




# Evaluation of indicators for desertification risk assessment in part of Thar Desert Region of Rajasthan using geospatial techniques

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Desertification has emerged as a major economic, social and environmental problem in the western part of India. The best way of dealing with desertification is to take appropriate measures to arrest land degradation, especially in areas prone to desertification. This requires an early warning system for desertification based on scientific inputs. Hence, in the present study, an attempt has been made to develop a comprehensive model for the assessment of desertification risk in the Jodhpur district of Rajasthan, India, using 23 desertification indicators. Indicators including soil, climate, vegetation and socio-economic parameters were integrated into a GIS environment to get environmental sensitive areas (ESAs) to desertification. Desertification risk index (DRI) was calculated based on ESAs to desertification, the degree of land degradation and significant desertification indicators obtained from the stepwise multiple regression model. DRI was validated by using independent indicators such as soil organic matter content and cation exchange capacity. Multiple regression analysis shows that 16 indicators out of 23 were found to be significant for assessing desertification risk at a 99% confidence interval with  $R^2 = 0.83$ . The proposed methodology provides a series of effective indicators that would help to identify where desertification is a current or potential problem, and what could be the actions to alleviate the problem over time.

**Keywords.** Desertification indicators; desertification risk assessment; environmental sensitive areas to desertification; stepwise multiple regression model.

## 1. Introduction

Land degradation and desertification are among the most serious environmental issues at global, regional and local scales (Imeson 1996; UNEP 1997). An assessment carried out by the Food and Agriculture Organization (FAO) of the United Nations based on data collected during the ‘Global

Assessment of Soil Degradation (GLASOD)’ (Oldeman 1988; Oldeman *et al.* 1990) showed that 19.5% of dry lands are affected by soil degradation. Another study carried out by the International Centre for Arid and Semi-Arid Land Studies (ICASALS) revealed that approximately 70% of arid lands show more or less intense signs of desertification (Dregne *et al.* 1991).

Desertification is land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climatic variations and human activities. Here, land is defined as a terrestrial bio-productive system and land degradation is defined as reduction or loss in biological and economic productivity (UNCCD 1994). Desertification can be considered to be a subset of land degradation, occurring in more arid areas. Recently, Land Degradation Assessment in Drylands (LADA) has further developed this definition as the reduction in the capacity of the land to provide ecosystem goods and services, over a period of time, for its beneficiaries. Ecosystem goods are products of land, which have an economic and/or social value, including land availability, animal and plant production, soil health and water quantity and quality. Ecosystem services include biodiversity and the maintenance of hydrological, nutrient and carbon cycles (LADA 2011). According to Adger *et al.* (2000), over 250 million people are directly affected by desertification and some one billion people in over 100 countries are at risk. India, being one of the leading developing countries of the world, is not exempted from the problem related to various natural hazards. In India, 29.32% of the total geographic area (TGA) was under the process of land degradation and 25.14% of TGA was under desertification (arid, semi-arid and dry sub-humid regions) during the year 2011–2013 (SAC 2016). Desertification has emerged as a major economic, social and environmental problem in the western part of India. The ‘Great Indian Desert’ or Thar, located in western India, is surrounded by the Indus plains in the west, Aravalli Range in the southeast, Rann of Kutch in the south and Punjab plains in the north and northeast. The Thar Desert covers an area about 3.2 lakh km<sup>2</sup>, out of which 60% lies in Rajasthan (Sharma and Mehra 2009). 62.90% of the total geographic area of Rajasthan is under desertification (SAC 2016). Encroachment of the Thar Desert towards its eastern border has become a serious problem to the adjoining districts of the desert. It is slowly capturing the arable lands and reducing its productivity. A large population of humans and animals of this region are at risk due to shifting of sand dunes and dust storms and the consequent decrease in agricultural productivity (Kundu and Dutta 2011). The main causes leading to the accelerated rate of conversion of fertile land to arid land are deforestation, drought, unsustainable agricultural practices, unsustainable water-management practices, land

use changes, industrial and mining activities and demographic pressures (Joshi and Solanki 2009). Most of the above drivers of land degradation, triggered and accelerated by anthropogenic activities, are mainly due to population pressure, poverty, illiteracy and lack of sufficient resources (Ajai and Dhinwa 2018). Human population pressure is the most crucial indicator of desertification in a country like India (MoEF 2001).

Di (2003) made a detailed study on recent progress of remote sensing on monitoring of desertification and mentioned that remote sensing is the only tool of choice for desertification studies at regional and global scales. Many initiatives in desertification mapping and monitoring, at various scales, have taken place in the recent past. Remote sensing has been successfully applied to the process of monitoring desert expansion and to the assessment of factors that cause desertification (Hanan *et al.* 1991). Grainger (2009) and subsequently Zucca *et al.* (2012) reviewed the attempts made to map desertification and land degradation at a global scale. There have been a number of mapping efforts using different methodologies (Dregne 1983; FAO/UNEP 1984; Oldeman *et al.* 1990; Dregne *et al.* 1991; UNEP 1997; Ajai *et al.* 2009). Desertification and land degradation status mapping of India has been carried out at 1:500,000 scale using the Indian Remote Sensing Satellite data by Ajai *et al.* (2009). Desertification and land degradation Atlas of India (based on IRS AWiFS data of 2011–2013 and 2003–2005) have also been brought out (SAC 2016). Land degradation mapping of entire India has also been carried out at 1:50,000 scale by the NRSA, Hyderabad, presently known as NRSC using Resourcesat-1 LISS III satellite data (NRSA 2007).

Apart from these desertification mapping and monitoring efforts, the development of early warning system of desertification is the need of the hour. Use of desertification indicators is one of such steps in this direction. They can help to capture the beginning of the desertification process, so that appropriate resilient measures can be taken in time. Rubio and Bochet (1998) tackled the subject of desertification indicators in considerable detail and proposed a synthesised list of criteria, and a procedure for the selection, evaluation and application of indicators. A notable attempt to define environmental sensitive areas (ESAs) to desertification was made in the context of the ‘MEDALUS’ (Mediterranean Desertification and Land Use) research project (Kosmas *et al.*

1999). In that approach, a set of key indicators describing different desertification factors (climate, soil, vegetation and management) was used to derive a composite index of land desertification. The ESAs methodology was widely used for over a decade directly or indirectly in different parts of the world including India (Sepehr *et al.* 2007; Affi *et al.* 2010; Hadeel *et al.* 2010; Parvari *et al.* 2011; Bahreini and Pahlavanravi 2013; Dutta and Chaudhuri 2015). But some researchers claimed that it contained a lack of socio-economic variables such as population density, population growth rate, etc. (Salvati *et al.* 2008; Salvati and Bajocco 2011). Darwish *et al.* (2012) and Singh and Ajai (2015) included socio-economic variables in the MEDALUS approach. Dasgupta *et al.* (2013) and Jafari and Bakhshandehmehr (2013) used GIS and fuzzy logic for mapping ESAs to desertification. Indicator systems for monitoring and assessment of desertification from national to global scale have been discussed by Sommer *et al.* (2011).

From the above literature review, it is evident that desertification is a multi-disciplinary process involving both natural and human factors. Hence, it is necessary to understand the causes, impacts and linkages among the different desertification indicators in order to combat the process. If the process of land degradation or more importantly, desertification is arrested at the very beginning by taking appropriate conservation measures, much harm to the land and nature can be avoided. This requires the development of an early warning system for desertification based on scientific inputs. The most important element of early warning system for desertification is the development of a model for identification of desertification risk. By looking at the severity of the issue, several research studies have been carried out across the world including India. However, these studies mainly concentrated on desertification status mapping and monitoring using remote sensing data and assessment of ESAs to desertification using different desertification indicators. These studies do not directly provide information like which are the most effective or important indicators for assessing the level of desertification risk in any particular study area. Work has been carried out in this direction by Kosmas *et al.* (2013), where the methodology was developed for assessing desertification risk by evaluation and selection of indicators. Our study is one such novel attempt in India with the objective of developing a comprehensive model for the assessment of desertification risk in Jodhpur

district of Rajasthan using indicators obtained from satellite-derived information layers and other ancillary data. The unique methodological framework evolved to derive the desertification risk index along with identification of effective desertification indicators for part of the Thar Desert Region of Rajasthan is the main research outcome of this study.

## 2. Study area

Jodhpur district, which comes under the arid zone of the Rajasthan state and Thar Desert of India, was selected as the study area (figure 1). The district extends from 25°51'10"–27°37'6"N in latitude and from 71°47'19"–73°52'23"E in longitude. It covers an area of 22,850 km<sup>2</sup>, of which 22,594.18 km<sup>2</sup> is a rural area and 255.82 km<sup>2</sup> is an urban area. The district is bounded by Jaisalmer district in the west, Bikaner district in the north, Nagaur district in the east and Pali and Barmer districts in the south. The total population of the Jodhpur district is 36,87,165. It is 5.38% of the state of Rajasthan, out of which 65.94% are literate. There are seven tehsils namely Phalodi, Osian, Bhopalgarh, Jodhpur, Luni, Shergarh and Bilara and 10 Panchayat Samitis (blocks) namely Bap, Phalodi, Bawari, Osian, Bhopalgarh, Luni, Mandor, Balesar, Shergarh, Bilara with 1838 villages in Jodhpur district (Census of India 2011).

The district experiences arid to semi-arid type of climate with average annual rainfall (1979–2013) ranging from 216 to 460 mm. Almost 80% of the total annual rainfall is received during the southwest monsoon, which enters the district in the first week of July and withdraws in the mid of September. As the district lies in the desert area, extremes of heat in summer and cold in winter are the characteristics of the district. Both day and night temperatures increase gradually and reach their maximum in May and June, respectively. The mean annual temperature (1979–2013) ranges from 26 to 28°C.

The district is covered by hills, rocky pediments, older alluvial plains, interdunal sandy plains and sand dunes. Sand dunes and interdunal plains are located in the northwestern and western parts of the district. The general slope of the terrain is towards west. The Luni River and its tributary Jojri form a drainage network in the eastern and southeastern parts of the district. These rivers are ephemeral and contribute water to

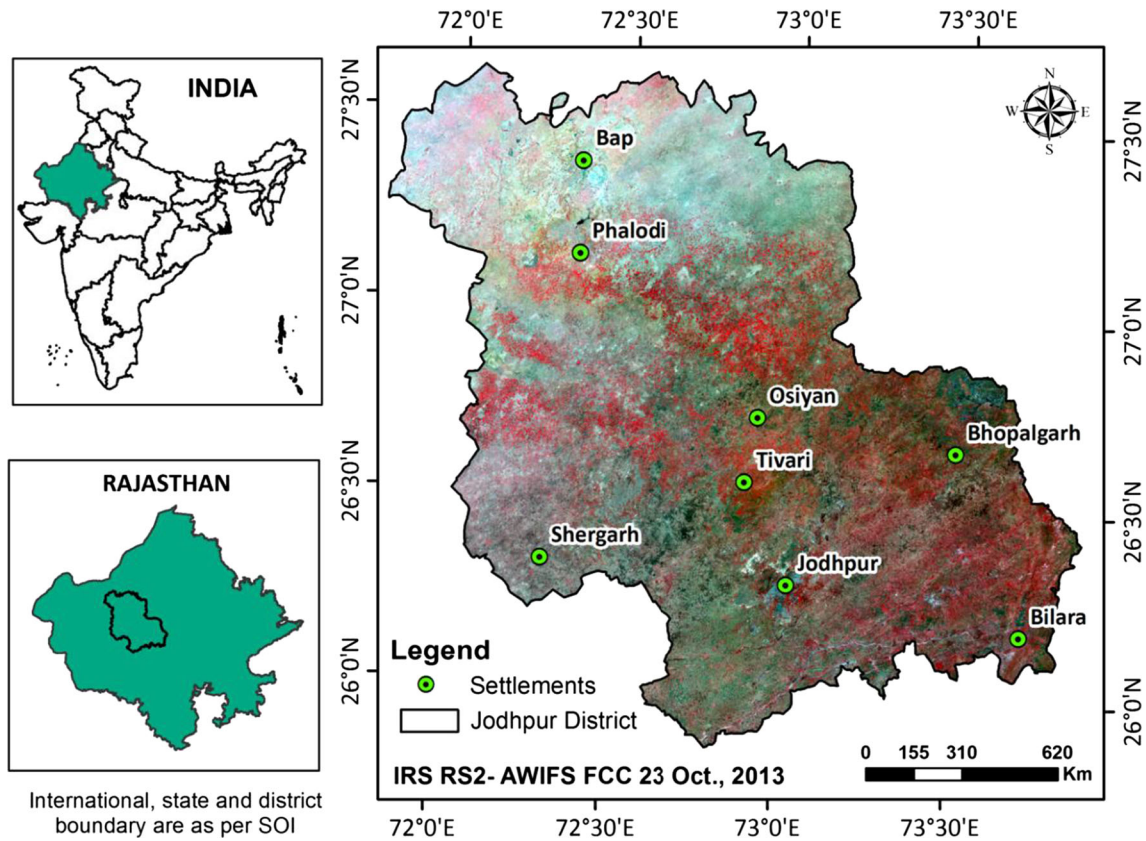


Figure 1. Study area: Jodhpur district, Rajasthan, India.

the existing reservoirs, tanks, anicuts, etc. during the rainy season. In the rest of the area, only internal drainage exists, emanating from the isolated hills and disappearing in sandy beds. The Jodhpur district is water scarce and largely dependent on rainfall, with the exception of the city of Jodhpur, which receives water for drinking from the Indira Gandhi lift canal. There are no perennial water sources in rural areas and, therefore, the population has to rely largely on harvested and conserved rainwater. Irrigated agriculture is practiced in fresh groundwater zones. Millet, jowar, pulses, groundnut and guar are the main kharif crops while wheat, barley, isabgol and mustard are the main rabi crops cultivated in the district.

### 3. Methodology

Desertification involves a complex set of factors, interacting in space and time leading to a decrease in land productivity. It is closely related to many environmental factors such as climate, soil, vegetation cover and morphology where their characteristics and intensity contribute to the evolution

and characterisation of different degradation levels. Desertification is also strongly linked to socio-economic factors, since human's behaviour and his social and economic actions can greatly influence the evolution of numerous environmental characteristics. There is much information for desertification assessment, but to assess this phenomenon in an effective way, it needs to select and use some simple and available key indicators and indices to tackle this complex process (Rubio and Bochet 1998). In this study, 23 indicators and 4 indices were chosen on the basis of literature survey (Kosmas *et al.* 1999, 2013; Basso *et al.* 2000; Sepehr *et al.* 2007; Afifi *et al.* 2010; Bahreini and Pahlavanravi 2013; Dutta and Chaudhuri 2015; Singh and Ajai 2015) and data availability. Methodology flow chart for the assessment of desertification risk is shown in figure 2.

#### 3.1 ESAs to desertification

Methodology for assessing ESAs was inspired from the model 'MEDALUS', developed by the European Commission (Kosmas *et al.* 1999). Grid-wise

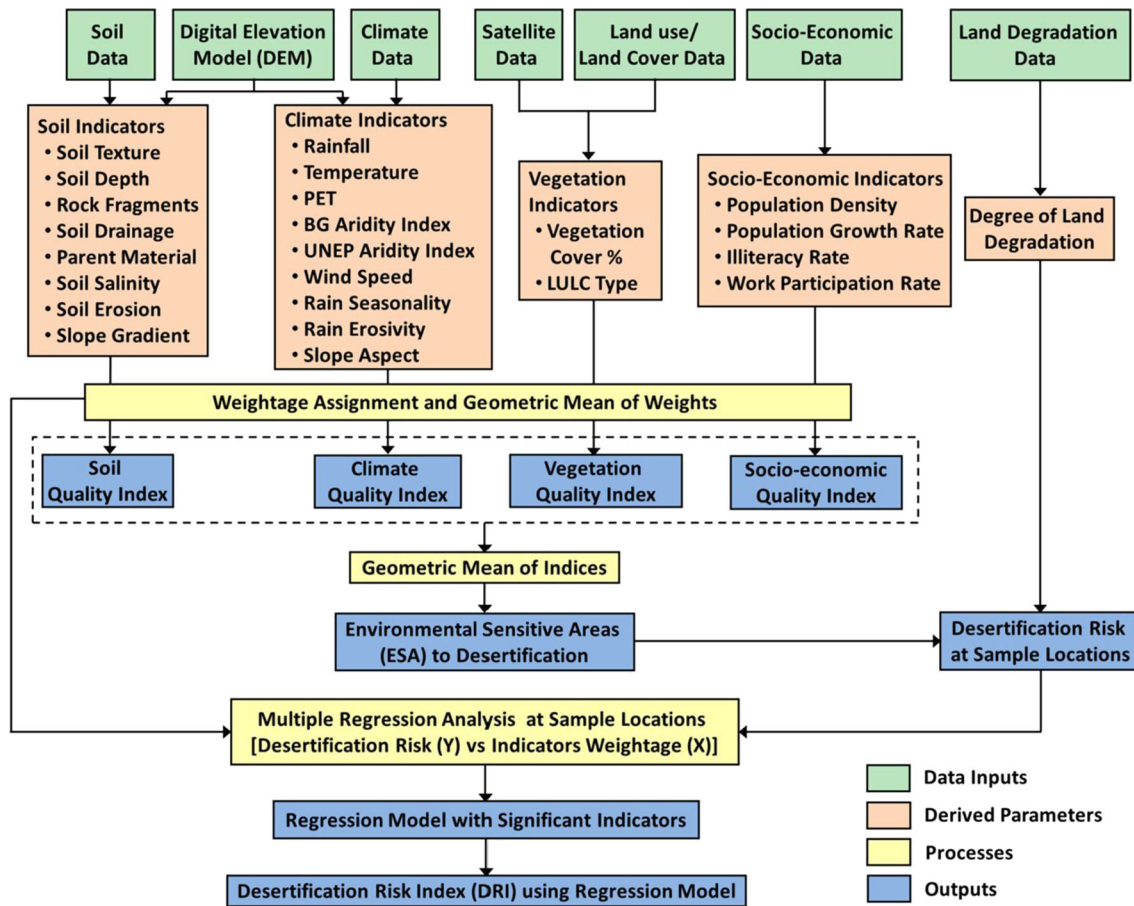


Figure 2. Methodology flow chart.

GIS database for 23 desertification indicators has been prepared from satellite-derived information layers and other ancillary data. Classes were designated to all indicators and sensitivity weights to desertification in the range of 1.0 (low sensitivity) to 2.0 (high sensitivity) were assigned to each class based on the literature (Kosmas *et al.* 1999, 2013; Basso *et al.* 2000; Sepehr *et al.* 2007; Pienaru *et al.* 2009; Afifi *et al.* 2010; Afifi and Gad 2011; Darwish *et al.* 2012; Dutta and Chaudhuri 2015; Vieira *et al.* 2015, etc.) and parameter's influence and contribution to desertification. Values between 1 and 2 reflect the relative sensitivity. The quality indices (soil, climate, vegetation and socio-economic) were calculated by the geometric mean of the sub-indicators related to each quality index as follows:

$$\text{Index}_x = [(Layer_1) \times (Layer_2) \times (Layer_3) \times \dots \times (Layer_n)]^{1/n}, \quad (1)$$

where  $x$  represents the quality index and  $n$  represents the number of sub-indicators (layers)

used to calculate each quality index. Finally, all four indices, i.e., soil quality index (SQI), climate quality index (CQI), vegetation quality index (VQI) and socio-economic quality index (SEQI) were combined to calculate a single index called ESAs to desertification as follows:

$$\text{ESA} = (\text{SQI} \times \text{CQI} \times \text{VQI} \times \text{SEQI})^{1/4}. \quad (2)$$

### 3.2 Soil quality index

The indicators used to assess soil quality, their classes and assigned weights are described in table 1. Non-soil categories such as water body and rock outcrops are given score 1 and 2, respectively. Soil maps (250k) prepared by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), India (Bhattacharyya *et al.* 2009) were used for obtaining different soil quality indicators. Slope gradient was calculated using Cartosat 30 m DEM of the National Remote Sensing Centre, Hyderabad (<http://bhuvan.nrsc.gov.in/data/download/index.php>) (NRSC 2014).

Table 1. *Classes and the corresponding weight assigned for the calculation of the SQL.*

Indicators	Class	Description	Weight
Soil texture	Loamy, sandy clay loam, sandy loam, loamy sand, clay loam	Good	1
	Sandy clay, silt loam, silt clay loam, loamy skeletal	Moderate	1.2
	Silt, clayey, silt clay	Poor	1.6
	Sandy	Very poor	2
Soil depth	Deep, very deep		1
	Moderately deep		1.2
	Moderately shallow		1.4
	Shallow		1.6
	Very shallow		1.8
	Extremely shallow		2
Rock fragments on soil surface (%)	>40%	Strong	1.6
	15–40%	Moderate	1
	0–15%	Slight	1.8
	0%	Nil	2
Soil drainage	Well, somewhat excessive, excessive		1
	Moderately well		1.2
	Imperfect		1.4
	Poor		1.6
	Very poor		1.8
	Extremely poor		2
Parent material	Granite, Gneiss	Coherent	1
	Sandstone	Moderately coherent	1.5
	Alluvium, colluvium, aeolian	Soft to friable	2
Soil salinity (dS/m)	<2	Negligible	1
	2–4	Slight	1.3
	4–8	Moderate	1.5
	8–15	Moderately strong	1.8
	15–25, 25–50, >50	Strong, severe, very severe	2
Degree of soil erosion	None to very slight		1
	Slight		1.2
	Moderate		1.5
	Severe		1.8
	Very severe		2
Slope gradient (%)	0–2		1
	2–6		1.2
	6–12		1.4
	12–18		1.6
	18–25		1.7
	25–35		1.8
	35–60		1.9
	>60		2

### 3.2.1 Soil texture

Soil texture greatly affects soil drainage, water holding capacity, soil temperature, soil erosion, as well as soil fertility and plant productivity (Agricultural University of Athens 2012). Clay holds more water available for plant growth than

sandy soils, but clay soils have poor drainage of excess water and may become waterlogged. The coarser the soil texture, the smaller the active surface area of the soil particles, and the smaller is the resistance of the soil to erosion. Soils containing a high amount of silt are sensitive to crust formation and generating high surface water

runoff and sediment loss. Loam soils have the best combination of physical and chemical properties in terms of cultivation and crop growth.

### 3.2.2 Soil depth

Percentage vegetation cover of a soil surface under semi-arid climatic conditions is largely controlled by soil water storage capacity and therefore soil depth (Agricultural University of Athens 2012). Soil productivity will decrease as the topsoil gets thinner by erosion.

### 3.2.3 Rock fragments on soil surface (%)

Rock fragments generally limit evaporative water loss during periods of no to moderate drought (e.g., from late fall to early summer), but they increase evaporation during the dry and hot summer (Agricultural University of Athens 2010a). The 15–40% rock fragments content on the soil surface is considered as the optimal for soil erosion protection. High amounts (40–80%) and very high amounts (>80%) are characterised as very gravelly or skeletal, resulting mainly from high erosion rates.

### 3.2.4 Soil drainage

Soil drainage is mainly related to desertification risk in areas affected by soil salinisation (Agricultural University of Athens 2012). Field sites located in poorly drained soils are more vulnerable to soil salinisation than in well-drained soils.

### 3.2.5 Parent material

The soil formed from the coherent parent material is less susceptible to desertification, moderately coherent parent material is moderately susceptible to desertification and soft to friable parent material is most susceptible to desertification (Pienaru *et al.* 2009).

### 3.2.6 Soil salinity

Salinisation involves the accumulation of salts in the soil through natural processes or human interventions. Higher soil salinity will have a negative effect on desertification.

### 3.2.7 Degree of soil erosion

The UNCCD has defined soil erosion as one of the main causes of land degradation and desertification. Higher soil erosion will lead to a higher risk of desertification and land degradations.

### 3.2.8 Slope gradient (%)

Slope gradient greatly affects the amount of surface water run-off and soil sediment loss. Soil erosion rates become acute when the slope angle exceeds a critical value and then increases logarithmically (Agricultural University of Athens 2010a). Therefore, a higher slope gradient will have a negative effect on desertification.

## 3.3 Climate quality index

The indicators used to assess the climate quality, their classes and assigned weights are described in table 2.  $0.25^\circ \times 0.25^\circ$  daily gridded rainfall data of Indian Meteorological Department, Pune (Pai *et al.* 2014),  $0.31^\circ \times 0.31^\circ$  daily gridded air temperature and wind speed data of the National Centers for Environmental Prediction (<https://globalweather.tamu.edu/>) (NCEP 2012) and  $0.50^\circ \times 0.50^\circ$  daily gridded potential evapotranspiration (PET) data of the Climate Research Unit, UK (<https://crudata.uea.ac.uk/cru/data/hrg/>) (Harris *et al.* 2014) for the period 1979–2013 were used for obtaining different climate quality indicators. Slope aspect was calculated using the Cartosat DEM with 30 m resolution.

### 3.3.1 Average annual rainfall

Arid and semi-arid climatic conditions with a lower amount of rainfall and higher rates of evapotranspiration will significantly decrease the soil moisture content available for plant growth causing lower biomass production (Agricultural University of Athens 2012). The average annual rainfall was calculated for the period 1979–2013.

### 3.3.2 Average annual air temperature

Air temperature is a critical environmental factor in determining water stress, transpiration of the growing vegetation, soil water evaporation, soil salinity and soil alkalinity (Agricultural University of Athens 2010a). Higher temperature will have a negative effect on desertification.

Table 2. Classes and the corresponding weight assigned for the calculation of the CQI.

Indicators	Class	Description	Weight
Average annual rainfall (mm)	>1000		1
	650–1000		1.3
	280–650		1.6
	<280		2
Average annual air temperature (°C)	<12		1
	12–15		1.3
	15–18		1.5
	18–21		1.8
	>21		2
Average annual PET (mm)	<500		1
	500–800		1.2
	800–1200		1.5
	1200–1500		1.8
	>1500		2
Bagnouls–Gausson aridity index	<50	Very low aridity	1
	50–75	Low aridity	1.2
	75–100	Moderate aridity	1.4
	100–125	High aridity	1.6
	125–150	Very high aridity	1.8
	>150	Extremely dry aridity	2
UNEP aridity index	>0.65	Humid	1
	0.50–0.65	Dry sub-humid	1.25
	0.20–0.50	Semi-arid	1.5
	0.05–0.20	Arid	1.75
	<0.05	Hyper-arid	2
Average wind speed at 10 m height (m/s)	0–2	Slight	1
	2–3.5	Moderate	1.3
	3.5–4.5	Severe	1.6
	>4.5	Very severe	2
	Rain seasonality	<0.20	Precipitation spread throughout the year
0.20–0.40		Precipitation spread throughout the year, but with a definite wetter season	1.2
0.40–0.60		Rather seasonal with a short drier season	1.4
0.60–0.80		Seasonal	1.6
0.80–1.00		Marked seasonal with a long dry season	1.8
1.00–1.20		Most precipitation in <3 months	1.9
>1.20		Extremely seasonal	2
Rain erosivity (mm/h)		<60	Very low
	60–90	Low	1.2
	90–120	Moderate	1.5
	121–160	High	1.8
	>160	Very high	2
	Slope aspect	Flat, north, northeast, east, northwest	
South, southeast, southwest, west			2



### 3.3.3 Average annual PET

This indicator is especially important for assessing desertification risk in areas affected by soil salinisation (Agricultural University of Athens 2012). Areas under high evapotranspiration are more vulnerable to salinisation and desertification.

### 3.3.4 Aridity index

The aridity index classifies the type of climate in relation to water availability. The higher the aridity index of a region, greater the water resources variability and scarcity in time and more the vulnerability of area to desertification (Agricultural University of Athens 2012). Bagnouls–Gausson aridity index (BGI) (Bagnouls and Gausson 1957) and United Nations Environmental Programme (UNEP) aridity index (UNEP 1997) were calculated for the period 1979–2013 using equations (3 and 4) as follows:

$$BGI = \sum_{i=1}^n (2t_i - P_i) \times k, \quad (3)$$

where  $t_i$  is the mean air temperature for month  $i$  ( $^{\circ}\text{C}$ ),  $P_i$  is the total rainfall for month  $i$  (mm) and  $k$  is the proportion of month during which  $2t_i - P_i > 0$ :

$$\begin{aligned} &\text{UNEP aridity index} \\ &= \frac{\text{Average annual rainfall (mm)}}{\text{Average annual PET (mm)}}. \end{aligned} \quad (4)$$

### 3.3.5 Average wind speed

Increase in the wind speed above the critical limit will cause land degradation and desertification in arid and semi-arid regions. The sand and dust-raising winds start blowing from March onwards in the study area, when the terrain is sufficiently dry and when a significant proportion of the natural vegetation, especially the annual vegetation is dead. During May and June, the wind strength increases manifold and sand storm activities increase. It continues unabated till the monsoon rains arrive, usually by the middle of July. As rain moistens the sandy terrain, it provides a greater resistance to the wind. Also, new plants start sprouting, which add to the resistance. The wind also falls gradually from the end of July. In other words, the period of strong sand shifting wind can be considered as that between March and July

(Narain *et al.* 2000). Therefore, the average wind speed from March to July for the period 1979–2013 was calculated. As the wind speed used in the study was measured at 2 m height, it was converted to the standard height of 10 m using the equation given by FAO (Allen *et al.* 1998) as follows:

$$u_{10} = \frac{\ln(67.8 \times 10 - 5.42) \times u_2}{4.87}, \quad (5)$$

where  $u_{10}$  and  $u_2$  are the wind speeds (m/s) at 10 and 2 m above the ground surface, respectively.

### 3.3.6 Rain seasonality

Rainfall seasonality affects soil erosion, plant species composition and growth rate. Very high inter-annual rainfall variability causes periods of particularly long drought and sudden and high-intensity rainfall (Agricultural University of Athens 2012). Therefore, higher rain seasonality will have a negative effect on desertification. Rain seasonality ( $SL_i$ ) was calculated for the period 1979–2013 using equation (6) (Agricultural University of Athens 2010a) as follows:

$$SL_i = \frac{1}{R_i} \sum_{n=1}^{12} \left| X_{in} - \frac{R_i}{12} \right|, \quad (6)$$

where  $R_i$  is the total annual precipitation for a particular year (mm) and  $X_{in}$  is the monthly precipitation for month  $n$  (mm).

### 3.3.7 Rain erosivity

High-rain erosivity indicates the greater erosive capacity of the overland water flow. Therefore, the high-rain erosivity will lead to high risk of desertification. Rain erosivity (Fournier index), mm/h, was calculated for the period 1979–2013 using equation (7) (Agricultural University of Athens 2010a) as follows:

$$FI = \sum_{i=1}^n \frac{P_i^2}{p}, \quad (7)$$

where  $P_i$  is the mean precipitation of month  $i$  (mm) and  $p$  is the mean annual precipitation (mm).

### 3.3.8 Slope aspect

Slopes with southern and western facing aspects will be warmer and have higher evaporation rates than northern and eastern aspects (Agricultural University of Athens 2010a). Therefore, a slower

recovery of vegetation and higher erosion rates is expected on southern and western aspects than on northern and eastern aspects.

### 3.4 Vegetation quality index

The indicators used to assess the vegetation quality, their classes and assigned weights are described in table 3. IRS Resorcesat-2 AWiFS satellite data of post-monsoon season (23 October 2013) obtained from NRSC, ISRO, Hyderabad and land use/land cover data (LULC) (250k) mapped from IRS Resorcesat-2 AWiFS multi-temporal data for year 2013–2014 of NRSC, ISRO, Hyderabad (NRSC 2015) were used for obtaining vegetation quality indicators.

#### 3.4.1 Vegetation cover (%)

Both runoff and sediment loss decrease exponentially with an increase in percentage of plant cover. A vegetation cover 45–50% is considered as a critical value, since above this value soils are adequately protected from the raindrop impact and the soil erosion is significantly reduced (Agricultural University of Athens 2012). For estimation of the vegetation cover (%), the mosaic-pixel model suggested by Liang *et al.* (2008) was used as follows:

$$\text{Vegetation cover (\%)} = \frac{\text{NDVI} - \text{NDVI}_0}{\text{NDVI}_\infty - \text{NDVI}_0} \times 100, \quad (8)$$

where NDVI is the normalised difference vegetation index, which was calculated from the satellite data as follows:

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}, \quad (9)$$

where NIR is the reflection of the near-infrared portion of the electromagnetic spectrum and RED is the reflection in the visible spectrum. The NDVI is usually sensitive to vegetation. However, NDVI of some special features will be similar to that of vegetation. It is difficult to identify vegetation and non-vegetation areas by using only the NDVI data. Hence, LULC data was used to identify the vegetated areas and non-vegetated areas. Out of the LULC categories present in the study area, the categories such as kharif crop, rabi crop, zaid crop, double/triple cropping, deciduous forest and degraded forest were considered as vegetated area and the remaining categories as non-vegetated area. The histogram of pixels in the vegetated area was used to determine  $\text{NDVI}_0$  and  $\text{NDVI}_\infty$  taking care to avoid contaminated pixels by leaving 1% into consideration on either end of the histogram. The vegetation cover percentage was calculated for all pixels using the global minimum and maximum value obtained from the vegetated area. For the non-vegetation cover area, the vegetation cover percentage was considered as zero.

#### 3.4.2 Land use/land cover type

Types of vegetation and land use are important factors controlling various processes affecting

Table 3. Classes and the corresponding weight assigned for the calculation of the VQI.

Indicators	Class	Weight
Vegetation cover (%)	>75	1
	50–75	1.3
	25–50	1.5
	10–25	1.8
	<10	2
Land use/land cover type	Water bodies, built-up land, evergreen/semi-evergreen forest, littoral/swamp/mangrove	1
	Deciduous forest	1.3
	Degraded forest	1.4
	Grassland and grazing land, plantation/orchard	1.5
	Double/triple crop land	1.6
	Scrub land	1.7
	Kharif only, rabi only, zaid only (crop lands)	1.8
	Current fallow land, shifting cultivation	1.9
	Rann, other waste lands, gullies/ravines	2

Table 4. Classes and the corresponding weight assigned for the calculation of the SEQI.

Indicators	Class	Description	Weight
Population density (people/km <sup>2</sup> )	<50	Low	1
	50–100	Moderate	1.3
	100–300	High	1.7
	>300	Very high	2
Population growth rate (%/yr)	<1.5	Low	1
	1.5–3	Moderate	1.3
	3–4.5	High	1.7
	>4.5	Very high	2
Illiteracy rate (%)	<40	Low	1
	40–50	Moderate	1.3
	50–60	High	1.7
	>60	Very high	2
Work participation rate (%)	>50	Very high	1
	40–50	High	1.3
	30–40	Moderate	1.7
	<30	Low	2

desertification. Land use and land use intensity is related to processes of land degradation and desertification such as soil erosion, soil structure decline, loss in organic matter content, soil salinisation, etc. (Agricultural University of Athens 2010a).

### 3.5 Socio-economic quality index

The indicators used to assess socio-economic quality, their classes and assigned weights are described in table 4. Village-wise data of Census of India (<https://data.gov.in/>) for the year 2001 and 2011 was used to calculate different socio-economic quality indicators. Village and block boundaries were obtained from the State Remote Sensing Application Centre (SRSAC), Department of Science and Technology, Government of Rajasthan, Jodhpur.

#### 3.5.1 Population density

Areas affected by soil erosion or water stress are more vulnerable to land degradation and desertification under high population densities. Also, areas with high population density have supported low plant cover due to overexploitation of natural resources promoting high desertification risk (Agricultural University of Athens 2012). Village-wise population density was calculated by dividing total population of the village for the year 2011 with its area.

#### 3.5.2 Population growth rate

Rapid population growth rate can be connected with poverty and high pressure on natural resources. The areas with a low population growth rate will be positively related to land degradation (Agricultural University of Athens 2012). Block-wise population growth rate (%/yr) was calculated by using the population of the year 2001–2011.

#### 3.5.3 Illiteracy rate

Illiteracy index has an effect on the general economic vitality of the area. Literate or educated farmers are more likely to adopt new technologies and will have higher returns from their land (The World Bank 1990). They are also more likely to adopt improved land management practices leading to less erosion and lower nutrient depletion (Pender *et al.* 2004). Therefore, higher illiteracy rates will lead to more land degradation and desertification. Village-wise illiteracy rate (%) was calculated by dividing a number of illiterate people with total population for the year 2011.

#### 3.5.4 Work participation rate

Work participation rate has an effect on the general economic vitality of the area. If work participation rate is low, the income of the people living in that area will be low. Therefore, the relationship of people with the land and its well-being will be very insecure, increasing emigration pressures and desertification (Basso *et al.* 2000). Therefore, low work participation rate will lead to more land degradation and desertification. Village-wise work participation rate (%) was calculated by dividing total workers (main + marginal) with total population for the year 2011.

### 3.6 Desertification risk assessment

A risk is nothing but the situation involving exposure to danger. Here the danger is land degradation and desertification. Risk assessment is nothing but the determination of a quantitative or qualitative estimate of risk related to a well-defined situation and a recognised threat (also called hazard). In the present study, qualitative desertification risk assessment has been done. Methodology for assessing the risk of desertification was inspired from the project ‘DESIRE’ developed by the European Commission (Agricultural University of Athens 2010b; Kosmas *et al.* 2013). ESAs to

Table 5. *Defining desertification risk.*

Sl. no.	Type of ESA	Degree of land degradation	Desertification risk	Assigned weight
1	Critical	Severe	Very high	5
		Moderate, slight	High	4
		No land degradation	Moderate	3
2	Fragile	Severe	High	4
		Moderate	Moderate	3
		Slight, no land degradation	Low	2
3	Potential	Severe	Moderate	3
		Moderate	Low	2
		Slight, no land degradation	Very low	1
4	Non-threatened	Severe, moderate	Low	2
		Slight, no land degradation	Very low	1

desertification describe the stage of land degradation or desertification sensitively under certain physical environmental characteristics and socio-economic conditions. The risk of desertification was assessed based on ESAs to desertification, the degree of land degradation and significant desertification indicators. The degree of land degradation was obtained from the land degradation data of Natural Resource Census Project of NRSA, Hyderabad at 1:50,000 scale, mapped from three seasons data (kharif, rabi and zaid) of IRS Resourcesat-1 LISS-III for year 2005–2006 (NRSA 2007).

### 3.6.1 *Defining desertification risk at sample locations*

Total 7000 sample locations were selected in the study area randomly. Desertification risk at each selected sample locations was obtained using ESAs to desertification and degree of land degradation as given in table 5. Weights ranging from 1 (very low risk) to 5 (very high risk) were assigned to desertification risk classes. For example, an area characterised as fragile to desertification will be subjected to high desertification risk under severe erosion or low risk under slight erosion.

### 3.6.2 *Selection of significant desertification indicators, model development and calculation of desertification risk*

All the 23 indicators were evaluated using the regression analysis of 7000 sample locations for identifying a number of significant indicators and for defining their relationship with desertification risk. Stepwise multiple regression analysis was performed using weights of desertification risk as

the dependent variable ( $Y$ ) and the weights of each candidate indicators as independent variables ( $X$ ) using the following linear model (Steel *et al.* 1997):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n, \quad (10)$$

where  $Y$  is the dependent variable (weights of desertification risk),  $\beta_0$  is the  $Y$  intercept,  $\beta_1, \beta_2, \dots, \beta_n$  are the slopes of the regression plane and  $X_1, X_2, \dots, X_n$  are the independent variables (weights of candidate indicators).

A linear regression model was chosen in the study because of its simplest form and its successful applications for assessing desertification risk (Kosmas *et al.* 2013). Further, it provides relative importance of the various independent variables as represented by  $\beta$  values. This helps in finding out which desertification indicator has more influence on desertification risk and for preparing an action plan to reduce desertification risk. A 99% confidence interval was used for the regression analysis. Exploratory regression and ordinary least-squares (OLS) tool of ARC-GIS spatial statistics tool bar were used to perform the regression analysis. As there are 23 potential independent variables, the exploratory regression tool was used to evaluate all possible combinations of independent variables to see which models pass all of the necessary OLS diagnostics. Multiple iterations have been performed using this tool to find out the best combination of input desertification indicators to explain the desertification risk, which gives the highest  $R^2$  value and meets all of the requirements and assumptions of the ordinary least-squares method. Variance inflation factor (VIF) was used to measure redundancy (multicollinearity) among the independent variables. Independent variables

associated with VIF values  $>7.5$  were removed (one by one) from the regression model. OLS tool was used to perform the regression analysis on a selected best combination of input desertification indicators obtained in the previous step. Significant  $\beta$  values of selected input desertification indicators, intercept, the estimated value of the dependent variable, the residuals of the regression model and different diagnostics of OLS method were obtained using the OLS tool. The residuals of the regression model were evaluated to test whether the pattern expressed is clustered, dispersed or random.

Spatial autocorrelation (Morans I) tool of ARC-GIS spatial statistics tool bar was used for this purpose. This tool measures spatial autocorrelation based on feature locations and attribute values using the global Moran's I statistic. Statistically significant clustering of high and/or low residuals (model under and over predictions) indicates that a key variable is missing from the model (misspecification). OLS results cannot be trusted when the model is incorrectly specified. Finally, desertification risk index (DRI) for the entire study area was calculated using the developed regression

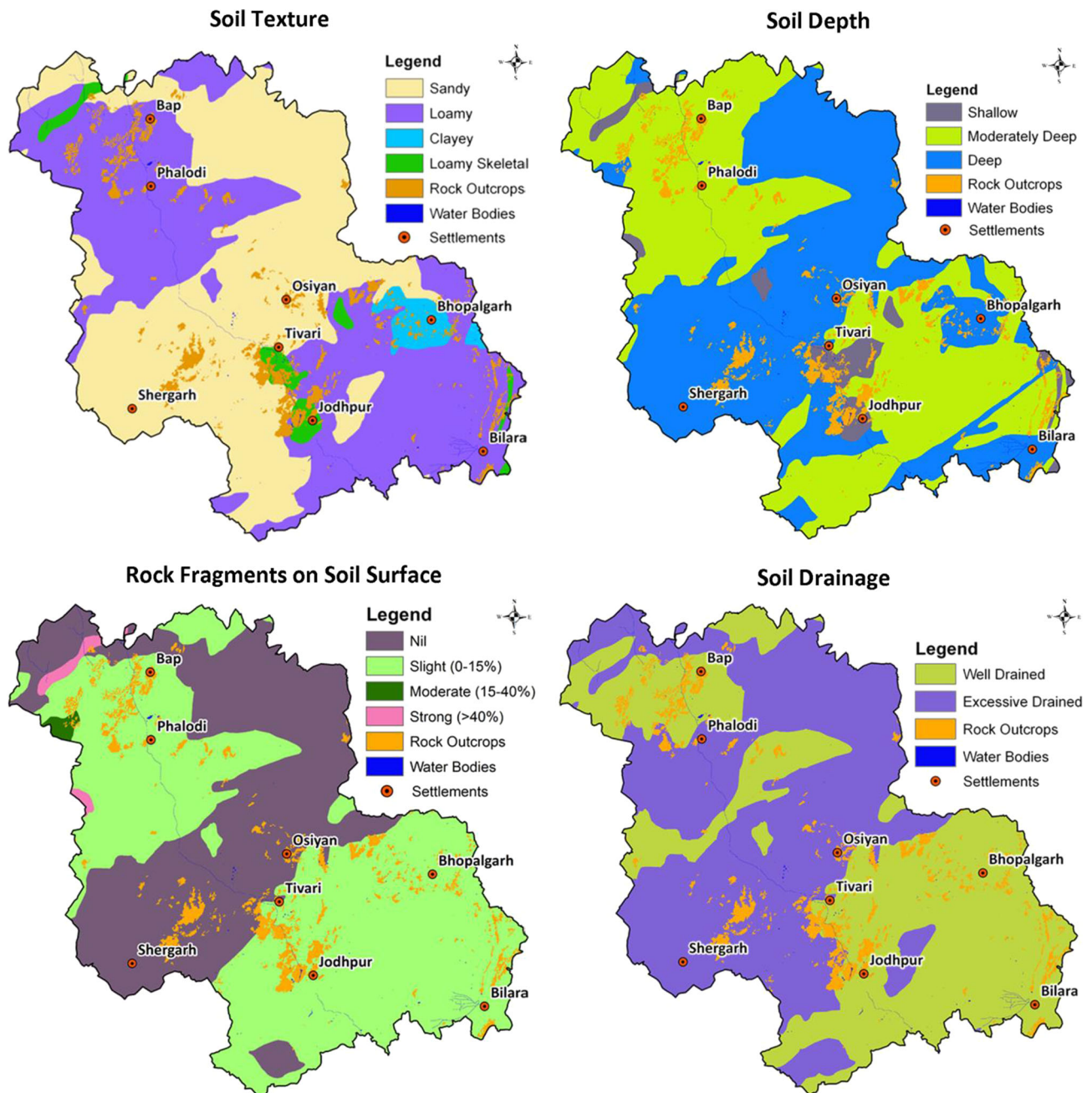


Figure 3. Soil quality indicators.

model. Village boundary was overlaid on DRI and the number of villages in each DRI class along with its total population has been estimated. This was done by assigning DRI class to each village having maximum area falling in that DRI class.

### 3.6.3 Validation of DRI

This methodology for defining land degradation and desertification risk was validated using independent indicators such as soil organic matter content (%) and cation exchange capacity (CEC,

meq/100 g) obtained from the Natural Resource Information System (NRIS) project – SAC, Ahmadabad (Dasgupta *et al.* 2000). In this project, soil resources of Rajasthan State were mapped on 1:50,000 scale by collaborating agency namely the State Remote Sensing Application Centre, Government of Rajasthan, Jodhpur, using IRS-P6 LISS-III data and field soil sample analysis results (SRSAC 2010). Correlation between desertification risks with the above two soil parameters was tested at 230 sample locations selected randomly.

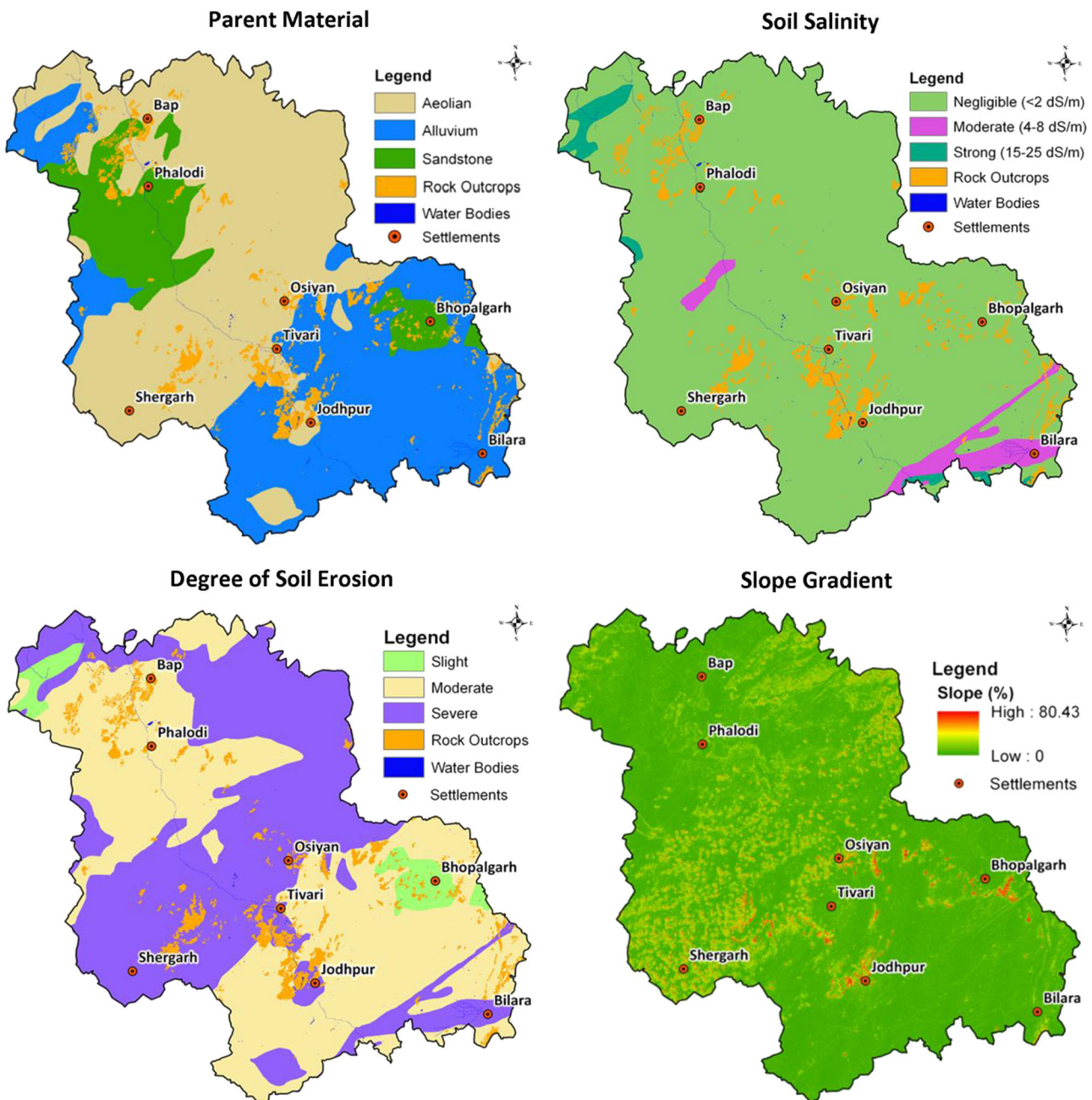


Figure 4. Soil quality indicators.

Soil organic matter is the fraction of the soil that consists of plant or animal tissue in various stages of breakdown (decomposition). It is a key indicator of soil quality, both for agricultural and environmental functions. Soil organic matter is a major indicator influencing physical, chemical and biological soil variables. Aggregation and stability of soil structure increases with organic matter content (Tisdal and Oades 1982; Milne and Haynes 2004). This, in turn, increases the infiltration rate and available water capacity of the soil,

as well as resistance to erosion by water and wind (Bissonnais and Arrouays 1997). The decrease of organic matter content is a key factor in accelerating soil erosion and irreversible land degradation and desertification.

CEC of a soil represents the total amount of exchangeable cations that the soil can adsorb. Cations are positively charged ions such as calcium ( $Ca^{++}$ ), magnesium ( $Mg^{++}$ ), potassium ( $K^+$ ), sodium ( $Na^+$ ), hydrogen ( $H^+$ ), aluminium ( $Al^{+++}$ ), iron ( $Fe^{++}$ ), manganese ( $Mn^{++}$ ), zinc

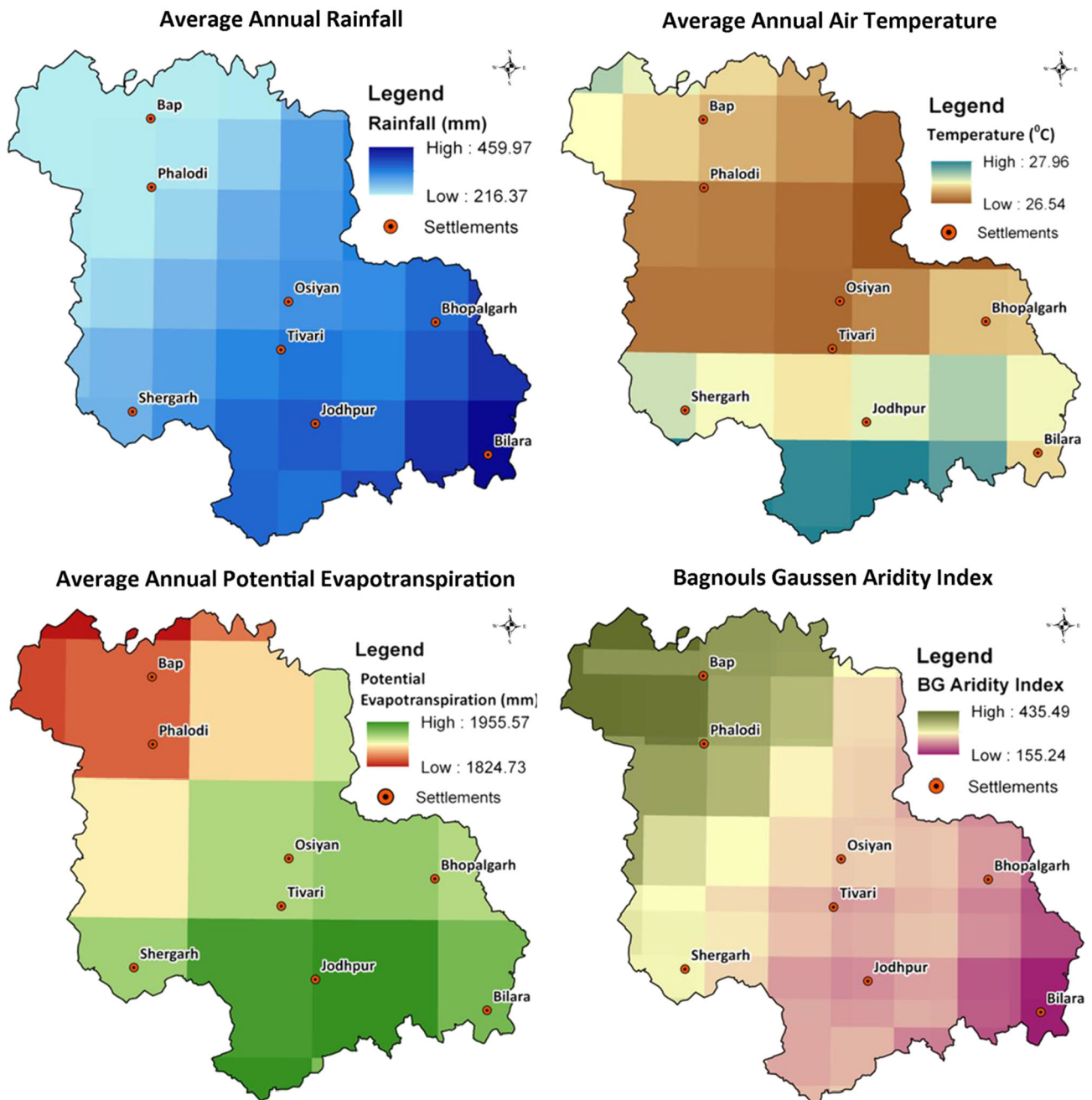


Figure 5. Climate quality indicators.

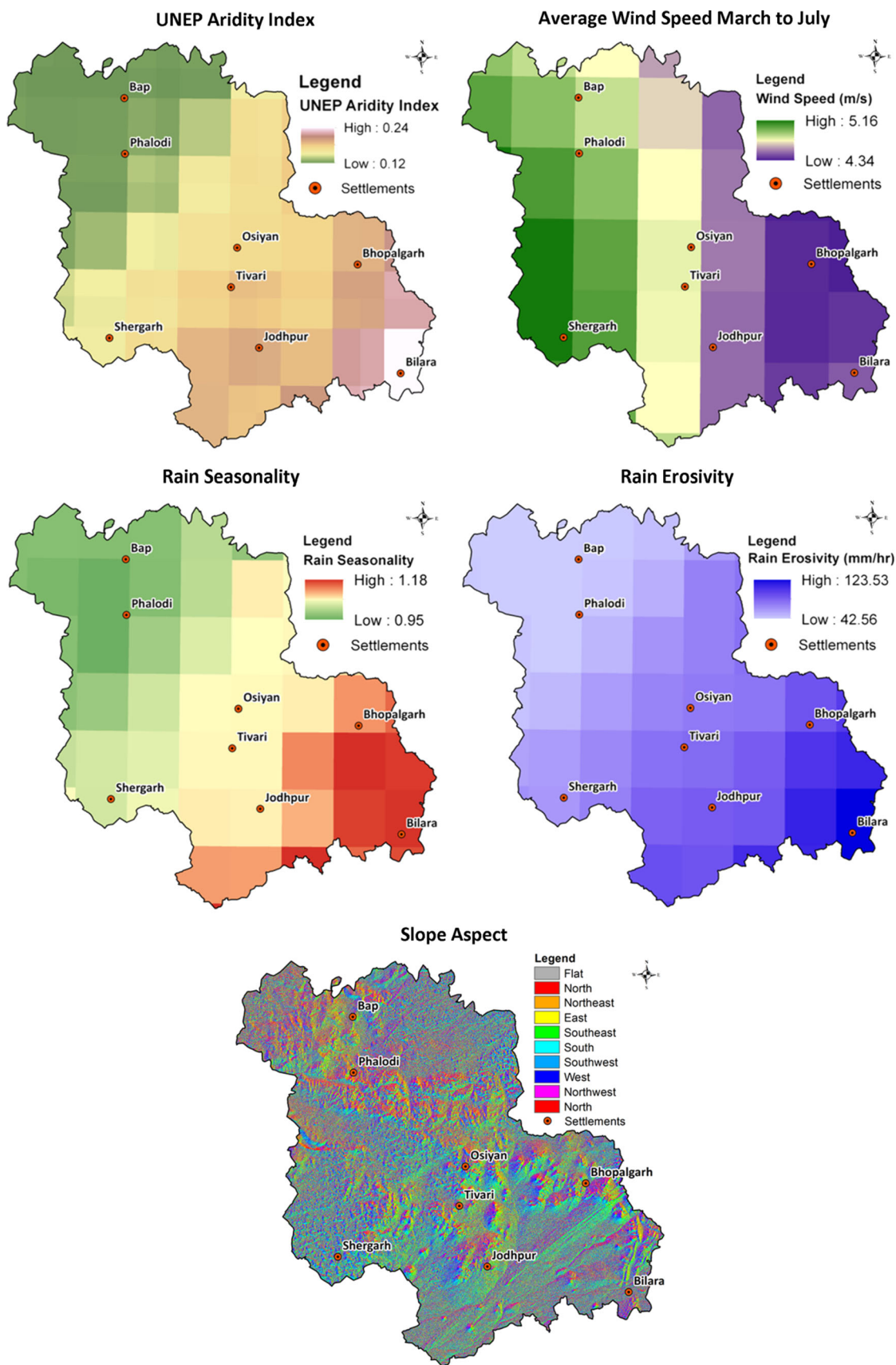


Figure 6. Climate quality indicators.



(Zn<sup>++</sup>) and copper (Cu<sup>++</sup>). The capacity of the soil to hold on to these cations is called the CEC. These cations are held by the negatively charged clay and organic matter particles in the soil through electrostatic forces. CEC can be called as the nutrient holding capacity of the soil. Therefore, the decrease in the CEC of soil will accelerate the land degradation and desertification.

#### 4. Results and discussion

The results of soil, climate, vegetation and socio-economic quality indicators, ESAs to desertification and regression analysis to obtain DRI are presented in this section.

##### 4.1 SQI, CQI, VQI, SEQI

Twenty-three desertification indicators which include eight soil parameters, nine climate parameters, two vegetation parameters and four socio-economic parameters are presented in figures 3–8. It can be seen from figures 3 and 4 that the majority of the study area falls under sandy and loamy texture, moderate to deep soil depth, nil to slight rock fragments, well to excessive soil drainage, aeolian and alluvium parent material, negligible soil salinity, moderate to severe soil erosion and gentle slope. It can be observed from figures 5 and 6 that the northwestern part of the district has

low rainfall, low PET, low-rain seasonality and low-rain erosivity as compared to the southwestern part. Also, aridity and wind speed are high in the northwestern part of the district as compared to the southwestern part. Temperature and aspect vary spatially over the district. It can be seen from figure 7 that the majority of the area falls under <10% vegetation cover followed by 10–25%, 25–50%, 50–75% and >75% vegetation cover. Further, the majority of the area falls under other waste lands, current fallow land and scrub land and the remaining area in crop land and forest land. It can be observed from figure 8 that the majority of the area is under high and moderate population density, very high and high illiteracy rate and moderate and low work participation rate. Further population growth rate varies from 1.27 (Bilara block) to 5.45 (Luni block).

Integrated soil, climate, vegetation and socio-economic quality indices were presented in figure 9 and table 6. It can be seen that the majority of study area comes under moderate soil quality (82.53%) distributed over entire study area followed by high soil quality (12.27%) in some portions of western and eastern areas, very low soil quality (4.97%) in some patches and low soil quality (0.22%) in very small patch at west. In the case of climate quality, it is found that the entire study area comes under very low climate quality (52.84%) followed by low climate quality (47.16%).

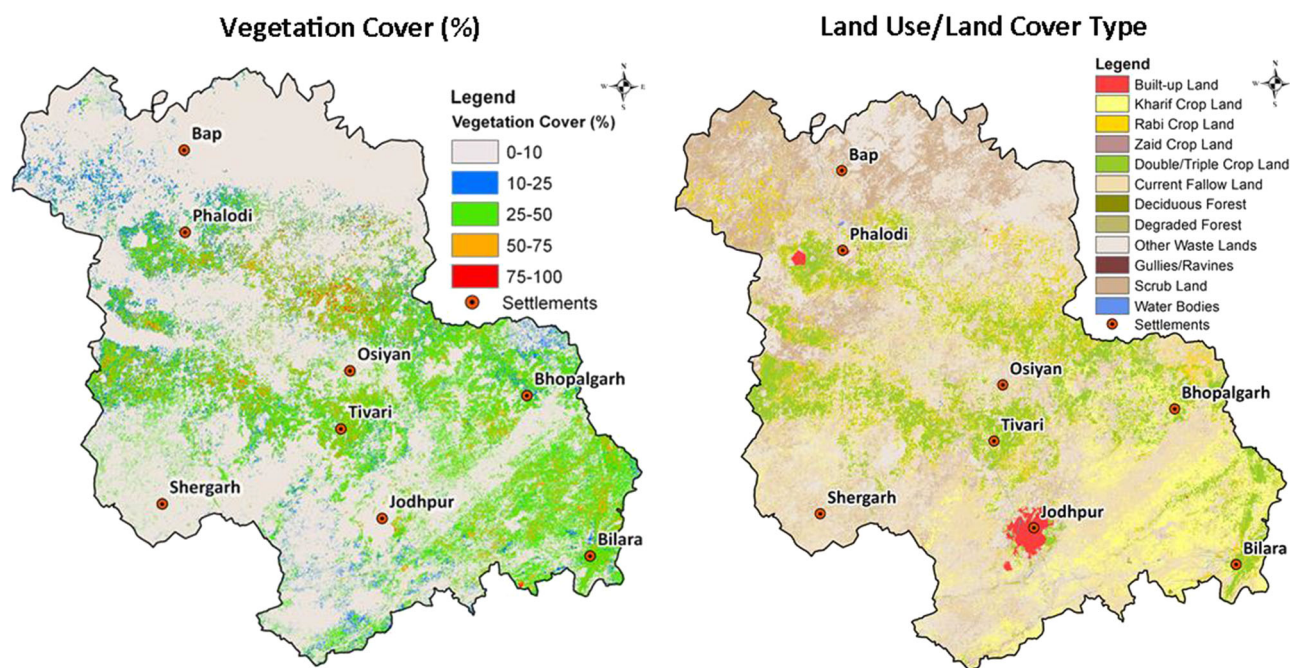


Figure 7. Vegetation quality indicators.

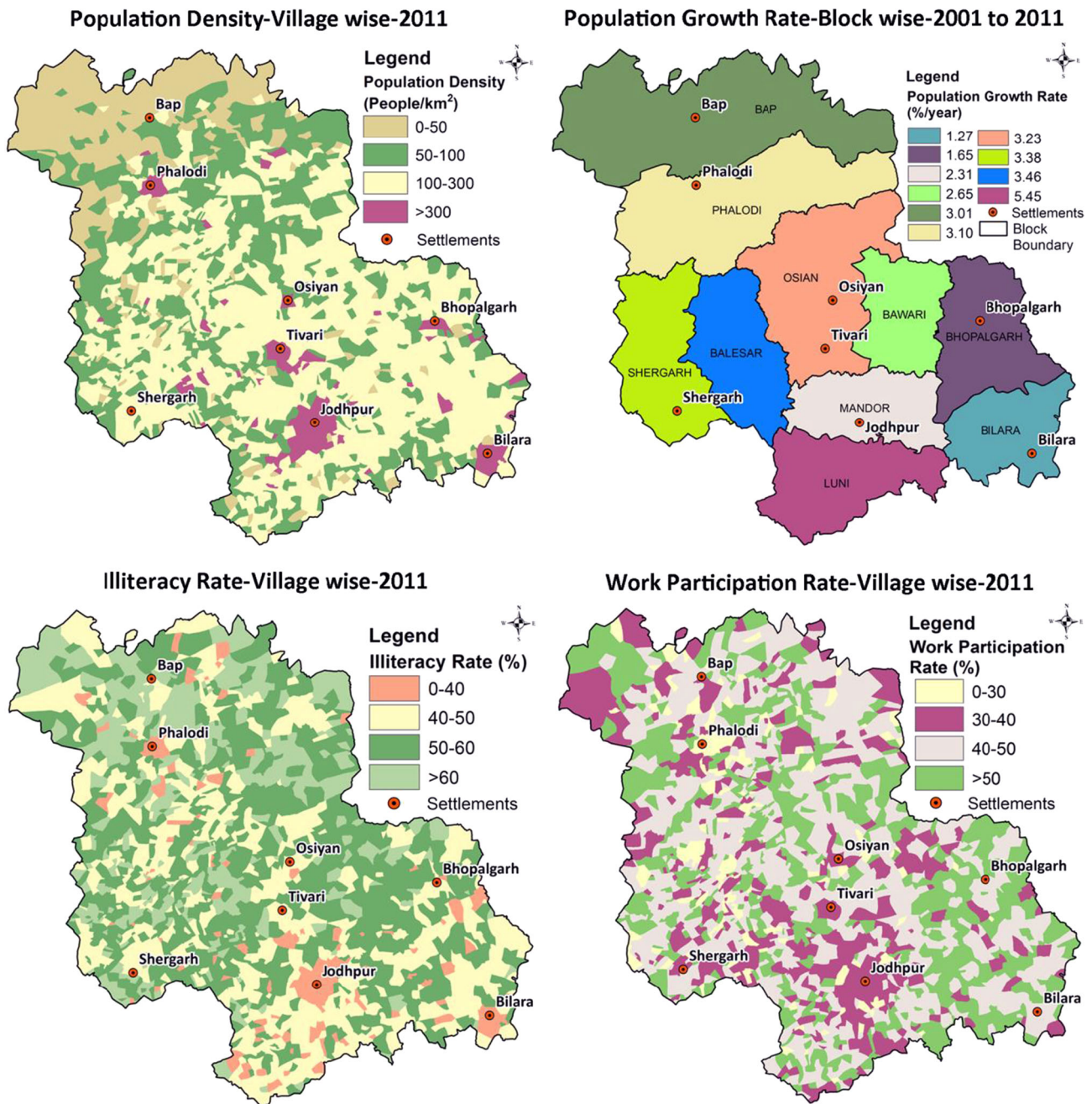


Figure 8. Socio-economic quality indicators.

It can be seen that the majority of study area comes under very low vegetation quality (72.61%) distributed over entire study area followed by low vegetation quality (23.14%) at western and southeast portions, moderate vegetation quality (4.23%) at small patches near urban areas and high vegetation quality (0.02%) in very small areas. Similarly, it can be seen that the majority of study area comes under moderate socio-economic quality (59.60%) followed by low socio-economic quality (32.40%), high socio-economic quality

(5.58%) and very low socio-economic quality (2.41%) spread over study area in patches.

#### 4.2 ESAs to desertification

ESAs to desertification obtained by integrating all four quality indices are presented in figure 10 and table 7. It can be seen that the majority of study area comes under the fragile category (86.17%) distributed over the entire study area followed by the potential (11.69%) in some portions

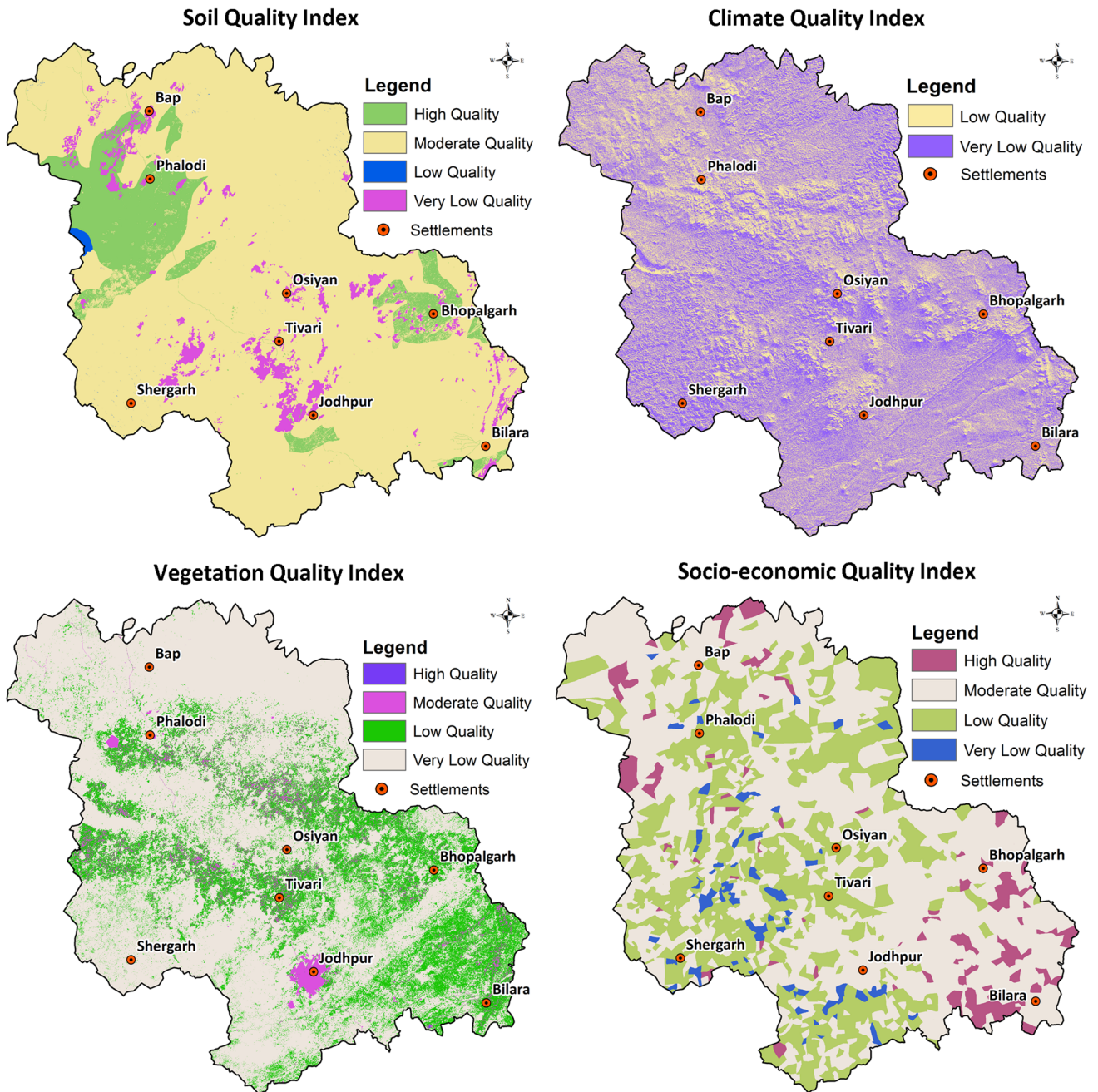


Figure 9. Integrated soil, climate, vegetation and socio-economic quality indices.

Table 6. Integrated soil, climate, vegetation and socio-economic quality indices.

Class	Score range	Description	SQI area (%)	CQI area (%)	VQI area (%)	SEQI area (%)
1	1.00–1.25	High quality	12.27	0.00	0.02	5.58
2	1.25–1.50	Moderate quality	82.53	0.00	4.23	59.60
3	1.50–1.75	Low quality	0.22	47.16	23.14	32.40
4	1.75–2.00	Very low quality	4.97	52.84	72.61	2.41

of western and eastern areas, critical (1.97%) and non-threatened areas (0.17%) in some patches. It can be seen that non-threatened areas are mainly

because of the presence of water bodies in that area. Area potential to desertification shows the presence of kharif/rabi crop land with moderate

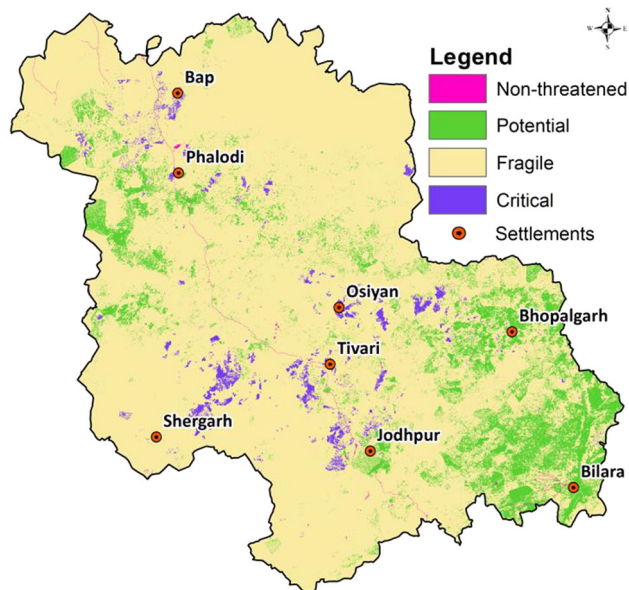


Figure 10. ESAs to desertification.

Table 7. ESAs to desertification.

Class	Score range	ESAs class	Area (%)
1	1.00–1.25	Non-threatened	0.17
2	1.25–1.50	Potential	11.69
3	1.50–1.75	Fragile	86.17
4	1.75–2.00	Critical	1.97

to high soil quality, low to very low climate and vegetation quality and high socio-economic quality. Similarly, area fragile to desertification shows the presence of current fallow land and other waste lands with moderate soil quality, low to very low climate quality, very low vegetation quality and moderate to low socio-economic quality. Area critical to desertification shows the presence of other waste lands and current fallow land with very low soil, climate and vegetation quality and low socio-economic quality.

#### 4.3 Desertification risk assessment using regression model

A developed regression model with a selected best combination of significant desertification indicators for the assessment of DRI is given below:

$$\begin{aligned}
 \text{DRI} = & -11.93 + 0.64 \times \text{soil texture} \\
 & + 0.24 \times \text{rock fragments} \\
 & + 0.19 \times \text{soil parent material} \\
 & + 1.37 \times \text{soil salinity} + 0.78 \times \text{slope gradient} \\
 & + 0.41 \times \text{average annual rainfall}
 \end{aligned}$$

Table 8. Significant  $\beta$  values of stepwise multiple regression analysis for assessing desertification risk.

Indicators	Significant $\beta$ values ( $R^2 = 0.83$ )
<b>Soil indicators</b>	
1 Soil texture	0.64
2 Soil depth	–
3 Rock fragments	0.24
4 Soil drainage	–
5 Parent material	0.19
6 Soil salinity	1.37
7 Soil erosion	–
8 Slope gradient	0.78
<b>Climate indicators</b>	
9 Average annual rainfall	0.41
10 Average annual air temperature	–
11 Average annual PET	–
12 BG aridity index	–
13 UNEP aridity index	0.70
14 Rain seasonality	0.82
15 Rain erosivity	–
16 Average wind speed	0.33
17 Slope aspect	0.13
<b>Vegetation indicators</b>	
18 Vegetation cover percentage	1.20
19 Land use/land cover type	0.73
<b>Socio-economic indicators</b>	
20 Population density	0.59
21 Population growth rate	0.21
22 Illiteracy rate	0.43
23 Work participation rate	0.38

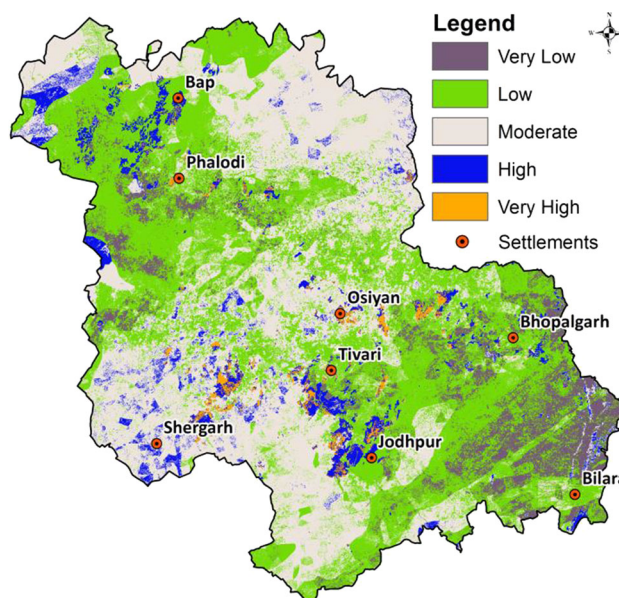


Figure 11. Desertification risk index.

Table 9. DRI using regression model.

Class	DRI class	Area (%)	No. of villages	Total population	Population (%)
1	Very low risk	9.63	130	2,43,913	6.62
2	Low risk	43.14	781	23,24,615	63.05
3	Moderate risk	40.26	864	10,43,846	28.31
4	High risk	5.56	56	58,456	1.59
5	Very high risk	1.42	15	16,335	0.44

$$\begin{aligned}
 &+ 0.70 \times \text{UNEP aridity index} \\
 &+ 0.82 \times \text{rain seasonality} \\
 &+ 0.33 \times \text{average wind speed} \\
 &+ 0.13 \times \text{slope aspect} \\
 &+ 1.20 \times \text{vegetation cover percent} \\
 &+ 0.73 \times \text{land use / land cover} \\
 &+ 0.59 \times \text{population density} \\
 &+ 0.21 \times \text{population growth rate} \\
 &+ 0.43 \times \text{illiteracy rate} \\
 &+ 0.38 \times \text{work participation rate.} \tag{11}
 \end{aligned}$$

Table 8 gives significant  $\beta$  values of the stepwise multiple regression analysis for assessing desertification risk. Sixteen indicators out of total 23 were found significant at a 99% confidence interval ( $p < 0.01$ ) with  $R^2 = 0.83$ . The most important indicators affecting desertification risk in the study area ( $\beta$  values  $> 0.55$ ) are soil salinity, vegetation cover percentage, rain seasonality, slope gradient, land use/land cover type, UNEP aridity index, soil texture and population density. Results of spatial autocorrelation (Moran's I statistic) of residuals of the developed regression model show that the pattern of residuals does not appear to be significantly different than random. Therefore, the results of the developed regression model can be trusted.

DRI calculated using the developed regression model is presented in figure 11 and table 9. It can be seen that the majority of study area comes under low risk (43.14%) mostly in northwest and southeast portions of study area and moderate risk (40.26%) category in northeast and southwest portions. The remaining area comes under very low risk (9.63%) in southeast portions and some patches in the northwest, high risk (5.56%) and very high risk (1.42%) in small patches distributed over the study area. It can be further observed that 63.05% and 28.31% populations of Jodhpur district fall under low risk and moderate risk category,

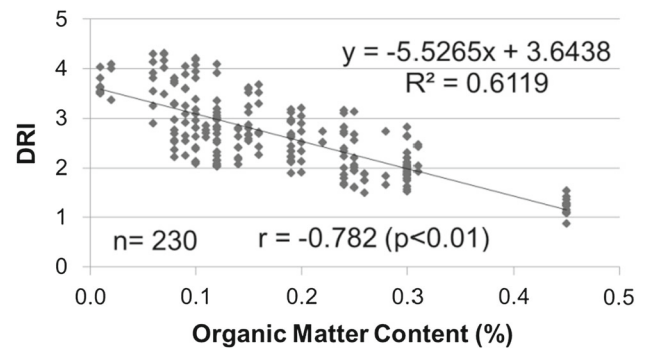


Figure 12. The relationship between DRI and soil organic matter content.

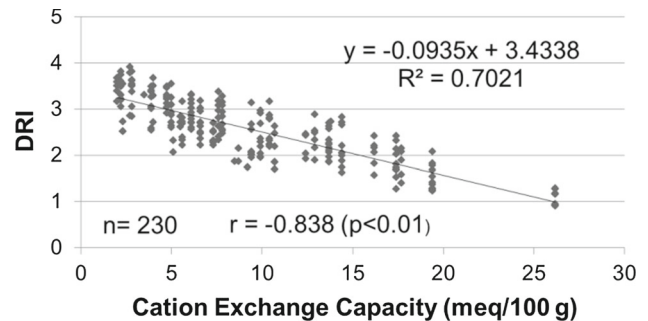


Figure 13. The relationship between DRI and CEC of a soil.

respectively, followed by very low risk (6.62%), high risk (1.59%) and very high risk (0.44%).

#### 4.4 Validation of DRI

Correlation of DRI with soil organic matter content and CEC of a soil at 230 sample locations is presented in figures 12 and 13, respectively. It can be seen that there is a significant negative correlation between DRI and both the soil properties. This means that DRI decreases with an increase in soil organic matter content and an increase in CEC of a soil. The trend of the relationship of DRI with the above two soil properties is as expected. Therefore, the developed model can be used to assess desertification risk in the study area.

## 5. Conclusions and future scope

This study demonstrates the development of a comprehensive model for the assessment of desertification risk in the western part of India using a multifactorial approach and geospatial techniques. This study reveals that the multiple regression approach and geoinformatics technique permit a detailed analysis of desertification indicators obtained from remotely sensed data as well as other ancillary data both individually and in combination. The developed methodology identifies desertification risk areas with their severity and associated effective indicators responsible for desertification. It would help to identify where desertification is a current or potential problem, and what could be the actions needed to alleviate the problem over time. The process of land degradation and desertification changes rapidly over time and requires continuous monitoring. Periodic monitoring (qualitative assessment) of effective desertification indicators will provide an early indication towards the extension of desertification in potential risk areas. Therefore, the developed model will serve as a base for an early warning system for desertification. There are relatively few important indicators affecting the desertification process in the study area which can be considered for preparing an action plan to reduce desertification risk. The comparison of desertification risk with independent indicators such as soil organic matter content and CEC showed clear relationships, indicating that these indicators may be used to assess desertification risk. The developed DRI can be used for selecting the appropriate measures to control land degradation and desertification in the study area.

As such, the methodology evolved is a generic one with no regional specificity and hence, the evolved methodology is replicable in any region where desertification issue needs to be addressed on a priority basis. However, the significant indicators used for assessing desertification risk will vary from place to place. The future scope of this study is to develop a comprehensive desertification risk mitigation plan using effective indicators and to validate the model with field measured parameters such as measured soil loss, soil respiration (CO<sub>2</sub>), etc. More precise results may be obtained by using the large-scale thematic layers and by modifying the weight assignments.

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