GIS Based Analytic Hierarchy Process Modeling Technique for Cotton Cultivation Potential Sites in Punjab, Pakistan

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Abstract

Evaluation of multidisciplinary variables is significant for crop land suitability for sustainable production. A Geographic Information Systems based Analytic Hierarchy Process Model was proposed to identify suitable areas for cotton cultivation in Punjab, Pakistan. GIS based model provides flexible and accurate decisions. In this model, rivers were used as constraint. Seven factors such as temperature, soil physical and chemical properties, soil pH, aridity classes, agro-ecological zones, and river command area were digitized in ArcGIS 10.2.2. The suitability map was modeled in Idrisi Selva by using Re-class approach to generate standardized factors and constraint maps. Weights were generated by Pair-Wise Comparison Matrix with accepted consistency ratio of 0.09. The result of composite suitability map showed that more cotton suitable potential sites exist along with existing cotton practiced area. The research result provided important information for farmers to establish linkage between policy decisions and regulatory actions and to improve agricultural land management.

Keywords: Cotton, Multi Criteria Evaluation, Analytic Hierarchy Process, Land Suitability, Geographic Information Systems, Pair-Wise Comparison Matrix

1. Introduction

Cotton is the main cash crop of Pakistan and contributes an important role to the national economy of Pakistan. Pakistan is the third largest exporter of raw cotton (Altaf, 2012) and fourth largest cotton producing country in the world with 2,215,000 metric tons in 2012 (FAO, 2013) . It is estimated that in Pakistan almost 26 % of all the farmers grow cotton, as far as almost 15 % of total Pakistan land is used for cotton cultivation (Altaf, 2012). Pakistan is a semi-industrialized country with heavy dependence on the agricultural sector. To meet the increasing demand of agri-products, it is not feasible to bring more area under cultivation due to limited water and land resources. To tackle this limitation, focus has shifted from extensive farming to intensive farming (Perveen et al., 2013) .

The increasing world population necessitates the application of Geographic Information Systems (GIS) to identify the most suitable areas for a sustainable agricultural production. Selecting the best location for agricultural production is a complex process involving technical, physical, economic, social, and environmental parameters. Such complexities necessitate the use of several decision support tools such as GIS and Multi Criteria Decision Analysis (MCDA), using Analytical Hierarchy Process (AHP) by modeling the suitability of the area for agricultural production. This approach provides benefit to farmers and decision makers in agriculture planning (Joshua et al., 2013). The GIS-based approaches to land-use suitability analysis have advanced the overlay techniques by mapping data on the natural and human-made attributes of the environment. The overlay procedures play a central role in MCDA (Malczewski, 2004).

The AHP is a MCDA approach and has effective mathematical properties of the method. In AHP, a hierarchical model consisting of objectives, criteria, sub-criteria and alternatives is used. After the problem is set on a hierarchical structure, the weights of the criteria forming the hierarchy are calculated. To evaluate the criteria included in a level compared with other criteria included in the next hierarchy level, scoring is made with the preference scale, and a Pair-Wise Comparison Matrix (PWCM) is created, while a certain level of inconsistency may occur. Therefore, logical consistency should be below 0.10 (Akıncı et al., 2013).

To analyze the suitability of land based on soil and water resource and predicts the yield, initially AHP evaluates the influence of these factors on productivity. Weighted Overlay Analysis derives the productivity map. GIS plays a significant role in spatial data analysis. AHP is used to discover the influential factors which in turn are given as an input to weighted overlay analysis (Parimala and Lopez, 2012). Identification of suitable areas for cropland is essential for sustainable land-use using a GIS-based Multi Criteria Evaluation (MCE) of biophysical factors, while MCE aggregates them into a land suitability index which can be used to identify priority areas for crop farming and sustainable land-use management (Khoi and Murayama, 2010).

For optimal allocation of agricultural land use especially for developing countries, the land use suitability are evaluated using linear weighted summation method in the land use suitability model to give out land area target for crops (Ying et al., 2012). The suitability of cotton cultivation using GIS for input and storing the data and land characteristics relate to the land evaluation, the requirements and limitations for the cultivation of cotton. Processing, analysis and building computer model for the classification of land suitability (Jamal and Al-Yaaquby, 2011). Land evaluation procedure for soil site suitability for rainfed agriculture helps assess the land suitability. Different soil chemical and physical parameters evaluate the soil site suitability using ArcGIS then overlaid and integrated in GIS environment to produce suitability criteria to compute composite suitability map with highly to marginally suitability (Das and Sudhakar, 2014).

The main research problem is the cotton requirements and limited cotton cultivation in the study area also a constant growth in Pakistani yarn exports is observed from 2009 to 2013 (Hussain, 2014). The technological advancements in geo-spatial domain provide numerous ways for crop land cultivation suitability. So this research aims to identify suitable land for cotton cultivation in Punjab, Pakistan using the GIS based AHP Modeling. It starts from geometric correction, digitization of the re-sampled maps to form the vector layers and also rasterization of all vector layers with appropriate cell size for all the factors and constraint. Standardization of these maps by re-classification for suitability maps, and then AHP is applied to weight the factors using PWCM by the scale for relative importance of all the factors for suitability analysis. Finally, the MCE technique is applied by utilizing the weighted linear combination for all the factors and constraints, to decide the suitability land for cotton cultivation in Punjab.

2. Materials and Methods

2.1. Site Description

Punjab is the second largest province of Pakistan in terms of land area at 205,344 km^2 with coordinate 31°N 72°E. The province is bordered by Kashmir to the north-east, the Indian states of Punjab and Rajasthan to the east, Sindh to the south, the Balochistan to the southwest, Khyber Pakhtunkhwa to the west and Islamabad to the north. Punjab temperature ranges from −2° to 45 °C. Climatically, Punjab has three major seasons namely hot weather (April to June); rainy season (July to September); mild weather (October to March). Six rivers of Punjab provide heavy irrigation system by canals throughout the province. The province is a mainly a fertile region along the river valleys. The region contains the Thal and Cholistan deserts. Despite its tropical wet and dry climate, extensive irrigation makes it a rich agricultural region. Wheat and cotton are the largest crops. Cotton and rice are important cash crops (Saif, 2014).

2.2. Criteria for Cotton Cultivation

In the study area, cotton is cultivated in Kharif summer season. It is sown in May or June and picking starts in September or October (Abbas, 2014). The data source (Table 1) describes the source for obtaining all the factors and constraint utilized for evaluating the cotton land suitability in this study. The suitable criteria (Arain et al., 2014) for cotton cultivation is characterized by the factors: canal command area; soil pH (6.6 to 8.4); soil chemical properties classes (Acid soils-slightly acid, Neutral soils-non to slight calcareous, Mildly alkaline soils-non to strongly calcareous, Moderately alkaline soils-non to strongly calcareous); mean maximum annual temperature (34°C); soil physical properties classes (River plain and terrace-non-calcareous and calcareous loamy soils); aridity classes (Arid-Kharif and Rabi, Arid-Kharif, Hyper-arid-Rabi); agro-ecological zones (Irrigated plains-D.G. khan irrigated and Irrigated plains-cotton zone). The River map is used as cotton cultivation constraint in this study. The detailed description of suitability (Table 2) for factors and constraint describes both suitable and not suitable criteria for cotton cultivation (Arain et al., 2014). These values are in agreement with those considered in the literature.

2.3. Developing GIS Based AHP Model

For the land suitability of cotton crop, the GIS-based Analytic Hierarchy Process model (Figure 1) describes all the steps used in this study.

2.4. Geometric Rectification

It is the process of projecting the data onto a plane and making it conform to a map projection system. It is a process by which the geometry of an image area is made planimetric by referencing to some standard map projection. Whenever accurate area, direction and distance measurements are required, rectification is performed (Lathrop, 2008). It transform the geometry of an image so that each pixel corresponds to a position in a real world coordinate system, in which the image is expanded or compressed and rotated as needed to align with a real world map (Liu and Klein, 2014). It is the process of transforming the data from one grid system into another grid system using a geometric transformation. Rectification is used where the pixel grid of the image must be changed to fit a map projection system or a reference image (ERDAS, 2010). The geometric rectification for the downloaded digital scanned maps for all the factors and constraints is performed in Erdas Imagine 9.2.

2.4.1. Rubber Sheeting

At large scales, however, ignoring the projection results in some unexpected, inaccurate spatial statistics, and in poor maps, especially, the best approach to coordinate transformations is to use statistical techniques such as rubber sheeting or adjustment (Clarke, 1995). It involves stretching and warping an image to geo-register control points to known control point locations on the ground. Reflectance values in the original scanned grid are assigned to the cells in the rectified grid (DiBiase et al., 2014). A Ground Control Point (GCP) is a point on the earth's surface where both image coordinates and map coordinates can be identified (Liu and Klein, 2014). In Rubber sheeting, only the areas bounded by GCP can be rectified (Heidi, 2010). Rubber sheet warping is recommended for datasets which are very distorted (Powlesland, 2007).

2.4.2. Geo-Referencing

Geo-referencing refers to the process of assigning map coordinates to image data. Since all the map projection systems are associated with map coordinates, it involves changing only map coordinate information. In this process grid of the image does not change. Latitude/Longitude is a spherical coordinate system that is not associated with map projection (ERDAS, 2010). Maps of all the criteria in this study are geo-referenced to geographic WGS 84 lat/long projection in degrees.

2.4.3. Polynomial Transformation

Polynomial equations are used to convert source file coordinates to rectified map coordinates. Depending upon the number of GCPs used and their locations relative to one another, the polynomial equations may be required to express the needed transformation. A transformation matrix is computed from the GCPs. The matrix consists of coefficients that are used in polynomial equations to convert the coordinates. The size of the matrix depends upon the order of transformation. The goal in calculating the coefficients of the transformation matrix is to derive the polynomial equations. A 1^{st} order transformation is a linear transformation and can be used to project raw imagery to a planar map projection and rectifying relatively small image areas (ERDAS, 2010).

2.5. Projection

Map projection transfers the spherical earth onto the 2-D surface. Mercator projection is suitable for making maps of area which have only a small extent of longitude and is used for small areas of the globe. The Universal Transverse Mercator (UTM) plane grid system divides the earth into 60 vertical zones that are 6 degrees of longitude wide, avoiding the poles (Heywood et al., 2001). In ArcGIS, projection and transformation convert geographic data from one map projection to another. Coordinate system of the output feature class or dataset specifies the projection of output feature without modifying the input data (esri, 2014). The projection of shape file of Punjab administrative boundary and all the factor and constraint maps is performed in ArcGIS 10.2.2.

2.6. Digitization

Vector data uses geometric objects of point, line, and polygon to represent simple spatial features. A point has zero dimensions and has only property of location. A line is 1-D and has a property of length along with location. A polygon is 2-D and has a property of area, and perimeter in addition to location and can represent land parcels or water bodies (Chang, 2012). The vector data structure is best choice for handling graphical data in GIS. With manual digitization like heads-up method, the operator manually traces all the lines from digital scanned map using a mouse and creates an identical digital map on computer screen. It requires experienced operator and is very time consuming. The accuracy of manual digitizing depends on accuracy of duplication of map on a computer by hand. As features are traced manually, the accuracy level is higher because the raster images are scanned at high resolution of the base map. With the help of zoom in and out, the operator can actually work with the resolution of the raster data (Wu, 1999). In ArcGIS 10.2.2 the digitization of all the factors and constraint is performed using the projected shape file of Punjab administrative boundary and the geometrically rectified downloaded digital scanned maps as base maps. In this work, the digitized factors: canal command area (Figure 2), soil pH (Figure 3), soil chemical properties classes (Figure 4), mean maximum annual temperature (Figure 5), soil physical properties classes (Figure 6), aridity classes (Figure 7), agro-ecological zones (Figure 8), and constraint: Punjab rivers (Figure 9), describe all the classes in a particular layer of the study area.

2.7. Rasterization

The conversion from vector data to raster data is called rasterization. In rasterization point data features will become the size of the cell. It changes the value of cells for point, line, and polygons. The value in each grid cell corresponds to the characteristic of a spatial phenomenon at the cell location. Cells are also called pixels and its cell values can be stored in 2-D array. Also it can have null data. Integer values are representation of categorical data while a floating point represents a continuous data. The cell size determines the resolution of a raster. A large cell size cannot represent the precise location of a spatial feature (Chang, 2012). All the digitized factors and constraint are rasterized in Idrisi Selva. In this work, the resolution in process of rasterization for all raster images is 100 x 100m.

2.8. Standardization

Standardization refers to the analysis of the inter-variable correlation. Standardization results in images that show the suitability of locations in the entire study area. Standardization is necessary to transform the disparate measurement units of the factor images into comparable suitability values (Eastman, 2012). The input factors and constraint are standardized to a common scale so that they can be compared against one another. The Re-class tool is used to standardize the input maps. Standardization assumes that the maximum or minimum value in the image is the optimum value. It is important to standardize on polarity, i.e. high values is considered as a good or low values is considered as good but not the both situations at the same time (Geog5021M, 2014). In Idrisi Selva the standardization of rasterized factors and constraint is performed. In this work the standardized factors: canal command area (Figure 10), soil pH (Figure 11), soil chemical properties classes (Figure 12), mean maximum annual temperature (Figure 13), soil physical properties classes (Figure 14), aridity classes (Figure 15), agro-ecological zones (Figure 16), and constraint: Punjab rivers (Figure 17), describe only the suitable and not suitable class in a particular layer for cotton cultivation.

2.9. Weighting the Factors

Different relative weights are given to each factor in the aggregation process and indicate importance of a factor relative to all other. In Weighted Linear Combination (WLC), factors with high suitability can compensate for other with low suitability in the same location. The degree to which one factor can compensate for another is determined by its weight. In Idrisi, the weight module utilizes a PWCM to develop a set of weights that sum to 1. Factors are compared two at a time in terms of their importance. The calculated Consistency Ratio (CR) indicates any inconsistency made in PWCM. Higher weight determines more suitability (Eastman, 2012). This step is performed in Idrisi Selva for all factors. Different hierarchy of weights for all the factors (Table 3) is used for generating final land suitability map.

2.10. Analytic Hierarchy Process

In AHP a matrix is constructed, where each criterion is compared with the other criteria, relative to its importance on a scale from 1 to 9, where 1 has equal preference between two factors; 9 represents a particular factor is extremely favored over the other. Weights are used to derive CR. If CR > 0.10, then some pair-wise values needs to be reconsidered until desired value of CR < 0.10 is reached (Estoque, 2011). Having a comparison matrix, priority vectors are computed, which are the normalized Eigen vector or priority vector of the matrix by normalizing each column of the matrix. Since it is normalized, the sum of all elements in priority vector is 1 (Teknomo, 2006). The formula for consistency ratio (Kihoro et al., 2013) is as follow is given in equation 1 and 2:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

Where, λ_{max} is maximum Eigen value, CI is Consistency Index, CR is Consistency Ratio, RI is Random Index and n is number of criteria in each PWCM. This step is performed in Idrisi Selva. In this work, eigenvector has acceptable consistency ratio of 0.09. In MCE model multiple layers are aggregated to yield a single output map (Geog5021M, 2014). WLC aggregation retains the variability from the factors. The final image is a measure of aggregate suitability for non-constrained locations (Figure 18).

The formula for WLC (Estoque, 2011) is given in equation 3:

$$S = \sum w_i x_i \, . \prod c_j \qquad (3)$$

Where, S is the composite suitability score, w_i is weight of a factor, x_i is factor, c_j are constraints, $\sum$ is the sum of weighted factors, and Π is product of constraint.

3. Result

In the suitability map generated from GIS based Analytic Hierarchy Process Modeling technique for cotton cultivation potential sites in Punjab, Pakistan (Figure 19), the number of hectares available to suitable class was 6,141,259 hectares with production capability 26,982,237 Bales (4,586,980,392 Kg) with highly suitable districts for cotton cultivation were Rahim Yar Khan, Bahawalpur, Bahawalnagar, Multan, Dera Ghazi Khan, Muzaffargarh, Vehari, Khanewal, Sahiwal, Lodhran, and Rajanpur. The area not suitable for cotton cultivation is 13,811,985 hectares. The result showed that suitable areas were found mostly in the areas under current cotton growing sites. According to Punjab Development Statistics 2013 (Rafique, 2013), the area sown under cotton for 2011-2012 was 2,533,000 hectares with production of 11,129,000 Bales (1,891,930,000 Kg). The suitability map for cotton cultivation is also in conformity with the findings of IWMI research report (Cai et al., 2010); Punjab districts cotton production (Latham, 2012); major and minor cotton crop areas (USDA, n.d.); cotton production regions (FAO, 2004) who concluded the sites suitable for cotton cultivation in Punjab, Pakistan.

4. Conclusion

For decision makers to select certain crop land suitability is a complicated issue especially when based on environmental factors. The MCE using AHP procedure based on GIS involve the utilization of geographical data, the decision maker preferences, manipulation of data, and preference according to specific decision rules. MCE method was adequate to integrate databases required for different kinds of environmental variables in a GIS context.

In this study, application of GIS technique to identify suitable areas for cotton crop in Punjab, Pakistan was successful. The results obtained from this study indicate that the use of GIS and application of MCE using AHP could provide a superior guide map for farmers and decision makers at local level to select the appropriate cultivation sites, crop management and diversification operations. The common thread in mapping cotton cultivation suitability is to utilize correct environmental variables to achieve greater accuracy. To accomplish this, the study has focused deeply on those environmental variables that are worth mentioning for cotton cultivation and accurate enough to provide perfect suitability map.

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Tables

Table 1. Data source for the research work.

S. No.	Data	Source
1	Statistical data for Cotton production for Punjab	(Rafique, 2013)
2	Statistical data for area sown under Cotton for Punjab	
3	Digital scanned map of Punjab rivers	(Panagos et al., 2011)
4	Digital scanned map of Soil physical properties	
5	Digital scanned map of Soil pH	
6	Digital scanned map of Soil chemical properties	
7	Shape file of Mean maximum annual temperature	(ICIMOD, 2008)
8	Digital map of Canal command area	(Brabben, 2000)
9	Shape file of Punjab administrative boundary	(Pakresponse, 2013)
10	Digital map of Aridity classes	(PARC, 2007)
11	Digital map of Agro-ecological zones	

Table 2. Standardized criteria for the constraint and factors used in this work.

S. No.	Layer	Standardization description of factors and constraints
1	Canal command area	Suitable: Canal command area Not suitable: 1. River 2. Non-canal command area
2	Soil pH	Suitable: 6.6 - 8.4 Not suitable: 1. 6.1 - 6.5 2. > 8.4
3	Soil Chemical properties	Suitable: 1. Acid soils_slightly acid 2. Neutral soils_non to slight calcareous 3. Mildly alkaline soils_non to slight calcareous 4. Mildly alkaline soils_moderately calcareous 5. Mildly alkaline soils_strongly calcareous 6. Moderately alkaline soils_non to slight calcareous 7. Moderately alkaline soils_moderately calcareous

		8. Moderately alkaline soils_strongly calcareous Not suitable: 1. Salt affected soil_saline 2. Salt affected soil_saline- sodic 3. Salt affected soil_slight to strong saline- sodic 4. Miscellaneous areas
4	Mean maximum annual temperature	Suitable: 34° C Not suitable: 1. 26° C 2. 28° C 3. 30° C 4. 32° C
5	Soil physical properties	Suitable: 1. River plain and terrace_noncalcareous loamy soil 2. River plain and terrace_calcareous loamy soils Not suitable: 1. River plain and terrace_noncalcareous clayey soil 2. River plain and terrace_calcareous sandy soil,dune 3. River plain and terrace_calcareous clayey soils 4. River plain and terrace_salt affected soils 5. Piedmont plains_noncalcareous loamy soils 6. Piedmont plains_noncalcareous clayey soils 7. Piedmont plains_calcareous sandy soils 8. Piedmont plains_calcareous loamy soils 9. Piedmont plains_calcareous clayey soils 10. Piedmont plains_salt affected soils 11. Loess and weathered rock plains 12. Mountains and hills 13. Seasonally flooded soils 14. Sand dunes and sandy soils
6	Aridity classes	Suitable: 1. Arid-kharif, rabi 2. Arid-kharif, Hyper-arid-rabi Not suitable: 1. Humid 2. Sub-humid 3. Semi-arid

7	Agro-ecological zones	Suitable: 1. Irrigated plains: D.G. khan irrigated 2. Irrigated plains: cotton zone Not suitable: 1. Barani region: high rainfall 2. Barani region: low rainfall 3. Thal region: arid zone 4. Thal region: irrigated zone 5. Marginal land: Suleiman mountains 6. Irrigated plains: central mixed zone 7. Marginal land: Cholistan 8. Irrigated plains: rice zone
8	River constraint	Suitable: Land Not suitable: River

Table 3. Weights of all the factors.

Factors	Weights
Canal Command Area	0.0397
Soil pH	0.0471
Soil Chemical Properties	0.0567
Mean Maximum Annual Temperature	0.0804
Soil Physical Properties	0.2072
Aridity Classes	0.2335
Agro Ecological Zones	0.3354

Figures

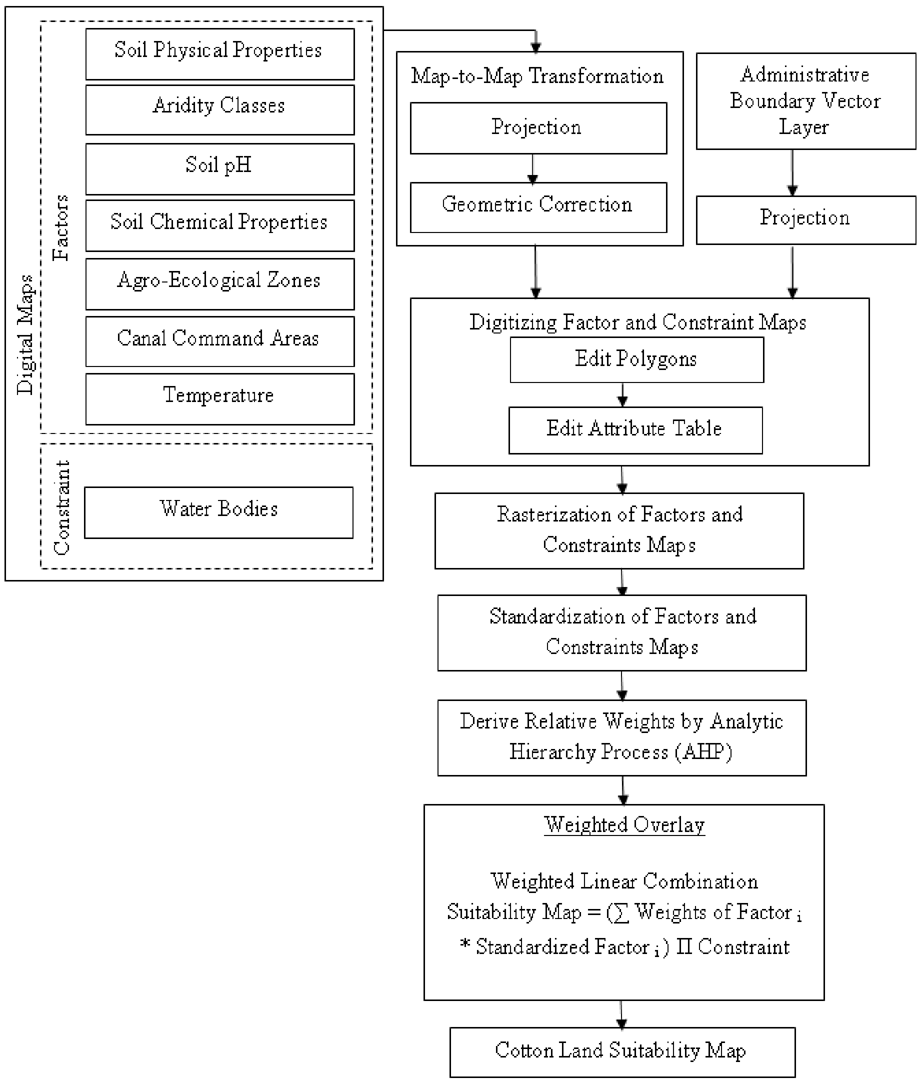

Fig. 1. Research procedure used in this study.

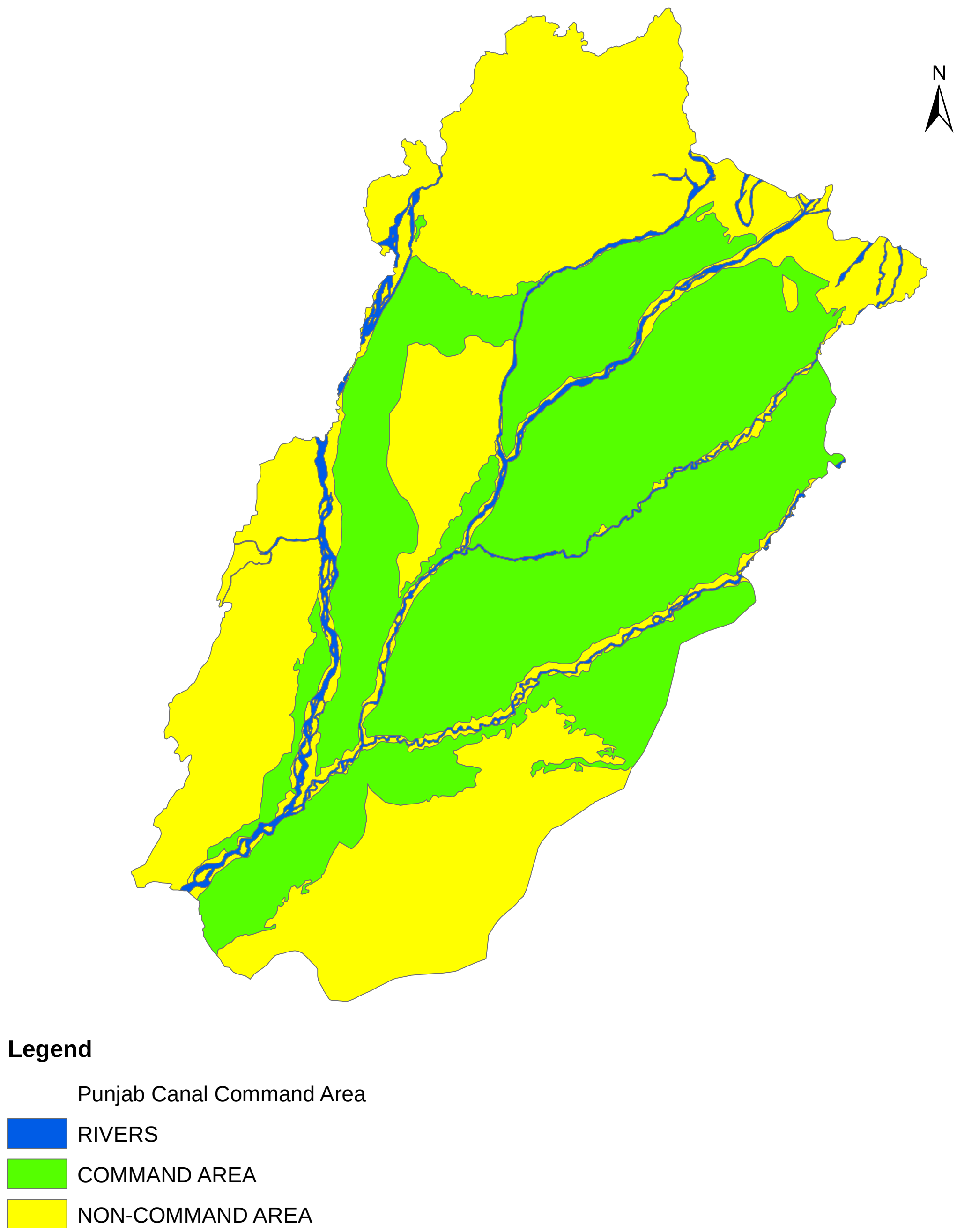

Fig. 2. Digitized map of Punjab canal command area.

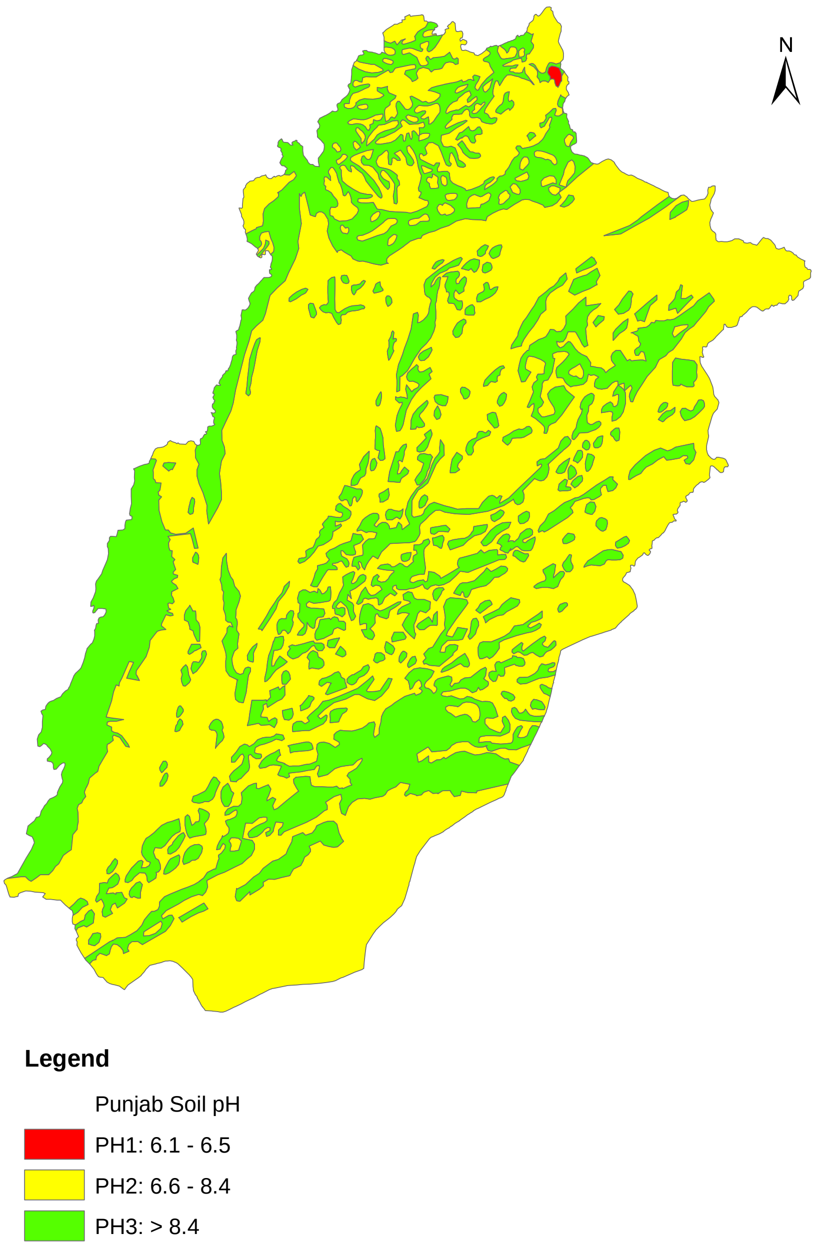

Fig. 3. Digitized map of Punjab Soil pH.

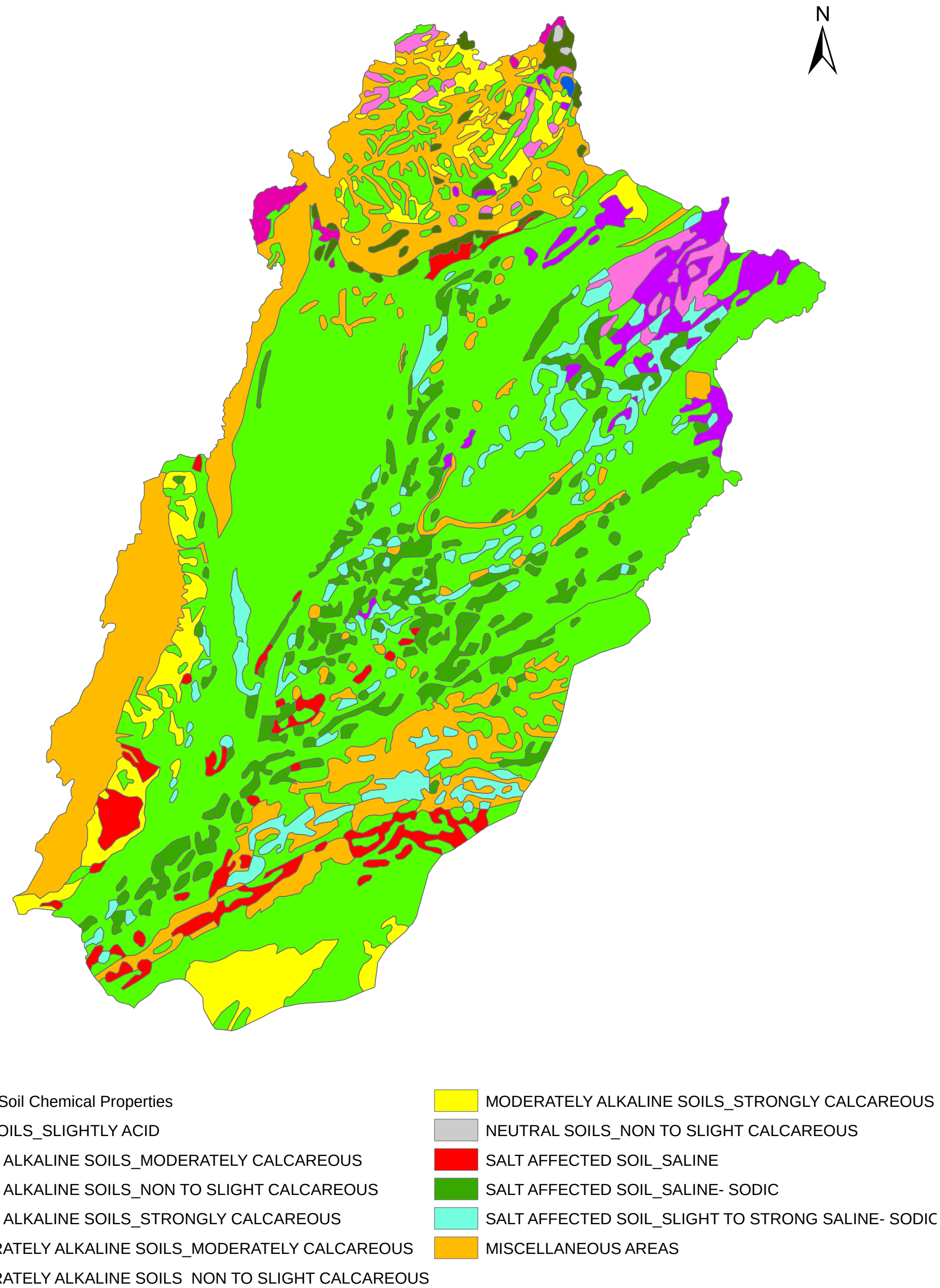

Fig. 4. Digitized map of Punjab soil chemical properties.

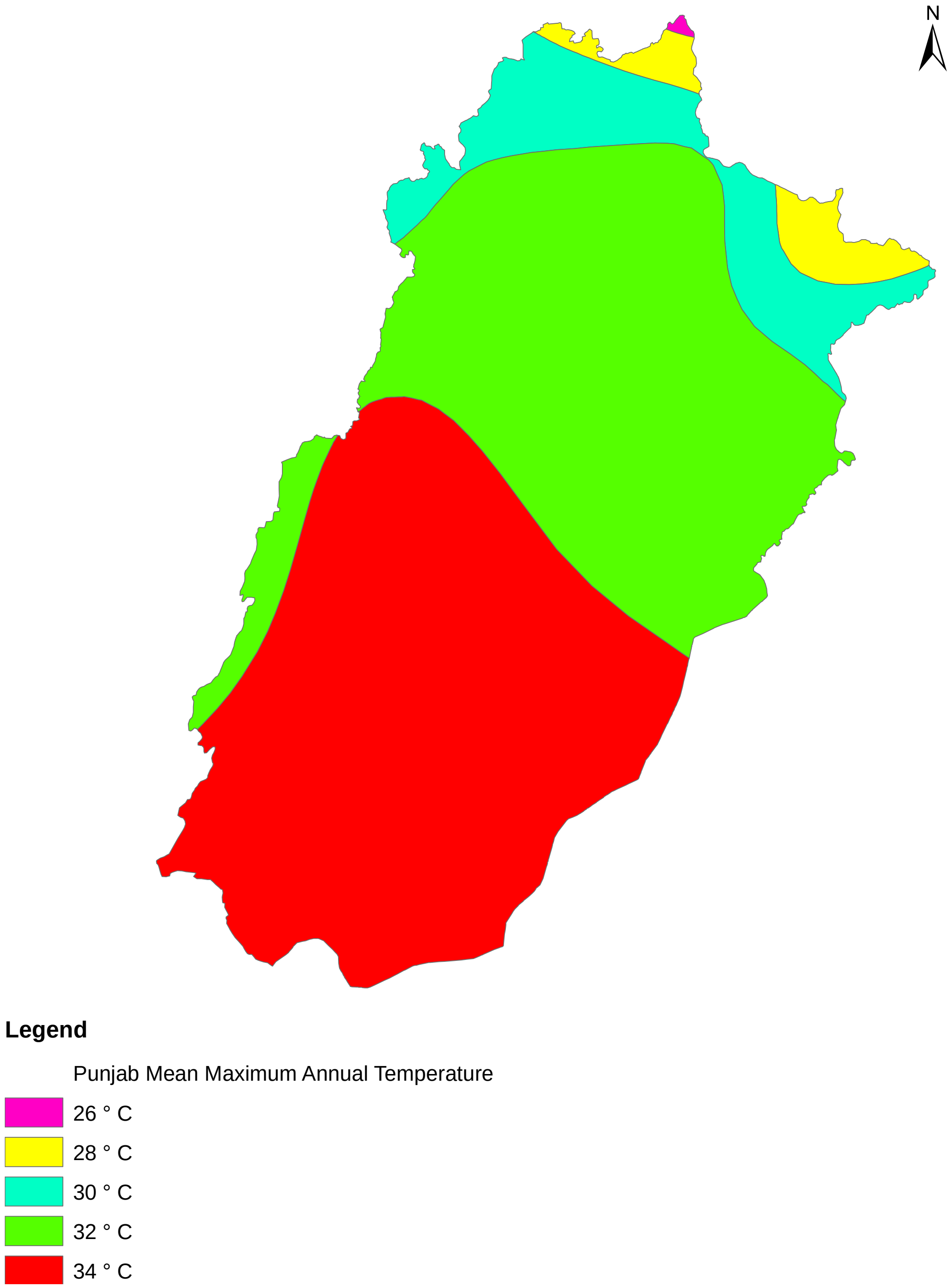

Fig. 5. Digitized map of Punjab mean maximum annual temperature.

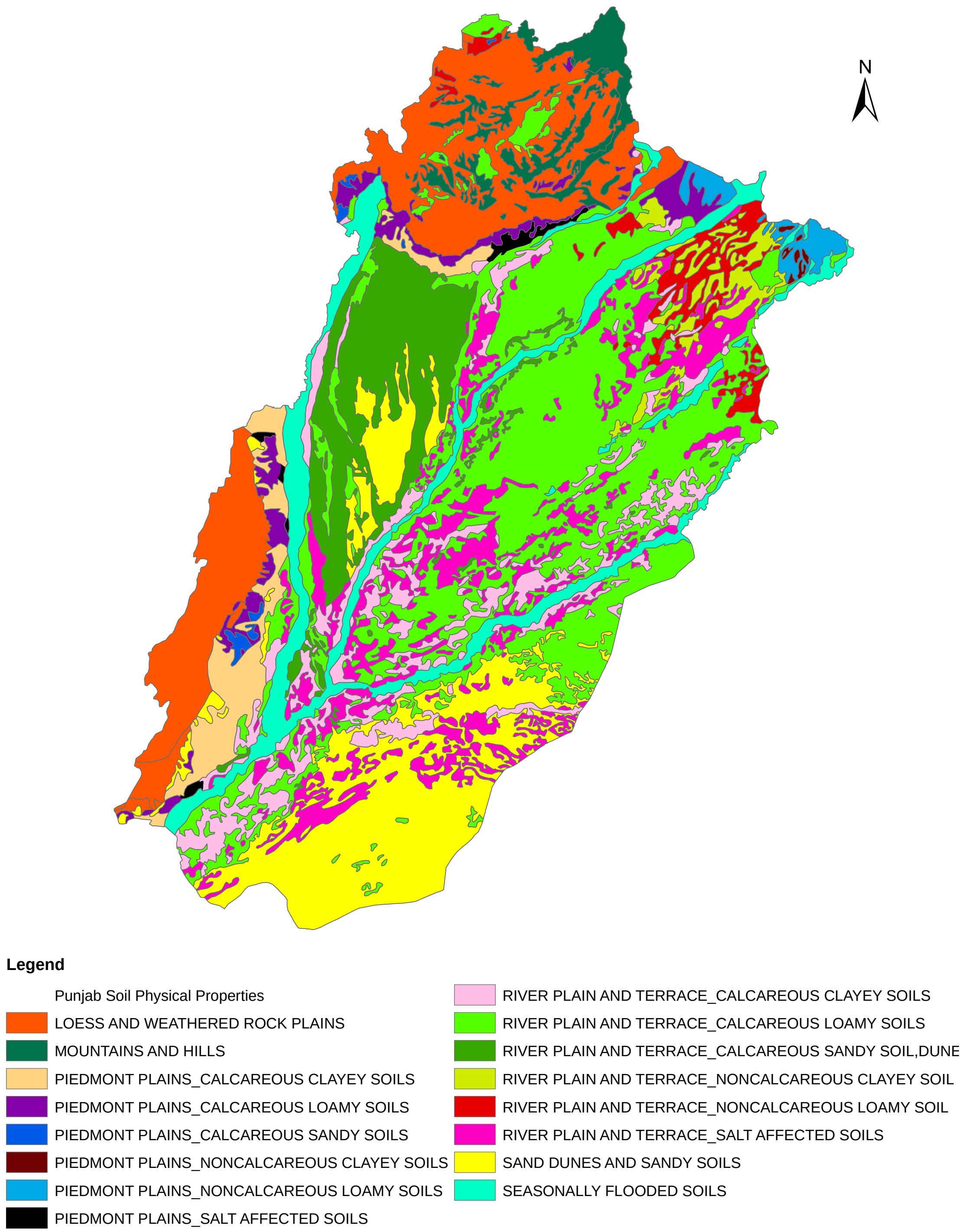

Fig. 6. Digitized map of Punjab soil physical properties.

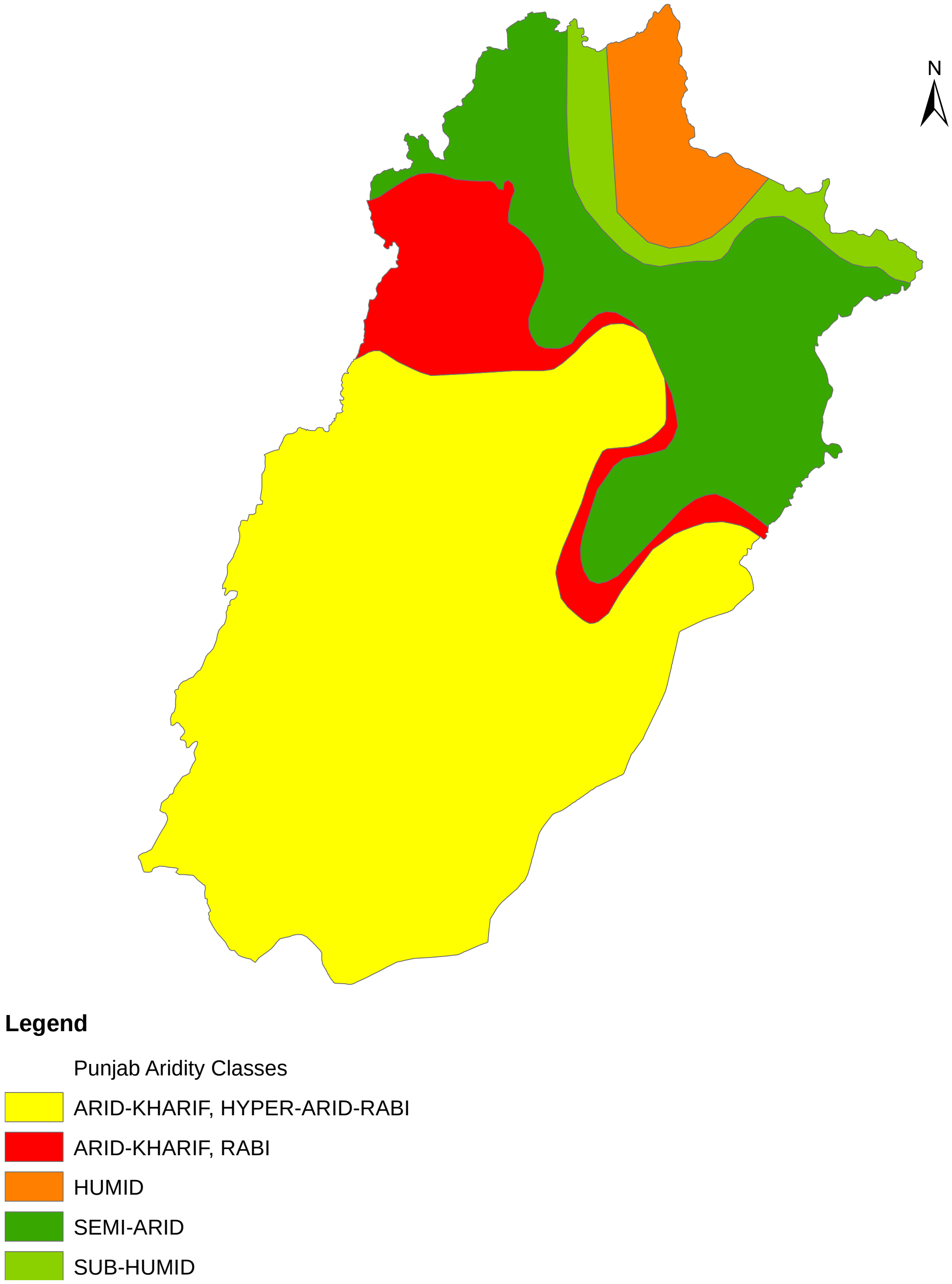

Fig. 7. Digitized map of Punjab aridity classes.

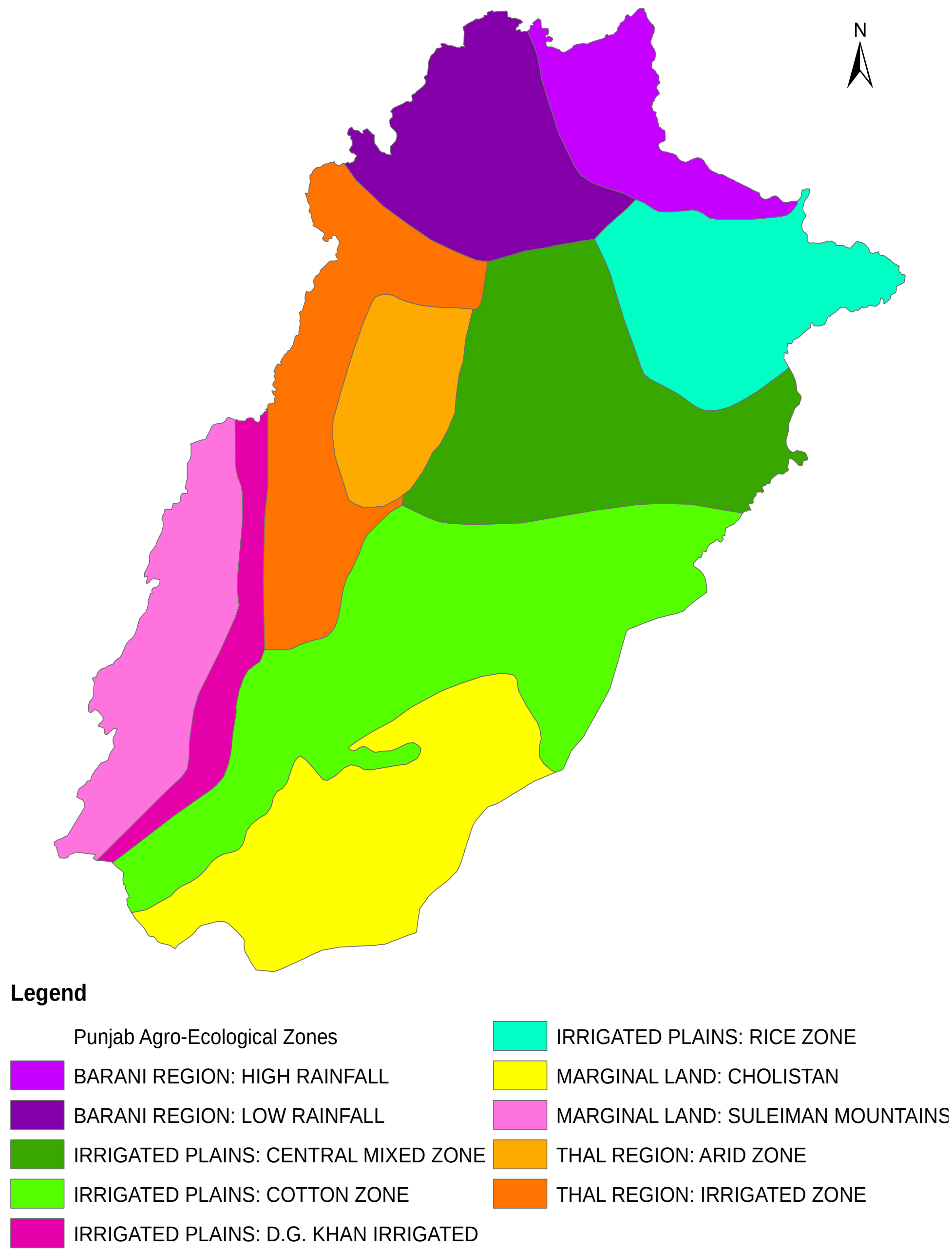

Fig. 8. Digitized map of Punjab agro-ecological zones.

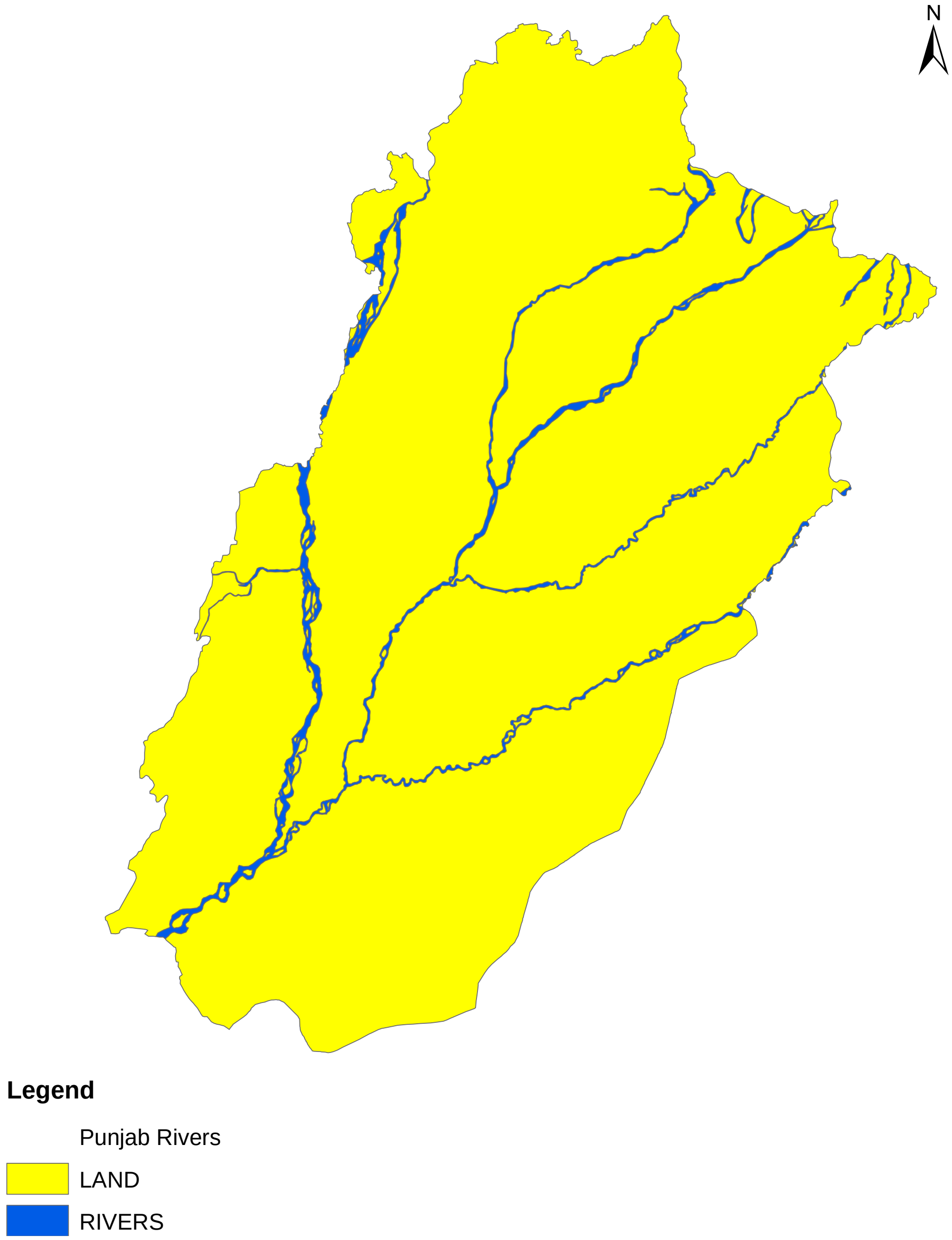

Fig. 9. Digitized map of Punjab river constraint.

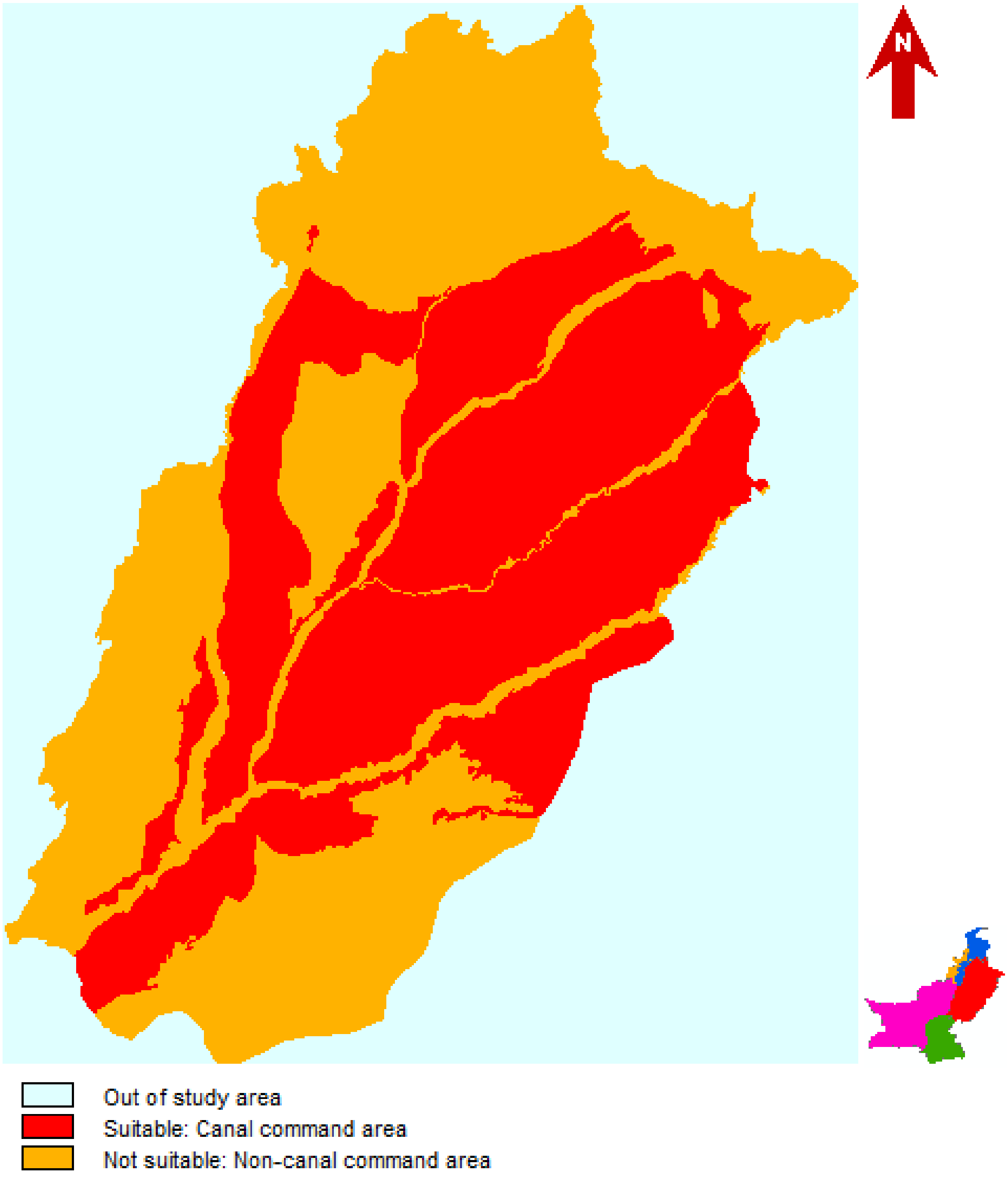

Fig. 10. Standardized factor map for Punjab canal command area.

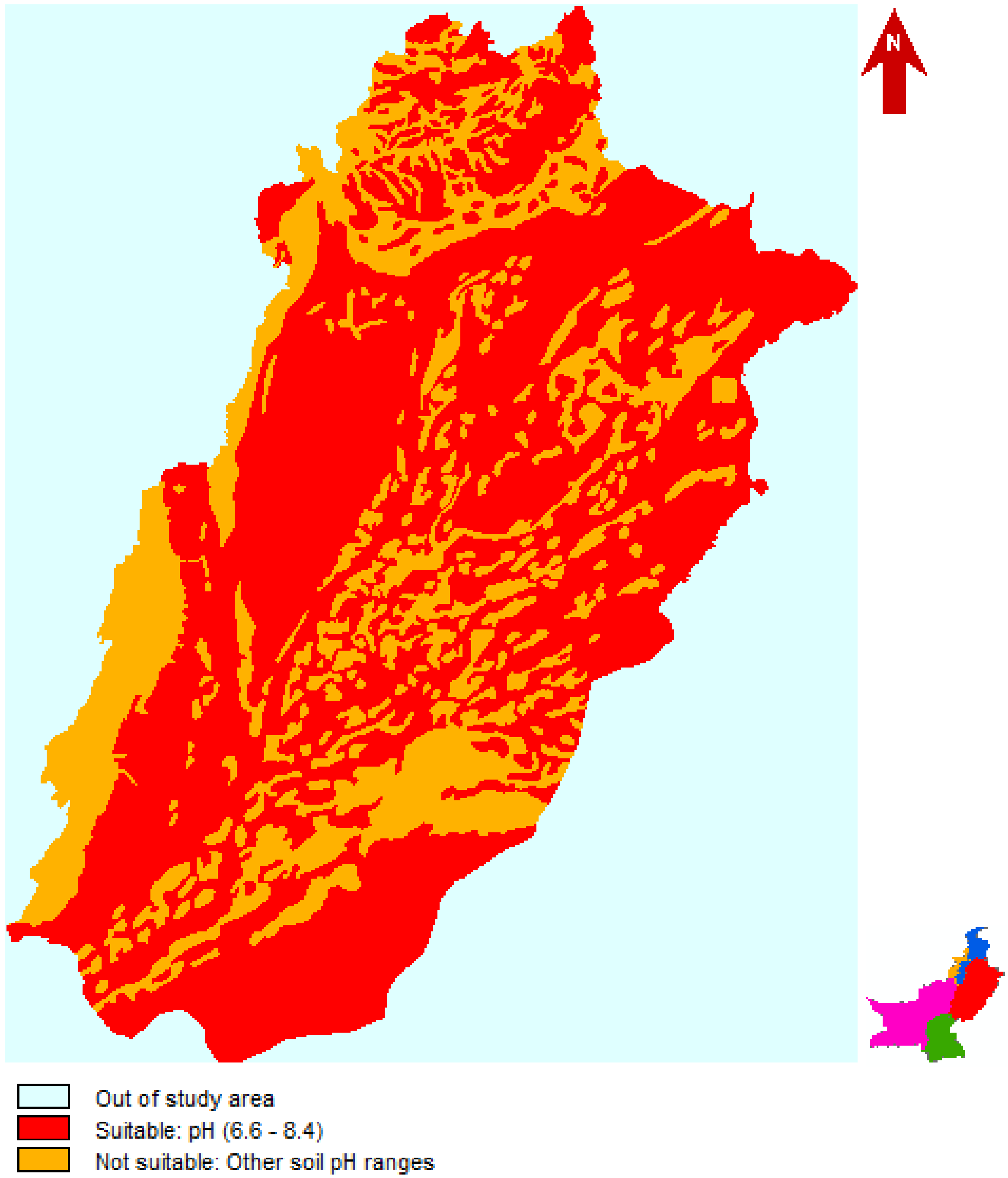

Fig. 11. Standardized factor map for Punjab soil pH.

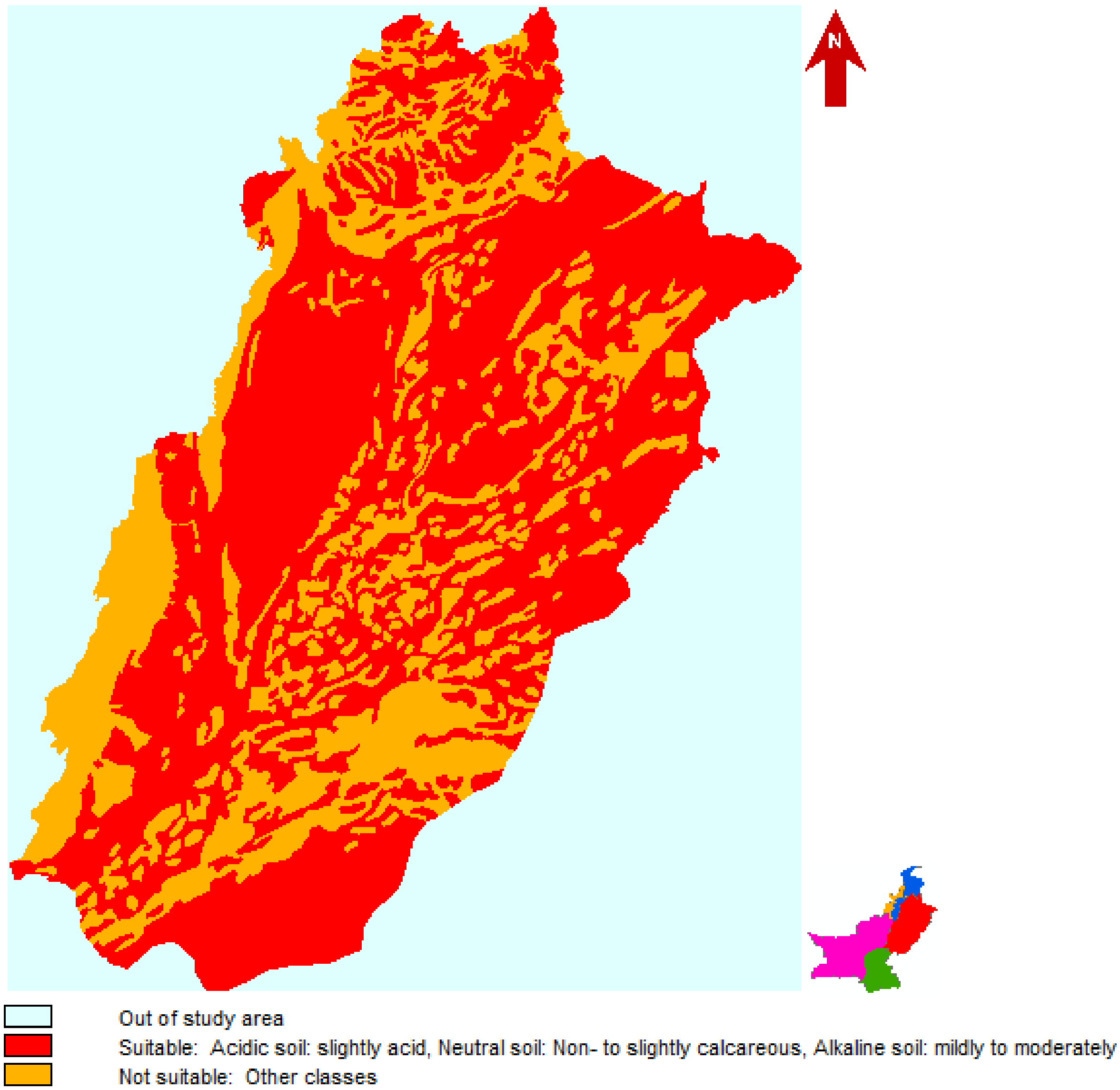

Fig. 12. Standardized factor map for Punjab soil chemical properties.

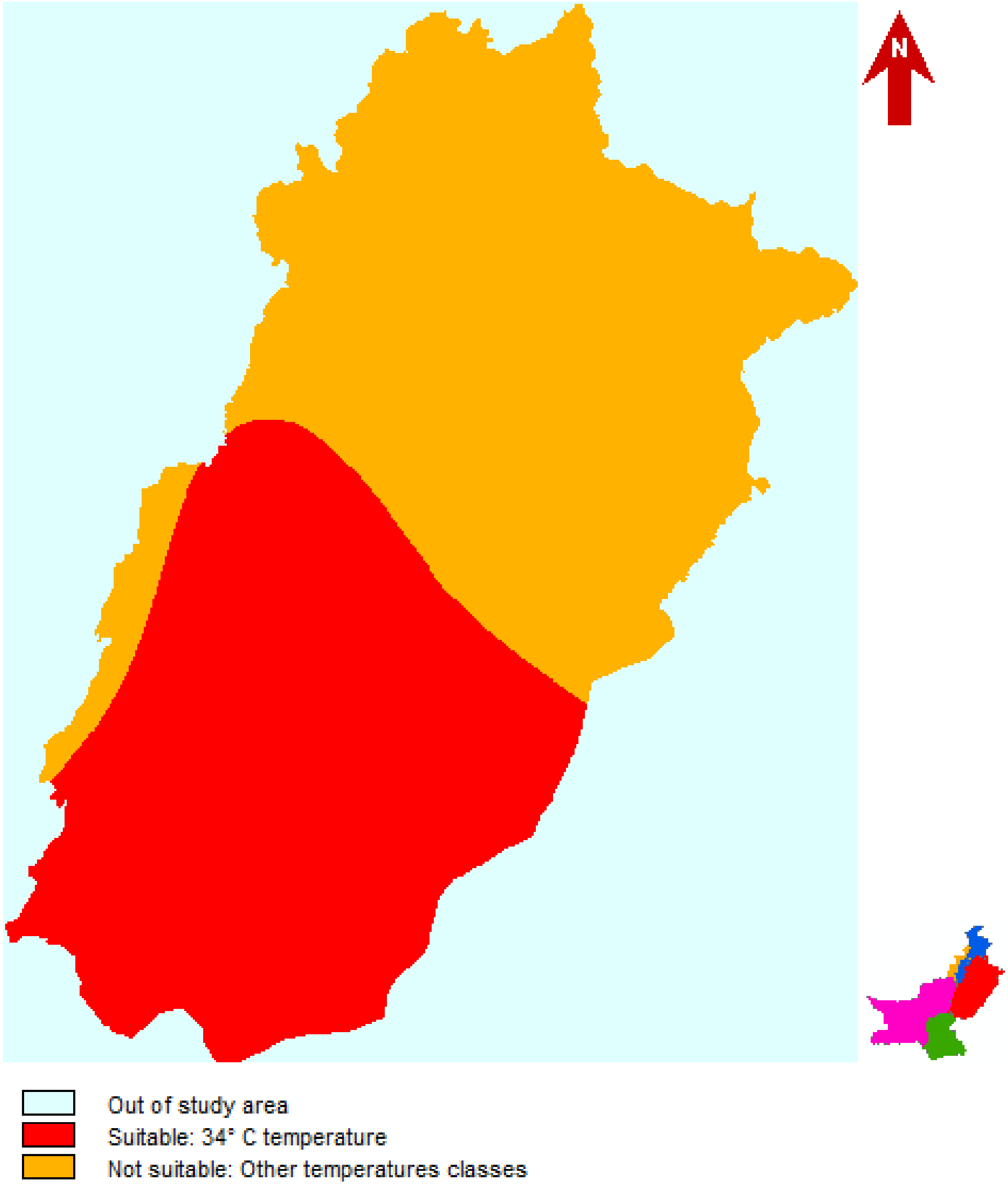

Fig. 13. Standardized factor map for Punjab mean maximum annual temperature.

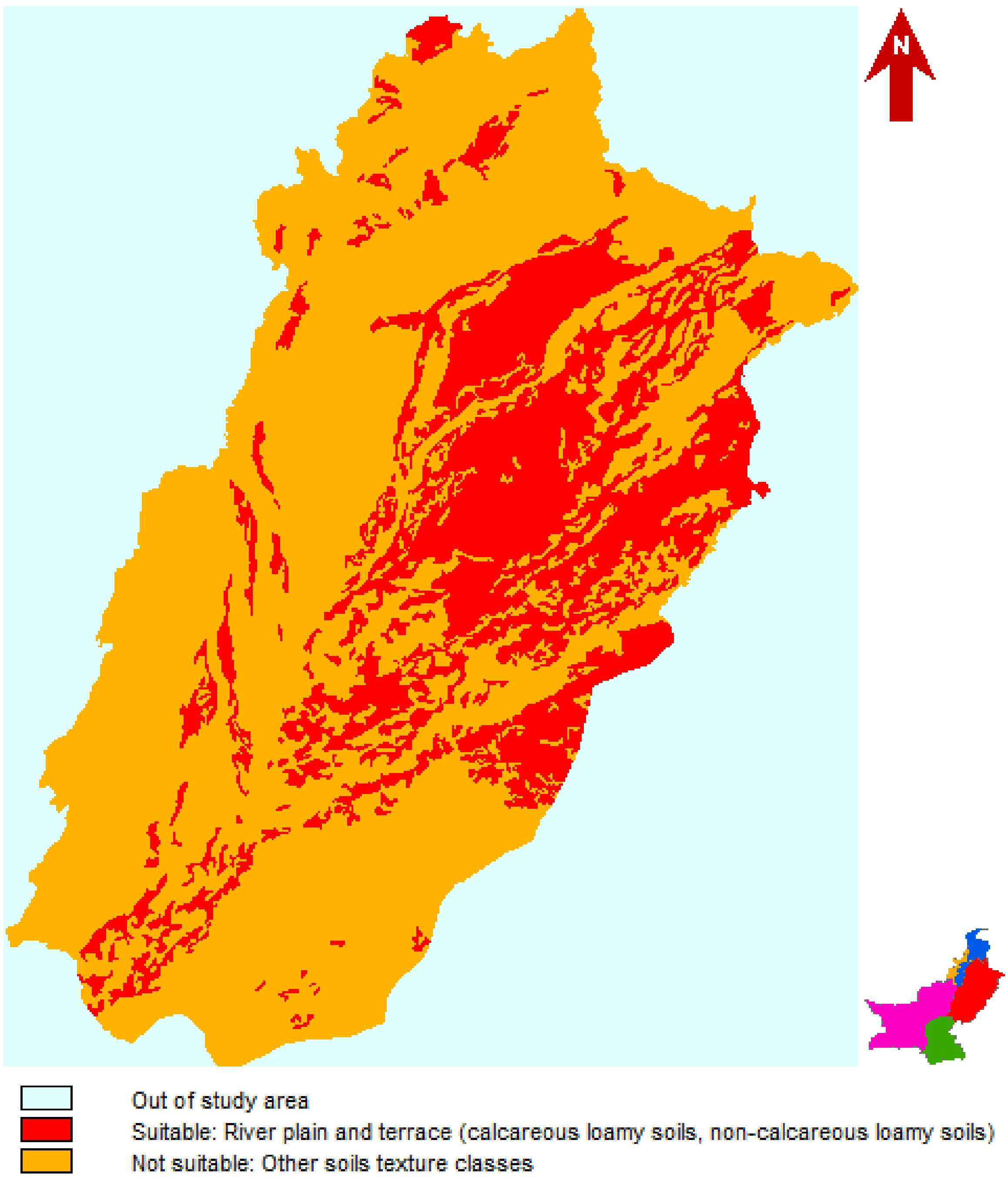

Fig. 14. Standardized factor map for Punjab soil physical properties.

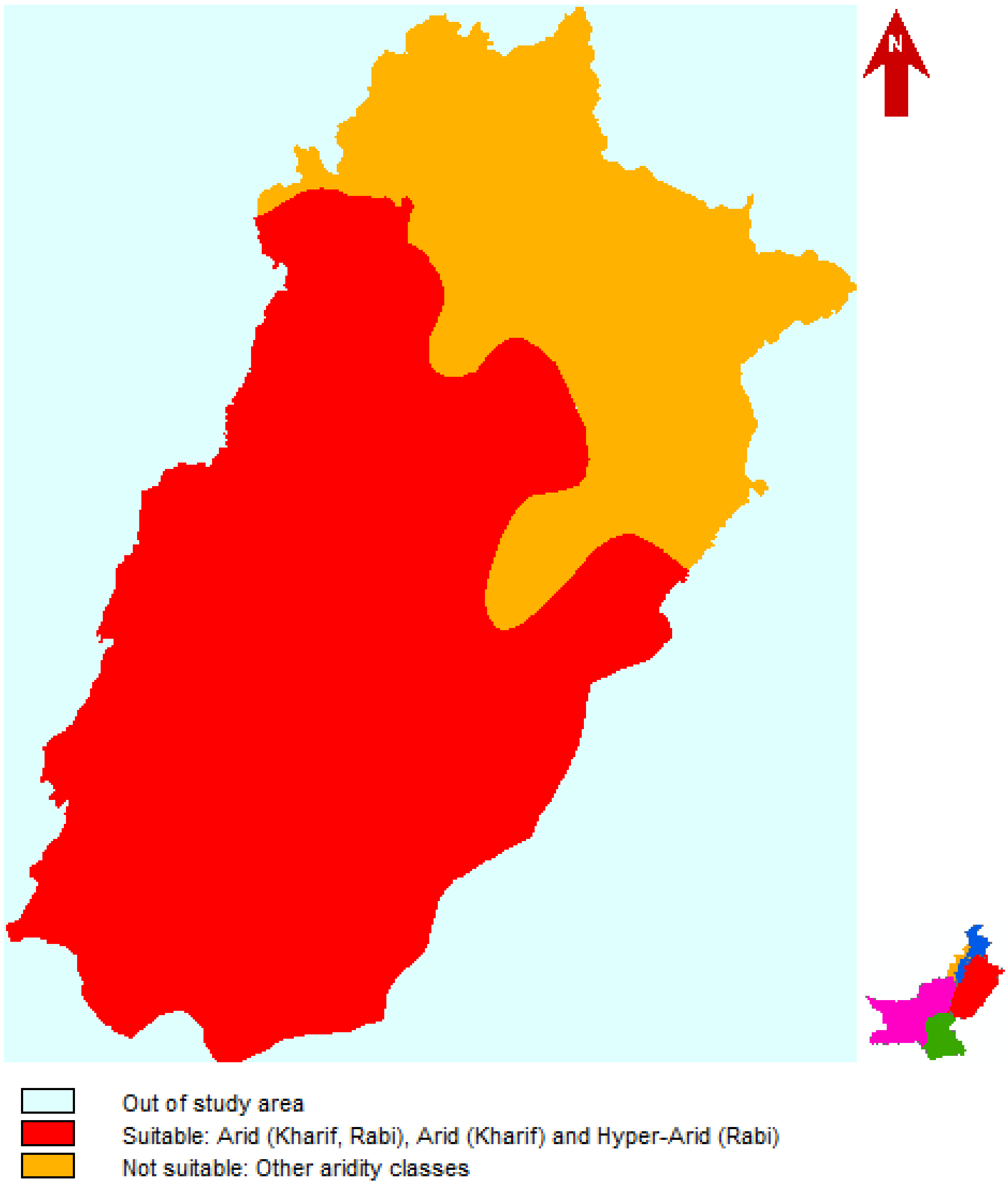

Fig. 15. Standardized factor map for Punjab aridity classes.

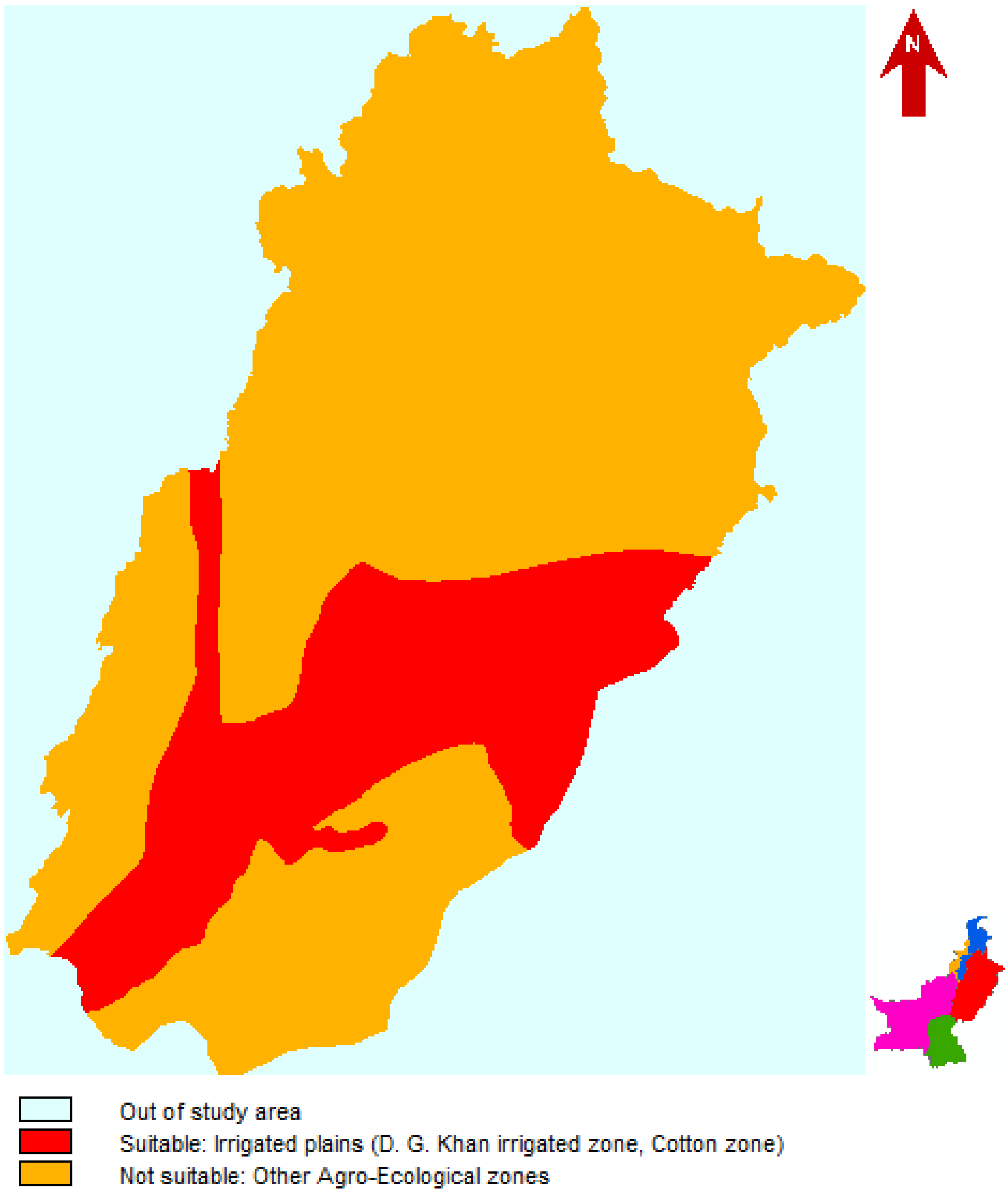

Fig. 16. Standardized factor map for Punjab agro-ecological zones.

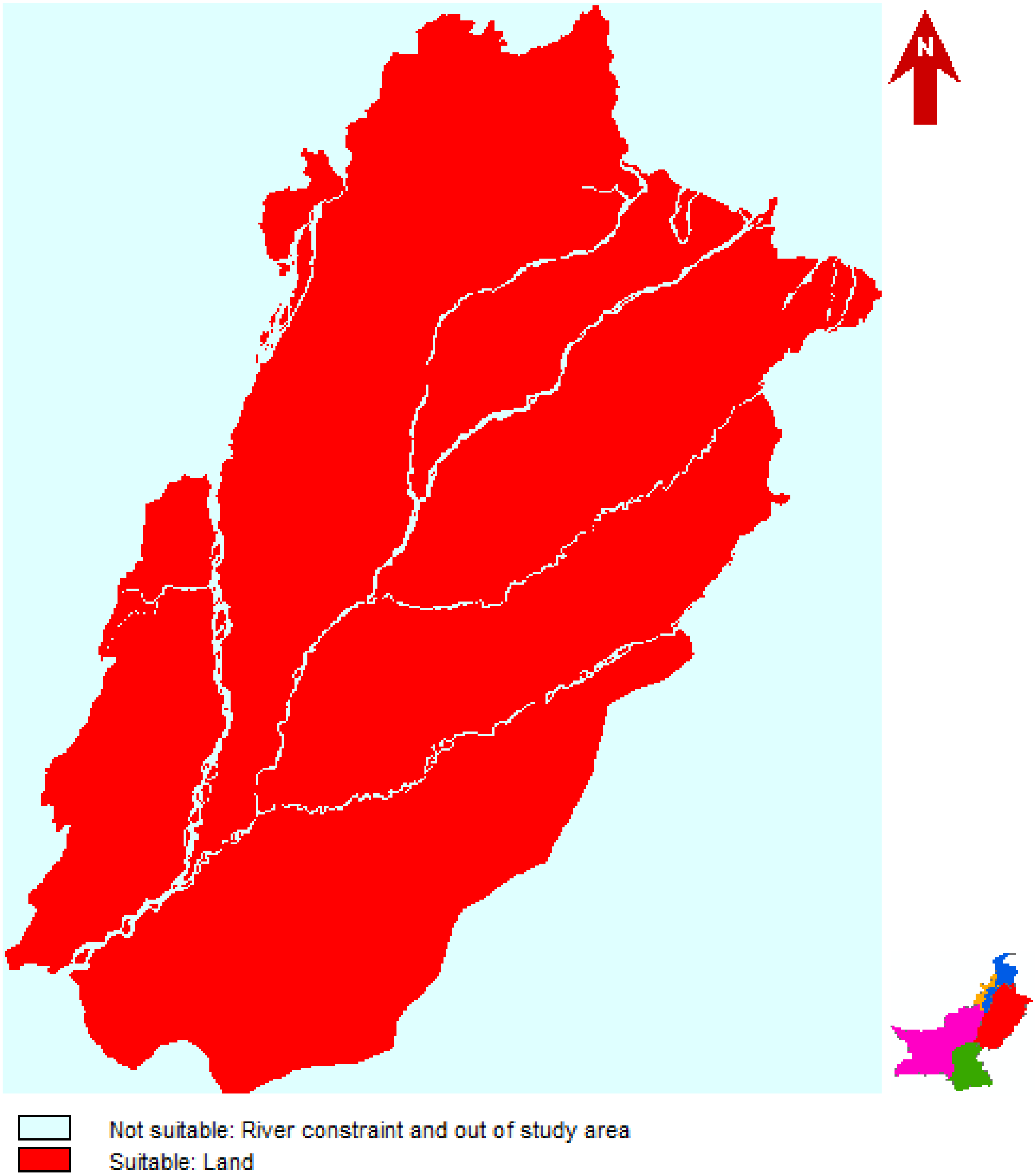

Fig. 17. Standardized constraint map for Punjab rivers.

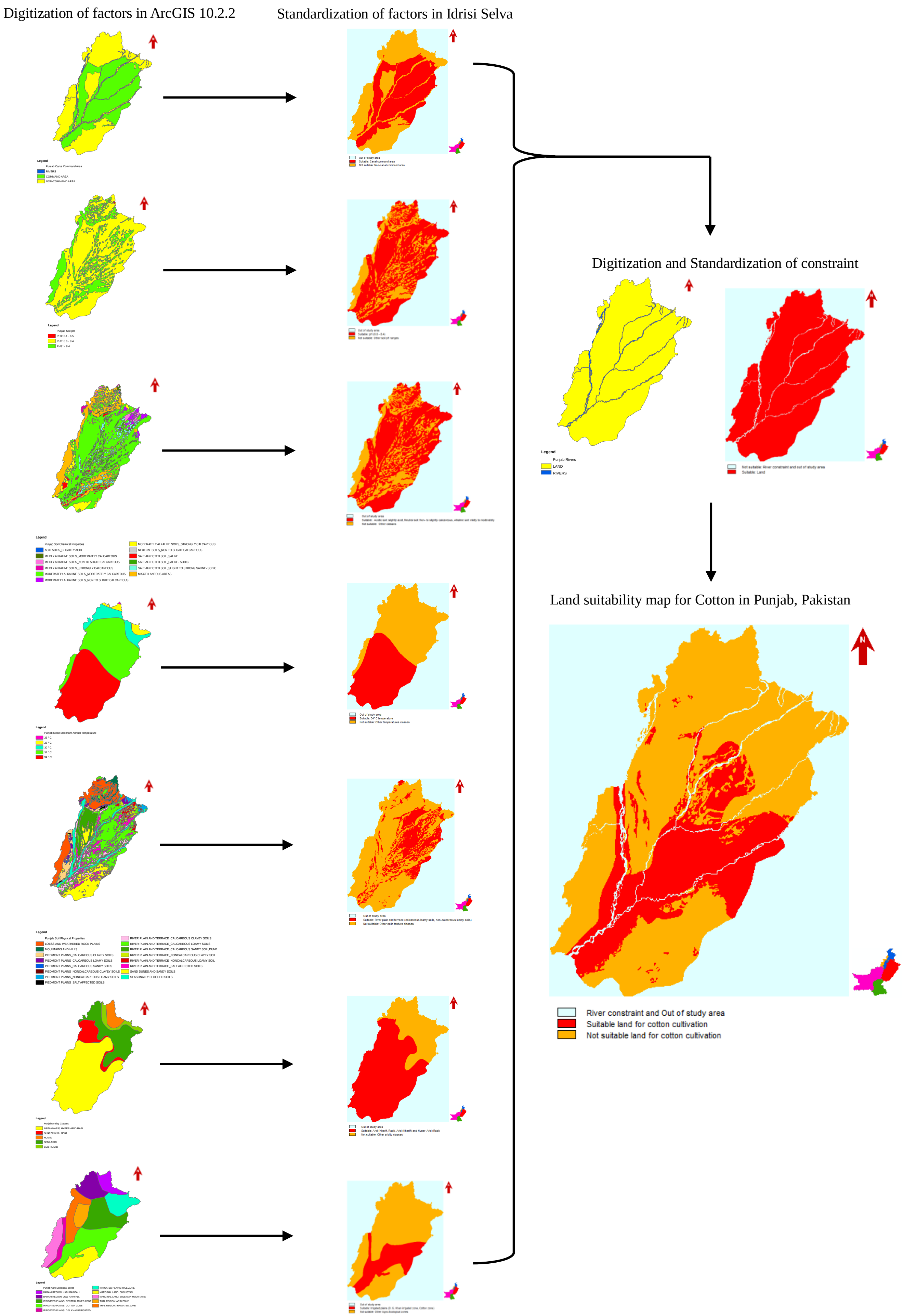

Fig. 18. The process of combining criteria maps for Cotton land suitability in Punjab, Pakistan, using GIS based AHP model.

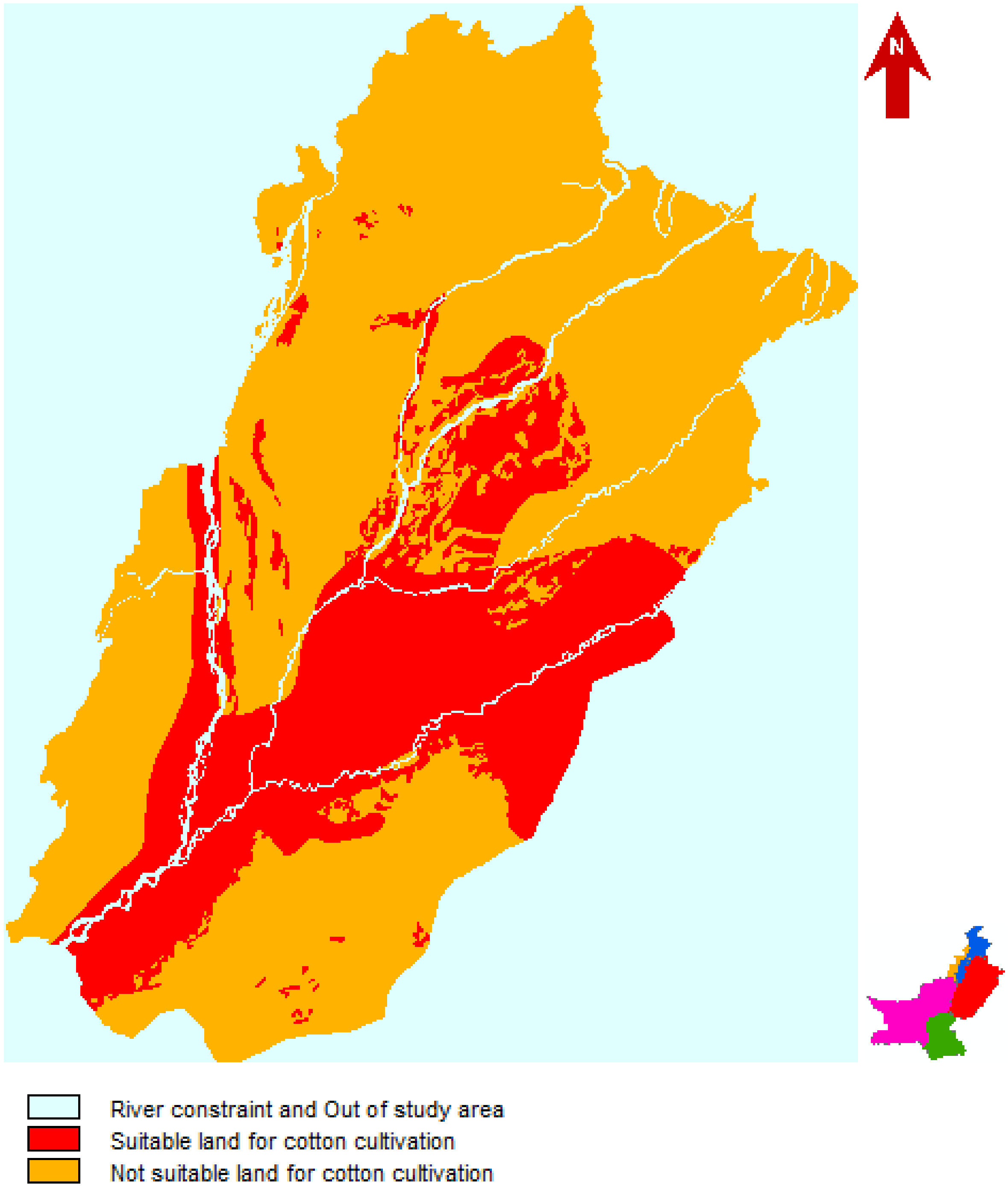

Fig. 19. Land suitability map for Cotton cultivation in Punjab, Pakistan, using GIS based AHP model.