moderately calcareous 3. Moderately alkaline soils: strongly calcareous 4. Salt affected soil: slightly saline 5. Salt affected soil: moderately saline	**Not suitable**: 1. Salt affected soil: strongly saline 2. Salt affected soil: slightly saline-sodic 3. Salt affected soil: moderately saline-sodic 4. Salt affected soil: strongly saline-sodic 5. Salt affected soil: slight to strong saline-sodic 6. Miscellaneous areas
Agro-ecological zones	**Suitable**: 1. Suaeda-salsola, typic salorthids estuarine plains 2. Acacia senegal, typic cammborthids river plain 3. Capparis-suaeda-tamaris, typic camborthid piedmont 4. Tamarix-phoenix dactylifera,typic camborthid river	**Not suitable**: 1. Arid warm tropical maritime winter rain region 2. Avicennia, typic salorthids tidal flat zone 3. Acacia senegal-calligonum, sandy desert zone 4. Calligonum, typic torripsammends sandy desert 5. Dry temperate continental winter rain region 6. Semi-arid warm subtropic continental 7. Arid hot subtropical continental 8. Acacia-populus, typic torriorthent river plain 9. Prosopis-capparis, typic camborthid river/piedmont

production and area sown [2], shape file of Sindh administrative boundary [13], map of ground water quality with its parameters as adopted by SMO-WAPDA [14, 15], shape file of Sindh mean maximum annual temperature [16], map of canal command area [15], digital scanned map of water bodies, soil physical and chemical properties, soil pH, and agro-ecological zones [17]. The detailed description of rice suitability in Sindh for all the criteria used in this work is given in Table **1**, as suggested by [3]. These values are in agreement with those considered in literature.

2.3. Framework for GIS-Based MCDA Model

To determine rice land suitability, GIS-based MCDA model, as shown in Figure **1** depicts all steps used in this research procedure. In Erdas Imagine 9.2, the downloaded digital scanned maps for all criteria, which were originally in geographic latitude/longitude projection, were geometric transformed into real world projected coordinate maps. In rectification module of Erdas, by triangulation geo-coding method, linear rubber sheet map transformation was used to rectify scanned maps. In order to geo-reference all the criteria maps to WGS84 projection, 10 Ground Control Points were used to assign coordinates. First order polynomial equation and nearest neighbor re-sampling method quantified new values for output image.

All geometrically rectified criteria maps were re-projected to WGS84 Universal Transverse Mercator (UTM) zone 42N in ArcGIS 10.2.2, as the projection of Sindh administrative boundary shape file was already in WGS84 UTM zone 42N. Manual digitization of all the

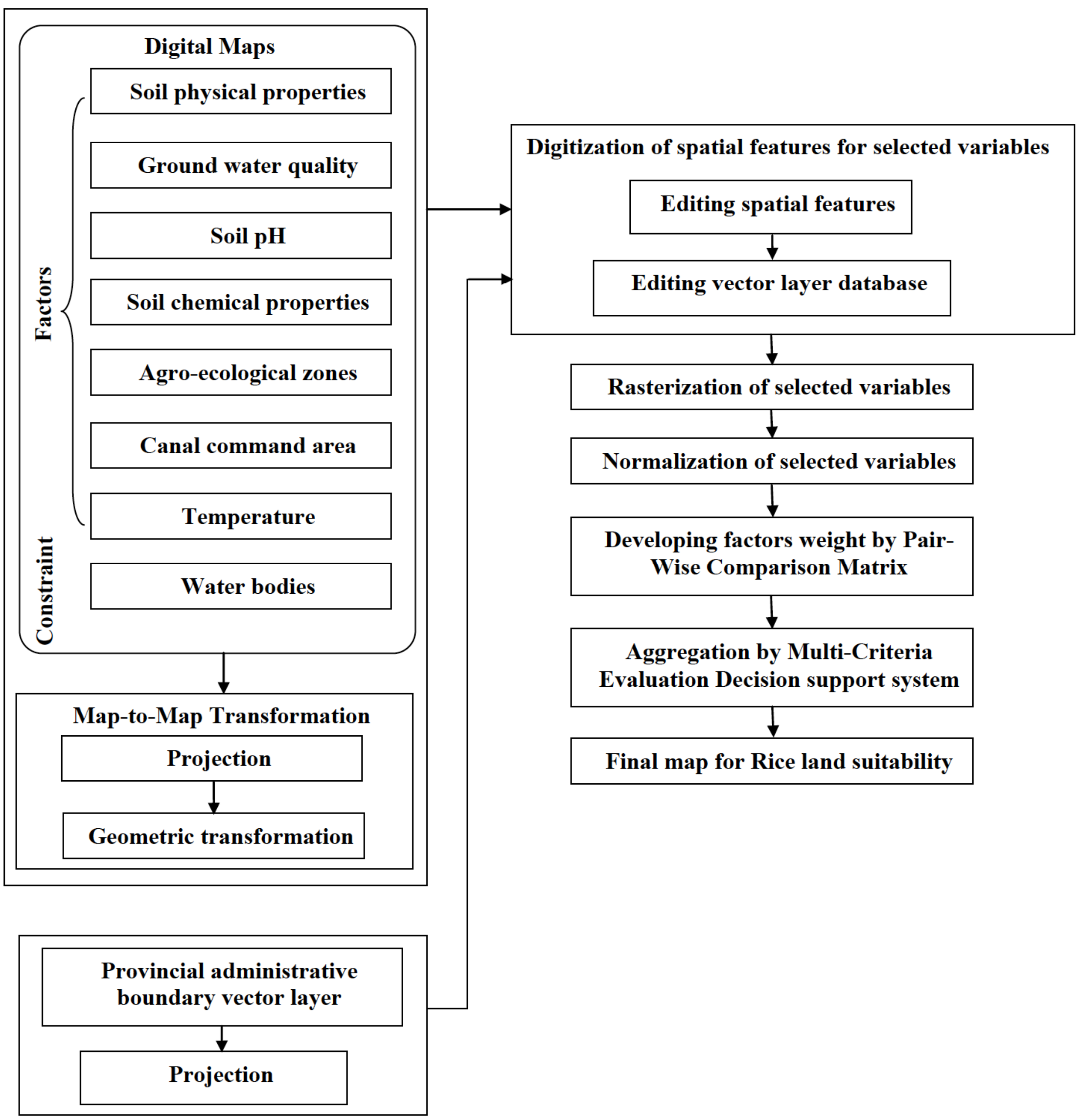

Figure 1: GIS-based MCDA model for evaluating rice land suitability in Sindh, Pakistan.

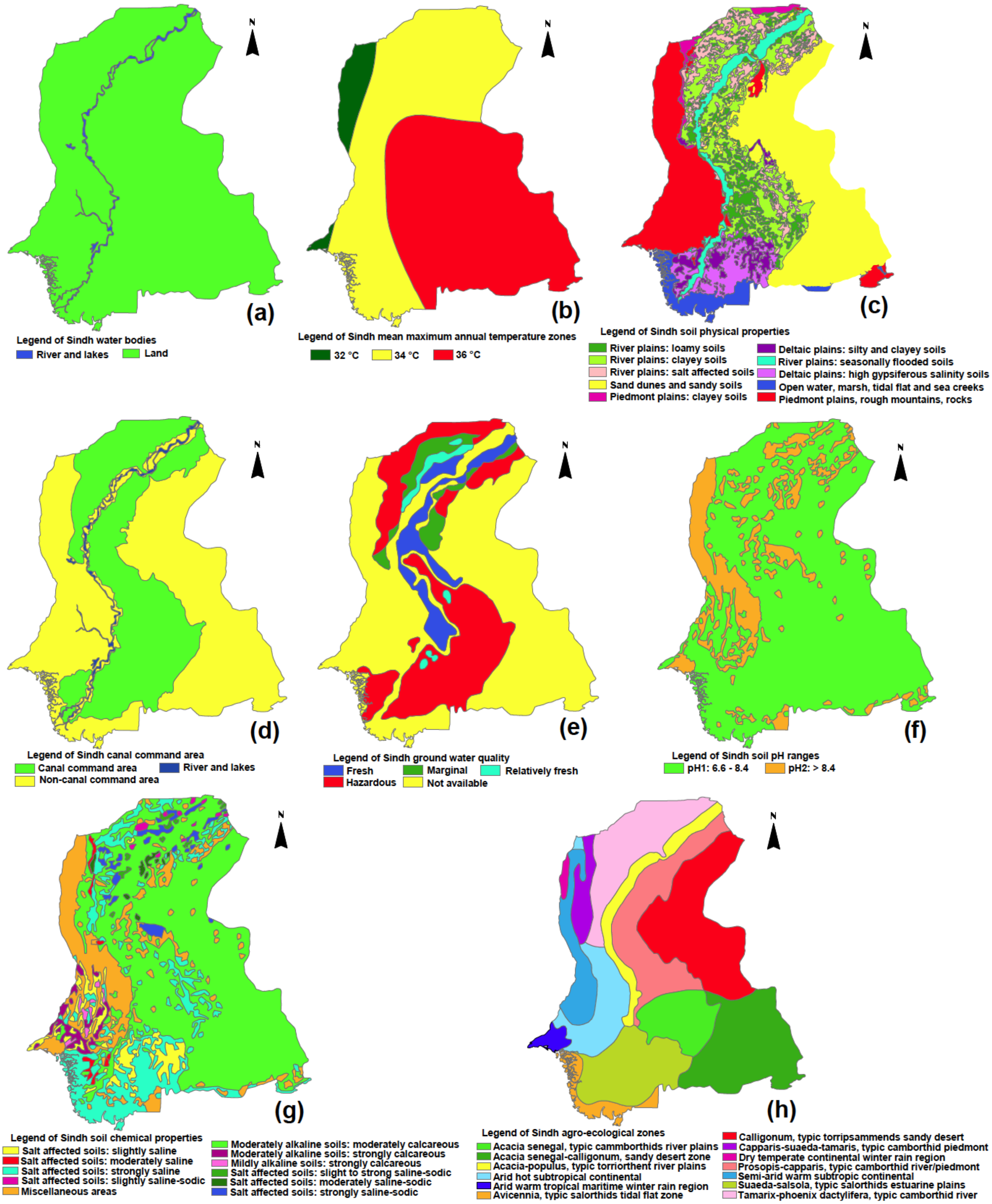

Figure 2: Manually digitized maps of Sindh, constraint: (**a**) water bodies and factors: (**b**) mean maximum annual temperature, (**c**) soil physical properties, (**d**) canal command area, (**e**) ground water quality, (**f**) soil pH, (**g**) soil chemical properties, (**h**) agro-ecological zones.

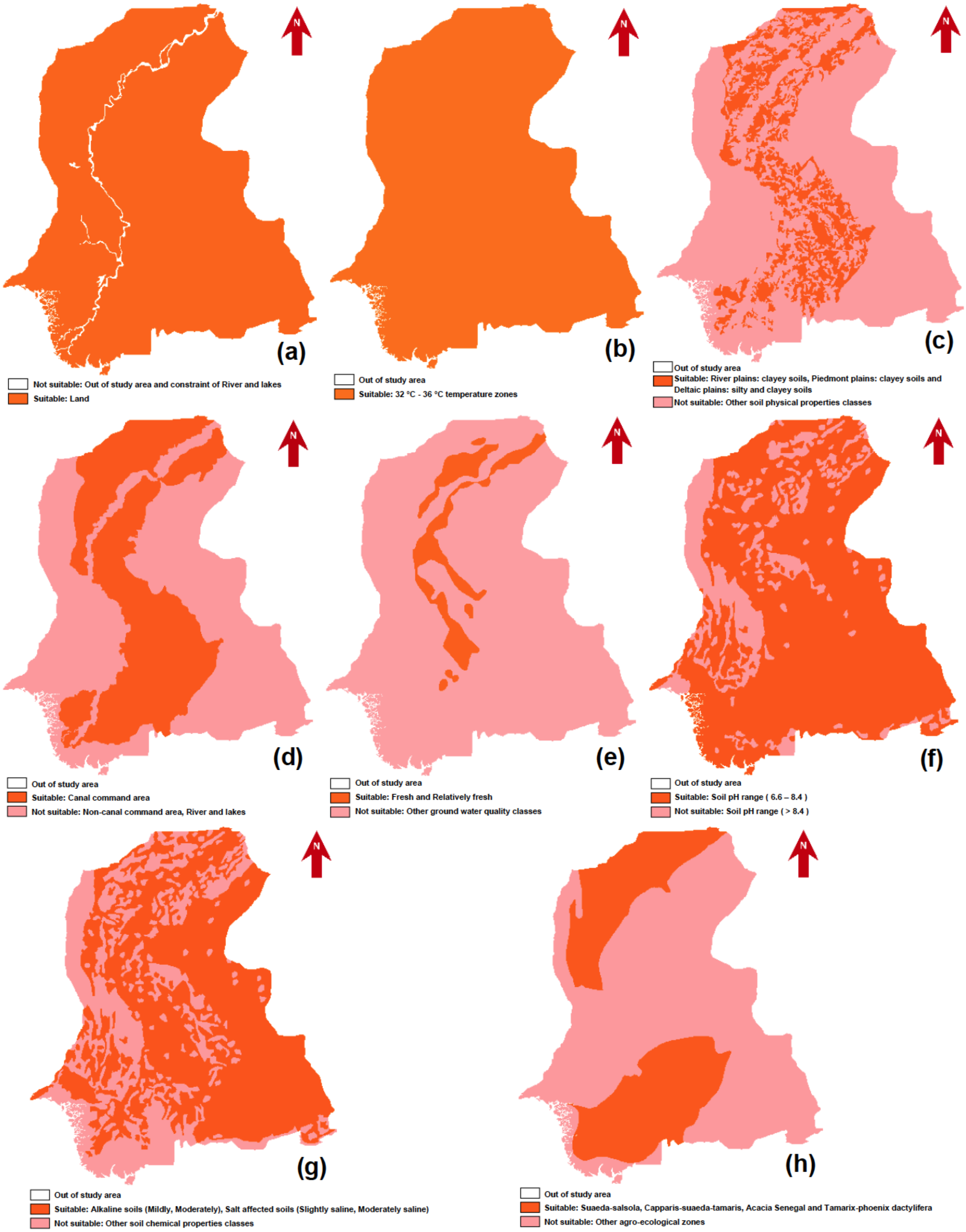

Figure 3: Rasterized suitability criteria for rice farming in Sindh, constraint: (**a**) water bodies and factors: (**b**) mean maximum annual temperature, (**c**) soil physical properties, (**d**) canal command area, (**e**) ground water quality, (**f**) soil pH, (**g**) soil chemical properties, (**h**) agro-ecological zones.

Table 2: PWCM of all the Factors Relevant to Rice Crop Land Suitability for Sindh, Pakistan

Factors	Mean maximum annual temperature	Ground water quality	Canal command area	Soil chemical properties	Soil pH	Soil physical properties	Agro-ecological zones
Mean maximum annual temperature	1						
Groundwater quality	1	1					
Canal command area	3	3	1				
Soil chemical properties	5	7	1	1			
Soil pH	7	3	5	3	1		
Soil physical properties	5	7	3	5	3	1	
Agro-ecological zones	7	5	7	3	5	1	1

criteria maps was performed in ArcGIS with projected administrative boundary shape file and using geometrically rectified digital scanned criteria maps as base maps. In this work, Figure **2** represents vector models denoting entire classes in a particular layer. For production of standardized criteria, rasterization of all digitized criteria maps was performed in Idrisi Selva with resolution of 100x100m. For standardization by re-class module of Idrisi, categories of interest that meet particular criterion were isolated by value of 1 while unconcerned categories were set to 0. Figure **3** illustrates suitable and not suitable classes of standardized criteria maps for this work.

Derivation of weights was central step for this work. In Idrisi, by employing AHP of decision support system, weights were derived for the factors by utilizing PWCM by Saaty's method. In developing weights, every possible pairing was compared by rating relative importance of factors on a 9 point rating scale and entered into a PWCM, where 1/9 indicates extremely less important and 9 indicates extremely more important [18]. For this work, PWCM of all factors is given in Table **2**; furthermore weights for all factors were calculated by Principal Eigen vector sum to 1 with acceptable CR of 0.10, as shown in Table **3**.

2.4. Multi-Criteria Decision Analysis

MCE was implemented by WLC using Idrisi, with additive weighting concept based on weighted average of the criteria. Total score is obtained by multiplying weights to the scaled value of each criteria and then summing the products over all attributes.

In final step constraint modifies the procedure by multiplying the suitability calculated from the factors by the product of the constraints. This overlay capability of GIS allows evaluation of criterion maps into a final composite map, by following mathematical formula:

$$S = \sum w_i x_i \cdot \prod c_j$$

Where, S is composite suitability score, w_i is weight of each factor i, x_i is criterion score of factor i, c_j is criterion score of constraint j, $\sum$ is sum of weighted factors, and Π is product of constraints [18]. The result of aggregation of weighted factors and constraint using WLC approach by our GIS-based MCDA model to create a map of situational weight-based sites is shown in Figure **4,** which demonstrates areas with favorable conditions ranked as suitable while unfeasible areas ranked as not suitable.

Table 3: Factor Weights Using AHP Method

Factors	Weights
Mean maximum annual temperature	0.0297
Ground water quality	0.0333
Canal command area	0.0678
Soil chemical properties	0.0986
Soil pH	0.1623
Soil physical properties	0.2790
Agro-ecological zones	0.3293

3. RESULTS AND DISCUSSION

According to our final rice land suitability map for Sindh, as shown in Figure **4**, obtained by integrating geographical data and decision maker's preferences, area of 4,940,961.6230345 hectares (35.6%) was permanently suitable for rice cultivation with production

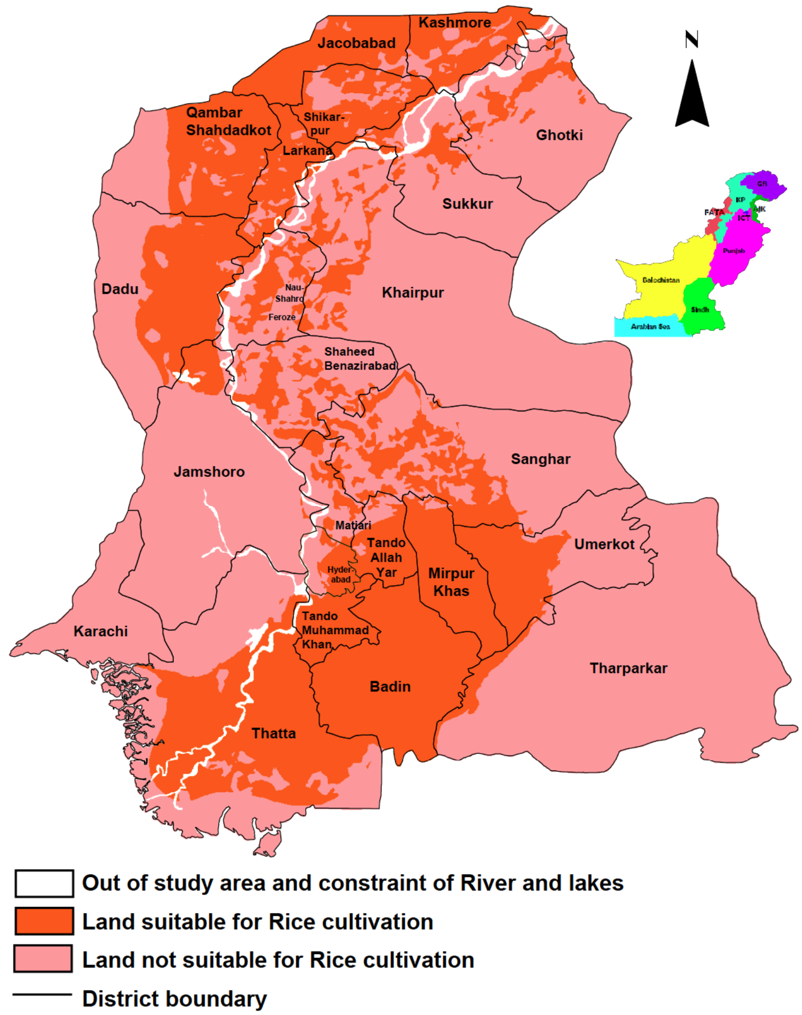

Figure 4: District-wise final rice land suitability map of Sindh, Pakistan, using GIS-based MCDA model.

capability of 17,333,892.17 tonnes and area not suitable was 8,938,120.3180755 hectares (64.4%).

According to Agriculture statistical report of Pakistan [2], rice planting area in Sindh was 746,091 hectares in 2013-14 with 2,617,300 tonnes production. According to this report, existing rice cropland area covers 5.4% while area not under rice cultivation was 94.6% of Sindh. Our final rice land suitability map presented a potential increase in suitable area of 4,194,870.623 hectares (30.2%) with an increased potential in production of 14,716,592.17 tonnes. This difference in the area and production of actual and potential land showed capability of our novel model.

According to Minister for agriculture [19] highly suitable rice Sindh districts were: Shikarpur, Larkana, Qambar Shahdadkot, Jacobabad, Kashmore, Thatta and Dadu. Our final rice land suitability map indicated that districts with large extent of suitable area were: Shikarpur, Larkana, Jacobabad, Kashmore, Thatta, Badin, Dadu, Qambar Shahdadkot, Tando Mohammad Khan, Hyderabad, Tando Allah Yar, Mirpurkhas and Umarkot. In addition: Tharparkar, Jamshoro, Matiari, Shaheed Benazir Abad, Sanghar, Naushahro Feroze, Sukkur, Khairpur and Ghotki had less extent of suitability. Karachi was not suitable for rice cultivation.

The final rice land suitability map was influenced mainly by agro-ecological zones, soil physical and chemical properties and soil pH. Results of this work were also in conformity with the findings of: Agriculture statistics of Pakistan [2], Minister for agriculture [19], Rice growing areas [20], Major rice growing areas [21], Rice production in Sindh districts [22], and Rice production regions [23] who concluded sites suitable for rice cultivation in Sindh, Pakistan.

4. CONCLUSION

Land suitability is a complex process that could significantly impact the profit and loss of principal investments of the country. Proper land evaluation is most important concern in agriculture to enhance crop production by utilizing feasible potentials. The application of our proposed GIS-based MCDA model was successful in providing a powerful tool to evaluate rice land suitability in Sindh, by transforming complex decision making problems into series of transparent steps. In this study it was observed that for suitability analysis, consideration of river constraint and factors: temperature, canal command area, soil physical and chemical properties, groundwater quality, soil pH and agro-ecological zones, with their suitability conditions, relative importance and weighting, were important in obtaining useful results having geographic precision. This model offered enhanced sustainable production by mapping accurate cropland with much required information for farmers and agricultural planners.

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