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Remote sensing and GIS based modeling for wind erosion assessment in parts of Indian Thar desert

Koyel Sur, Rimjhim B. Singh, A.S. Arya, Prakash Chauhan and Ajai
Space Applications Centre, ISRO, Ahmedabad
Email: koyelsur3@gmail.com

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ABSTRACT: Wind erosion process is often found to be one of the major causes of land degradation in arid and semi-arid areas. Apart from the soil and geomorphology of an area, climatic factors such as rainfall, wind and temperature makes an area vulnerable towards land degradation. The assessment was carried out based on the empirical model of wind erosion equation. The basic equation was integrated with qualitative decision rules based on the geometric mean relationship and hierarchical organization of the data represented by different thematic maps. Research efforts of the past decades have provided several technologies but limited investigations were done for assessing the severity of wind erosion in the Jaisalmer district, Rajasthan. Thus, an attempt was made to model wind erosion sensitivity of this region using remote sensing and Geographic Information System (GIS). Each of the thematic maps like climate, vegetation, surface roughness, unsheltered distance and soil erodibility forms an input to the model. All the factors were integrated together to find the sensitivity of wind erosion in the region. The resultant map shows the severity levels of wind erosion in Jaisalmer district. The wind erosion map thus obtained may be used to formulate mitigation and adaptation strategies for diverse land development management activities.

Keywords: Wind erosion, Surface roughness, Unsheltered distance, Vegetation density, Soil erodibility

1. Introduction

Wind contributes immensely to the soil erosion which is a cause of global environmental concern (Shi et al., 2002). It acts as the major source of soil degradation in arid and the semiarid regions. Top soil affects the productivity of the land creating both on-site and off-site effects, leading to decline of land quality of the region. Soil erosion due to wind is more pronounced in hyper arid, arid and semi-arid regions. Wind erosion not only impacts just the land but the whole ecosystem as it adversely affects socio-economic conditions of the population. The wind erosion affected region is normally characterized by sandy soils, extremely low precipitation exhibiting extremely dry climatic characteristics. Activities by wind erosion processes, known as Aeolian processes, involve removal of loose and fine grained particles including organic matter from the surface of the earth and then transportation by various modes and finally the deposition of the particles. Wind erosion is thus a very complex phenomenon and is controlled by several factors such as wind velocity, rainfall pattern, stability of the surface on which the wind is acting upon, vegetation cover and also the socio economic pattern of the region. For many years, researchers have been engaged in evolving suitable model the mechanisms of wind transportation, deposition and erosion and finally analyze the wind erosion so that it can be controlled. The studies regarding wind erosion dates back to 1941, when Bagnold identified the relationships between soil texture and wind characteristics (Bagnold, 1941). The idea of Bagnold worked as a stage for further development in this field creating the empirical Wind Erosion Equation (WEQ) (Woodruff and Siddoway,1965) and Revised Wind Erosion Equation (RWEQ) (Fryrear, 1986) and in more subsequent years there was formulation of Wind Erosion Prediction System (Hagen, 1991) and the Simulation Model of Daily Wind Erosion Loss (Cole et al., 1983), Empirical Wind Erosion Model with Dust Storm Index (Shao and Leslie, 1997), Integrated Wind Erosion Management System (Hua and Yaping, 2001). A different type of wind erosion model was developed by (Wang et al., 2001) based on stochastic theories of wind erosion. Further models that came up in due course were Wind Erosion on European Light Soils (Bohner et al., 2003) and the Australian land erodibility model (Webb et al., 2006). However, all the above models had their basic input from extensive field measurements. All the equations and models however can only be rooted to local condition based on widespread empirical experiments at fine scales. Several methods exist as of today but each of them has methodological limitations of its own (NAM, 2002). WEQ and RWEQ are empirical models used to assess wind erosion in case of agricultural fields. Thus, these are effective only on the scale of plot-sized analysis (Funk et al., 2004). All these models are typically, process based which are considered as the application of mathematical and physical relationships that cannot be scaled up to regional applications (Webb et al., 2006).

In this study, an attempt has been made to analyze the wind erosion vulnerability over Jaisalmer district of Rajasthan, which falls in the heart of the great “Thar Desert” in the western part of India by employing the qualitative scaling of various input parameters. The qualitative assessment of wind erosion mapping, generated with the integration of geo-statistical thematic inputs in GIS environment would act as a major guide to understand the spatial spread of wind erosion in the study region. The output maps thus produced may be used for planning the combating measures for wind erosion of varying severity at various locations.

2. Study area

Jaisalmer, the largest district of Rajasthan, in the western part of India (Figure 1) has been taken as the study area.

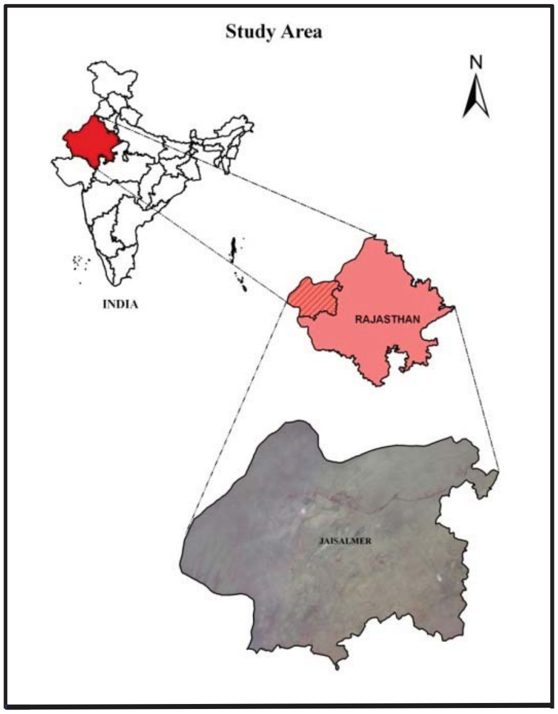

Figure 1: Study area

The district extends between 24º 37' 00" to 30º 10' 48" North latitude and 69º 29' 00" to 76º 05' 33" East longitude. The district covers an area of about 38401 km^2 and is situated in the north western part of Rajasthan. Jaisalmer is bounded by Barmer district in the south, Jodhpur in the east and Bikaner in the northeast; it also shares the international boundary between Pakistan and India on the eastern side. Physiographically, the district has a flat topography without any plateaus or hills. The landform features of Jaisalmer are heterogeneous mainly due to shift in climate from warm humid to the present hot arid conditions (Swain et al., 1983). Quaternary sediments of the study area reflect varied forms of residual, fluvial, lacustrine and aeoline features (Ramakrishna et al., 1990). Thus in the sandy area most of the tertiary limestone and shales have been eroded to pediplaination surface. Low angle pediments like pebbles cover extensive areas and are generally associated with structural plains and gravelly pavements often known as the desert pavements. There is not even a single perennial river crossing the district. However, the Indira Gandhi Canal in the recent times is the one and only source of irrigational facility in this district. Jaisalmer district has extreme climate conditions; the entire district is characterized by low erratic rainfall (less than 280mm of annual rainfall). Apart from this, the region remains dry for most parts of the year. High air and soil temperature ranging above 42ºC in summers and very low temperature below 10ºC prevails in winters. Intense solar radiation and high wind velocity upto 85km/h are prevalent in the study area.

3. Materials and methods

3.1 Data used

Details of the spatial data used in the present study are given in (Table 1) LISS-III sensor on board IRS-P6 satellite data of October, 2011 has been used for generation of Normalized Differential Vegetation Index (NDVI) which indicates the vegetation density and from that unsheltered distance is estimated. In addition to LISS-III data, ASTER DEM (Digital Elevation Model) available from (http://www.gdem.aster.ersadac.or.jp) of the study region and soil maps have also been used. Aster DEM has been used for the purpose of calculation of the surface roughness parameter for the model. Weather data used in the study include air temperature, precipitation and wind speed. Air temperature has been taken from NASA's Global Model and Assimilation office (GMAO- http://gmao.gsfc.nasa.gov), Goddard Earth Observing System (GEOS) model version from GEOS-5 for the time period from January 1, 2001 to December 31, 2011. Daily precipitation values are from the Global Precipitation Climate Project (GPCP-http://precip.gsfc.nasa.gov/) currently from January 1, 2001 to December 31, 2011. Daily wind data above 10m from ground is based upon the NASA/GNAO GEOS version 5 (GEOS-5) for the time period January 1, 2001 to December 31, 2011.

Table 1: Details of data used

Data	Specifications	Year
IRS-P6 LISS-III Satellite Imagery	Spatial Resolution - 23m Band Spectral Ranges 0.52-0.59µm 0.62-0.68µm 0.77-0.86µn 1.55-1.70µm Radiometric Resolution-10Bit	October, 2011
ASTER Digital Elevation Model (DEM)	Spatial resolution 30m Accuracy (+/-)20m	
Soil Map	Major Soil Groups of Jaisalmer District, Scale 1:250000	1983
Meteorological Data	Daily Temperature 1°×1°, Average Wind speed 1°×1°, Average Rainfall 1°×1°,	2001-2011

3.2 Methodology

Wind Erosion Equation (WEQ) as given by Woodruff and Siddoway (1965) has been used in the present work. The Equation is:

$$E = f(I, C, K, L, V) \qquad (1)$$

where, E is the annual soil loss, I the soil erodibility factor, C the climate factor, K the soil ridge roughness factor, L the unsheltered distance of wind across a field, V is the equivalent vegetative cover. In this study, WEQ has been used as the basic structure of the model and the model integration and analysis was done in GIS environment.

The study area comprises of a variety of geomorphologic classes. Thematic layers pertaining to the surface roughness, soil erodibility, according to the soil properties, long distances of unsheltered area due to absence of the vegetation cover, climate index and vegetation density index have been integrated in GIS environment for the assessment of soil sensivity to erosion at pixel level. The first step of the model involves evaluation of the data using qualitative decision rules, represented by the thematic maps discussed above. The subsequent step involves quantification of the results of the previous step, by giving scores ranging from 100 to 200 at an interval of 25. These have been decided based on the discretion of the values obtained after analysis of each parameter.

3.2.1 Soil erodibility factor

Soil erodibility gives an estimate of the ability of soils to combat erosion, based on the physical characteristics of each soil (Ritter, 2012). Texture, soil structure, organic matter etc. contribute to the soil erodibility. Generally, soil with faster infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion. Sand, sandy-loam and loamy textured soils tend to be less erodible than silt, very fine sand and certain clay-textured soils. Presence of soil aggregates help in erosion protection by maintaining the soil structure. Hence, the soil map of the study area was used to generate erodibility classes according to the soil aggregate method defined by Narain et al. (2000). The erodibility classes were further assigned scores ranging from 100 to 200 (Table 2).

Table 2: Soil erodibility by wind using soil aggregate method

Soil character	Erodibility	Score
Very deep fine sand of dune complex	Very High	200
Deep, Loamy fine sand and fine sand of sandy plains, some dunes shallow loamy fine sand and sandy plains	High	175
Loamy medium sand of small dunes on flood plains, Deep brown sandy loam and loamy fine sand on flat alluvial plains	Medium	150
Deep flood plain soils, fine sand, sandy loam, loam Seirozem soils with sandy loam, clay loam and silty clay loam	Low	125
Medium to fine textured gray brown Soil	Very Low	100

3.2.2 Climatic Quality Factor (CQF)

Long term information on the wind speed, moisture profile and temperature regimes mainly explain the climatic conditions of the area. Moisture profile and temperature are accounted in this work through aridity index and have been used to compute climatic factor of the study area. Climatic factor based on aridity index and wind speed, has been computed using the following equation:

$$\mathrm{CQF} = (\text{Aridity Index} * \text{Wind Speed})^{1/2} \qquad (2)$$

3.2.2.1 Aridity index: Aridity index is the numerical expression indicating the dryness of a region. Aridity Index was computed using the Bagnouls-Gaussen aridity index classification method (Bagnouls and Gaussen, 1953). This classification is based on average monthly temperature and precipitation. It gives more precise climatic classification and the climate identification is obtained by determining separately the numbers of dry and wet months. The Bagnouls-Gaussen aridity (BGI) is calculated as:

$$\mathrm{BGI} = \sum_{I=1}^{12} (2\mathrm{ti} - \mathrm{Pi}) * \mathrm{ki} \qquad (3)$$

where t is the average monthly air temperature (ºC), k is a coefficient indicating number of months in which 2t>p and pi is the average rainfall of the month (mm), i is the number of months (values ranges from 1 to 12). The aridity index classes were further assigned scores ranging from 100 to 200 (Table 3).

Table 3: Aridity index range

Index	Climate type	Score
<50	Humid	100
50-75	Moist	125
75-100	Medium	150
100-125	Dry	175
>125	Very Dry	200

3.2.2.2 Wind speed: Wind speed affects the rate of erosion because of the change in strength of the wind. According to the magnitude of wind speed, the surface soil gets abraded, eroded and suspended. Hence, wind speed was classified according to the Beaufort scale (WMO, 1970) and each class was given a score (Table 4) so that it can be integrated with the aridity index to calculate the climate quality index.

Aridity index and wind speed were used to generate the Climate Quality Factor and then the scores was given after grouping the climate quality factor in five prominent classes (Table 5).

3.2.3 Surface roughness factor

Surface roughness is a key term used to both identify the individual landforms and determine the processes acting upon them (Hobson, 1972). Surface roughness is measured or rather described in terms of geomorphometry as surface elevation values. We have used surface roughness as an expression of the variability of elevation of the topographic surface of the study area. Surface roughness is determined in the terms of variability of elevation values, generally expressed as the absolute standard deviation of all values with in a window (Frankel and Dolan, 2007). Surface roughness was computed by the following formula (Frankel and Dolan, 2007)

$$Surface\ roughness\ factor = \sqrt{\frac{1}{n}\sum_{n=1}^{n} hn^2} \qquad (4)$$

where N= number of pixels in the moving window of (3×3 pixels), h_n=difference of elevation between the n^{th} pixel in the concerning patch and mean value. Surface roughness values are assigned (Table 6)

Table 4: Classification of wind speed

Beaufort scale number and description	Wind speed equivalent at a standard height of 10 meters above open flat ground (m/s)	Score
Calm, Light Air	0-1.5	100
Light breeze, Gentle breeze	1.6-5.4	125
Moderate breeze, Fresh breeze	3.4-10.7	150
Strong breeze, Near gale, Gale	10.8-20.7	175
Strong Gale, Storm, Violent Storm	20.8->32.7	200

Table 5: Climate quality index with respect to wind erosion

Erodibility class	Score
Very High	175-200
High	150-175
Medium	125-150
Low	100-125

Table 6: Scores of surface roughness with respect to wind erosion

Surface roughness Index	Erodibilty class	Score
1-14	Very High	200
14-27	High	175
27-40	Medium	150
40-53	Low	125
53-66	Very Low	100

3.2.4 Vegetation density

Normalized Differential Vegetation Index (NDVI) has been used for generating vegetation density map. LISS-III image of October, 2011 has been used for creating NDVI map of the study area. Wind erosion shows a significant reduction in effect when vegetation cover exceeds beyond 20-30% (Armbrust and Bilbro, 1997; Munson et al., 2011). NDVI is computed using the formula.

$$\text{NDVI}= \frac{\rho(NIR)-\rho(RED)}{\rho(NIR)+\rho(RED)} \qquad (5)$$

ρ_{RED} and ρ_{NIR} are the per pixel reflectance in red (0.62-0.68μm) and near infra-red (0.77-0.86μm) regions of LISS III instrument. NDVI is unit less quantity and for a given pixel always results in a number that ranges from minus (-1) to plus (+1), where +1 indicates highest canopy cover. Scores for vegetation density with regards to wind erosion are provided in Table 7.

Table 7: Scores of vegetation density class with respect to wind erosion

Vegetation density	NDVI	Erodibility class	Score
No vegetation to Very Low	-1 to -0.60	Very High	200
Low	-0.60 to -0.20	High	175
Medium	-0.20 to 0.20	Medium	150
High	0.20 to 0.60	Low	125
Very High	0.60 to 1.00	Very Low	100

3.2.5 Unsheltered distance

Unsheltered Distance is the portion of land facing direct threat to erosion due to absence/ shortage of shelter. It is measured across an erodible land surface, along the direction of wind in the study area. The distance is usually measured from the places which have more vegetation concentration to low to bare concentration areas. Soil erosion takes place due to three major processes, detachment, transport, and deposition of soil. There are many principal sources of energy physically acting on soil, which leads to the degradation of soil in the study among which wind act as a strong agent on the surface so as to curve the deformations in the topography of the study area. Erosion begins with detachment, which is caused by break down of aggregates by impact of wind, sheering or dragging force of wind. Detached particles are transported by flowing wind, and deposited when the velocity of wind decreases by the effect of barriers on its way. However, if wind encounters a physical barrier or shelter, it loses its energy and hence its potential to erode soil reduces. Trees/ plants act as natural shelter towards wind erosion. This was done by moving a window of 3×3 pixels over the vegetation density map generated from the satellite imagery and the distance was measured from the maximum density of vegetation to the minimum vegetation density. The unsheltered distance was then graded and given scores (Table 8).

After all the input parameters were graded, they were integrated in GIS environment to obtain the condition of wind erosion in the study area. The integration was done by finding the geometric mean of the five factors that are taken into consideration. Geometric mean was considered so as to give equal bias to all input components (Basso et al., 2002). Consequently, the model is not influenced by the number of the basic indicators, each of them represents together one layer which means that none of the main quality indices (soil erodibility factor, climate quality factor, surface roughness factor, vegetation density, unsheltered distance) is either penalized or favored by the fact of having a different number of layers compared to the other indices.

$$WES = (I * C * K * L * V)^{1/5} \qquad (6)$$

Wind erosion severity (WES) Index was then graded into five classes in accordance with its maximum and minimum range and finally assigned using the scores as given in Table 9.

Table 8: Range of unsheltered distance in the region

Unsheltered distance (in m)	Erodibility class	Score
>2000	Very High	200
1000-2000	High	175
500-1000	Medium	150
200-500	Low	125
0-200	Very Low	100

Table 9: Scores for wind erosion severity

Score	Wind erosion severity
200-175	Very High
175-150	High
150-125	Medium
125-100	Low

Executing the rendered process, the output map thus generated provides qualitative information on the degree of severity of wind erosion in the study area.

4. Results and discussions

A total of five thematic layers are obtained through the above mentioned processes and are shown in Figure 2 (a-e).

Long term weather data analysis (about 10 years 2002-2012) of the study area was done to find the average values of temperature, rainfall and wind speed. The study area has an average rainfall of less than 280mm and average temperature of 30°C. Both of these quantities independently indicate that the area is hot and dry thereby making wind as the prime cause of erosion. The output Climate Quality Factor CQI has been computed using equation (2) and the CQI map of the study area is given in (Figure 2a).

As may be seen from Figure 2a, whole of the study area falls into homogeneous climate factor (CQI value of 175) which almost has no variability but using this layer helps us to find out that the region is under extreme arid conditions and is thus influenced by the wind greatly. As per agro-climatic zonation of India, prepared by National Bureau of Soil survey and Land Use Planning (NBSS&LUP, 2001) the study area falls in the arid class.

The soil of the study area compromises of fine sandy soil followed by deep sandy loam etc. The area has large dune field as well as deep sandy plains. Thus, even if wind strength is low, the geomorphology of the area tends to accelerate the aeolian processes and thus leads to erosion of top soil. On grading the study area according to the soil types using Table 2 soil erodibility map is generated for Jaisalmer district as shown in (Figure 2b).The map shows that a large portion of the study area falls under low levels of stable aggregates (<10%). Soil aggregates provide structural length to the soil. Hence, as per the condition of soil aggregates in the study area, the soil erodibility factor reaches a high value for majority part.

As may be seen from the Figure 2b, large part of the study area along North-West, (comprising mainly of vast sand dunes), falls under high erodibility class. Some of these sand dunes are stabilized and have sparse succulent annuals following brief spells of rainfall. Largely the regions with fine to medium fine textured soil, having less to moderate soil aggregates, match closely with high to low erodibility classes respectively. A significant portion of the study area belongs to moderate erodibility class corresponding to very deep sandy to loamy soils having gypsum as parent material whiles soils made from sand stone exhibit low erodibility, as is apparent from the map. The map also displays regions of very shallow soils/ barren hills which were masked out from the final computations.

The study area is moderately undulating. The undulations are mainly due to the presence of vast sand dunes of different types and sizes. Figure 2c is the surface roughness map of the study area prepared using equation 4 and Table 6. From the figure it is apparent that low surface roughness occurs for North-West part of the study area which is obvious because this area comprises of vast sand fields having low variability observed in the 3×3 pixel window over DEM. The barren hills present in the study area offer high resistance to wind erosion by acting as physical barriers. Such regions have high surface roughness in the map. Apart from small portions along the barrier hills, the study area experiences low surface roughness and consequently wind easily sweeps over this area and supplements wind erosion.

Vegetation density map of the study area generated using NDVI is given in (Figure 2d). It shows that significant portion of the study area, comprising of dune complex along South-East and sand dunes along North -West, fall under low vegetation density class. These areas are therefore more susceptible to wind erosion. It may be observed from the figure that along the Indira Gandhi Canal as well as along its feeder canals, the vegetation density is high. The canals serve dual purpose of preventing wind erosion as well as support agriculture. It's evident from (Figure 2d) that soils formed in sandstone support vegetation better in moisture stressed conditions (Kosmos et al., 1999) as compared to soils formed on hard lime concretions. Hence, vegetation density map as per wind erosion susceptibility is along the middle region of the study area while high in areas having dune.

Unsheltered distance map, given in Figure 2e indicates that the whole region lies within moderate to high wind erosion susceptibility. Regions along dune area offer low shelter in comparison the region around canal.

The above five thematic layers as given Figure 2(a-e) obtained through the above mentioned processes have been integrated in GIS environment to produce the final wind erosion map (Figure 2f).

The wind erosion map thus produced depicts the wind erosion severity level of the region. This corresponds to the value of WES in equation 6 ranging between 100 and 200.

This type of map provides understanding about the local variation in the wind erosion severity owing to geomorphology of the region. For example, the geomorphology of the SW region shows immense cluster of transverse and linear sand dunes which shows high severity of wind erosion in Figure 2f. The central portion shows rock out crop in the satellite data which corresponds to comparatively low wind erosion than SW region in Figure 2f, however the WES value is high in both cases. The SE region shows scattered agriculture along with dispersed barchans which in wind erosion map shows low severity despite having moderate WES value for SW and central regions. So, in totality, the study area bears moderate, low to high severity of wind erosion while the map shows the local variation within this range.

Limited validation of the wind erosion map generated from the above method was done through two ways first, by conducting field survey at a few selected points in the study area and second, by using the available Desertification Status Map (DSM) of the study area (Figure 3).

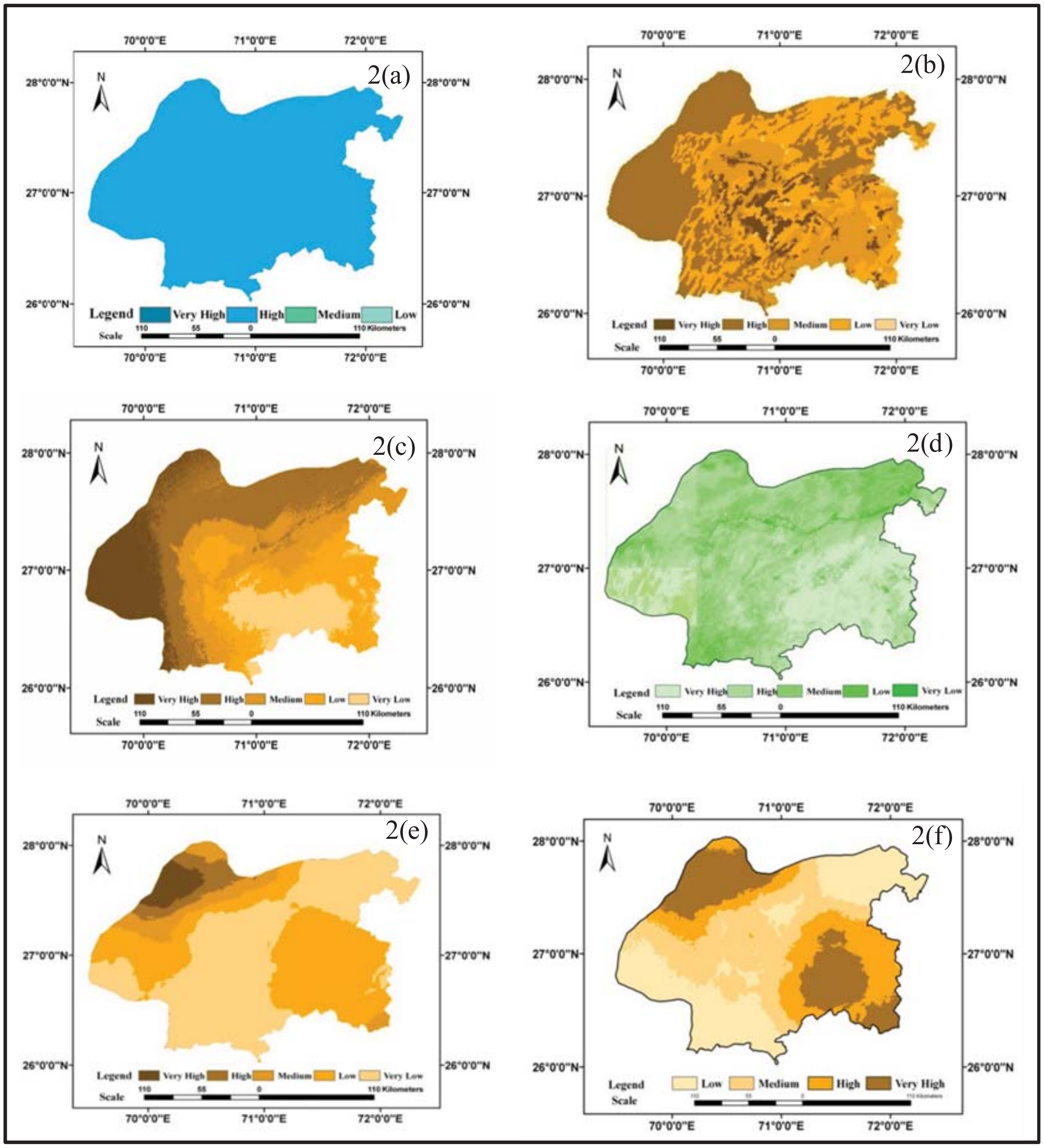

Figure 2: Thematic maps of (a) Climatic quality factor, (b) Soil erodibility, (c) Surface roughness, (d) Vegetation density, (e) Unsheltered distance and (f) wind erosion

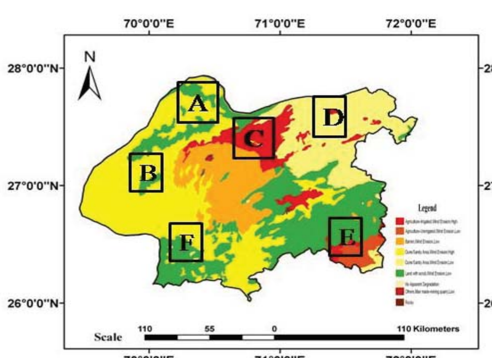

Figure 3: Validation points (A, B, C, D, E, F) placed over the Desertification Status Map (DSM) of Jaisalmer using the classification system of TPN-1 (UNCCD) at regional level of 2003-2004

Field visit to the study area was carried out during April 2013. The condition of the land degradation process active in the field was recorded based on visual inspection. The field validation points are shown in (Figure 3). These points were further geotagged in the DSM map to validate with the results of the model. For validation using the DSM, the available DSM map developed under Desertification Status Mapping project was used. The DSM map depicts land degradation processes along with levels of severity. The classification system for this is in tune with the classification system adopted by TPN-1 (UNCCD) at regional level (Ajai et al., 2007). The DSM map of the study area is shown in figure 3. The classification system adopted here is a three level hierarchical classification system, which shows that the major agent of erosion over the study area is wind. Wind erosional, depositional, features are common throughout the surface in the study area on which validation were carried out (shown in figure 3) and corresponding to these points, wind erosion severity from the map (figure 2f) were noted and tabulated below (Table 10). It is clear that most of the points show same level of wind erosion severity as it is shown by DSM map.

Table 10: Comparison of validation points

Validation Points	DSM Map Category	Wind erosion severity	Observation on ground
A	Dune sand area with wind erosion high	Very High	Bare sand dunes subjected to wind erosion
B	Land with scrub, wind erosion low	Medium	Sand dunes being stabilised by scrubs over it so wind action is limited.
C	Agriculture Irrigated, wind Erosion High	Low	Extensive agricultural land due to introduction of canal
D	Sandy area with low wind erosion	Low	Agricultural land due to introduction of canal has controlled the wind erosion
E	Agriculture unirrigated wind erosion Low	Medium	Scattered plots of agriculture being effected by wind erosion
F	Land with scrub wind erosion low	Low	The scrub has arrested the wind erosion.

5. Conclusion

In terms of erosion, there are two main concepts i.e. loss of the thick top soil cover due to natural or anthropogenic reasons. A scheme, based on the integration of five factors, has been developed to compute the wind erosion. The factors include climate, vegetation density, unsheltered distance, surface roughness and soil. These five factors have been computed for the study area and integrated in GIS environment to create wind erosion map. The wind erosion map so generated provides identification of those arable surfaces which require priority intervention for the protection of the soil. The highest wind erosion affected identified in the Western side of the district due to the very deep fine sandy soils in these areas with negligible vegetation cover. The wind blowing in this region rolls on easily over the surface and creates deflational hollows over the entire region resulting in formation of valley and troughs. Most of the dunes in this area are stabilized with time and vegetation cover has begun to show. Such wind erosion maps help policy makers for regional management and planning.

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