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RESEARCH ARTICLE

Site Suitability Analysis for Urban Settlements along River Jhelum, Pakistan using GIS and Remote Sensing Techniques

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Abstract Infrastructure development is critical to the success of economic growth policies. Remote sensing and GIS tools have an important role to play in the development of various urban infrastructures. Due to the rapid growth of urban population and urbanization, it is necessary to find out the site's suitability for sustainable urban development. The main aim of the study is to study the growth and trend of urbanization, as well as to find out suitable sites for further urban development in northern Punjab, along the river Jhelum, Pakistan. The study illustrates the use of geographic information system (GIS) and Remote Sensing based techniques i.e. Human Natural Environment Index (HNEI) applied with a foundation of Relief Degree of Land Surface (RDLS), Temperature Humidity Index (THI), Water Resource Index (WRI), and Land Cover Index (LCI) for selection of the suitable site for urban settlements along river Jhelum, Pakistan. For this purpose, Toposheet and Landsat satellite data were used to generate various thematic layers using ArcGIS software. The results were generated in form of five categories i.e., highly suitable, moderately suitable, relatively low suitable, low suitable, and non-suitable. The final results indicated that district Sargodha is most suitable for long-term sustainable urban settlements favored by relief, climate, water availability, land cover scenario, and flood hazard-free area. Eventually, a site suitability map is prepared for further urban development. The present study allows the local people as well as urban planners for the appropriate plans of land use planning in sustainable urban development.

1. Introduction

Urban Development and Migration of the population from rural to urban areas are global phenomena. Due to the population growth and urbanization sprawl, it is desirable to find out the site's suitability for city development. The human settlement environment is defined as a space where mankind persists and flourishes. The nature of the human settlement environment influences precisely, the fitness of mind and body of human beings and periphrastically influences the advancement and growth of living society or environment in terms of economy and socialism as specified by some remarkable researchers (Li et al., 2011). Human settlements emphasize sustainable development which is primarily based on the prevailing natural environment in a certain area of development (Feng et al., 2008; Wei et al., 2013; Musakwa et al., 2017). It is means of forestalling the prospective inhabitants the possible recurrence of any hazard in the future is that area is hazard-prone therefore underpinning the development of cities and nations (Rusdi et al., 2015; Musakwa et al., 2017). Human settlements fundamentally determine the spatial distribution pattern of population in districts under study (Li et al., 2011).

The conception of the science of habitat or living environment suitability was pre-eminently advanced by Greek scholar Doxiadis in 1958 (Doxiadis, 1970; Feng et al., 2009; Li et al., 2011). Long-term sustainable development is made effective by out looking at natural environmental features to develop human settlements as specified and enumerated by United Nations in the second habitat conference which forwarded the “Habitat Agenda” for sustainable human development concerning comfortable housing for urban development. In today’s post-industrial age, Pakistan should also take part in sustainable development protecting human settlements' environment suitability (Song et al., 2019). Similarly, in the 1980s, 1994, and, 2000; China, the US, and the Dutch structured their RS and GIS-based principle assessment system for urban development namely; the State Environment Protection Administration of China (SEPAC) Model, Leadership in Energy and Environmental Design Standard (LEEDS) and, Eco Quantum Standard respectively. As a ripened fruit of these efforts, in China, the concentration of the Human population is found in a natural environment of favorable land (Feng et al., 2009). Synonymously in South Africa, cities and towns are developed on basis of spatial planning, which accounts for the availability and accessibility of land concerning environmental and physical setup (Musakwa et al., 2017). In

Sydney and Australia concordantly, studies were conducted keeping in view the thermal conditions of the natural environment in subtropical areas (Li et al., 2011).

Many factors manipulate the habitat environment usability of land and its resources. The most elementary determinants are relief, climatic conditions, hydrological circumstances, and land use land cover scenarios such as elevation, temperature, humidity, and Normalized Difference Vegetation Index (NDVI) respectively. All these determinants play a pivotal role in the determination of a human settlement's environmental suitability. It is a key mechanism for foreseeing natural conditions for sustainable development. In this context; geomorphology, topography, and land geology play a vital role, which necessitates the consideration of relief for desired sustained development (Li et al., 2011; Rusdi et al., 2015). The leading factors for human settlements to develop sustainably are derived from affinity between human, natural, and, geographic environments. When these factors are neglected; environmental and ecological degeneration in form of falling groundwater levels, salinization, and, desertification (Wei et al., 2013). The human environment index maintains a relationship between the human population and the natural setup, which determines the spread of the population in terms of space. Consequently, it enlightens a roadmap for planning efficient policies for sustained Human environment settlements (Li et al., 2011). In foreign, mostly developed countries geospatial techniques are utilized as suggested by (Feng et al., 2008; Feng et al., 2009) and the suitability of natural setup in elevated areas has been achieved successfully as specified by Wei et al (2013) while in contrary Pakistan has to produce subsequent efforts in this regard for its sustainable urban developments.

Despite expanding already setup built-up and urban areas; new cities should be developed in new suitable settlement sites compatible with the natural environment. Megacities and metropolitan areas encounter management and other issues so vast and almost insoluble, paving the way to develop new cities smaller and much easier to manage all available resources in the best possible way. Modern technology of remote sensing and GIS helps us to analyze the data spatially, offering possibilities of generating various options (modeling), thereby optimizing the whole planning process. It is in this context, that the suitability analysis attempted in this study must be viewed as a basic "Prioritization of land for urban development. Bearing in mind these issues, we propose an improved GIS and RS-based approach for land-use suitability assessment for urban development. The study aims to illustrate the use of geographic information system (GIS) and Remote Sensing based techniques i.e. Human Natural Environment Index (HNEI) applied with a foundation of Relief Degree of Land Surface (RDLS), Temperature Humidity Index (THI), Water Resource Index (WRI), and Land Cover Index (LCI) for selection of the suitable site for urban settlements along river Jhelum, Pakistan. The specific objective of the study is to analyze the Analytic Hierarchy Process (AHP) and Preparation of suitability map by overlaying the thematic maps with suitable weightage.

Study Area

The latitudinal and longitudinal extent of the study area is defined as 32° 4'27.24"N and 72°47'42.79"E (Figure 1). The study area accommodates all districts partially or accommodating the flow of the Jhelum River through them. There are six districts along River Jhelum including Jhelum, Khushab, Mandi Bahauddin, Gujrat, Sargodha, and Jhang; which are included in the study area. The total area of the selected study area is 30626 km2. The total population according to the census 2017 is 14.67 million (GoP, 2013). According to Food Agriculture Organization (FAO), the topography of the study area is composed of rangeland, forests, plain area, desert land, and river (Rusdi et al., 2015).

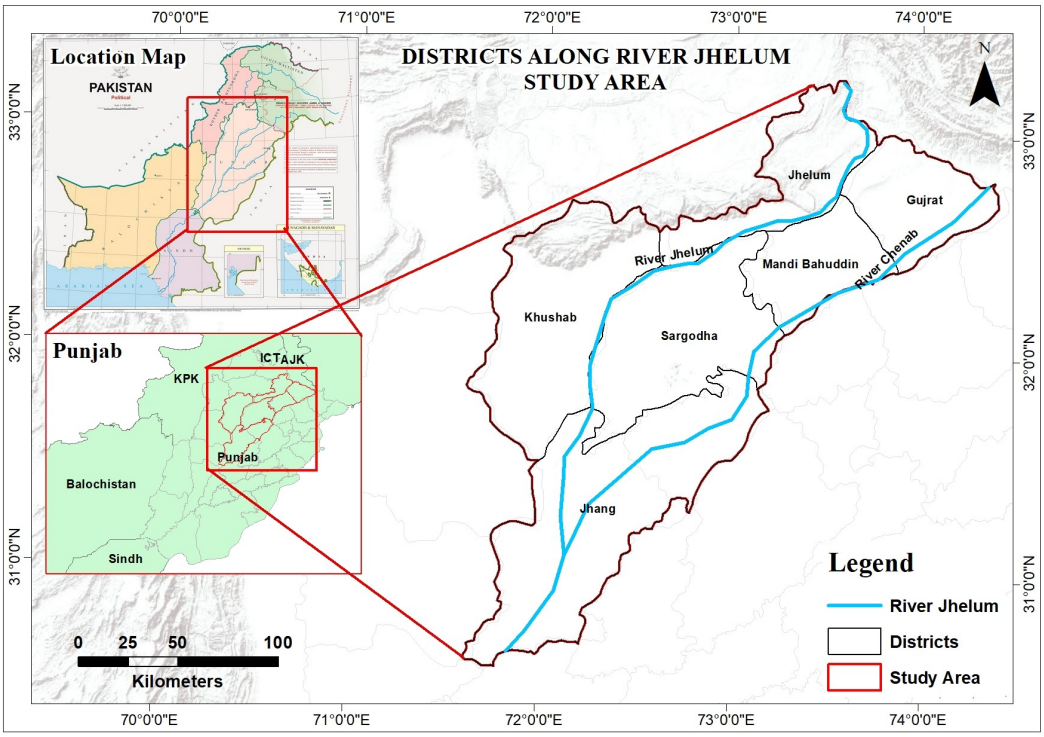

Figure 1. Depicting the study area showing districts along the Jhelum River

2. The Methods

The methodology followed in this study is shown in Figure 2.

Data and its Sources

Our investigation was directed in the Bali Strait with the The digital elevation model was recorded by Shuttle Radar Topography Mission (SRTM) and attained by the United States Geological Survey (USGS) website. The SRTM data is globally accessible which strengthens the research studies (Bamberger, 2017). Pakistan Meteorological Department (PMD) is a scientific service department that contributes by the provision of climatological and hydro-meteorological data. The rainfall and temperature datasets for three districts were acquired from the following stations for the years 2006 to 2017. The source is mentioned in Table 1.

The population data was attained from Punjab Development Statistics (PDS). It is an official report published by an agency named the Pakistan Bureau of Statistics (PBS). It provides a national statistical service, very useful for statistical research purposes. Keeping in view the purpose of the current study, only estimated urban population district-wise was obtained for further analysis (GoP, 2013). The satellite imagery of Landsat 8 for the year 2020 is acquired from the United States Geological Survey. Landsat 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) C1 Level-2 provides on-demand data and imagery applicable for research purposes in varied areas of; technology and science, crops, and agriculture, governmental uses (Song et al., 2019). The study area is covered by five tiles and the details of satellite imagery retrieved are listed in Table 2.

Table 1. Meteorological Stations details

Sr. No	Index No.	Station name
1	41597	Mandi Bahauddin
2	41593	Sargodha
3	41636	Jhang

Table 2. Details of Landsat satellite images used in the study

Acquisition date	Sensor	Resolution	Path/Row
2020-05-21	OLI/TIRS	30m	149/037
2020-05-21	OLI/TIRS	30m	149/038
2020-04-10	OLI/TIRS	30m	150/037
2020-03-09	OLI/TIRS	30m	150/038
2020-05-12	OLI/TIRS	30m	150/039

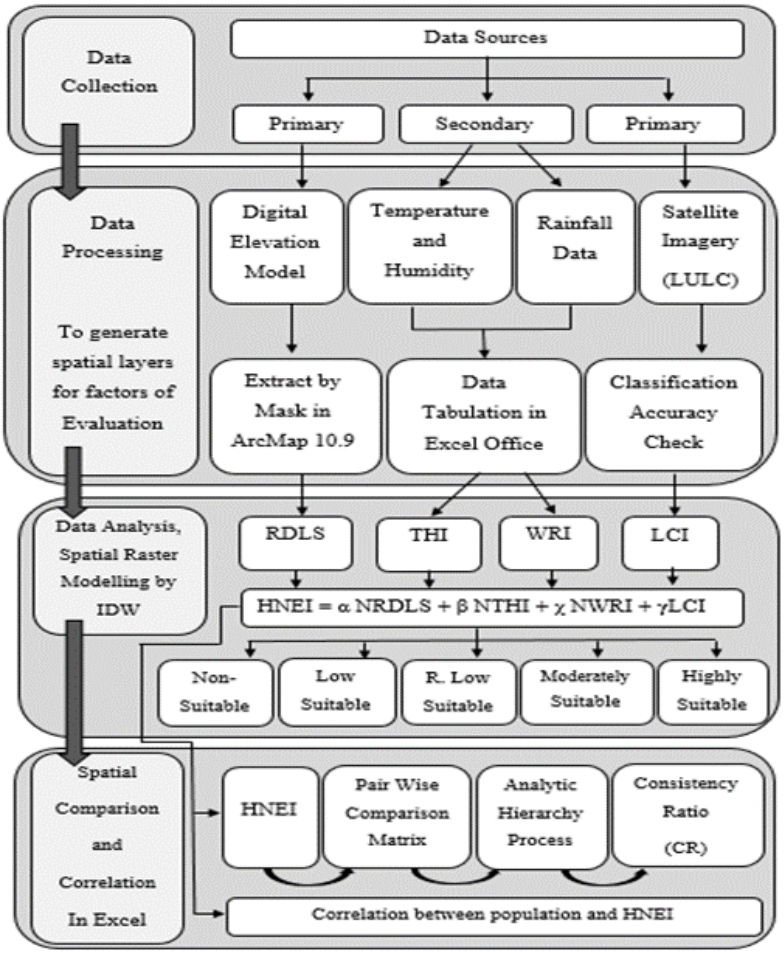

Figure 2. The schematic sketch of the research methodology

Metodhology

Image Classification

The classification of the study area utilizing satellite imagery was acquired from Earth Explorer US Geological Survey. Landsat-8 OLI/TIRs were classified to generate a Land use Land cover (LULC) map of the study area and its districts. The classification was accomplished after radiometric correction of satellite imagery explained in the data pre-processing section. The pre-processed bands were then utilized to make a composite for each imagery separately using band 2 to band 7. Then supervised image classification was applied to classify individual composite then, these classified rasters were then mosaicked which generated the final layer of the classified land use map. This study area along with its classes was checked with the report published by a collaboration of the government of Pakistan, SUPARCO, and FAO. The accuracy was checked by applying Remote Sensing using Google Earth Pro. The land was classified into 11 subtypes namely; orchards, flood plain crops, crops rain-fed, irrigated crops, forests, natural vegetation, built-up, bare land without vegetation/shrubs, bare land with shrubs, rangeland, and water resources encompassed into three main types of land use namely; built-up, bare land, water bodies, and vegetation cover (Malczewski, 2004; Jain and Subbaiah, 2007; Yang et al., 2008; Xu et al., 2011). Figure 3 shows the classified map of the study area.

Normalized Difference Vegetation Index (NDVI)

This index indicates the healthy vegetation of an area. The formula was applied using two bands for Landsat 8 i.e. band 5 as the NIR band and band 4 as the R band (Wei et al., 2013; Song et al., 2019). The formula for NDVI is given as:

NDVI = (NIR–R) / (NIR+R) ----------(VI)

Table 3 shows the calculated values of land use types for each district. These values are generated by multiplying the total area with weights; where NDVI, built-up, water bodies, and barren land have been assigned the weights as 0.15, 0.2, 0.17, and 0.05 respectively. These weights have been derived from one previous study (Song et al., 2019). The results of the analysis will be depicted in the result section.

Relief Degree of Land Surface (RDLS) Model

Relief Degree of Land Surface (RDLS) is defined as, an integrated depiction of the elevation and relief extent of an area. It echoes the macroscopic transformation of the area's

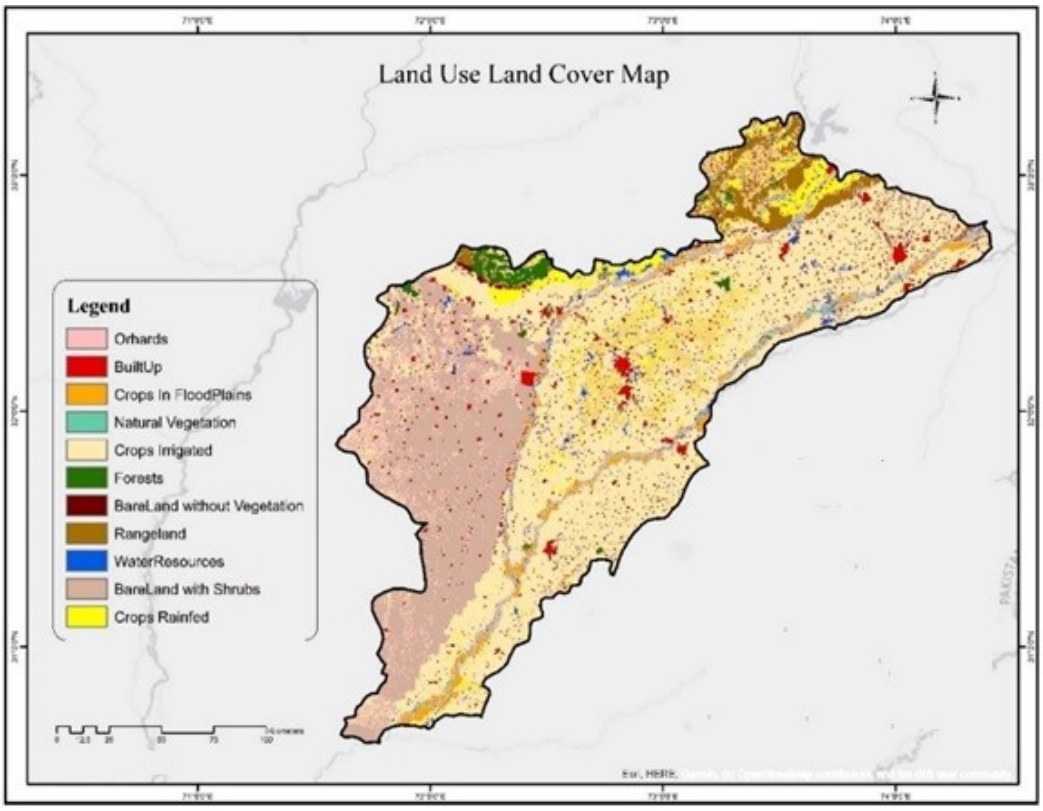

Figure 3. The classified map of the study area shows districts along River Jhelum

Table 3. Land use values are generated by multiplying the total area of land use by the weights

Districts (weightage)	NAVI (0.15)	LT1 (Built-up) (0.2)	LT2 (Water bodies) (0.17)	LT3 (Barren land) (0.05)
Gujrat	440.7375	37.618	12.0853	0.667
Jhang	731.8245	26.544	26.1256	50.8505
Jhelum	493.716	20.928	38.2296	0.288
Khushab	515.844	41.048	25.4405	138.1175
Mandi Bahauddin	377.4495	19.292	12.3335	0.118
Sargodha	810.0105	55.6	28.3458	0.4125

terrain; which is a reference value for human settlements site selection (Li et al., 2011; Wei et al., 2013; Song et al., 2019). The formula of RDLS is as follows:

RDLS =ALT/1000+[max(H)–min(H)]×[1−P(A)/A]/500 (1)

Where, ALT refers to the average altitude of the study area, max (H) refers to maximum altitude, min (H) refers to minimum altitude, and P(A) refers to the flat area within the area of study, while A refers to the total area of study. The three indexes namely ALT, max (H), and min (H) are derived from Digital Elevation Model (DEM) directly. This is accomplished by applying neighborhood analysis of Arc Map the calculation of a flat area in the area with the soap less than 500 is undertaken by the usage of spatial analysis tool for the neighborhood. The total number of pixels of the flat area within the study area is calculated according to definitions of Morphology, the flat area is always less than 300 altitude. Then the flat area is divided by the total area resulting in statistics generated for P(A)/A. The grid size taken as a computational/calculation unit is 554.74 × 554.74 accounting for 307736.4676 km total area (Feng et al., 2008; Feng et al., 2009). Figure 4 shows digital elevation with districts included in the area of interest defined as a study area regarding River Jhelum. The maximum elevation is 5116 and the lowest elevation is 84 as depicted in symbology (Bamberger, 2017).

Temperature Humidity Index (THI) Model

Temperature Humidity Index (THI) was pre-eminently recommended by Thom, in 1959. THI is the most sophisticated index to ensure the measurement of adequate extent for a comforting climatic environment for human beings (Feng et al., 2009). The components of these comfortable climatic conditions are primarily based on temperature, the intensity of heat in the environment, and humidity, the intensity of water vapors in the environment. Thus, according to the standard formula:

THI= 1.8t- 0.55(1- f) (1.8t -26) ----------(2)

Where; t denotes monthly average temperature and F denotes monthly average humidity. These averages have been calculated using raw data from six districts; namely Jhelum, Mandi Bahauddin, Sargodha, Khushab, Jhang, and Gujrat. First of all, the data was organized and statistical analyses were applied using above mentioned standard which is already discussed in the data tabulation Section. Table 4 shows the final calculated values of temperature and humidity for eleven years from 2006 to 2017 for each district separately. The result of the analysis will be displayed in the results section.

Water Resource Index (WRI) Model

Water Resource Index (WRI) model is based on water resource quantity and precipitation. The model used in the present study was first issued by SEPAC China (Feng et al., 2009). The formula of the WRI model is as follows;

WRI = αP + βWa----------(3)

Where α and β denote the weight of precipitation and water resource respectively, P denotes normalized precipitation,

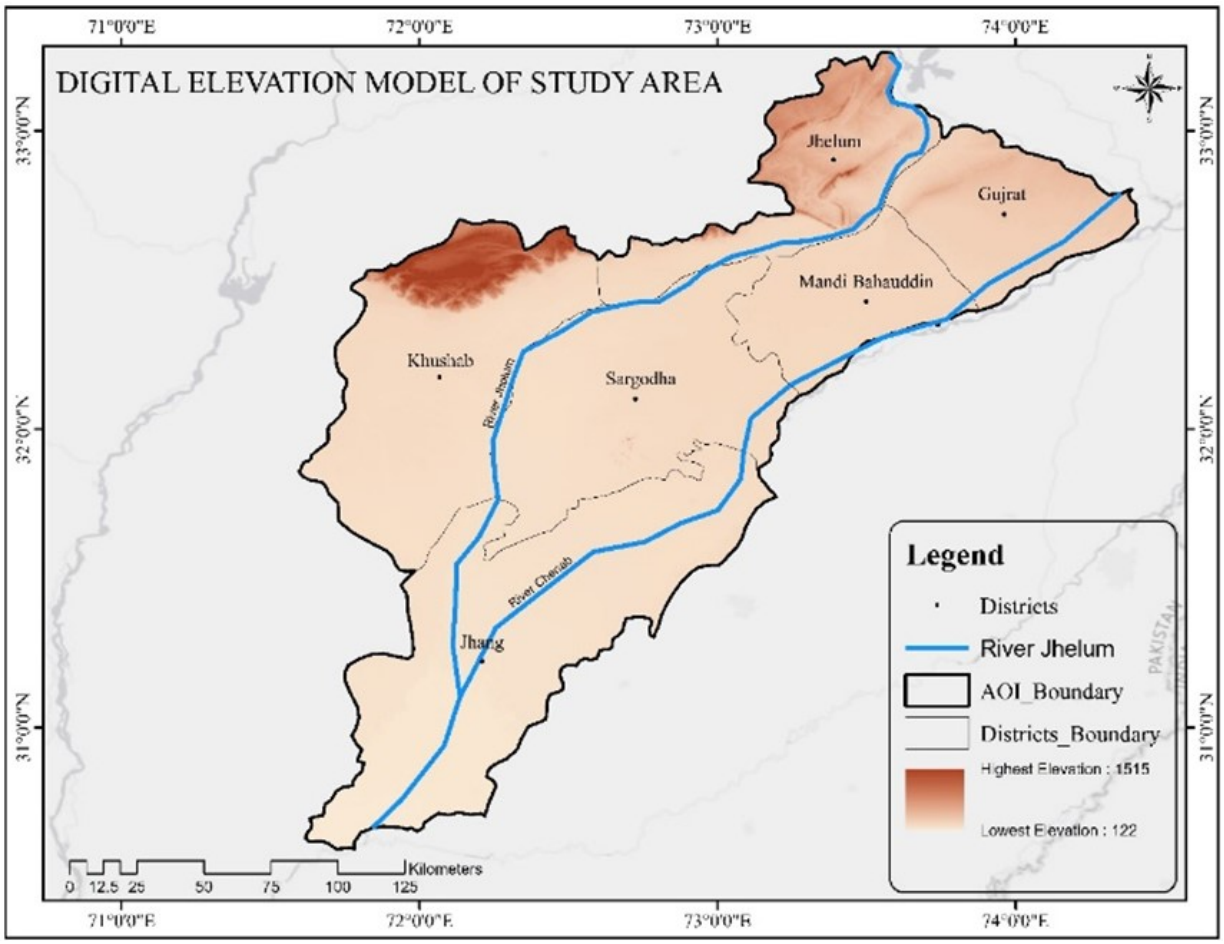

Figure 4. Digital elevation model of the study area along River Jhelum

Table 4. Average temperature and humidity for 2006-2017

Name of District	Average Temperature (t)	Average Humidity (f)
Gujrat	29.08	48
Jhang	32.00	69
Jhelum	21.54	64
Khushab	20.18	34
Mandi Bahauddin	26.50	38
Sargodha	24.30	29

Table 5. District-wise values of precipitation and water area

Name of District	Precipitation (P) (mm)	Water Area (Wa)
Gujrat	55.81	71.09
Jhang	23.83	153.68
Jhelum	71	224.88
Khushab	44.3	149.6
Mandi Bahauddin	26.3	72.55
Sargodha	33.867	71.09

while Wa denotes normalized water area. Water is the source of life. Almost 70% of the living beings are composed of water and the same proportion of earth is also composed of water. So, among nature-based elements, the water resource index should also be considered a fundamental priority as water availability serves as a base for the foundation of human settlements to be developed in a certain area. Hydrological conditions affect the physiological environment it affects the economy, population, and settlement it has been used by several researchers such as (Feng et al., 2009; Li et al., 2011; Wei et al., 2013; Song et al., 2019). The WRI model executes itself by embodying the capacity of water supply in a natural environment. The calculated values are shown in Table 5, which depicts the precipitation and water area.

Land Cover Index (LCI) Model

The land is an essential asset, which is utilized in a sustained manner indicating the long-term productivity of human social development and human economic development. Land utilization and land cover affect the durability of the natural environment (Feng et al., 2009; Song et al., 2019). Land Cover Index (LCI) is characterized as follows;

LCI = NDVI × LTi----------(4)

Where NDVI refers to the Normalized Difference Vegetation Index while LTi refers to the four land-use types. The LTi in the present study refers to the four land-use types namely; vegetation, built-up, bare land, and water bodies. These land-use types and their total area in sq. km in each district extracted from a report generated by FAO, SUPARCO, and GOP are summarized in Table 6.

Human Natural Environment Index (HNEI) Model

Human Natural Environment Index (HNEI) is developed by operating a mono-factor assessment of relief, climatic conditions, water availability conditions, and land use land cover situation. Each Index; RDLS, THI, WRI, LCI corresponds to the weightage assigned to each of it as; α, β, χ, and δ (Feng et al., 2009; Wei et al., 2013). The sum of all indexes multiplied by the weightage gives the final scene of the Human Natural Environment Index. The formula for HNEI is as follows:

HNEI = α NRDLS + β NTHI + χ NWRI + γ LCI----------(5)

Where; NRDLS denoted normalized relief degree of the land surface, NTHI denotes normalized temperature-humidity index, NWRI denotes normalized water resource index, NLCI denotes normalized land cover index, and α, β, χ, γ indicates the weights assigned to each index. The weights α, β, χ, γ represents the value of 0.2324, 0.0794, 0.3579, 0.0435, 0.1697, and 0.1172 respectively. These weights are extracted from previous studies (Mazahreh et al., 2019; Song et al., 2019) which were computed by applying Analytic Hierarchy Process (AHP). Table 7, shows the computed value for the mono-factor index which was obtained by multiplying the weights with corresponding indexes for each district individually.

Analytical Hierarchy Process (AHP) Model

AHP stands for Analytical Hierarchy Process, pre-eminently introduced by Saaty in the 1990s to make decision making of this complex world, simplified. The application of AHP for decision-making for land suitability for urban development is a valuable asset because it integrates smaller units of criteria into the final decision, it also inculcates the expert's vision and ground experiences for analysis. It is Multi-Criteria Decision Making method (MCDM) based on Pairwise Comparison Matrix which is generated to evaluate the factors used in the present study (Yang et al., 2008; Youssef et al., 2011; Kumar and Shaikh, 2013;Musakwa et al., 2017). These factors are RDLS, THI, WRI, and LCI. The comparison matrix generated according to relative importance is depicted in Table 8.

Table 6. Land use Land cover statistics for each district

Name of District	Land Use Classes Area (sq. Km)			
District	Vegetation	Built-Up	Bare land	Water Bodies
Jhelum	3291.44	104.64	5.76	224.88
Khushab	3438.96	205.24	2762.35	149.65
Jhang	4878.83	132.72	1017.01	153.68
Gujrat	2938.25	188.09	13.34	71.09
Mandi Bahauddin	2516.33	96.46	2.36	72.55
Sargodha	5400.07	278	8.25	166.74

Table 7. Depiction of all indexes district-wise

District Name	αNRDLS	βNTHI	χWRI	γLCI
Gujrat	0.02220038	0.035485	0.010096086	0.07316
Jhang	0.01176544	0.060476	0.014122586	0.261306
Jhelum	0.07822524	0.023485	0.023540031	0.111688
Khushab	0.0853809	0.010915	0.015426565	0.352466
Mandi Bahauddin	0.01438916	0.023874	0.007864445	0.041715
Sargodha	0.02043888	0.015464	0.008350288	0.233365

Table 8. Depiction of weights assigned to each factor

	RDLS	THI	WRI	LCI
RDLS	1.00	2.00	3.00	4.00
THI	0.50	1.00	2.00	3.00
WRI	0.33	0.50	1.00	2.00
LCI	0.25	0.33	0.50	1.00

Correlation between Population and HNEI

Correlation between population density and population is a Nature-based Socio-Spatial Analysis, which encompasses the designed assessment of space such as the natural environmental setup and the population living in it (Steinberg and Steinberg, 2015). It discussed in detail in the results section will indicate the land-use scenario of the existing population in the study area; districts along River Jhelum. It will take into account all the natural environmental setup factors integrated with HNEI as relief, climatic situation, water conditions, and land use land cover calculated as RDLS, THI, WRI, and LCI (Feng et al., 2009; Li et al., 2011).

3. Result and Discussion

The present study inculcates an analytical approach to the derivation of results objectively. This analytic approach required four major phases of modeling i.e. evaluation of real-world phenomena in the form of primary and secondary result collection, conceptualizing spatial model in form of data processing and generation of spatial layers, organizing logical approach in form of final HNEI model, and implementing software-based geospatial analysis generating final results. These results keeping the objectives in focus are discussed in this section.

Identification of nature-based locational conditions

The human settlement environment is the main indicator of human survival sustainability. In this study, four factors for site suitability of urban settlements and a comprehensive index model named HNEI of the human settlement natural environment were substantiated. These natural factors included relief/elevation, climatic factors such as temperature and humidity, water resources such as rivers and precipitation, and land cover scenarios.

Relief/Elevation

The elevation of an area plays a pivotal role in deciding the settlement types in a certain area. To look over the elevation extent of the Area of Interest (AOI), the DEM model was used to extract by a mask the elevation of the relevant district. This was done using the spatial analyst tool of Arc Map namely extract by mask under the section of data management tools. The relevant values for the highest elevation and lowest elevation were extracted and then; the flat area and the total area were then calculated. Figure 5 is used for the extraction of elevation values containing individual districts and their highest and lowest extent of elevation. The relief map of the study area is depicted in Figure 6. The values of DEM used for the inculcation of relief type are as defined by terms in morphology for that particular feature. These types are defined as; plain area, plateau, hilly area, and mountains.

Climatic Factors

The climate is another significant factor for proposing human settlements. Temperature and humidity are two integral elements of human survival the data tabulation lead to the computation of THI values according to the defined formula in the methodology section is depicted in Table 10 .

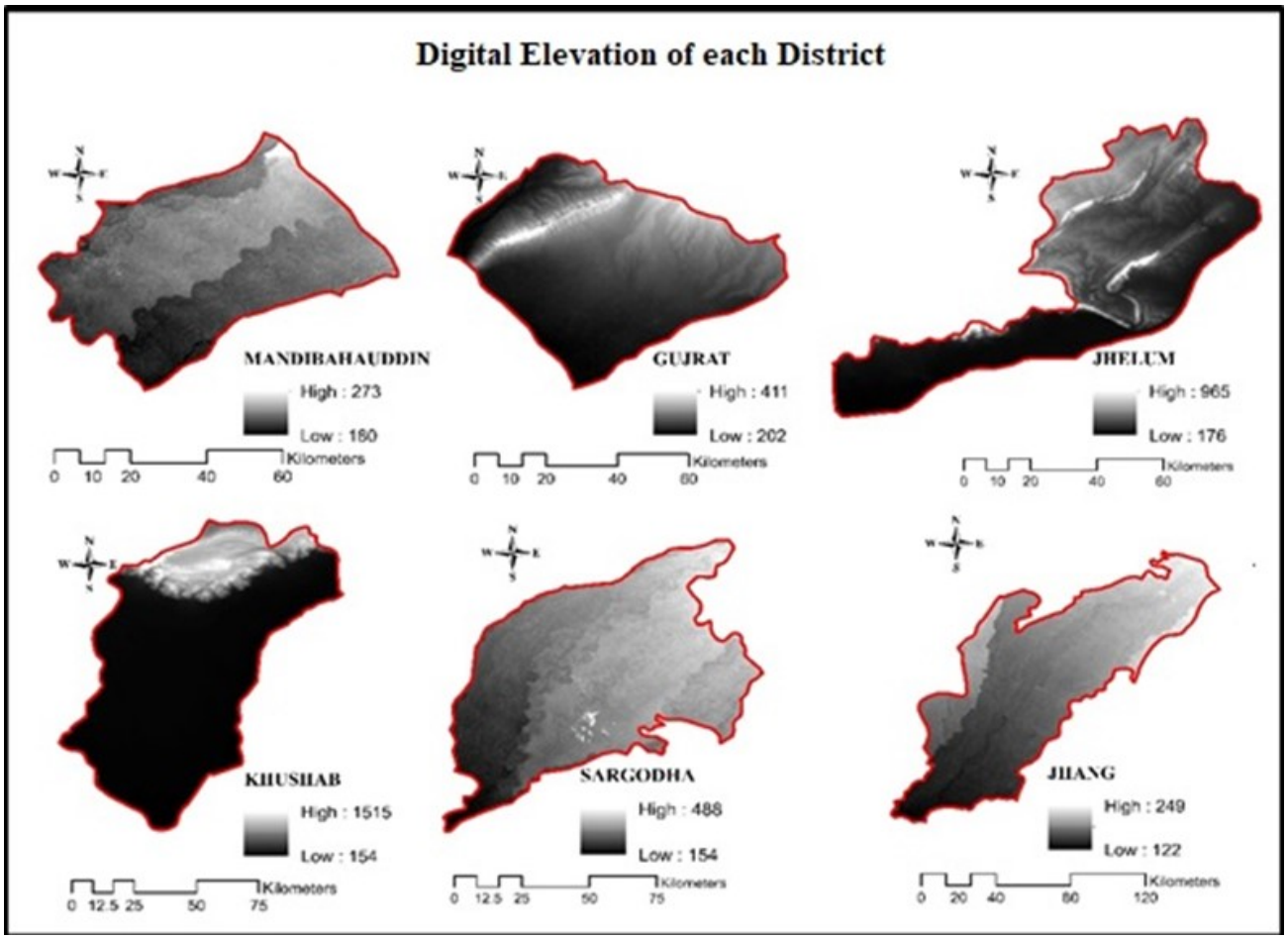

Figure 5. Depiction of digital elevation map for individual districts

Table 9. Depiction of computation of final RDLS value district-wise

District	(ALT)	Min(H)	Max(H)	P(A)	A	RDLS
Gujrat	306.5	202	411	2880.8	3210.8	0.349
Jhang	185.2	122	249	6182.0	6182.0	0.185
Jhelum	570.5	176	965	2107.8	3626.7	1.231
Khushab	818.5	122	1515	5319.6	6556.2	1.344
Mandi Bahauddin	226.5	180	273	2687.7	2687.7	0.227
Sargodha	321	154	488	5846.7	5853.1	0.322

Table 10. Depiction of final THI values district wise

District	Average Temperature (t)	Average Humidity (f)	THI value
Gujrat	29.08	47.58	727.3
Jhang	32	69	1239.4
Jhelum	21.54	64.00	481.3
Khushab	20.18	34	223.7
Mandi Bahauddin	26.5	38	489.3
Sargodha	24.3	29	316.9

Table 11. Depiction of final WRI values district-wise

District	(α)	(P) (mm)	(β)	(Wa)	WRI
Gujrat	50	55.81	50	71.09	6345
Jhang	50	23.83	50	153.68	8875.5
Jhelum	50	71	50	224.88	14794
Khushab	50	44.3	50	149.6	9695
Mandi Bahauddin	50	26.3	50	72.55	4942.5
Sargodha	50	33.867	50	71.09	5247.83

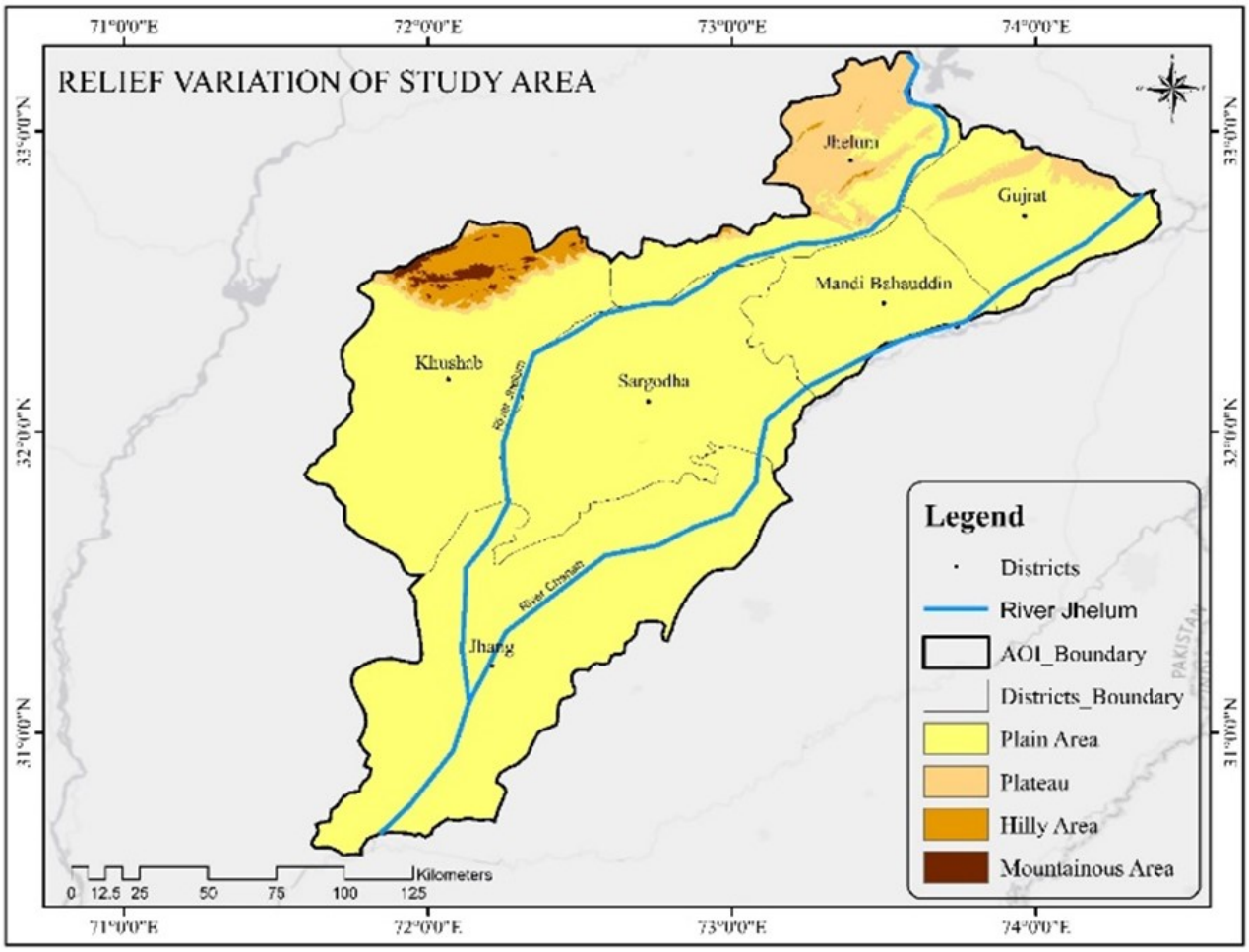

Figure 6. Relief map of the study area

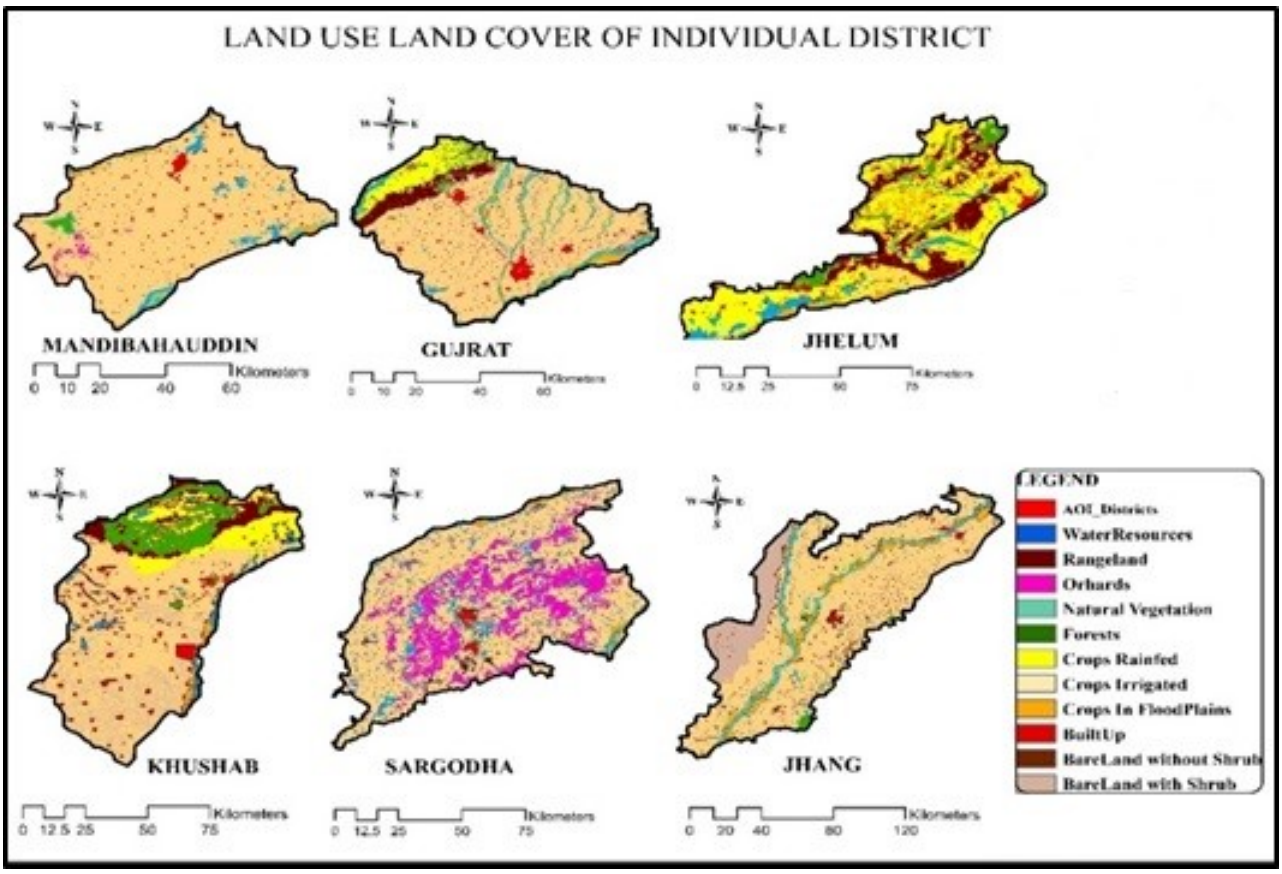

Figure 7. land use land cover map of each district

Water Resources

Water is the essence of life; it is also one of the most important factors of sustainable human survival. The tabulation of data and computation of the acquired values generated the final values of WRI by the formula specified in this section. The computed values are depicted in Table11.

Land Cover Scenario

The land cover situation of the study cannot be looked at in detail without a land use land cover map. The final map for the individual district is depicted in Figure 7.

Afterward, the suitability for NDVI for settlement of the human population was generated this was done using the values of NDVI extracted from FAO reports. The suitability of human settlements by NDVI is depicted in Figure 8. The highly suitable and moderately suitable districts for urban development or human settlements concerning the prevalence of the land cover situation are Jhang and Sargodha. Whereas overall low suitable and non-suitable districts for human settlement concerning natural environmental factors i.e. vegetation, are Jhelum, Gujrat, Mandi Bahauddin, and Khushab respectively. While some area of Khushab under the vegetation situation suggests relatively low suitable area than moderately suitable area. The details for the degree of suitability concerning the Normalized Difference Vegetation Index in depicted in the Vegetation suitability map. The calculated values step-wise are given in Tables 12, 13, and 14 next with LT1, LT2, and LT3 showing built-up, water resources, and barren land respectively. Consider the following map for the depiction of the final suitability of human settlements for urban setup by vegetation index depicted in Figure 8.

Relationship and Natural Environment Suitability Analysis

This section objectively illustrates the usage of geospatial techniques. Using GIS and RS-based suitability analysis models the results of individual sub-models/indexes and the final HNEI model are depicted in this section.

Normalization and Correlation with Population

After computation of the final values of four Sub-Indexes; normalization is applied to simplify further analysis and computation of final HNEI values. Meanwhile, suitability and correlation with population are embellished in this section. Normalization of each sub-index is carried out district-wise to generate final values using a formula for normalization on a zero to one scale. The normalization of RDLS, THI, and WRI measures the total sum as value one. The normalization of LCI generates a sum of value three because it is the sum of normalized values of each land-use type; which was three land-use types in accordance to NDVI depicted in Table 15

After the computing NRDLS, NTHI, NWRI, and NLCI; the next step is to illustrate the results with suitability values in form of a suitability map for each sub-index individually. These results are depicted separately in the following headings. The following section also inculcates the correlation between each sub-index and population individually. Table 16 narrates the population density and all sub-indexes by weightages applied.

Relief Degree of Land Surface (RDLS)

The suitability of human settlements for relief is depicted in Figure 9. The highly suitable and moderately suitable districts for urban development or human settlement concerning elevation are Gujrat and Mandi Bahauddin.

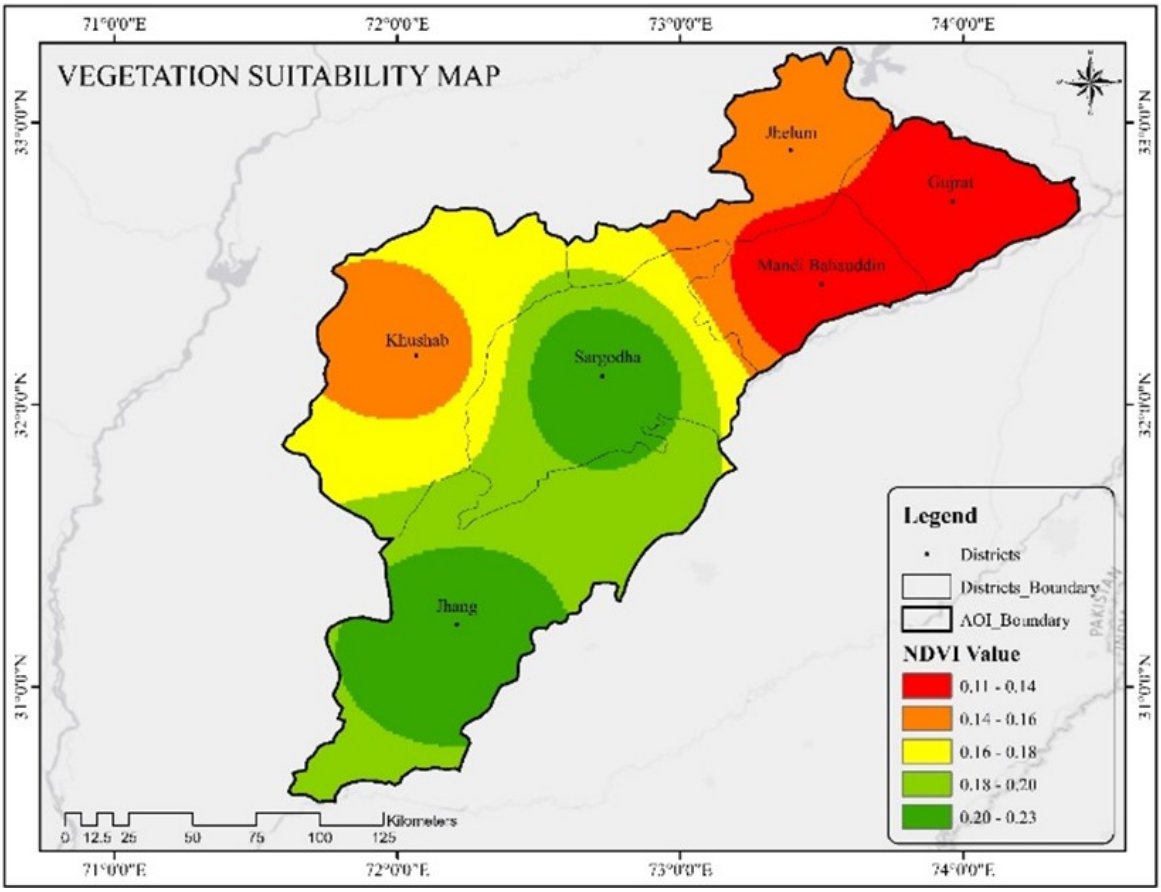

Figure 8. Site suitability for urban development based on vegetation

Sargodha, and Jhang. Whereas overall low suitable and non-suitable districts for human settlement concerning natural environmental factors i.e. elevation, are Jhelum and Khushab. While some area of Jhelum and Khushab by the elevation suggests relatively low suitable area than moderately suitable area. The reason behind this suitability and non-suitability is plain area and elevated areas such as plateaus, hills, and mountains respectively as depicted in the relief map in Figure 9.

The graph above shows a correlation between population and the relief degree of the land surface. The graph depicts a negative correlation as the linear population density shows a constant decrease in the population density concerning the increase in RDLS values. This indicates the suitability of settlements already existing concerning the elevation of the study area as high elevation values depict the non-suitability of the physical environment for human settlements.

Temperature Humidity Index (THI)

The suitability of human settlements to climatic factors such as temperature and humidity is depicted in Figure 10. The highly suitable and moderately suitable district for urban development or human settlements concerning the

Table 12. Land use types in accordance to weightage assigned district-wise

Districts (Weightage)	NDVI (0.15)	LT1 (0.2)	LT2 (0.17)	LT3 (0.05)
Gujrat	440.74	37.62	12.09	0.67
Jhang	731.82	26.54	26.13	50.85
Jhelum	493.72	20.93	38.23	0.29
Khushab	515.84	41.05	25.44	138.12
Mandi Bahauddin	377.45	19.29	12.33	0.12
Sargodha	810.01	55.60	28.35	0.41

Table 13. Land use types in accordance with vegetation cover district-wise

Districts	LT1×NDVI	LT2×NDVI	LT3×NDVI
Gujrat	16579.66	5326.44	293.97
Jhang	19425.55	19119.35	37213.64
Jhelum	10332.49	18874.57	142.19
Khushab	21174.36	13123.33	71247.08
Mandi Bahauddin	7281.76	4655.27	44.54
Sargodha	45036.58	22960.40	334.13

Table 14. Normalized land use type and final LCI values district-wise

Districts	NLT1	NLT2	NLT3	LCI
Gujrat	0.1384	0.0634	0.0027	0.2044
Jhang	0.1621	0.2275	0.3405	0.7301
Jhelum	0.0862	0.2245	0.0013	0.3121
Khushab	0.1767	0.1561	0.6520	0.9848
Mandi Bahauddin	0.0608	0.0554	0.0004	0.1166
Sargodha	0.3758	0.2731	0.0031	0.6520

Table 15. Depiction of normalized land use type and final LCI values district-wise

Districts (Normalization)	RDLS	NRDLS (0-1)	THI	NTHI (0-1)	WRI	NWRI (0-1)	NLCI
Gujrat	0.3495	0.0955	727.25	0.2091	6345	0.1272	0.2044
Jhang	0.1852	0.0506	1239.44	0.3564	8875.5	0.1779	0.7301
Jhelum	1.2313	0.3366	481.32	0.1384	14794	0.2965	0.3121
Khushab	1.3440	0.3674	223.70	0.0643	9695	0.1943	0.9848
Mandi Bahauddin	0.2265	0.0619	489.30	0.1407	4942.5	0.0990	0.1166
Sargodha	0.3217	0.0879	316.94	0.0911	5247.8	0.1052	0.6520
SUM	3.6582	1.0000	3477.95	1.0000	49899.83	1.0000	3.0000

Table 16. Population density and index values district-wise

Districts	Population Density	αRDLS	βTHI	χWRI	γLCI
Gujrat	858.40	0.0222	0.0023	0.0101	0.0732
Jhang	443.77	0.0118	0.0605	0.0141	0.2613
Jhelum	337.12	0.0782	0.0235	0.0235	0.1117
Khushab	195.43	0.0854	0.0109	0.0154	0.3525
Mandi Bahauddin	592.80	0.0144	0.0239	0.0079	0.0417
Sargodha	632.76	0.0204	0.0155	0.0084	0.2334

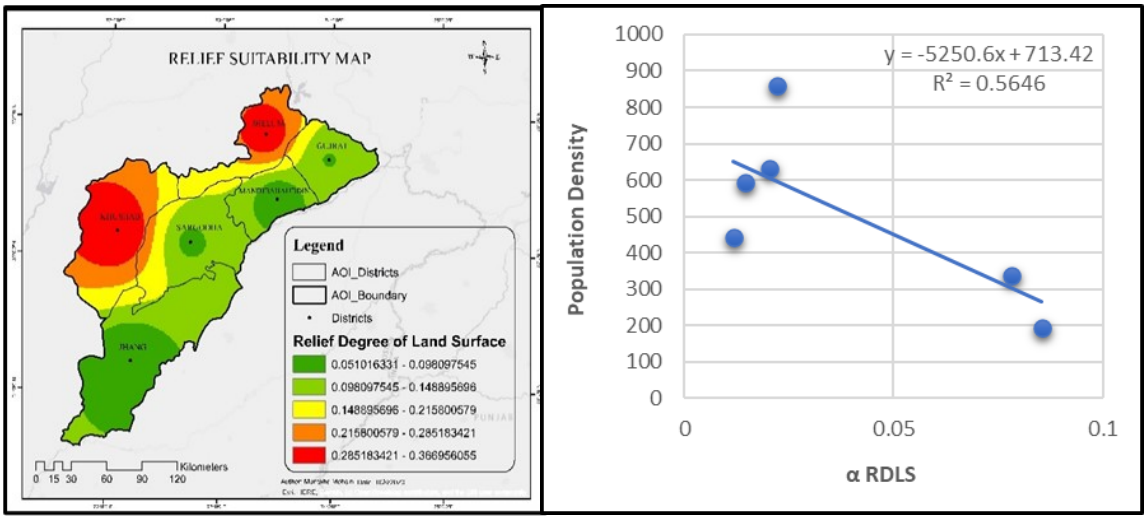

Figure 9. The figure depicts on the left: Relief suitability map, and on right: The correlation between population density and RDLS

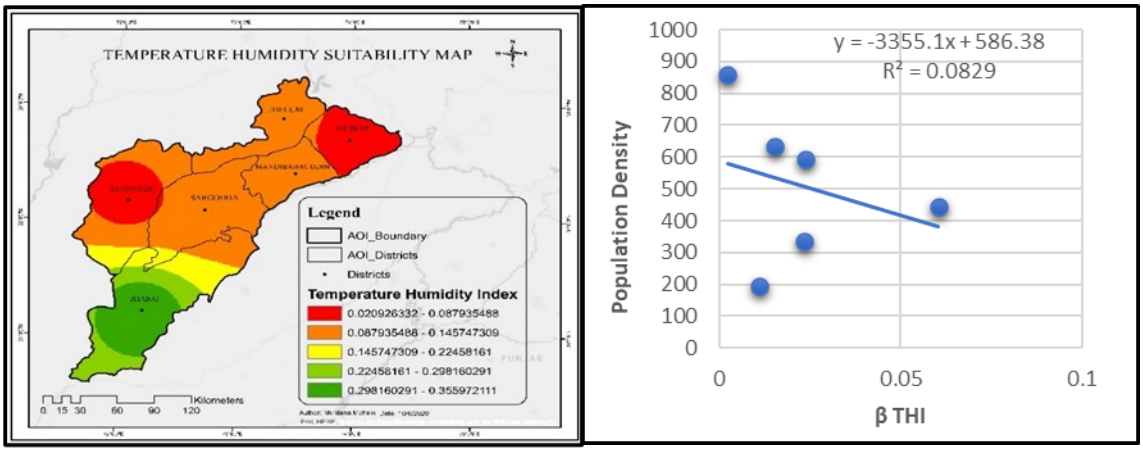

Figure 10. Depicts on left: temperature humidity suitability map, and on right: Correlation between population density and THI

prevalence of climate is Jhang. Whereas overall low suitable and non-suitable districts for human settlement concerning natural environmental factors i.e. temperature and humidity, are Jhelum, Mandi Bahauddin, Sargodha, and Khushab respectively. While some area of Gujrat, Jhang, and Khushab under the climatic situation suggests relatively low suitable area than moderately suitable area. The degree of suitability for urban development on basis of THI is depicted in Figure 10.

The above graph shows a correlation between population density and Temperature Humidity Index. The graph depicts a negative correlation as the linear population density shows a constant decrease in the population density concerning a decrease in THI values. This indicates the non-suitability of settlements already existing concerning the climate of the study area as low THI values depict the non-suitability of the natural physical environment for human settlements.

Water Resource Index (WRI)

The suitability of human settlements to available water resources is depicted in Figure 11. The highly suitable and moderately suitable district for urban development or human settlement concerning accessible water resources is Jhelum. Whereas overall low suitable and non-suitable districts for human settlement concerning natural environmental factors i.e. water resources, are Khushab, Jhang, Gujrat, Mandi Bahauddin, and Sargodha respectively. While some areas of Jhelum and Khushab by the water resources availability suggest relatively low suitable area than moderately suitable area. The water resource suitability map for urban development is given in Figure 11.

The figure shows a correlation between population and Water Resource Index. The graph depicts a negative correlation as the linear population density shows a constant decrease in the population density concerning a decrease in WRI values. This indicates the non-suitability of settlements already existing concerning the water resources of the study area as low WRI values depict the non-suitability of the natural physical environment for human settlements.

Land Cover Index (LCI)

The suitability of human settlements by the prevailing land cover scenario is depicted in Figure 12. The highly suitable and moderately suitable districts for urban development or human settlement concerning predominating land cover is Jhang, Khushab, and Sargodha.

Whereas overall low suitable and non-suitable districts for human settlement concerning natural environmental factors i.e. land cover, are Jhelum, Gujarat, and Mandi Bahauddin respectively. While some areas of Khushab, Sargodha, and Jhang under the predominant land cover suggest relatively low suitable areas than moderately suitable areas. The water resource suitability map for urban development is given in Figure 12.

The graph in the Figure 12 shows a correlation between population and Land Cover Index. The graph depicts a negative correlation as the linear population density shows a constant decrease in the population density concerning a decrease in LCI values. This indicates the high suitability of settlements already existing concerning the land cover scenario of the area of interest (AOI) as low LCI values depict the high suitability of the natural physical environment for human settlements.

Human Natural Environment Index (HNEI)

Human Natural Environment Index indicates the quantitative and geospatial analysis of four sub-indexes namely; RDLS, THI, WRI, and LCI. Table 17, depicts the finally calculated values of HNEI components and HNEI itself district-wise. The component values were summed up to generate the final HNEI values for each district. The relevant degree of suitability based on these HNEI values is explained in the next paragraph. However, after the application of MCDM's AHP these values certainly change due to the weightage assigned to each of the four factors.

According to the HNEI and its corresponding index values of RDLS, THI, WRI, and LCI, the criterion for natural environment suitability evaluation are set and classified into five types; non-suitable area, critical suitable area, low suitable area, middle suitable area, high suitable area. Specifically; Non-suitable areas, where the HNEI is less than 20 including Gujarat, Sargodha, and Mandi Bahauddin. These environments are found restricted by terrain, climate, water, and land use condition simultaneously and are not suitable for long-term settlement according to the Human settlement environment index. On the other hand, the Critical suitable area, where the HNEI is between 20–40 includes Jhelum and Jhang districts in AOI. Interestingly, the Khushab district is found suitable for a long-term settlement plan as shown in Table 15.

Multi-Criteria Decision Making

GIS technology is insubstantial in decision-making proficiency. It cannot address complexities affiliated with resource supervision problems such as pinpointing strategically suitable land for human settlements. However, the Geographic Information System (GIS) is an effective tool for physical suitability analysis. Consequently, there is a need of combining GIS with other approaches such as Remote Sensing (RS) and Analytic Hierarchy Process (AHP)

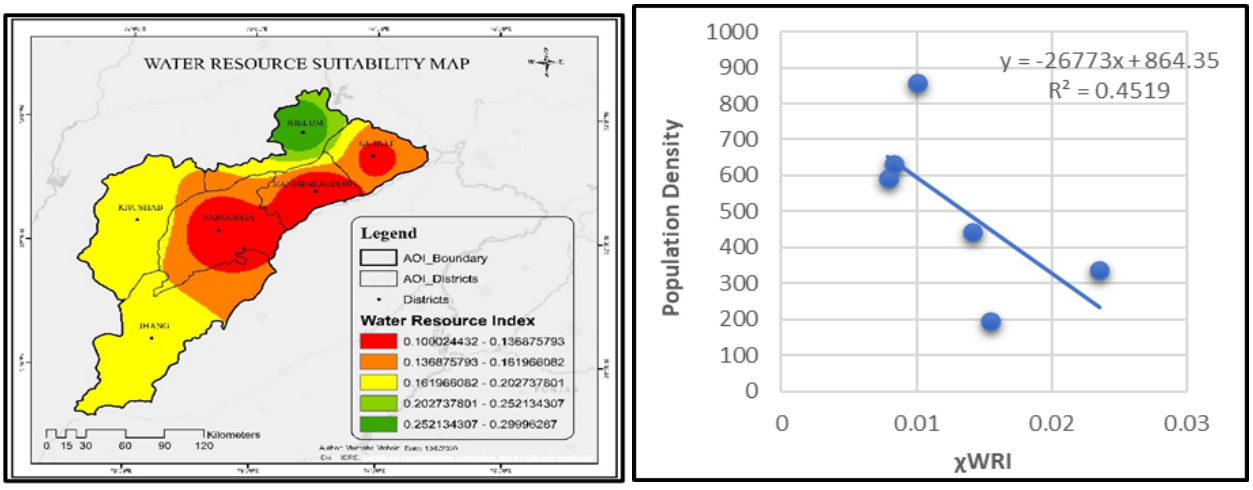

Figure 11: Depicts on left: Water resource suitability map, and on right: Correlation between population density and WRI

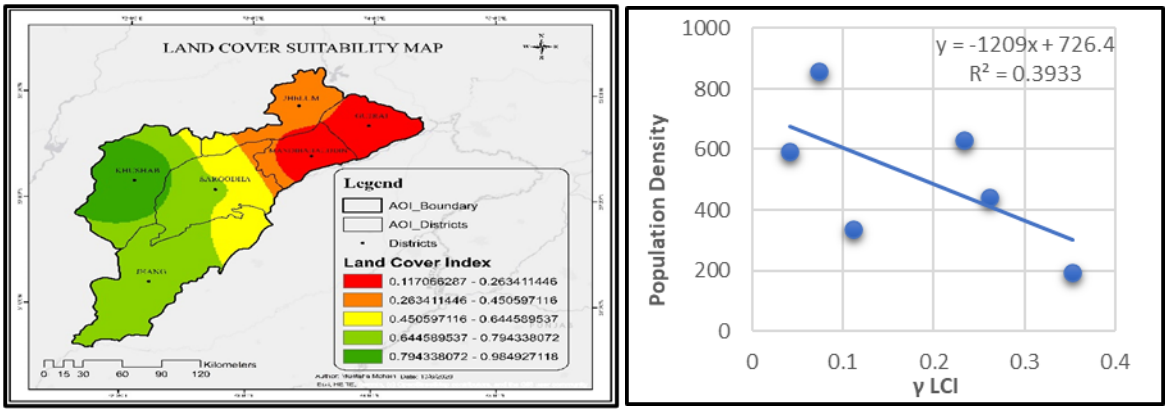

Figure 12: Depicts on left: Landcover suitability map, and on right: Correlation between population density and LCI

Table 17. Depiction of HNEI values

District	αRDLS	βTHI	χWRI	γLCI	Sum	HNEI
Gujrat	0.0222	0.0355	0.0101	0.0732	0.1409	14.0941
Jhang	0.0118	0.0605	0.0141	0.2613	0.3477	34.7670
Jhelum	0.0782	0.0235	0.0235	0.1117	0.2369	23.6939
Khushab	0.0854	0.0109	0.0154	0.3525	0.4642	46.4189
Mandi Bahauddin	0.0144	0.0239	0.0079	0.0417	0.0878	8.7843
Sargodha	0.0204	0.0155	0.0084	0.2334	0.2776	27.7618

Table 18: Depiction of pair-wise comparison matrix for each index

	Matrix							
	RDLS	THI	WRI	Flood Extent	LCI	Weighted Sum	Criteria Weights	Percentages
RDLS	1	2	3	4	5	2.07	0.4245	42.45
THI	0.5	1	2	3	4	1.29	0.2668	26.68
WRI	0.33	0.5	1	2	3	0.77	0.1635	16.35
Flood Extent	0.25	0.33	0.5	1	2	0.47	0.1000	10.00
LCI	0.2	0.1	0.15	0.24	1	0.21	0.0452	4.52
Sum	2.28	3.93	6.65	10.24	15			

used during land suitability analysis to create smart human settlements suitability plan for this purpose, Multi-Criteria Decision Making method (MCDM) is applied in the present study. Analytic Hierarchy Process (AHP) is applied to four factors namely; RDLS, THI, WRI, and LCI. The pair-wise comparison matrix is generated as shown in Table 18. The values for the priority vector were calculated to generate the weightage of each index in form of a percentage. This value was further used in overlay analysis to generate a combined suitability map depicted as the Final suitability map in Figure 13.

Overlay Analysis

The overlay analysis is essential to generate a final suitability map to locate a strategic location for urban development. For this purpose, the weighted sum overlay is applied on individual spatial layers for four sub-indexes; RDLS, LCI, WRI, and THI applying the Spatial Analyst tool called weightage sum overlay tool from the data management tool in Arc Map.

Flood Extents

Floods are hazardous for sustainable human settlements. The areas/districts along rivers encounter riverine or flash floods annually. The suitable settlement sites are selected while keeping in view the flood extents as depicted in Figure 14.

Final Suitability

The final suitability map generated as a result of the weighted sum overlay was then classified into five degrees of land suitability for urban settlements discussed in detail in the following paragraphs.

Non-Suitable

This area encompasses a fragile natural environment. Jhelum and Khushab specifically are depicted as non-suitable areas for urban development. However, before applying weighted sum overlay analysis, Khushab was depicted to be the most suitable district for urban development according to the calculated HNEI values before applying weightage to each factor i.e. relief, climate, water availability, and land cover. According to the weighted sum overlayer method Khushab is found to be a non-suitable area for urban development.

Low Suitable

Specifically, Jhang and Jhelum are included in a low suitable area for urban development. Some area of Khushab is also included.

Relatively Low Suitable

Specifically, Gujrat is included in this category. However, some area of Mandi Bahauddin, Sargodha, Khushab, and Jhang is also included.

Moderate Suitable

Specifically, Mandi Bahauddin and Sargodha are included in this category. New urban settlements could be set up in this district excluding the area of these districts exposed to flood hazards.

Highly Suitable

The most highly suitable area/district for urban settlements is Sargodha keeping in view all the aspects of weights applied to each factor of evaluation. For future sustainable urban settlements, this district remains the best option supported by relief, climate, water resource availability, and land cover but excluding the sites prone to flood disasters.

Correlation

The correlation between population density and HNEI is a sound indicator of the population residing in a natural environment. Table 17 depicts the population density of each district with its corresponding HNEI value to be illustrated in form of a graph for a final deduction of results in Figure 19. The graph depicts a negative correlation as the

linear population density shows a constant decrease in the population density with an increase in HNEI values. This indicates population density residing in an area with the least natural environment suitability and non-sustainable long-term urban settlements.

4. Conclusion

The present study indicated the useful application of geospatial techniques supported by MCDM-AHP which inculcates five factors of evaluation namely; RDLS, THI, WRI, LCI, and flood extents representing relief/elevation, climatic conditions over twelve years i.e. temperature and humidity, available water resources, land cover situation, and previous flood hazards. Urban settlements previously neglected the natural environmental conditions. The sustainability of any settlement is dependent on considering the natural environment as it supports overall human survival. HNEI model applied in the present study, evaluated the suitability of the natural environment for long-term urban development using four factors of natural environment evaluation i.e. RDLS, THI, WRI, and LCI. According to HNEI, the least suitable districts for urban development were having the highest proportion of urban settlements such as Gujarat. Furthermore, when weighted sum overlay was

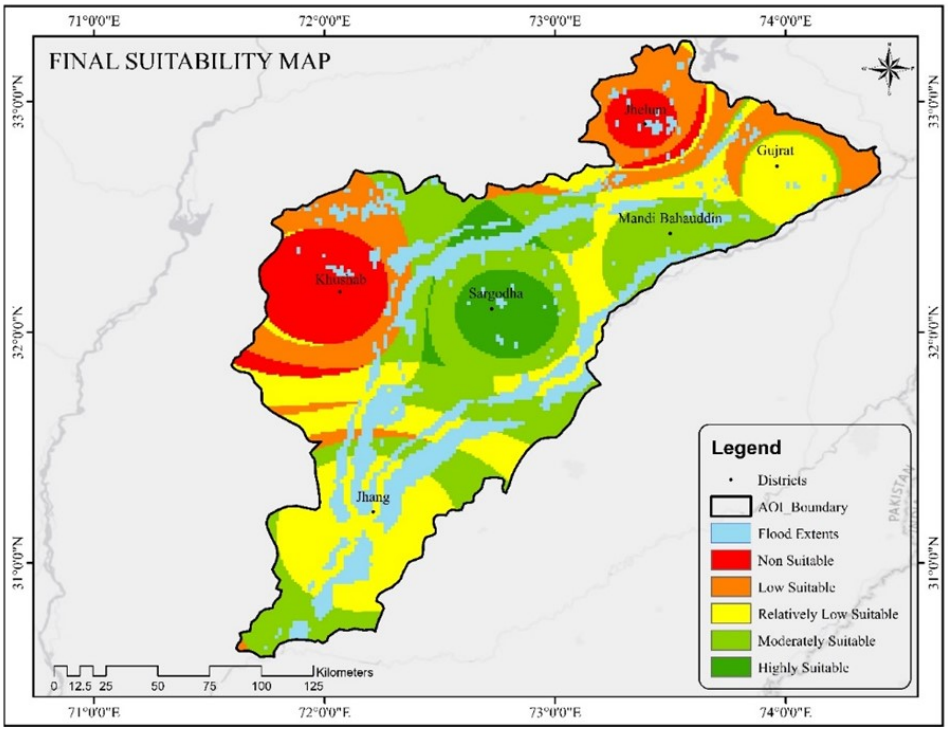

Figure 13. Final Suitability Map of Area of Interest (AOI)

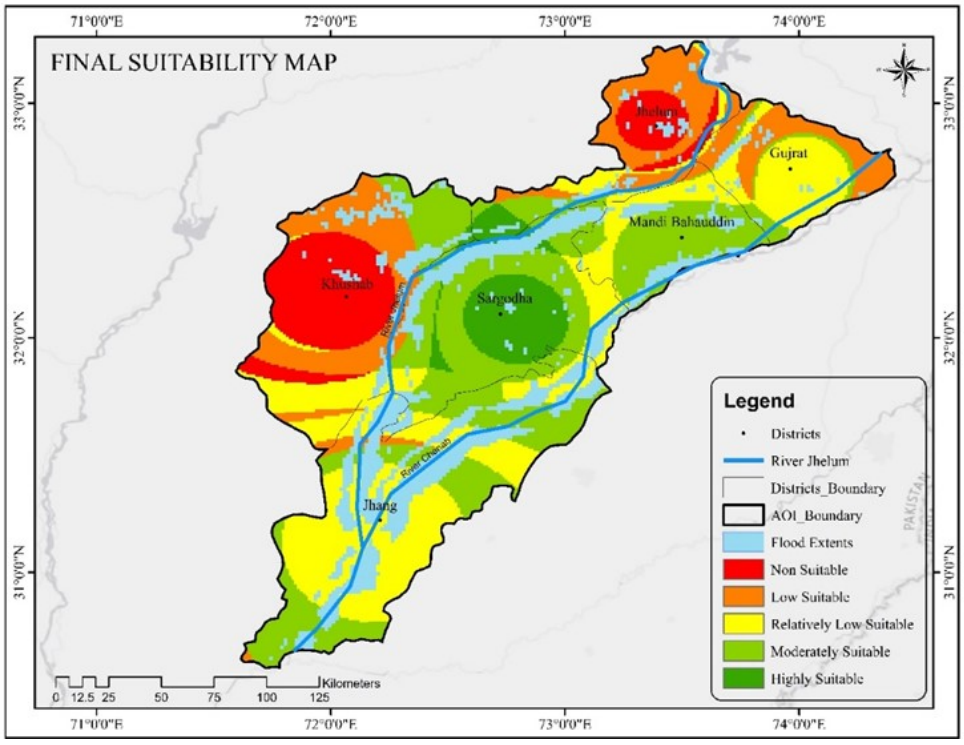

Figure 14. Final Suitability Map showing districts along River Jhelum.

Table 19. Depiction of population density and HNEI district-wise

District	HNEI	Population density (km^2)
Gujrat	14.09	858.40
Jhang	34.77	443.77
Jhelum	23.69	337.12
Khushab	46.42	195.43
Mandi Bahauddin	8.78	592.80
Sargodha	27.76	632.76

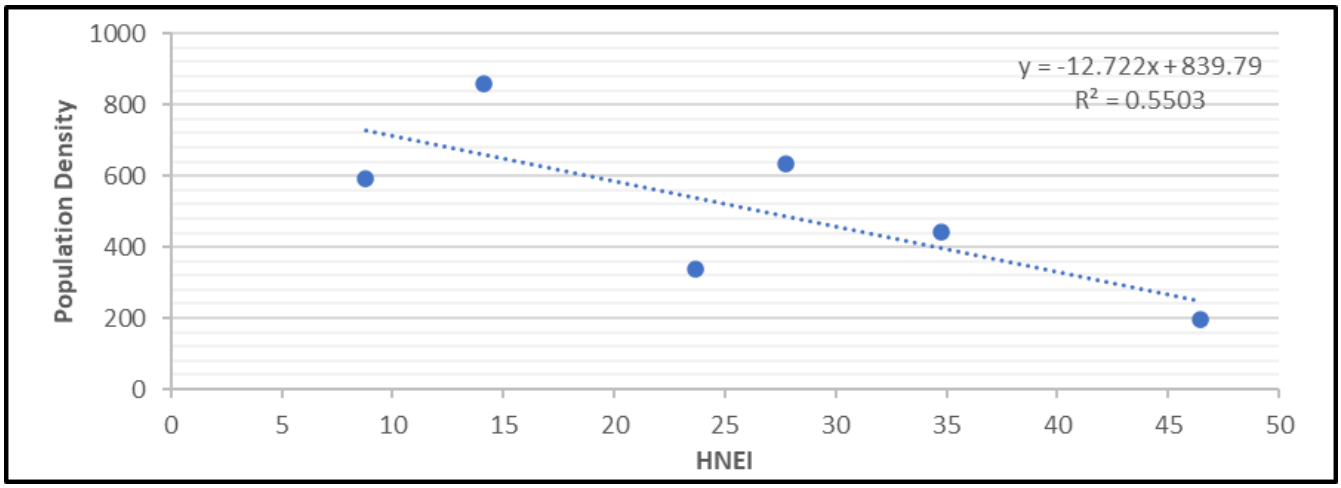

Figure 15. Illustration of correlation between population density and HNEI

applied; on the same four factors including flood extents; after application of generated pairwise comparison matrix and calculation of relative weights for each factor of evaluation, it was revealed that Sargodha is a highly suitable district for long-term sustainable human urban settlements neglecting the areas of district prone to flood hazards. Afterward, Mandi Bahauddin is moderately suitable for urban settlement. The correlation between population density and HNEI indicated a negative correlation. This negative correlation directs that areas with the least natural environment suitability are more populated than areas not restricted by relief/elevation, climate, water availability, and land cover. It is suggested to development authorities of concerned districts to foresee future urban settlements based on natural environment suitability. Similarly, in the 1980s, 1994, and, 2000; China, the US, and the Dutch structured their RS and GIS-based principle assessment system for urban development namely; the State Environment Protection Administration of China (SEPAC) Model, Leadership in Energy and Environmental Design Standard (LEEDS) and, Eco Quantum Standard respectively. As a ripened fruit of these efforts, in China, the concentration of the Human population is found in a natural environment of favorable land (Feng et al., 2009). Synonymously in South Africa, cities and towns are developed on basis of spatial planning, which accounts for the availability and accessibility of land concerning environmental and physical setup (Musakwa et al., 2017). In Sydney and Australia concordantly, studies were conducted keeping in view the thermal conditions of the natural environment in subtropical areas (Li et al., 2011). The present research will benefit society in the context of equal distribution of population in the province of Punjab. This equal distribution will not only impact the individual well-being but also it will reduce the pressure of the high density of population from the eastern part of the province to the whole province. This will not only ensure human survival and comfort but also sustainable urban settlements.

Data Availability Statement (DAS)

Satellite data used in this article was Landsat 8 acquired from USGS Earth Explorer which is freely available data. The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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